US Army Corps of Engineers ®
San Francisco District

Redwood City Harbor, California, Navigation Improvement Feasibility Study

Appendix E

Water Resources Engineering

May 2015

Contents

1. Purpose of Report

This report summarizes the water resource engineering analyses required to support the planning and Federal interest determination of a civil works navigation project in the Redwood City Harbor Channel and San Bruno Shoal Channel. This project is referred to as the "Redwood City Harbor, California, Navigation Improvement Feasibility Study", or more generically as the "study" or "study area" in this report. This report will serve as an appendix to the study's integrated feasibility study and environmental impact statement report.

2. Background

2.1 Study Area

The study area is Redwood City Harbor, which is located in San Mateo County, California, on the southwest side of San Francisco Bay, approximately 18 miles south of San Francisco, California. The study area includes two existing navigation channels: the Redwood City Harbor Channel and San Bruno Shoal Channel (Figure 1). The Redwood City Harbor Channel extends from the mouth of Redwood Creek to deep water in the San Francisco Bay, while the San Bruno Shoal Channel is located in San Francisco Bay. Both channels currently have an authorized depth of 30 feet mean lower low water (MLLW) and 2 feet of allowable over depth.

Figure 1. Study area

2.2 Sediment Supply for San Francisco Bay

The Redwood City Harbor Channel currently requires operations and maintenance (O&M) dredging to remove sediment deposition and ensure safe navigation by vessels in and out of the channel. Within the last decade, O&M dredging of the channel has not occurred on annual basis, but has occurred when funding was available.

An analysis conducted for the Regional Sediment Management Program of the San Francisco District provides background about the sediment supply for San Francisco Bay (Zoulas, 2013). The primary source of sediment to the San Francisco Bay is delivery from streams draining a network of 483 contributing watersheds covering approximately 165,142 square kilometers. These contributing watersheds are often divided into two categories: the Central Valley, and small local tributaries. The Central Valley includes the Sacramento and San Joaquin Rivers, which drain a large portion of northern and central California (approximately 154,000 square kilometers) and converge east of the San Francisco Bay to form a large delta. The small local tributaries comprise a much smaller area (approximately 8,145 square kilometers), but still contribute a significant amount of sediment to the San Francisco Bay. The tributaries that contribute sediment to South San Francisco Bay, adjacent to the study area, include, but are not limited to: Alameda Creek, Coyote Creek, and San Francisquito Creek.

3. Water Resource Engineering Analyses for the Study

To help determine a Federal interest of a civil works navigation project in the study area, it is necessary to evaluate impacts to coastal hydrodynamics and sediment transport as a result of potential navigation channel deepening and/or realignment. The Water Resources Section (of the San Francisco District) evaluated these impacts by reviewing previous hydrographic survey data information of the study area and by conducting simulations via a numerical model of the study area.

The project delivery team (PDT) determined that a National Economic Development (NED) plan would potentially involve navigation channel deepening ranging from 32 feet to 37 feet mean lower low water (MLLW), plus 2 feet of over depth. As a result, all water resource engineering analyses for this study did not evaluate dredging depths shallower than the current authorized project depth nor deeper than this range.

3.1. Hydrographic Surveys

A review of hydrographic surveys was conducted of the study area from years 2004 to 2014. The purpose of the review was to identify areas where shoaling or erosion may have been prevalent within the within the study area since 2004. Areas of repeated shoaling or erosion would inform the PDT of potential needs for advanced dredging activities or realignment of navigation channels for without and/or with-project conditions.

The hydrographic surveys consisted of condition, before dredging, and after dredging surveys. Some surveys included the entire navigation channels while a select few were only partial surveys. The partial surveys were not used in the analysis that is described later in this report.

3.2. Numerical Hydrodynamics and Salinity Modeling

3.2.1. Background on the Model

The UnTRIM Bay-Delta Model (UnTRIM) was applied together with the Simulating WAves Nearshore (SWAN) wave model and the SediMorph sediment transport model to simulate three-dimensional hydrodynamics, wind waves, and sediment transport in the study area for without and with-project conditions. UnTRIM as a standalone hydrodynamic model and the coupled UnTRIM-SWAN-SediMorph model have been utilized for various other studies within the San Francisco District. These studies include, but are not limited to: Sacramento River Deep Water Ship Channel Project, San Francisco Bay to Stockton Navigation Project, the South San Francisco Bay Shoreline Study, the Central Bay and Oakland Harbor Sediment Transport Modeling Study, and sediment transport modeling for support of the Dredged Material Management Plan (DMMP). The setup and results of UnTRIM as a standalone hydrodynamic model and the coupled UnTRIM-SWAN-SediMorph model for these studies have been reviewed by various resource agencies in the San Francisco Bay Area, and have been published in numerous papers and peer-reviewed publications (e.g. Bever and MacWilliams, 2013; Bever et al., 2014; MacWilliams et al., 2014; MacWilliams et al., 2015). These resource agencies include, but are not limited to: U.S. Environmental Protection Agency, San Francisco Bay Conservation and Development Commission, Contra Costa Water District, and the California Department of Water Resources (DWR).

3.2.2. Model Setup

The coupled model domain extends from the Pacific Ocean near San Francisco to the San Francisco Bay and Sacramento-San Joaquin Delta (Figure 2). The coupled model utilizes an unstructured grid system with very fine grid cells at the two navigation channels contained within the study area (Figure 3). The coupled model boundary conditions include inflows, drinking water export facilities, wind stations, evaporation and precipitation, and flow control structures. The UnTRIM Bay-Delta model has been calibrated and validated using water level, flow, and salinity data collected in San Francisco Bay and the Sacramento-San Joaquin Delta at National Oceanic Atmospheric Administration, United States Geological Survey (USGS), and DWR monitoring stations. The SediMorph model has been calibrated and validated using sediment concentration data collected in San Francisco Bay and the Sacramento-San Joaquin Delta at USGS monitoring stations and hydrographic survey data of Redwood City Harbor Channel and San Bruno Shoal Channel.

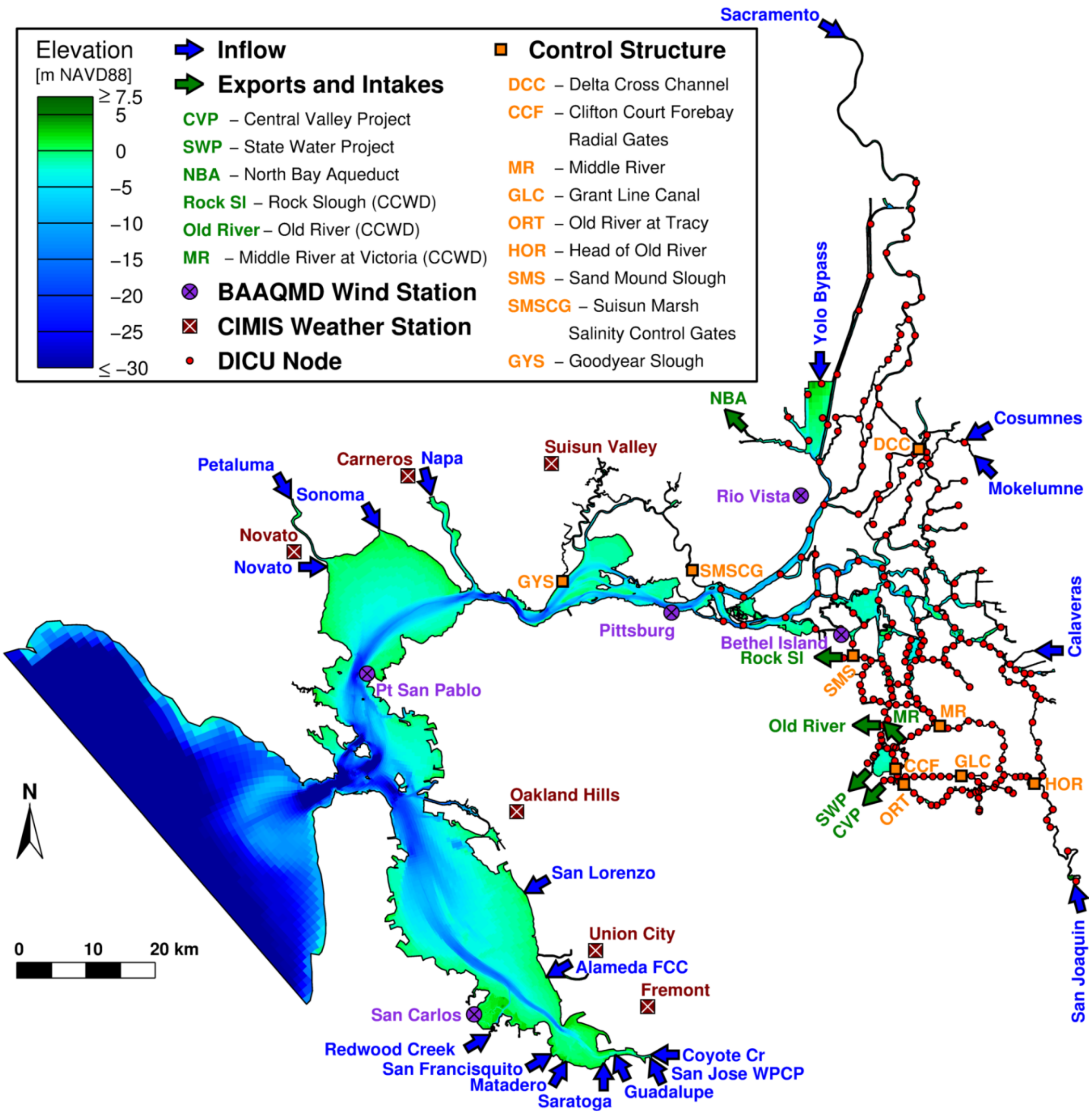

Figure 2. Coupled model domain

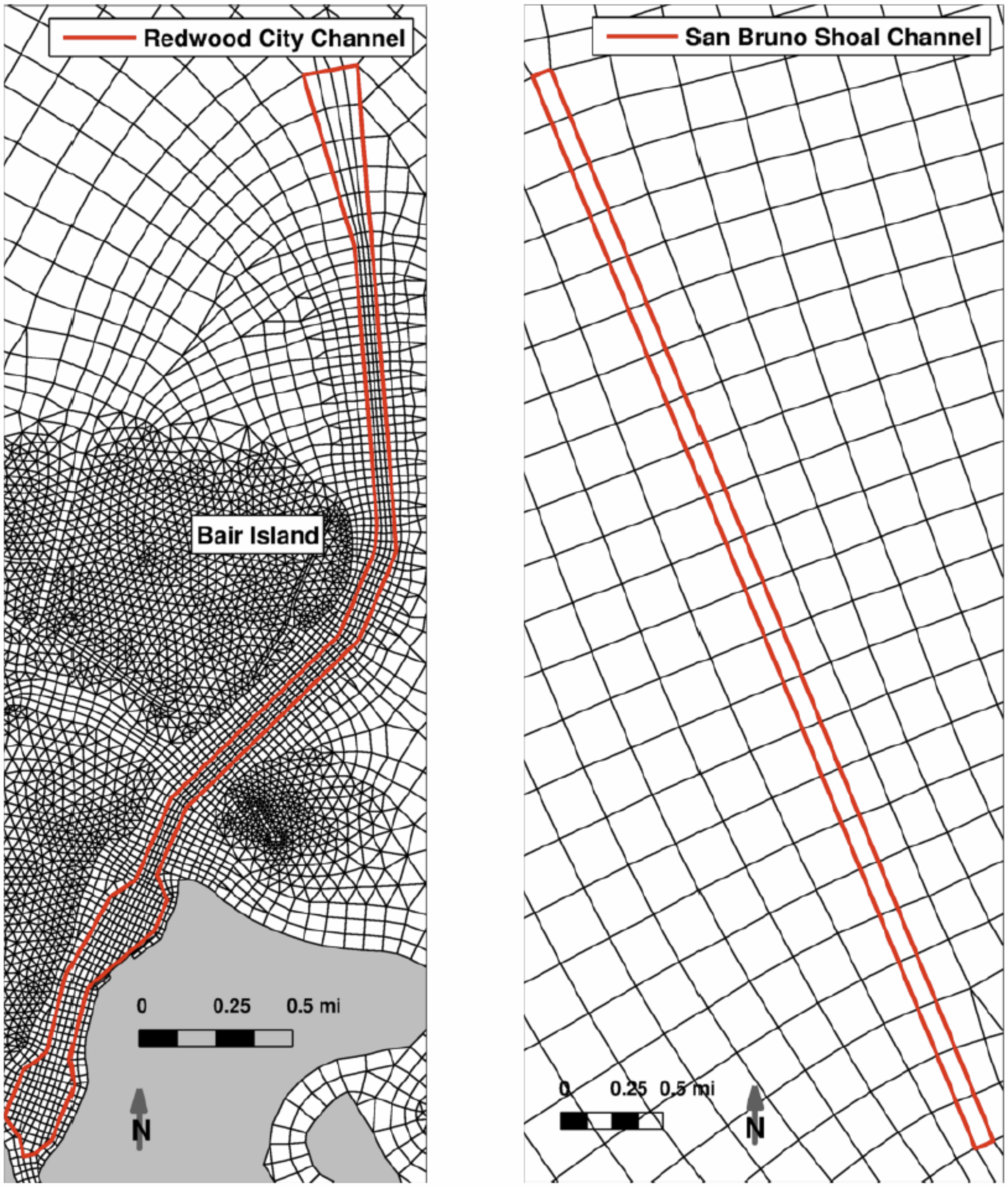

Figure 3. Coupled model grid system for Redwood City Harbor Channel and San Bruno Shoal Channel

3.2.3. Model Assumptions

It is assumed that any potential navigation channel deepening and/or realignment for either Redwood City Harbor Channel or San Bruno Shoal Channel would result in channels with 3:1 (horizontal:vertical) side slopes. This side slope configuration was based on input from the Geosciences Section of the San Francisco District and was incorporated into the model grid system.

For the potential realignment of the Redwood City Harbor Channel, it is assumed that the section of the old (existing) alignment would not be filled in the match the grade of the surrounding mudflat elevation, but would be rather left as the relatively deep existing channel conditions.

The coupled model grid includes Bair Island and the restoration measures that are expected to be implemented prior to 2018 by USFWS, such as levee breaches, channel blocks, flow constrictors, and flooded areas.

3.2.4. Completed Sediment Transport Model Run Scenarios

The coupled model was run to evaluate effects of deepening the two navigation channels within the study area on shoaling rates. All of the coupled model runs that were conducted with respect to sediment transport are summarized in Table 1. The depths considered were 30 feet (the current authorized depth), 32 feet, and 37 feet MLLW plus two feet of allowable overdepth. In addition to deepening, the coupled model was also used to evaluate the effects of realigning the Redwood City Harbor Channel adjacent to Outer Bair Island on shoaling rates. Realignment was proposed as a measure by the PDT per results that were obtained in the review of previous hydrographic surveys, which indicated that certain areas of the channel were prone to shoaling (results that are discussed in further detail in section 4.1 of this report). The configuration of the channel realignment was reviewed by the San Francisco Bar Pilots Association. A comparison of the existing channel alignment vs. the channel realignment is shown in Figure 4. This realignment measure was combined with channel deepening of 37 feet MLLW plus two feet of allowable overdepth. Water Year 2006, a wet water year, was chosen as the simulation period for all of the coupled model run scenarios. For the analysis, Water Year 2006 was divided into two seasonal periods: fall-winter and spring-summer. The fall through winter period contains the first flush from the Sacramento-San Joaquin Delta and relatively high tributary sediment input to San Francisco Bay. The spring through summer period has elevated daily winds that drive wind waves and local sediment resuspension, but relatively low tributary sediment supply to San Francisco Bay.

Table 1. Completed sediment transport model run scenarios

Scenario	Depth (feet, MLLW)	Seasonal Period of Water Year 2006	Channel Alignment	Note
1	30 (+2 over depth)	Fall-Winter	Existing	Currently Authorized Depth
2	32 (+2 over depth)	Fall-Winter	Existing	Deepening
3	37 (+2 over depth)	Fall-Winter	Existing	Deepening
4	30 (+2 over depth)	Spring-Summer	Existing	Currently Authorized Depth
5	32 (+2 over depth)	Spring-Summer	Existing	Deepening
6	37 (+2 over depth)	Spring-Summer	Existing	Deepening
7	37 (+2 over depth)	Fall-Winter	Realignment	Deepening
8	37 (+2 over depth)	Spring-Summer	Realignment	Deepening

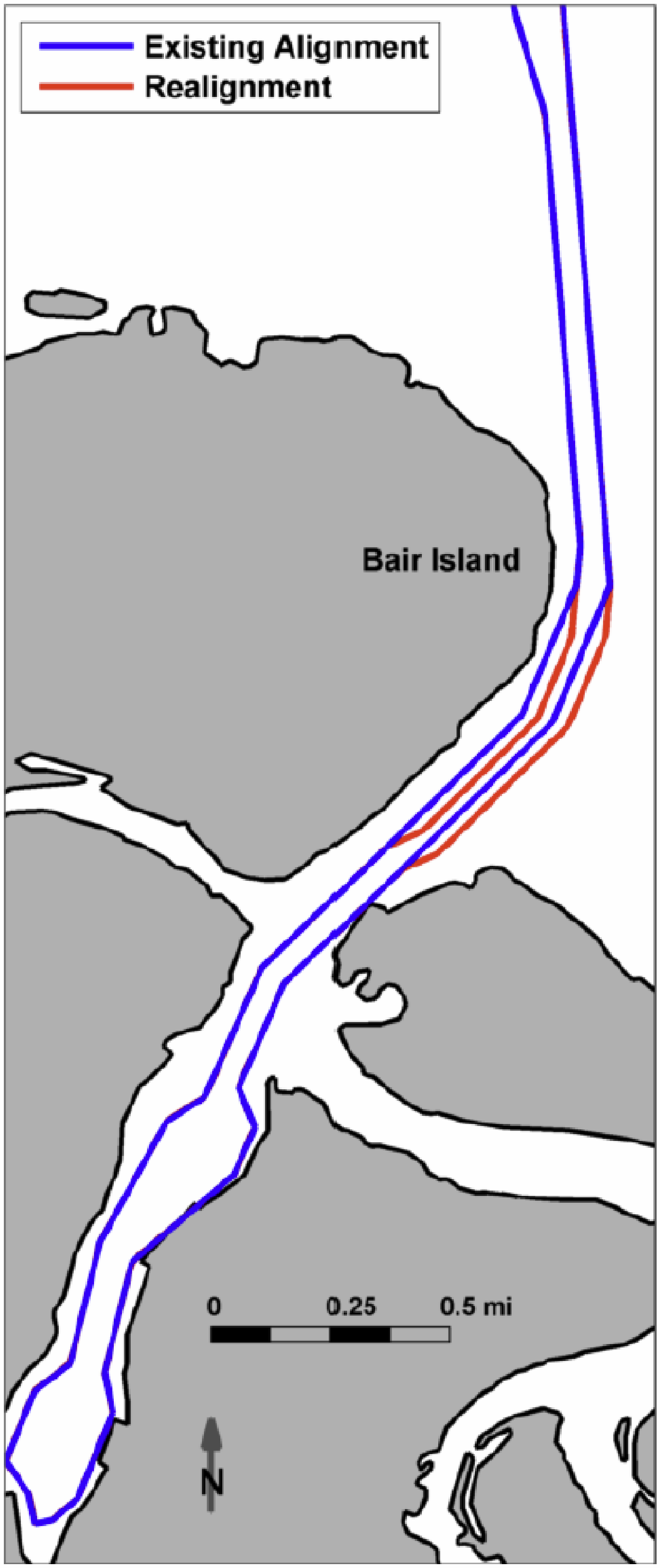

Figure 4. Channel alignments considered in the coupled model runs

3.2.5. Completed Hydrodynamics Model Run Scenarios

The coupled model was run to evaluate effects of deepening the two navigation channels within the study area on hydrodynamics for Year 0 and Year 50 conditions. Year 0 was assumed to be 2018 and Year 50 was assumed to be 2068. Because weather, hydrology, and operating conditions cannot be predicted years in advance, water conditions for 2018 and 2068 were developed using 2005 hydrology but modified to account for both sea level rise and to include changes to the Bair Island Restoration Project that are expected to occur prior to 2018. Sea level rise was included in the model scenarios by adjusting the water level from the model forcing year of 2005 for the projected sea level rise from 2005 to the project start year (Year 0, 2018) and from 2005 to 50 years after the project start year (Year 50, 2068). A projected sea level rise of 0.09 foot from the model forcing year (2005) to Year 0 (2018) was applied based on the NRC Curve 1. The NRC Curve 1 was used to adjust for sea level rise from 2005 to 2018 instead of the more conservative NCR Curve 3 because the sea level rise in the San Francisco Bay over the last 30 years has been below the historic trend. A projected sea level rise of 2.51 feet from the model forcing year (2005) to Year 50 (2068) was applied based on NRC Curve 3. All of the coupled model runs that were conducted with respect to hydrodynamics are summarized in Table 2.

Table 2. Completed hydrodynamic model run scenarios

Scenario	Depth (feet, MLLW)	Project Year	Note
1	30 (+2 over depth)	Year 0	Currently Authorized Depth
2	32 (+2 over depth)	Year 0	Deepening
3	30 (+2 over depth)	Year 50	Currently Authorized Depth
4	32 (+2 over depth)	Year 50	Deepening

4. Results from Analyses of Hydrographic Surveys for Without-Project (30 feet MLLW) Conditions

The review of the hydrographic surveys indicated that Redwood City Harbor Channel has an average shoaling rate of approximately 183,000 cubic yards per year. The hydrographic surveys indicated there are two areas within this channel that are prone to shoaling: one is located near the entrance of the channel and another is adjacent to the southeast side of Outer Bair Island (Figure 5).

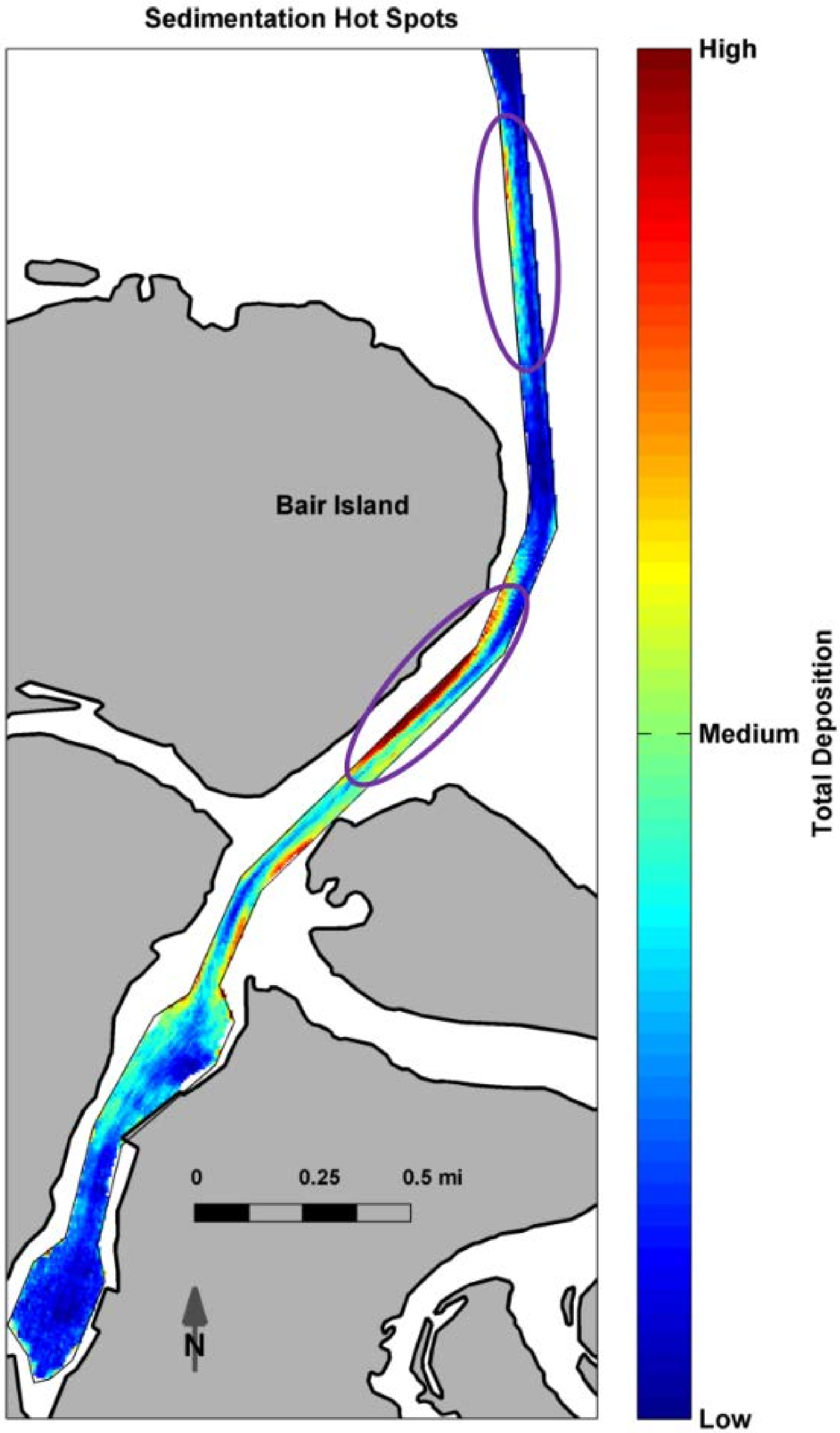

Figure 5. Sedimentation hot spots in Redwood City Harbor Channel

Because of the two identified hot spots, channel realignment was considered by the PDT to address this shoaling issue and was modeled in the coupled UnTRIM-SWAN-SediMorph model (as mentioned in section 3.2.4 of this report). The PDT had hypothesized that moving the channel away from Bair Island would potentially reduce shoaling. The review of the hydrographic surveys also indicated that San Bruno Shoal Channel does not have a consistent rate of shoaling, but rather both periods of shoaling and erosion that lead to relatively little long term net change of sediment volume in the channel. Full results from the analysis of the hydrographic surveys can be found in a report that is included as an attachment to this appendix (Anchor QEA, 2015).

5. Results from Analyses of Sediment Transport Model Runs for With-Project (32 feet and 37 feet MLLW) Conditions

The coupled model runs predicted that deepening the two navigation channels within the study area would increase shoaling rates (Table 3). Predicted channel sediment thicknesses for various channel depths are depicted in Figure 6 and Figure 7. Results from the coupled model runs also predicted that realigning the Redwood City Harbor Channel in the manner that is depicted in Figure 4 would have a small effect on shoaling rates, as illustrated in Figure 8. Full results from the coupled model runs evaluating effects on sediment transport rates can be found in a report that is included as an attachment to this appendix (Anchor QEA, 2015).

Table 3. Predicted Increase in sedimentation rates due to channel deepening

Navigation Channel	Proposed Deepening Depth (feet, MLLW)	Increase in Sedimentation Rate Relative to the Currently Authorized Depth of 30 feet MLLW Plus 2 feet of Overdepth
Redwood City Harbor Channel	32 (+2 over depth)	13%
Redwood City Harbor Channel	37 (+2 over depth)	51%
San Bruno Shoal Channel	32 (+2 over depth)	54%
San Bruno Shoal Channel	37 (+2 over depth)	86%

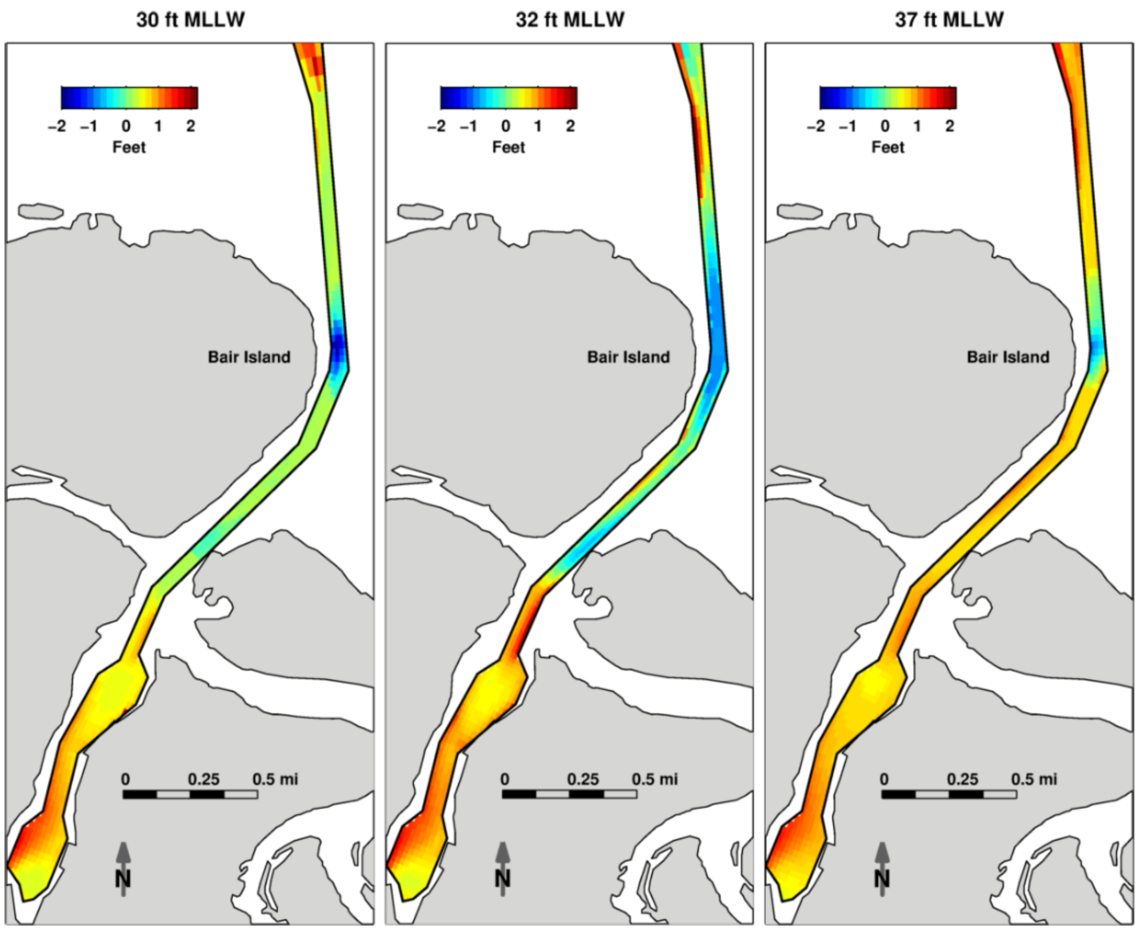

Figure 6. Predicted sediment deposition thickness in Redwood City Harbor Channel for various channel depths

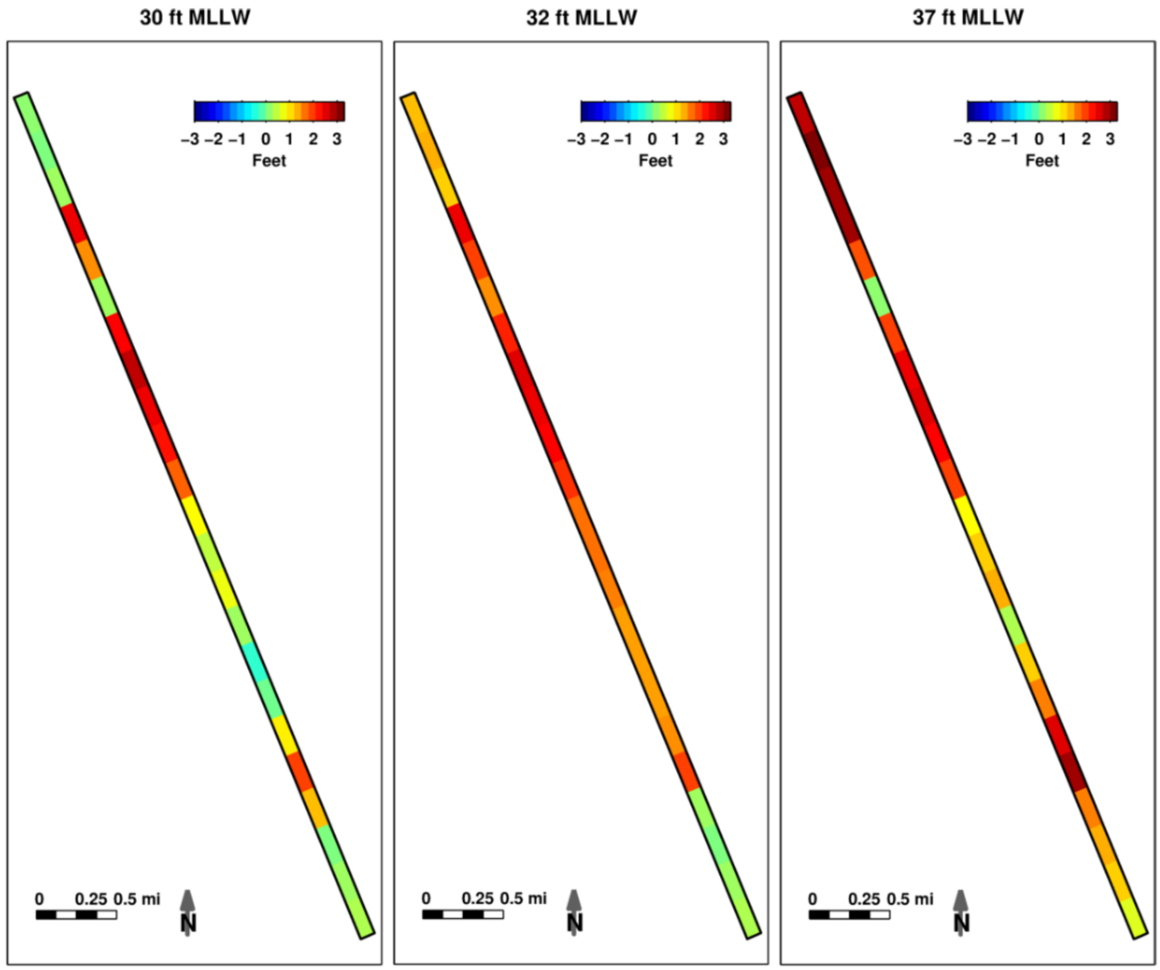

Figure 7. Predicted sediment deposition thickness in San Bruno Shoal Channel for various channel depths

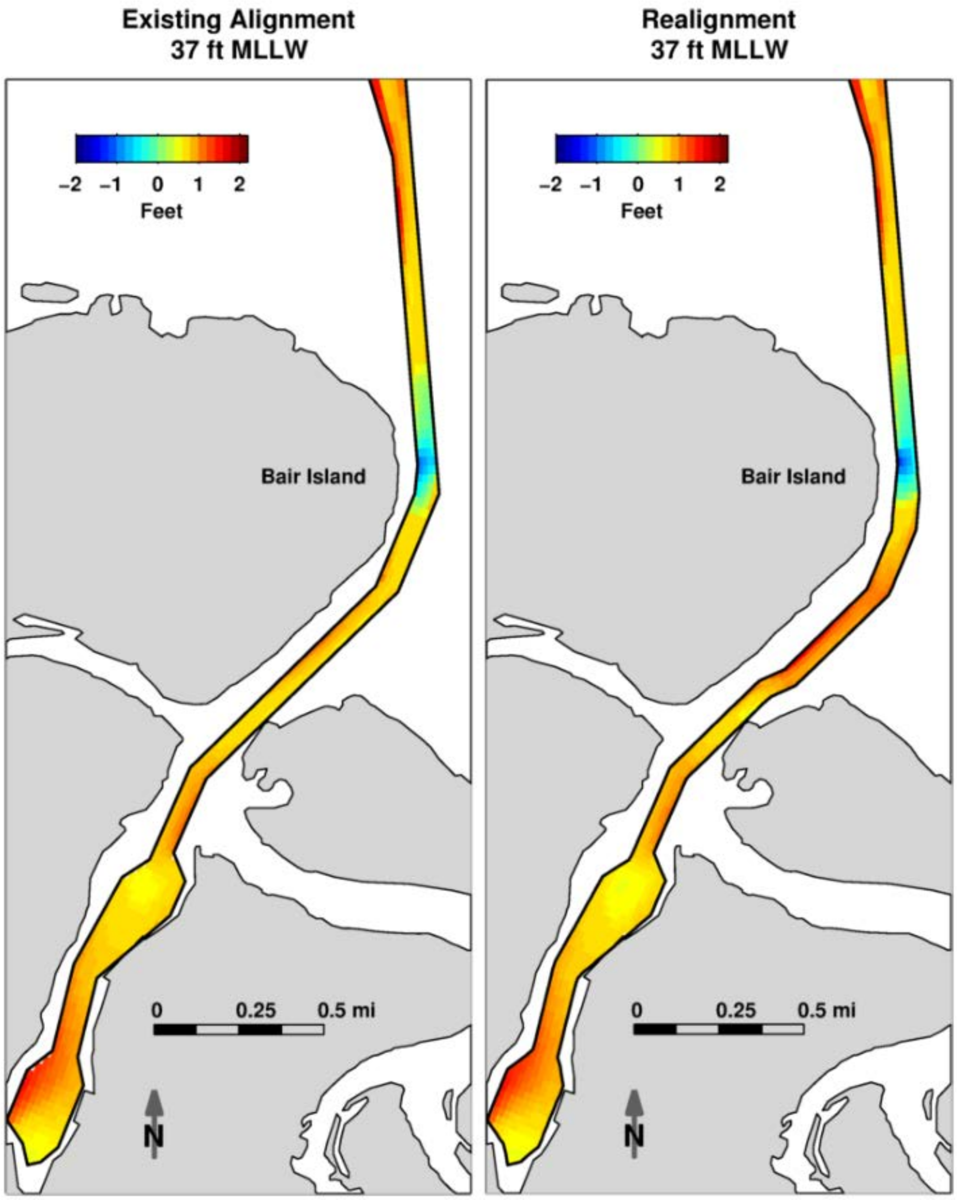

Figure 8. Predicted Sediment Deposition Thickness in Redwood City Channel for the Existing Alignments vs. Proposed Realignment

6. Results from Analyses Hydrodynamic Model Runs for With-Project (32 feet and 37 feet MLLW) Conditions

The coupled model runs predicted that deepening the two navigation channels within the study area would essentially have no effect on hydrodynamics within Redwood City Harbor Channel and Bair Island for both Year 0 and Year 50 conditions. The locations within the model domain that were evaluated for water levels are shown in Figure 9. The locations within the model domain that were evaluated for flow rates are shown in Figure 10. Predicted water elevations at the Redwood City Harbor Channel station for Year 0 and Year 50 conditions are shown in Figure 11 and Figure 12. Note that the bottom panel of the three panels illustrates the predicted change in water levels between the existing 30 ft and deepened 32 ft MLLW depths. Predicted flow rates at the Redwood City Harbor Channel north station for Year 0 and Year 50 conditions are shown in Figure 13 and Figure 14. Note that the bottom panel of the three panels illustrates the predicted change in flow rates between the existing 30 ft and deepened 32 ft MLLW depths. Full results from the coupled model runs evaluating effects on hydrodynamics can be found in a report that is included as an attachment to this appendix (Anchor QEA, 2015)

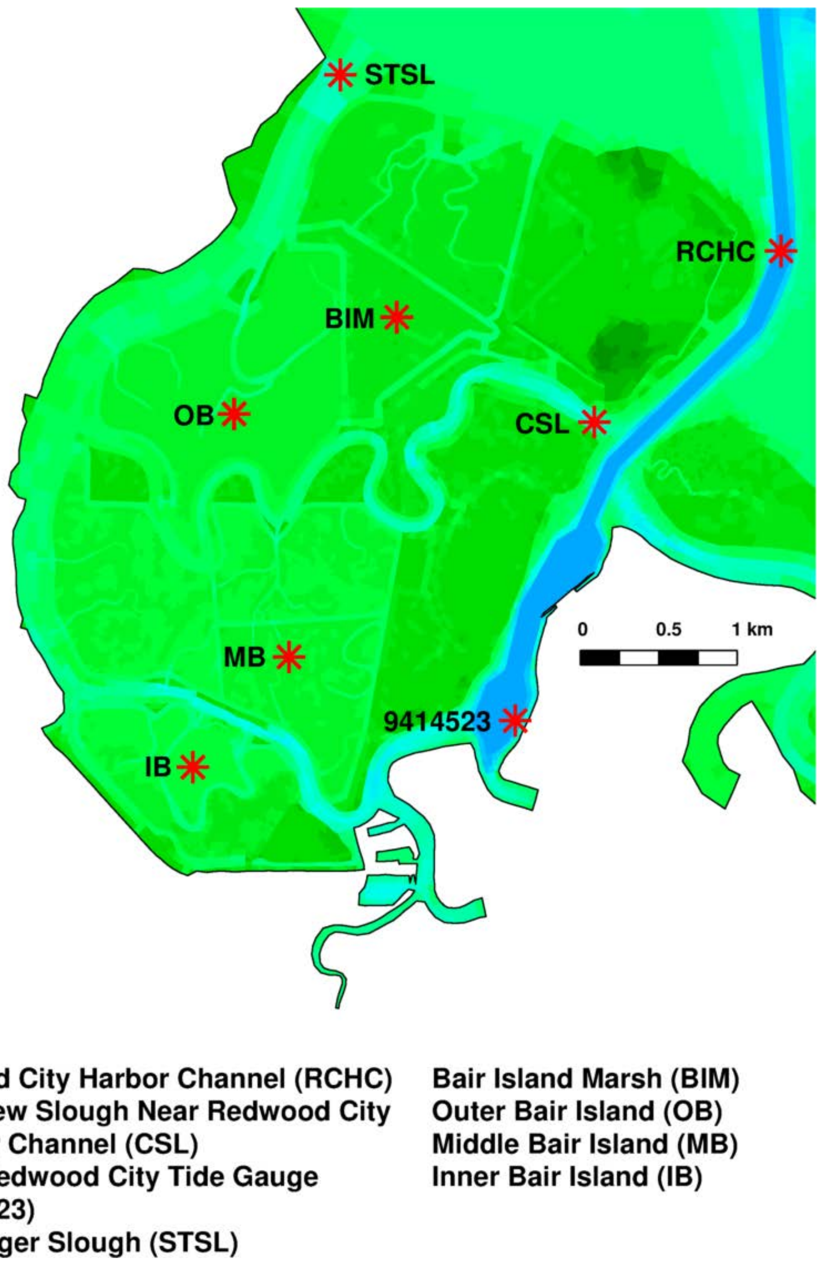

Figure 9. Locations within the coupled model domain where water levels were evaluated

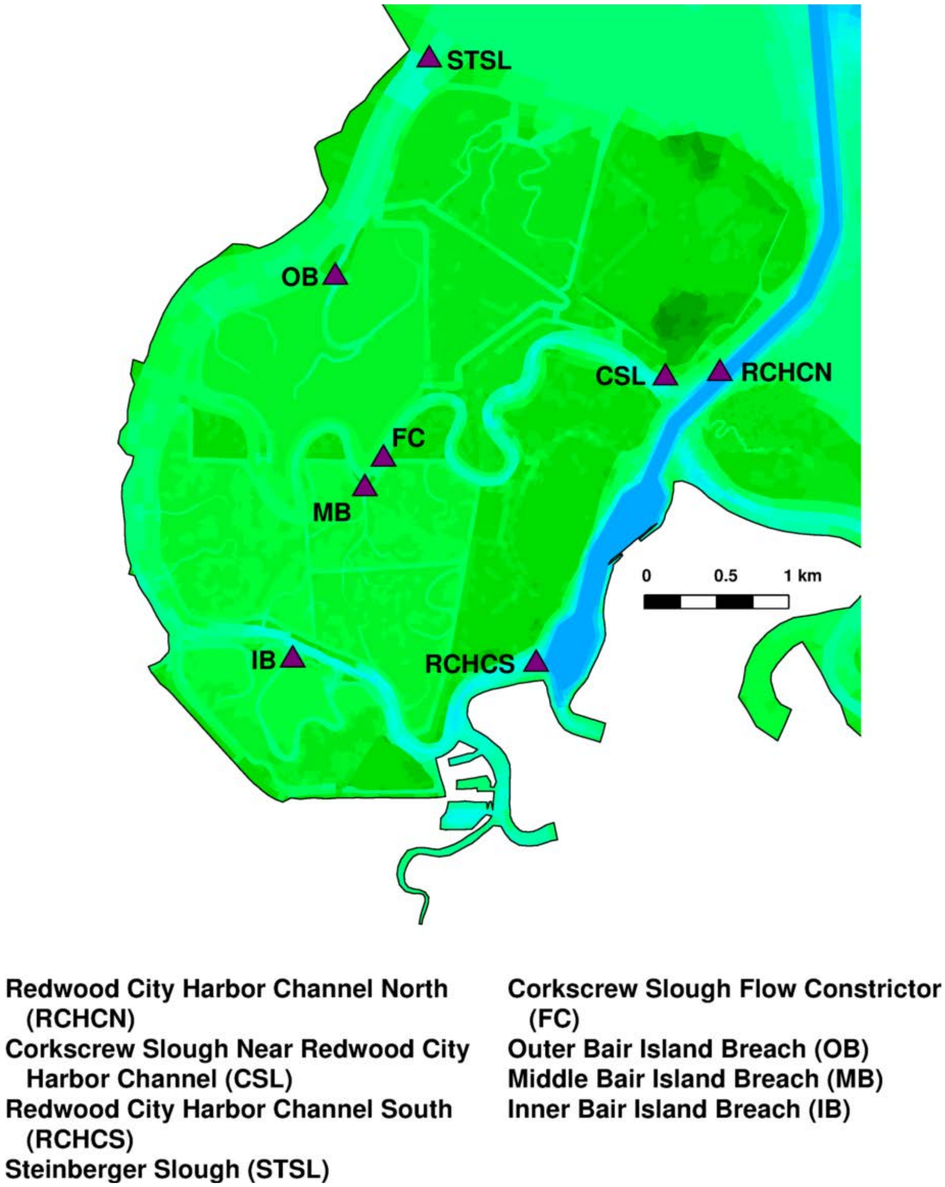

Figure 10. Locations within the coupled model domain where flow rates were evaluated

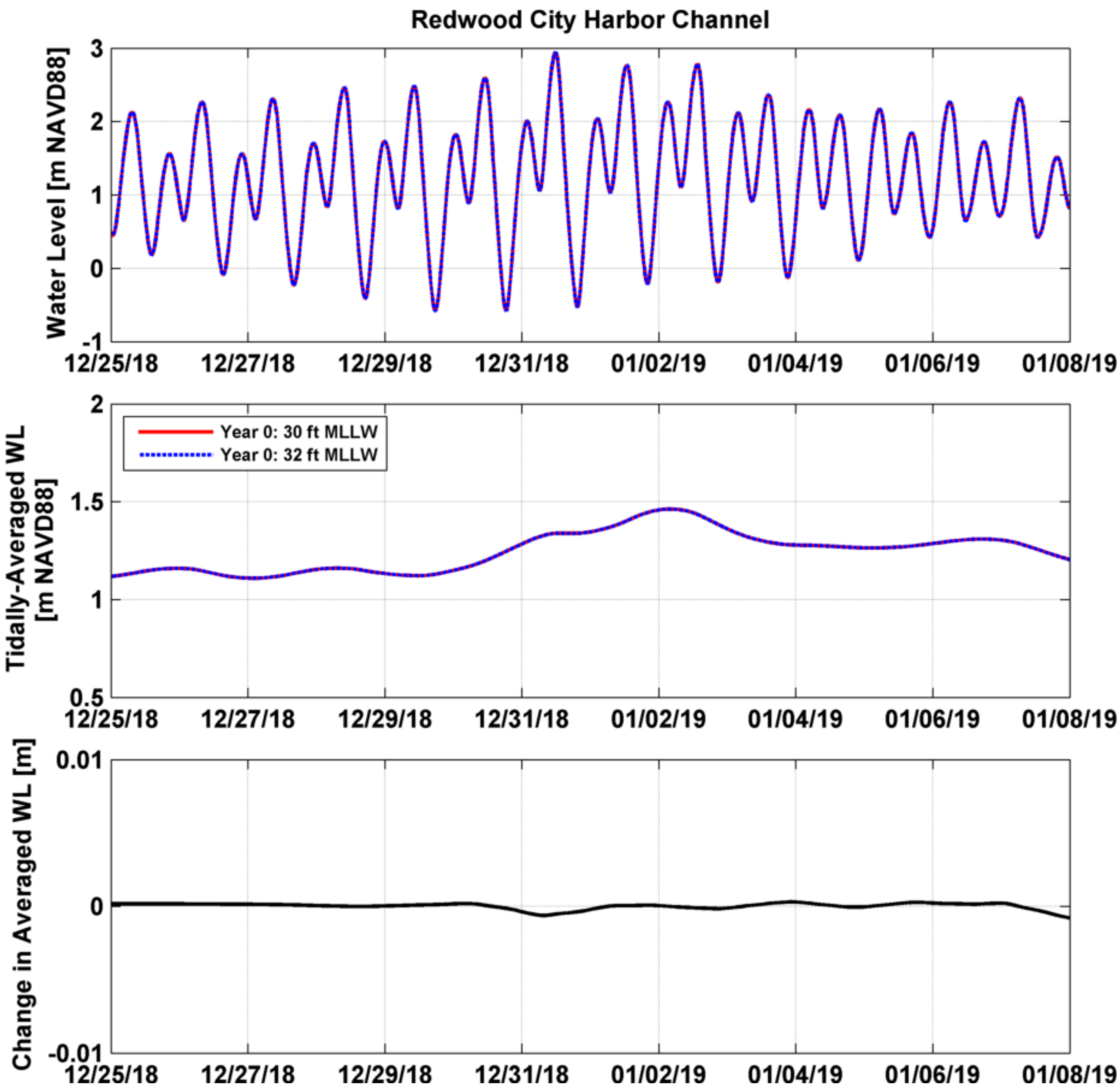

Figure 11. Predicted water elevations at the Redwood City Harbor Channel station for Year 0 conditions

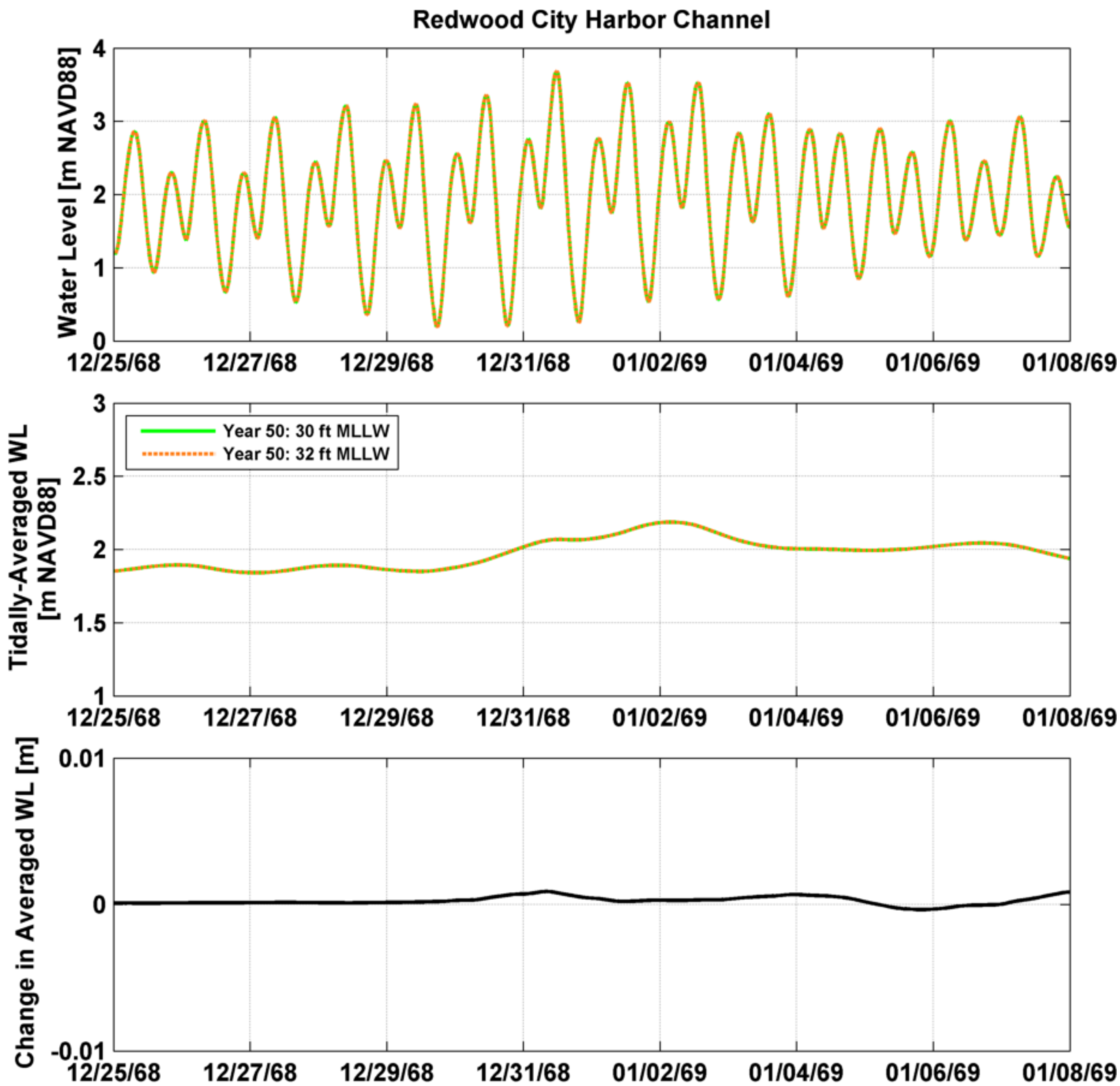

Figure 12. Predicted water surface elevations at the Redwood City Harbor Channel station for Year 50 conditions

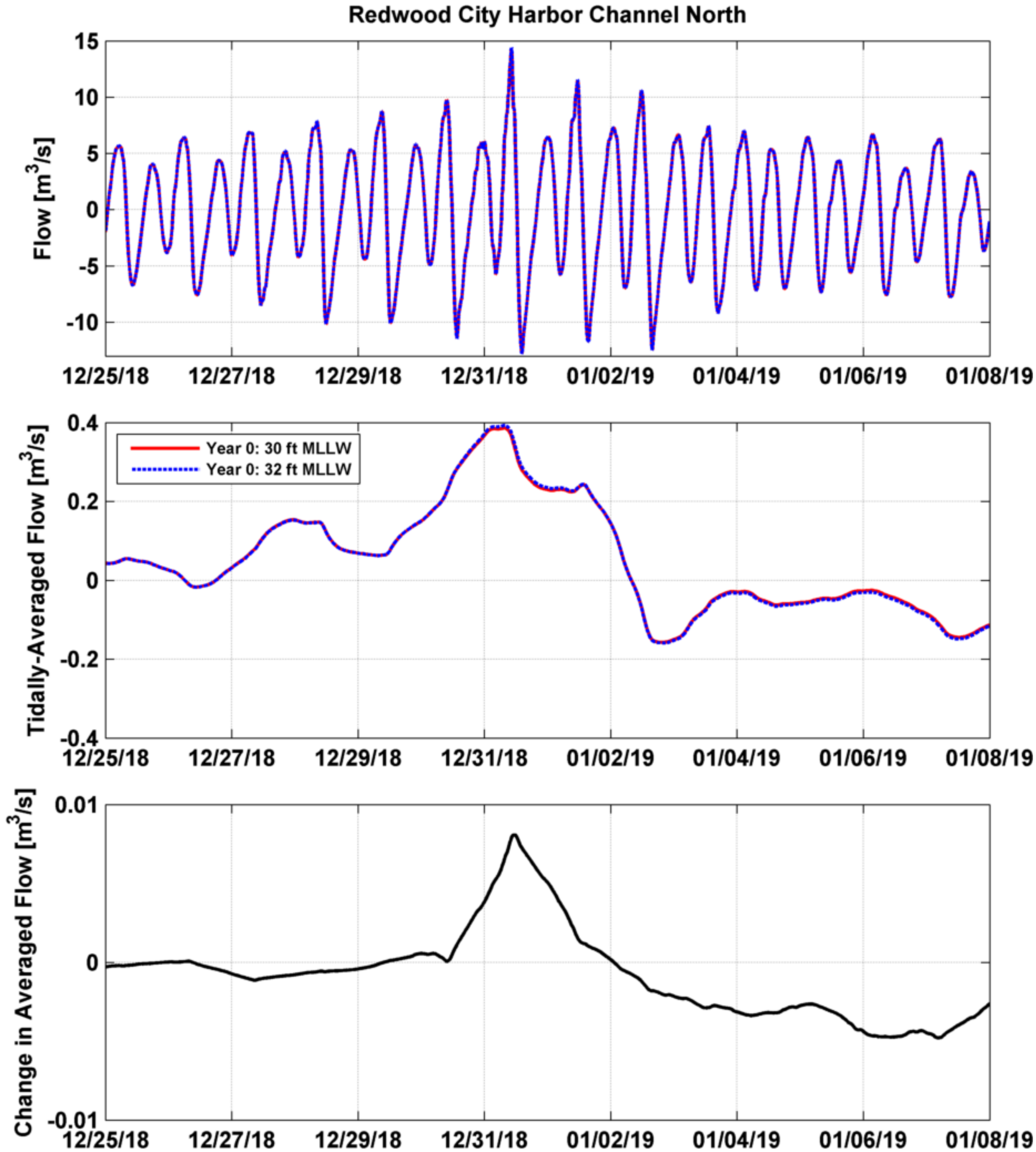

Figure 13. Predicted flow rates at the Redwood City Harbor Channel North station for Year 0 conditions

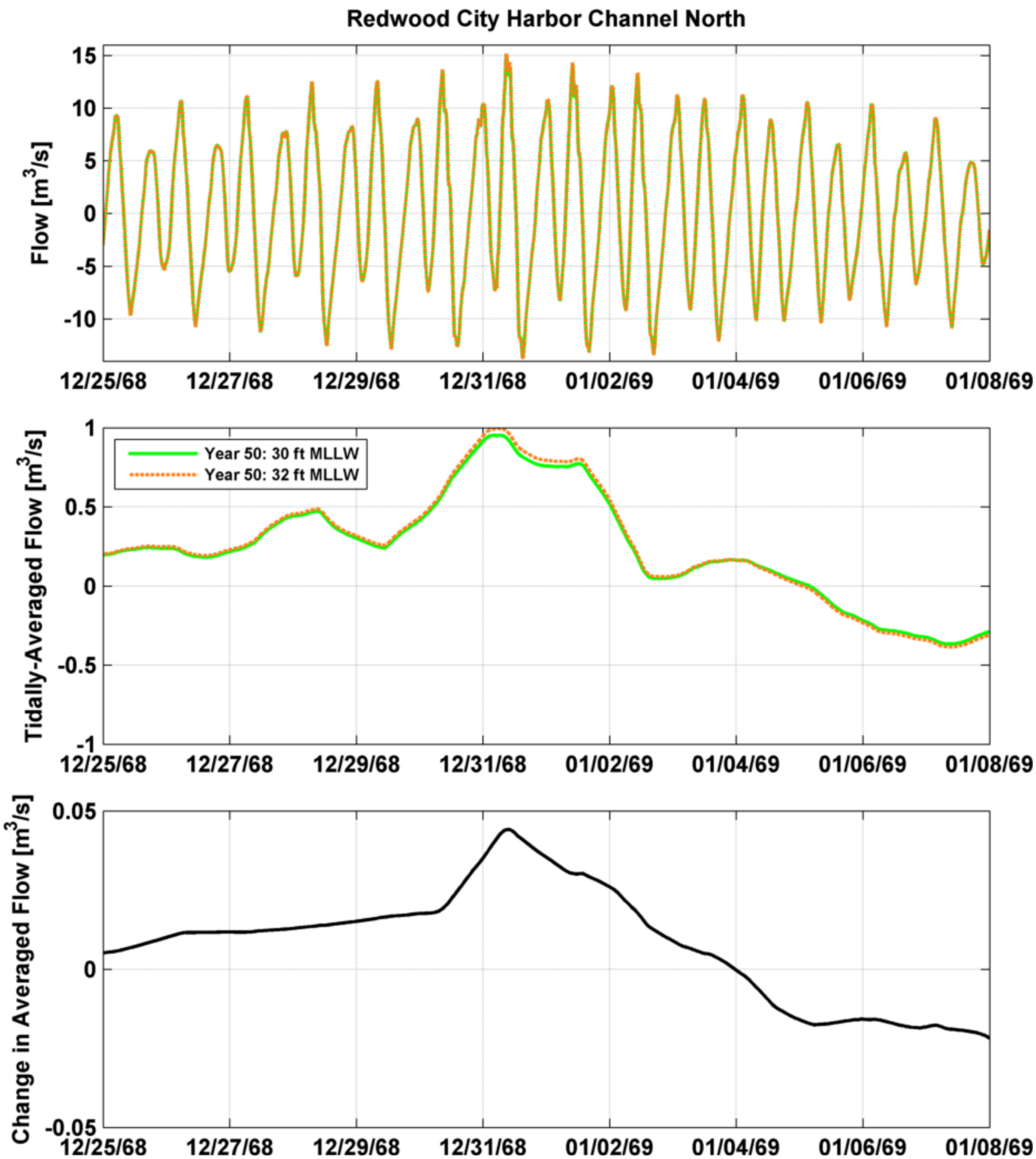

Figure 14. Predicted flow rates at the Redwood City Harbor Channel North station for Year 50 conditions

7. References

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REDWOOD CITY HARBOR NAVIGATION IMPROVEMENT FEASIBILITY STUDY

HYDRODYNAMIC AND SEDIMENT TRANSPORT MODELING FOR NAVIGATION CHANNEL DEEPENING OF REDWOOD CITY HARBOR
DRAFT FINAL REPORT

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May 2015

EXECUTIVE SUMMARY

This project was conducted for the U.S. Army Corps of Engineers (USACE) San Francisco District in support of the Redwood City Harbor Navigation Improvement Feasibility Study. The objective of this project was to investigate shoaling rates under a range of conditions of the Redwood City Harbor Channel and San Bruno Shoal Channel. To this end, the Unstructured Tidal, Residual, Intertidal & Mudflat (UnTRIM) Bay-Delta Model (MacWilliams et al. 2007, 2008, 2009, 2015) coupled with the Simulating WAves Nearshore (SWAN) wave model (SWAN Team 2009a) and the SediMorph (BAW 2005) sediment transport model was used to simulate three-dimensional hydrodynamics, wind waves, and sediment transport in San Francisco Bay and the Sacramento-San Joaquin Delta. The focus of this model application was on sediment deposition in the Redwood City Harbor Channel and the San Bruno Shoal Channel under different project depths. Sediment deposition was also evaluated for a potential realignment of the Redwood City Harbor Channel to assess whether the realignment of the channel could potentially decrease the above grade shoaling. The potential influence of channel deepening and sea level rise on water levels, flow, salinity, and shear stress in the vicinity of the Redwood City Harbor Channel was also evaluated.

Data from 21 repeated USACE bathymetric surveys of the Redwood City Harbor Channel were used to estimate a yearly sedimentation rate within the channel. Based on the evaluation of the available hydrosurveys since 2004, it was estimated that the annual average shoaling rate within the Redwood City Harbor Channel is approximately 183,000 cubic yards per year ($yd^3\ yr^{-1}$). Further analysis of the hydrosurvey data highlighted two "hot spots" within the channel that experienced relatively more extensive shoaling than the other portions of the channel (see Figure 4.3-12). One hot spot is located southeast of Bair Island on the northwest side of the channel and the other hot spot is located on the west side of the northern portion of the channel. The hydrosurvey data indicate that these two locations are potential candidates for advanced maintenance dredging to limit the duration and thickness that these regions aggrade above the project depth. Nine bathymetric surveys of the San Bruno Shoal Channel were used to estimate shoaling rates since 2002. The analyses of these surveys indicated that the San Bruno Shoal Channel has not undergone a consistent rate of sediment accretion since 2002, but rather periods of sediment accretion and erosion leading to relatively little net change.

The model predictions of sediment transport were validated using observations of suspended sediment concentration in Central Bay and South Bay, sediment deposition volumes and thicknesses in the Redwood City Harbor Channel and the San Bruno Shoal Channel, and the percentage of the Redwood City Harbor Channel that shoaled to above project depth. Water years 2006 and 2008 were simulated for the model validation. Water year 2006 is classified as a wet water year, and water year 2008 is classified as a critical (dry) water year, so the simulation of these two years allows for an assessment of model accuracy under both wet and dry hydrologic conditions.

The model predicted a lower total volume of sediment deposited in the Redwood City Harbor Channel than was estimated from the hydrosurvey data; however, the model prediction was within the error bars of the hydrosurvey derived deposition volumes for both years simulated. The model correctly predicted the locations of the two shoaling hot spots south of Bair Island and near the northern end of the channel that were identified in the hydrosurvey analysis. The model also predicted the correct across-channel location of the hot spots on the western side of the channel in the 2006 simulation. The predicted reduction in the sedimentation rate in the Redwood City Harbor Channel from the wet water year in 2006 to the critically dry water year in 2008 agreed with the observed reduction in shoaling rate derived from the hydrosurvey data (23% vs. 21%). This indicates that the model very accurately predicted the relative change in the sedimentation rate due to different channel depths and environmental conditions between the 2006 and 2008 simulation periods. The model also predicted the same order of magnitude change in the area of the channel that shoaled to above project depth as the hydrosurvey data for the Redwood City Harbor Channel. The model predicted a larger volume of sediment deposition in the San Bruno Shoal Channel than was estimated from the hydrosurvey data; however, the predicted deposition volume was the same order of magnitude as the deposition volume derived from the hydrosurvey data and was within the error bars of the hydrosurvey derived deposition volumes for both years simulated.

The model validation indicated that the model was sufficiently accurate for investigating relative changes in the sediment deposition volume due to channel deepening of the Redwood City Harbor Channel and San Bruno Shoal Channel. The validation also indicated that the predicted percentage difference in the sedimentation rate between scenarios will have less uncertainty and likely be more accurate than the corresponding absolute differences in deposition volumes between scenarios. Because there is less uncertainty in analyses that compare the relative difference in sediment depositional volumes between scenarios, the analyses in this report focused on the relative difference between scenarios and less on absolute differences between the scenarios. That is, the effect of channel deepening on sedimentation rates in the navigation channels is discussed predominantly as a percentage increase from the currently authorized 30-foot mean lower low water (MLLW) project depth and not as absolute deposition volume increases.

The base year conditions are defined based on the expected bathymetric, hydrologic, and operating conditions in year 2018 for the Redwood City Harbor Channel and the San Bruno Shoal Channel. The base year scenario represents the "Year 0" conditions, which are an estimate of conditions that may exist at the approximate time that the project is completed. Because the exact weather, hydrology, and operating conditions cannot be predicted in advance, representative conditions for 2018 were developed for the sediment transport simulations using 2006 hydrology, and modified to account for both sea level rise and to include changes to the Bair Island Restoration Project that are expected to occur prior to 2018. The planned changes to the Bair Island Restoration Project were included based on information provided by the U.S. Fish and Wildlife Service (E. Mruz, Pers. Comm. 2014; A. Payne, Pers. Comm. 2014).

Six scenarios were used to investigate how deepening the Redwood City Harbor Channel and San Bruno Shoal Channel project depths would affect the shoaling rates in the channels under base year conditions (Table ES-1). Increasing the project depth from 30 feet MLLW (Baseline) to either 32 feet MLLW or to 37 feet MLLW was predicted to result in an increase in sedimentation rates in both the Redwood City Harbor Channel and the San Bruno Shoal Channel. This suggests that the proposed channel deepening would result in an increase in annual maintenance dredging in both the Redwood City Harbor Channel and the San Bruno Shoal Channel. The annual sedimentation rate in the Redwood City Harbor Channel was predicted to increase by 13% as a result of increasing the project depth from 30 feet MLLW to 32 feet MLLW. A larger increase in annual sedimentation rate was predicted for the 37 feet MLLW deepening scenario, with the annual sedimentation rate in the Redwood City Harbor Channel predicted to increase by 51% as a result of increasing the project depth from

30 feet MLLW to 37 feet MLLW. Based on the hydrosurvey derived average sedimentation rate of about 183,000 $yd^3\ yr^{-1}$, the predictions suggest an average future dredging requirement for the Redwood City Harbor Channel of about 207,000 $yd^3\ yr^{-1}$ with the 32 feet MLLW project depth. The average future dredging requirement for the Redwood City Harbor Channel with the 37 feet MLLW project depth was predicted to be about 276,000 $yd^3\ yr^{-1}$. However, these should be treated as approximations due to uncertainty in the model predictions, and potential variations due to interannual variability or future changes to sediment supply to San Francisco Bay.

The annual sedimentation rate in the San Bruno Shoal Channel was predicted to increase by 54% as a result of deepening the San Bruno Shoal Channel from 30 feet MLLW to 32 feet MLLW. For the 37 feet MLLW project depth, the annual sedimentation rate in the San Bruno Shoal Channel was predicted to be 86% higher than for the baseline 30 feet MLLW project depth. The change in the sedimentation rate predicted for the San Bruno Shoal Channel may underestimate the increase in dredging requirements resulting from deepening the San Bruno Shoal Channel relative to the existing 30 feet MLLW project depth. This is because the results suggest that a larger portion of the channel may begin to experience above grade shoaling and may require dredging for both the 32 feet MLLW and 37 feet MLLW project depths than currently occurs for the 30 feet MLLW project depth.

Two additional scenarios were used to evaluate the influence of a proposed realignment of the Redwood City Harbor Channel on sedimentation in the channel for the 37 feet MLLW project depth and to evaluate whether or not the realignment of the channel would decrease the above grade shoaling south of Bair Island or decrease the annual maintenance dredging requirements (Table ES-1). For the 37 feet MLLW project depth, the proposed realignment of the Redwood City Harbor Channel was predicted to have a minimal effect on the annual sedimentation rate in the channel. The sedimentation rate was predicted to increase by 3% in the realignment scenario compared to the existing alignment. The thickness of the hot spot south of Bair Island was also predicted to increase in the realignment scenario relative to the existing alignment. This suggests that the proposed channel realignment would not be likely to result in decreased shoaling south of Bair Island. Although the channel realignment was evaluated only for the 37 feet MLLW project depth, it is not expected that a different result would occur for either the 30 feet MLLW or the 32 feet MLLW project depths.

Simulations were conducted to evaluate the effect of deepening the project depth on hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island under both Year 0 and Year 50 conditions. Without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions were evaluated under Year 0 and Year 50 conditions over a 2-week period that included elevated outflow from Redwood Creek, high winds, and spring tides, resulting in a total of four scenarios (Table ES-2). The influence of deepening the project depth on the hydrodynamics was determined by examining the water level, tidal flows, salinity, and shear stress in the vicinity of the Redwood City Harbor Channel and Bair Island. These comparisons demonstrated that the deepening of the project depth from 30 feet MLLW to 32 feet MLLW resulted in essentially no effect on the water level, flows, salinity, or shear stress in the vicinity of Redwood City Harbor and Bair Island for both the Year 0 and the Year 50 scenarios.

The four scenarios used to evaluate the effect of deepening the project depth on hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island under both Year 0 and Year 50 conditions were also used to provide flow fields for future ship navigation simulations. The predicted flow field was provided for two different regions: one in the vicinity of the Redwood City Harbor Channel and another in the vicinity of the San Bruno Shoal Channel. The depth-averaged velocity at each model grid cell in the two flow field regions was calculated at times of peak flood velocity, peak ebb velocity, and slack water. These four scenarios used for the ship navigation simulation output included both without-project and with-project channel bathymetry and Year 0 and Year 50 conditions (Table ES-2). These flow field data were provided to the USACE for future ship navigation simulations which are expected to be conducted during a later phase of this project.

Five additional scenarios were used to evaluate the effects of the channel deepening on peak water levels and storm surge in the Redwood City Harbor during a large storm event. One simulation was used to validate the peak water levels during the December 1983 storm, which had the highest peak water level ever measured at the National Oceanic and Atmospheric Administration (NOAA) Redwood City station. Without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions were then simulated for both Year 0 and Year 50 conditions, which included sea level rise (Table ES-2). These four scenarios were used to determine the effect of increasing the project depth on water level resonance in

Redwood City by examining the peak water levels in each scenario. Deepening the project depth from 30 feet MLLW to 32 feet MLLW was predicted to have almost no effect on the peak water levels and harbor resonance at Redwood City. The peak water level was predicted to change by less than 0.01 foot after deepening the project depth from 30 feet MLLW to 32 feet MLLW for both the Year 0 and Year 50 scenarios.

Table ES-1
The scenario matrix used to evaluate how the Redwood City Harbor Channel and San Bruno Shoal Channel project depths and the proposed realignment of the Redwood City Harbor Channel influence sedimentation in the channels.

<table>
<tr><th>Scenario</th><th>Channel Project Depth (feet MLLW)</th><th>Seasonal Period</th><th>Water Year</th><th>Notes</th></tr>
<tr><td>1</td><td>30</td><td rowspan="3">Fall – Winter</td><td rowspan="8">2006</td><td rowspan="6">Bathymetry set as deeper of existing conditions or project depth, plus 2 feet of overdepth.</td></tr>
<tr><td>2</td><td>32</td></tr>
<tr><td>3</td><td>37</td></tr>
<tr><td>4</td><td>30</td><td rowspan="3">Spring - Summer</td></tr>
<tr><td>5</td><td>32</td></tr>
<tr><td>6</td><td>37</td></tr>
<tr><td>7</td><td>37</td><td>Fall – Winter</td><td rowspan="2">Realignment of Redwood City Harbor Channel. Bathymetry set the same as in Scenarios 1 through 6.</td></tr>
<tr><td>8</td><td>37</td><td>Spring - Summer</td></tr>
</table>

Table ES-2
The scenario matrix used to determine how deepening the project depth will affect the hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island and the water level resonance in the Redwood City Harbor Channel.

Model Forcing Year	Scenario	Channel Project Depth (feet MLLW)	Project Year For Sea Level Rise	Notes
2005	1	30 (Without-Project)	Year 0 (2018)	Deepening the project depth had almost no effect on water level and flow in the vicinity of the Redwood City Harbor Channel and Bair Island. The predicted flow fields were provided for ship navigation simulations.
	2	32 (With-Project)		
	3	30 (Without-Project)	Year 50 (2068)	
	4	32 (With-Project)		
1983	1	2005 Hydrosurvey Data	No Sea Level Rise	The model accurately predicted peak water levels from historic storm conditions.
	2	30 (Without-Project)	Year 0 (2018)	Deepening the project depth had a less than 0.01 foot effect on the peak water level at Redwood City.
	3	32 (With-Project)		
	4	30 (Without-Project)	Year 50 (2068)	
	5	32 (With-Project)		

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LIST OF ACRONYMS AND ABBREVIATIONS

µm	micrometer
3-D	three-dimensional
BAAQMD	Bay Area Air Quality Management District
BAW	Bundesanstalt für Wasserbau (German Federal Waterways Engineering and Research Institute)
CCWD	Contra Costa Water District
CDEC	California Data Exchange Center
CDWR	California Department of Water Resources
CIMIS	California Irrigation Management System
dbSEABED	database SEABED
DEM	Digital Elevation Model
DICU	Delta Island Consumptive Use
DWR	Department of Water Resources
ft	feet
GLS	generic length scale
kg	kilogram
L	liter
LTMS	long-term management strategy
m	meter
mm	millimeter
MLLW	mean lower low water
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
Pa	Pascals
PSU	Practical Salinity Unit
r^2	coefficient of determination
RDMMP	Regional Dredged Material Management Plan

RMS	root-mean-square
s	second
SCCOOS	Southern California Coastal Ocean Observing System
SFPORTS	San Francisco Physical Oceanographic Real-Time System
SWAN	Simulating WAves Nearshore
TRIM	Tidal, Residual, Intertidal & Mudflat Model
ubRMSD	unbiased root-mean-square difference
UnTRIM	Unstructured Tidal, Residual, Intertidal & Mudflat Model
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
yd^3	cubic yard

1 INTRODUCTION

This report documents the three-dimensional (3-D) hydrodynamic, wind wave, and sediment transport modeling that was completed in support of the Redwood City Harbor Navigation Improvement Feasibility Study. This report also includes a description of the hydrographic survey data in the Redwood City Harbor Channel and the San Bruno Shoal Channel and the estimated sediment volume accretion rates from this data. This report is divided into ten major sections and three appendices:

- **Section 1. Introduction.** This section provides a summary of the scope and organization of the report.
- **Section 2. Redwood City Harbor Sediment Transport Modeling Project Overview.** This section provides a brief overview of the project study area, project approach, and project objectives.
- **Section 3. Numerical Model Descriptions.** This section provides brief descriptions of the Unstructured tidal, Residual, Intertidal & Mudflat (UnTRIM) hydrodynamic model, the UnTRIM Bay-Delta model, the Simulating WAves Nearshore (SWAN) wave model, and the SediMorph seabed morphology model.
- **Section 4. Analysis of Hydrographic Survey Data.** Repeated bathymetric surveys and dredged sediment volumes from the U.S. Army Corps of Engineers (USACE) were used to estimate the rate of sediment deposition and locations of relatively high sediment accumulation in the Redwood City Harbor Channel and the San Bruno Shoal Channel.
- **Section 5. Validation of the Modeled Sediment Transport in Central Bay and South Bay.** Model predictions of suspended sediment concentration in the Central Bay and South Bay were compared to continuous monitoring data and sediment deposition in the two navigation channels to hydrographic survey data.
- **Section 6. Influence of Project Depth on Shoaling.** The effects of increasing the project depth on shoaling in the two navigation channels were evaluated using the hydrodynamic, wave, and sediment transport numerical model.
- **Section 7. Influence of Channel Alignment on Shoaling.** The effects of a proposed realignment of the Redwood City Harbor Channel on shoaling were evaluated using the hydrodynamic, wave, and sediment transport numerical model.

- **Section 8. Influence of Project Depth on Hydrodynamics in the Vicinity of the Redwood City Harbor Channel.** The effects of deepening the project depth on hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island were evaluated using numerical modeling.
- **Section 9. Flow Field for Ship Navigation Simulations.** This sections details the scenarios and output format for the predicted flow field velocities that were provided to USACE for future ship navigation simulations.
- **Section 10. Summary and Conclusions.** This section presents a brief summary of the analysis and the results.
- **Appendix A. Assumptions and Limitations of the Coupled Modeling System.** This appendix details some of the major assumptions inherent in the numerical modeling effort and the limitations that arise because of them.
- **Appendix B. Coupling of the UnTRIM, SWAN, and SediMorph Numerical Models.** This appendix explains the mechanics of the coupling between the UnTRIM, SWAN, and SediMorph models.
- **Appendix C. Validation of Central Bay and South Bay Water Level and Salinity.** This appendix includes validation figures for predicted water level and salinity near the study region.

2 REDWOOD CITY HARBOR SEDIMENT TRANSPORT MODELING PROJECT OVERVIEW

This project was conducted for the USACE San Francisco District in support of the Redwood City Harbor Navigation Improvement Feasibility Study. An existing 3-D hydrodynamic, wind wave, and sediment transport model was applied to estimate sediment transport in San Francisco Bay and the Sacramento-San Joaquin Delta. The objective of the project was to estimate the rate of sediment accretion within the Redwood City Harbor Channel and the San Bruno Shoal Channel to estimate how future maintenance dredging volumes could potentially change as a result of the proposed deepening of the project depth and as a result of a proposed realignment of the Redwood City Harbor Channel near Bair Island. The project also evaluated the effects of deepening the Redwood City Harbor Channel on the hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island.

2.1 Project Study Area

The project study area is located in South San Francisco Bay and includes the Redwood City Harbor Channel and the San Bruno Shoal Channel (Figure 2-1). However, the model domain for this study encompasses all of San Francisco Bay and the Sacramento-San Joaquin Delta region (see Figure 3-1). Because the Sacramento-San Joaquin Delta region has historically been one of the largest sediment sources to San Francisco Bay, it is essential that the entire system is simulated so that sediment dynamics throughout the system and their effect on shoaling rates within the project study area can be evaluated.

2.2 Modeling Approach

The UnTRIM Bay-Delta model (MacWilliams et al. 2008, 2009, 2015) was applied together with the SWAN (SWAN Team 2009a) wave model and the SediMorph (BAW 2005) sediment transport and seabed morphology model, as a fully coupled hydrodynamic-wave-sediment transport model. The coupled model predicts the continuous erosion, deposition, and transport of sediment by waves and currents throughout the Bay-Delta system. This coupled model has been used in previous studies to evaluate sediment transport processes in the San Francisco Estuary (MacWilliams et al. 2012a; Bever and MacWilliams 2013, 2014; Delta Modeling Associates 2014) and sediment deposition in the Oakland Harbor Channel resulting from deepening project depths and differing water year types (Delta Modeling Associates 2015). The model was calibrated and verified to sediment deposition volumes within the Redwood City Harbor Channel and the San Bruno Shoal Channel. The model was then applied to evaluate how channel deepening and proposed channel realignment will influence future dredging requirements within the channel. Descriptions of the UnTRIM Bay-Delta model, the SWAN wave model, and the SediMorph sediment transport model are provided in Section 3.

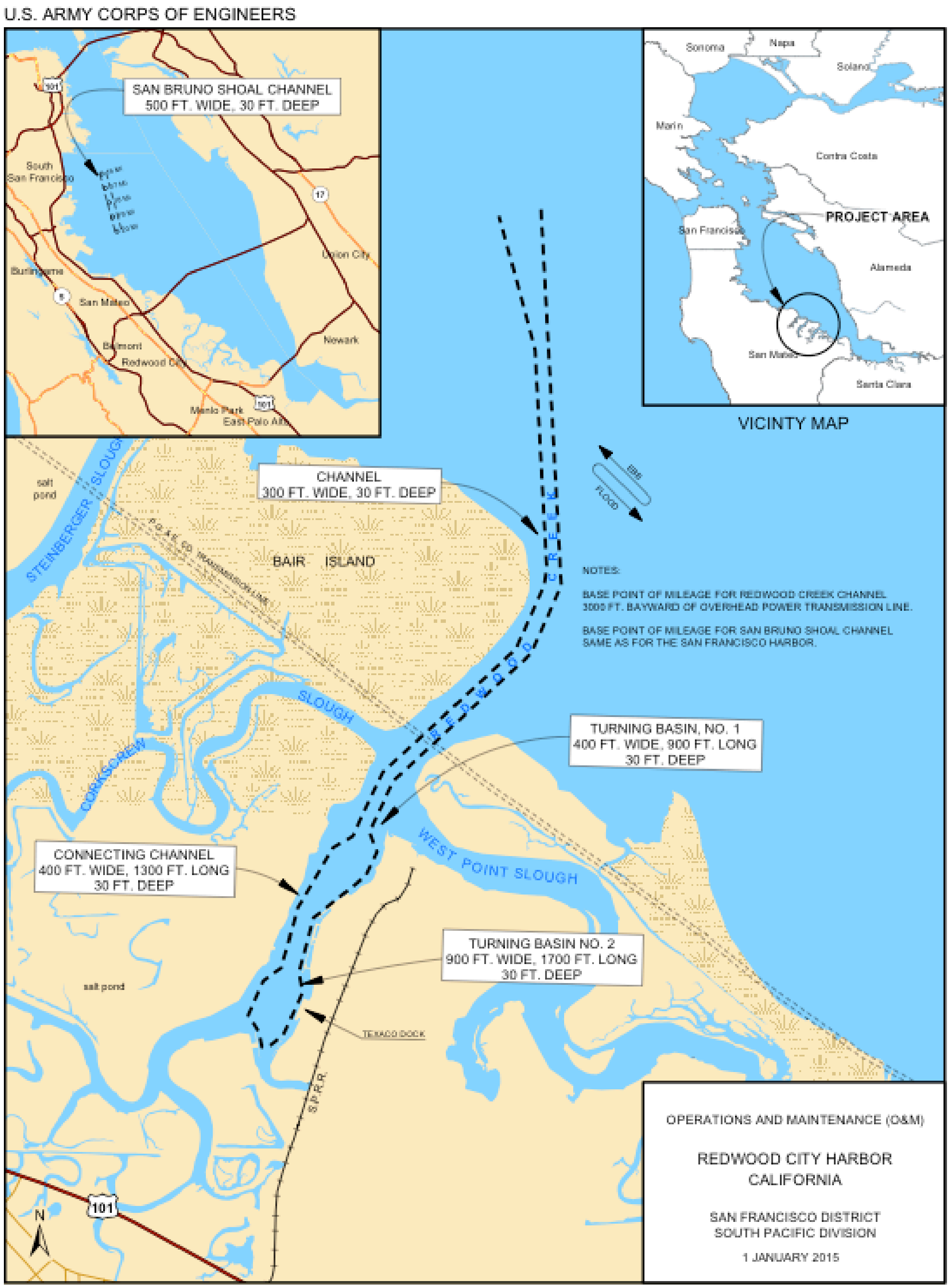


Figure 2-1
Location of project area which includes Redwood City Harbor and the San Bruno Shoal Channel (Source: USACE, San Francisco District).

2.3 Project Objectives

The primary objective of this project was to apply the coupled 3-D hydrodynamic, wind wave, and sediment transport model to evaluate how a deepening project depth and a proposed channel realignment could potentially impact the sediment deposition within the Redwood City Harbor Channel and San Bruno Shoal Channel. The model was also applied to evaluate the effects of deepening the project depth on the hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island. These objectives were accomplished by the following:

- Estimating the sedimentation rate and locations of depositional "hot spots" in the two channels from repeated USACE hydrographic surveys (Section 4)
- Validating model predictions of sediment depositional volumes within the Redwood City Harbor Channel and San Bruno Shoal Channel based on repeated USACE hydrographic survey data (Section 5)
- Evaluating changes to shoaling in the Redwood City Harbor Channel and San Bruno Shoal Channel as a result of channel deepening (Section 6) and proposed channel realignment (Section 7)
- Determining the effects of deepening the Redwood City Harbor Channel project depth on hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island (Section 8)
- Provide flow field velocities for future ship navigation simulations under both Year 0 and Year 50 conditions (Section 9)

3 NUMERICAL MODEL DESCRIPTIONS

The UnTRIM Bay-Delta model (MacWilliams et al. 2008, 2009, 2015) was applied together with the SWAN (SWAN Team 2009a) wave model and the SediMorph sediment transport and seabed morphology model (BAW 2005), as a fully coupled hydrodynamic-wave-sediment transport model. The simulations were conducted such that SWAN was run and the waves were updated every hour, while the SediMorph model exchanged information with UnTRIM at every hydrodynamic time step. In this way, the erosion and deposition on the seabed was calculated on the same time step as the hydrodynamic model (90 seconds) and the morphologic change of the seabed directly affected the hydrodynamics.

Abbreviated backgrounds of the three models are provided in this section, along with citations to full descriptions of the numerical models, model coupling, and previous applications. Validation of the coupled modeling system, including validation of the coupling of the models and initial wave and sediment transport results within San Francisco Bay is presented in MacWilliams et al. (2012a) and Bever and MacWilliams (2013, 2014). Appendix A presents some of the main areas of uncertainty within the numerical models. Appendix B provides more detail on the coupling of the three models.

3.1 UnTRIM Model Description

The hydrodynamic model used in this technical study is the 3-D hydrodynamic model UnTRIM (Casulli and Zanolli 2002). A complete description of the governing equations, numerical discretization, and numerical properties of UnTRIM are described in Casulli and Zanolli (2002, 2005), Casulli (1999), and Casulli and Walters (2000).

The UnTRIM model solves the 3-D Navier-Stokes equations on an unstructured grid in the horizontal plane. The boundaries between vertical layers are at fixed elevations, and cell heights can be varied vertically to provide increased resolution near the surface or other vertical locations. Volume conservation is satisfied by a volume integration of the incompressible continuity equation, and the free-surface is calculated by integrating the continuity equation over the depth, and using a kinematic condition at the free-surface as described in Casulli (1990). The numerical method allows full wetting and drying of cells in the vertical and horizontal directions. The governing equations are discretized using a finite difference-finite volume algorithm. Discretization of the governing equations and model boundary conditions are presented in detail by Casulli and Zanolli (2002). All details and numerical properties of this state-of-the-art 3-D model are well-documented in peer reviewed literature (Casulli and Zanolli 2002, 2005).

3.1.1 Turbulence Model

The turbulence closure model used in the present study is a two-equation model comprised of a turbulent kinetic energy equation and a generic length-scale equation. The parameters of the generic length-scale (GLS) equation are chosen to yield the k-ε closure (Umlauf and Burchard 2003). The Kantha and Clayson (1994) quasi-equilibrium stability functions are used. All parameter values used in the k-ε closure are identical to those used by Warner et al. (2005), including the minimum eddy diffusivity and eddy viscosity values, which were 5×10^{-6} m^2 s^{-1}. The numerical method used to solve the equations of the turbulence closure is a semi-implicit method that results in tridiagonal positive-definite matrices in the water column of each grid cell and ensures that the turbulent variables remain positive (Deleersnijder et al. 1997).

3.1.2 Previous Applications

The Tidal, Residual, Intertidal & Mudflat (TRIM) 3-D model (Casulli and Cheng 1992) and UnTRIM model have been applied previously to San Francisco Bay (Cheng and Casulli 2002; MacWilliams and Cheng 2007; MacWilliams and Gross 2007; MacWilliams et al. 2007, 2008, 2015). The TRIM3-D model (Casulli and Cattani 1994) which follows a similar numerical approach on structured horizontal grids has been widely applied in San Francisco Bay (e.g., Cheng et al. 1993; Cheng and Casulli 1996; Gross et al. 1999, 2006), and a 2-D version, TRIM2D, was used in the San Francisco Bay Physical Oceanographic Real-Time System (SFPORTS, Cheng and Smith 1998). Thus, the UnTRIM numerical approach has been well-tested in San Francisco Bay, and is very well suited to perform the types of analysis used in this study.

3.1.3 UnTRIM Bay-Delta Model

The UnTRIM San Francisco Bay-Delta model (UnTRIM Bay-Delta model) is a three-dimensional hydrodynamic model of San Francisco Bay and the Sacramento-San Joaquin

Delta, which has been developed using the UnTRIM hydrodynamic model (MacWilliams et al. 2007, 2008, 2009, 2015). The UnTRIM Bay-Delta model extends from the Pacific Ocean through the entire Sacramento-San Joaquin Delta (Figure 3-1). The UnTRIM Bay-Delta model takes advantage of the grid flexibility allowed in an unstructured mesh by gradually varying grid cell sizes, beginning with large grid cells in the Pacific Ocean and gradually transitioning to finer grid resolution in the smaller channels of the Sacramento-San Joaquin Delta. This approach offers significant advantages both in terms of numerical efficiency and accuracy, and allows for local grid refinement for detailed analysis of local hydrodynamics, while still incorporating the overall hydrodynamics of the larger estuary in a single model. The UnTRIM Bay-Delta model has been calibrated using water level, flow, and salinity data collected in San Francisco Bay and the Sacramento-San Joaquin Delta (MacWilliams et al. 2008, 2009, 2015). Predicted water levels were compared to observed water levels at National Oceanic and Atmospheric Administration (NOAA) and Department of Water Resources (DWR) stations in San Francisco Bay, and DWR and United States Geological Survey (USGS) flow and stage monitoring stations in the Sacramento-San Joaquin Delta.

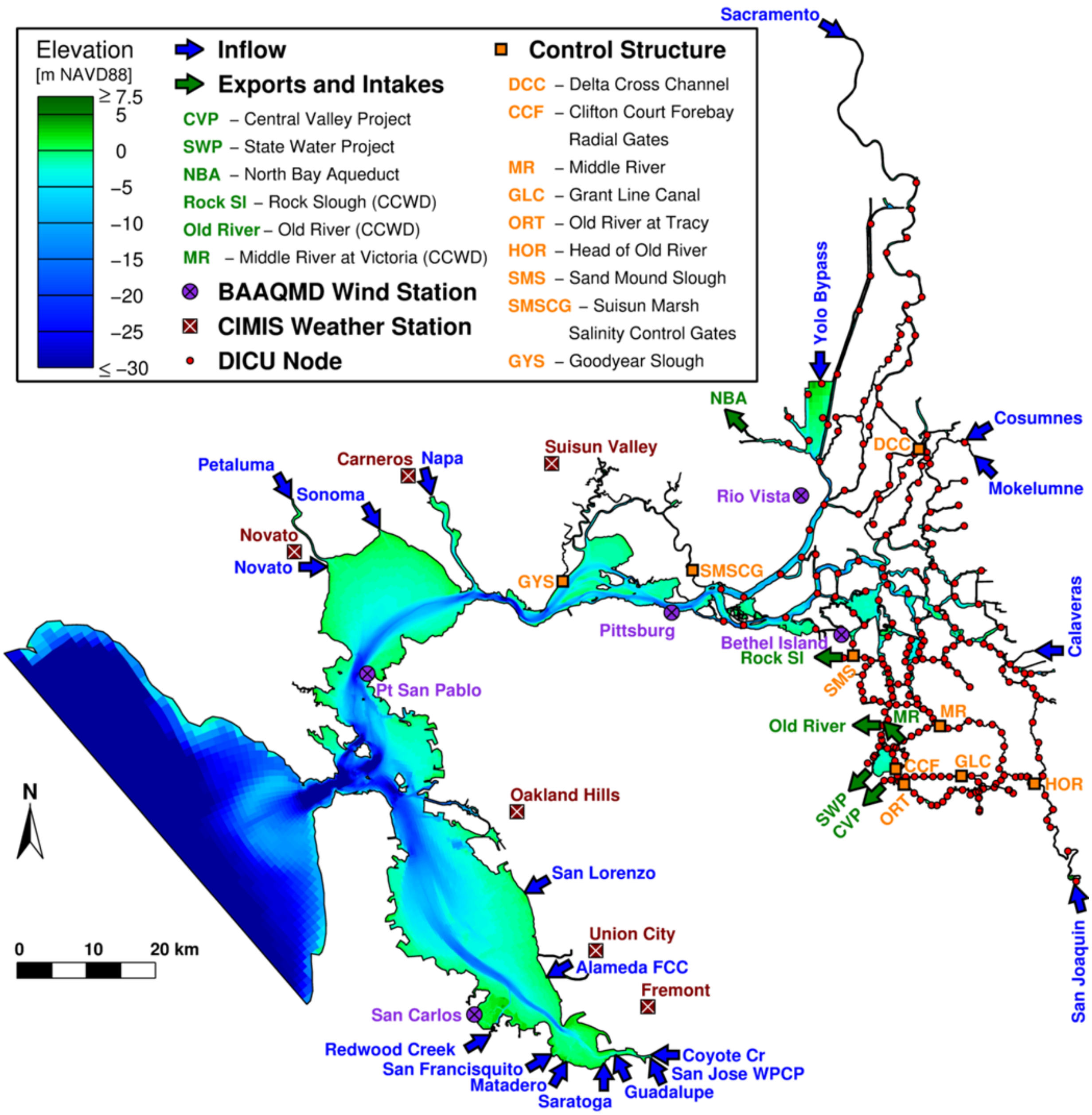


Figure 3-1.
UnTRIM San Francisco Bay-Delta model domain, bathymetry, and locations of model boundary conditions which include inflows, export facilities, intakes for the Contra Costa Water District (CCWD), wind stations from the Bay Area Air Quality Management District (BAAQMD), evaporation and precipitation from California Irrigation Management Information System (CIMIS) weather stations, Delta Island Consumptive Use (DICU), and flow control structures.

3.2 SWAN Model Description

Wind wave properties must be estimated in order to accurately calculate bottom stress in SediMorph for the sediment transport calculations. In the approach documented here, the wind wave properties are predicted by the SWAN model (SWAN Team 2009a). SWAN supports the use of unstructured grids (Zijlema 2010) allowing fairly straightforward application with UnTRIM. A one-way coupling of SWAN and UnTRIM has been implemented in which information is written by UnTRIM for use in SWAN. After each SWAN wave prediction is complete, the significant wave height, peak wave period, and wave direction are passed back to UnTRIM to be used by SediMorph to calculate bottom shear stress.

3.2.1 SWAN Overview

The SWAN model (SWAN Team 2009a) is a widely used model for predicting wind wave properties in coastal areas (e.g., Funakoshi et al. 2008). SWAN "represents the effects of spatial propagation, refraction, shoaling, generation, dissipation and nonlinear wave-wave interactions" on wind waves (SWAN Team 2009b). Therefore, SWAN can estimate the wind waves in coastal regions with variable bathymetry and ambient currents. SWAN can also accommodate spatial variability in bottom friction parameters and wind velocity. SWAN is a freely available model developed at Delft University of Technology (SWAN Team 2009a).

The SWAN options used for this project were in most cases the model's default values. As such, the model included wind generated waves, whitecapping, wave refraction, quadruplet wave-wave interactions, and wave breaking. A Madsen et al. (1988) bottom friction formulation was used based on the seabed grain size provided by UnTRIM. SWAN also included the influence of the UnTRIM current velocities in the wave calculations. A method from Rogers et al. (2003) to reduce the artificial reduction of lower frequencies by dissipation was included. A functionality to limit the wave turning from refraction based on the Courant-Friedrichs-Lewy (CFL) condition was included based on Dietrich et al. (2013) to limit unreasonably large wave periods near steep bathymetric gradients.

3.2.2 Previous Applications

SWAN has been widely applied in many settings, including estuaries. Published applications of SWAN in the San Francisco Estuary include studies of wind waves in South San Francisco Bay by Bricker (2003) and Bricker et al. (2004). Bricker et al. (2004) found that the representation of wave breaking and refraction are important capabilities of SWAN. In contrast, an approach using analytical equations, documented by Inagaki et al. (2001), which does not represent effects of wave breaking and refraction provided substantially different estimates of wave properties at the study site near Coyote Point (Bricker et al. 2005). Zimmerman et al. (2008) applied SWAN to study wind waves near Hunter's Point and predicted significant wave height accurately during periods with strong winds. van Der Wegen (2010) applied SWAN in morphological modeling of San Pablo Bay. Bever and MacWilliams (2013) used the coupled UnTRIM-SWAN-SediMorph model to investigate wave dynamics across the San Pablo Bay shoals. SWAN wave predictions were also used in the South Bay sediment transport modeling of Bever and MacWilliams (2014).

3.3 SediMorph Model Description

The seabed morphologic model SediMorph was originally developed by the German Federal Waterways Engineering and Research Institute (BAW) in Hamburg. SediMorph is currently being used and developed in a framework of several hydraulic research institutes (Weilbeer 2005). The SediMorph model is used with several different hydrodynamic models at BAW, including UnTRIM (Casulli and Zanolli 2002, 2005) and TELEMAC (Electricité de France 2000). For the current study, the SediMorph module was coupled with the UnTRIM Bay-Delta model to allow for sediment transport and seabed morphological change calculations in San Francisco Bay.

3.3.1 SediMorph Overview

The primary purpose of the SediMorph module is to compute the sedimentological processes at the alluvial bed of a free-surface flow, including the following (Weilbeer 2005):

- The roughness of the bed resulting from grain and form roughness (ripples and/or dunes)
- The bottom shear stress as a result of roughness, flow, and waves
- Bed load transport rates (fractioned)

- Erosion and deposition rates (fractioned)
- Bed evolution
- Sediment distributions within the bed exchange layer

A full description of the model capabilities of SediMorph and the validation of the SediMorph model is presented by BAW (2005). The physics modeled in SediMorph is described in detail by Malcherek (2001). A full description of the governing equations for the SediMorph model is presented by BAW (2005). A full description of the numerical setup of the SediMorph model as used in the UnTRIM-SWAN-SediMorph modeling system is presented in Bever and MacWilliams (2014).

3.3.2 Treatment of the Sediment Bed

SediMorph is designed to use the same horizontal computational mesh as the UnTRIM hydrodynamic model. In the vertical, the SediMorph module allows for evolution of the bed elevation above a pre-defined rigid layer in each cell. Above the rigid layer, SediMorph includes at least one exchange layer, in which sediments are mixed and exchange processes such as erosion and deposition occur. Figure 3-2 shows the horizontal and vertical grid structure of the UnTRIM and SediMorph models and provides a schematic representation of the location of the sediment transport processes within the model grid structure.

SediMorph allows for the use of multiple seabed layers that can help the model armor the seabed, or keep deposited yet easily erodible fine sediment at the surface. With the use of multiple seabed layers, sediment is eroded or deposited into layers at the sediment water interface that have a set maximum thickness (approximately 1.7 centimeters in this modeling work). These layers can be winnowed of fine sediment, creating an armored sediment bed. The layers can also store easily erodible fine sediment on the bed surface for later resuspension. Physically, these layers behave like a surface mixed layer, where the deposited sediment is mixed within a thin layer at the surface without being mixed within the entire sediment bed, and then remains near the sediment surface for later resuspension. When one seabed layer fills up with sediment through deposition, subsequent sediment deposition is then added to the layer above. Conversely, when the thickness of the upper seabed layer is less than the thickness of the exchange layer, the upper layer is mixed with the layer below and is considered eroded away. The thickness of the exchange layer between the seabed and the water column is dictated by the seabed grain size and the bed shear stress, and only sediment within this layer is available for sediment mobilization during any one time-step. The exchange layer thickness is calculated similarly to that from Harris and Wiberg (1997) using:

If $\tau_b > \tau_C$ $\quad ELT = \frac{\tau_b}{\tau_C} D_{90}(1 - P)$

otherwise $\quad ELT = D_{90}(1 - P)$

where ELT is the exchange layer thickness, τ_b is the bed shear stress, τ_C is the critical Shields shear stress using the grain size of the 50th percentile, D_{90} is the grain size of the 90th percentile sediment and P is the porosity of the exchange layer.

SediMorph runs concurrently with UnTRIM, and uses the hydrodynamics and wave properties in the calculation of seabed shear stress, which feeds into the sediment erosion and bedload calculations. In the shear stress calculations, the Nikuradse and ripple roughnesses at each grid cell are used to allow for a spatially varying roughness.

SediMorph allows for the use of multiple sediment classes, and these classes are considered well mixed within any single seabed layer. A single porosity value is specified for the entire seabed within the model. All sediment classes are used in their relative proportions within a layer in the calculation of bulk seabed properties, such as determining the average grain size. For sediment deposition and erosion, however, all the sediment classes are treated individually within a seabed layer. If the shear stress is above the critical shear stress of any given sediment class, then that class can be eroded from the surface exchange layer according to Ariathuria and Arulanandan (1978). The sediment density of each sediment class is used with the single porosity value to determine the deposition and erosion thickness (from the calculated deposited or eroded sediment mass) of each sediment class individually. These thicknesses are summed and combined with the bedload transport based on Meyer-Peter and Müller (1948) to calculate the net seabed deposition or erosion, dependent on each sediment class eroded from the layer or deposited from the overlying water column.

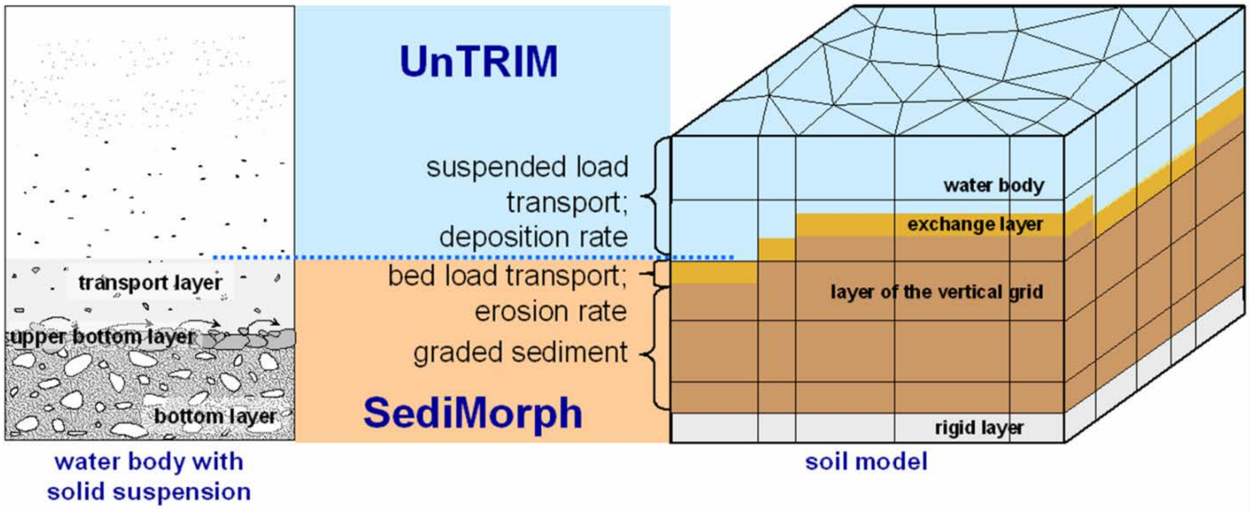


Figure 3-2
Horizontal and vertical grid structure of the UnTRIM and SediMorph models (right); schematic (left) and process list (middle) show the location of the sediment transport processes within the model grid structures (Source: BAW).

3.3.3 Sediment Transport Modeling Setup

To limit the number of grain classes within the model, the continuously varying grain size distribution within the real world was simplified to represent the most dominant constituents, as has previously been done in 3-D sediment transport modeling of San Francisco Bay (Ganju and Schoellhamer 2009; van der Wegen et al. 2011; Bever and MacWilliams 2013). Increasing the number of sediment classes within the modeled grain size distribution increases the complexity of the calibration because of the increased number of tunable parameters and increases the run time of each model simulation. Sediment transport calculations for this project included four sediment classes, each with different particle size, settling velocity, critical shear stress, density, and erosion rate parameter (Table 3.3-1). The four sediment classes were chosen to represent the dominant constituents in the real San Francisco Bay grain size distribution, and were single particle silt, flocculated silts and clays called “flocs,” sand and gravel. The final sediment class parameters shown in Table 3.3-1 were determined as described in Bever and MacWilliams (2014).

Table 3.3-1
The sediment grain class parameters used in the sediment transport modeling.

Sediment class	Settling Velocity (mm s^{-1})	Critical Shear Stress (Pa)	Diameter	Density (kg m^{-3})	Erosion Rate Parameter (kg m^{-2} s^{-1})
Silt	0.0774	0.0275	11 µm	2,650	3.5×10^{-5}
Flocculated Silt and Clay	2.25	0.15	200 µm	1,300	5×10^{-5}
Sand	23	0.19	250 µm	2,650	5×10^{-5}
Gravel	N/A	N/A	8 mm	2,650	N/A

Observed surface grain size distributions were used to generate a realistic initial sediment bed for the entire San Francisco Bay-Delta system. Grain size distribution data was compiled from a USACE Long Term Management Strategy (LTMS) report (Pratt et al. 1994), the west coast surface grain size distribution database (dbSEABED, Jenkins 2010), the USGS sand provenance study (Barnard et al. 2013) and the Delta sediment grain size study (S. Wright, Pers. Comm. 2012). The method presented in Bever and MacWilliams (2013, 2014) was used with more than 1,300 surface grain size distributions to generate the initial sediment bed (Figure 3-3). A porosity of 70% was specified for the seabed. This porosity is near the average of values reported for the San Francisco Bay in Caffrey (1995) of about 65%.

Suspended sediment was supplied through river input to the Sacramento-San Joaquin Delta, the North Bay and the South Bay. Sediment was supplied to the Delta by the Sacramento, San Joaquin, Cosumnes, and Mokelumne Rivers and the Yolo Bypass as described in Bever and MacWilliams (2013, 2014), representing nearly 100% of the sediment inflow to the Delta (Wright and Schoellhamer 2005). Sediment was supplied to the South Bay by Alameda Creek, San Lorenzo Creek, Coyote Creek, and the Guadalupe River as described in Bever and MacWilliams (2013, 2014). Sediment was supplied to the North Bay by the Napa River in the same manner as the South Bay tributaries.

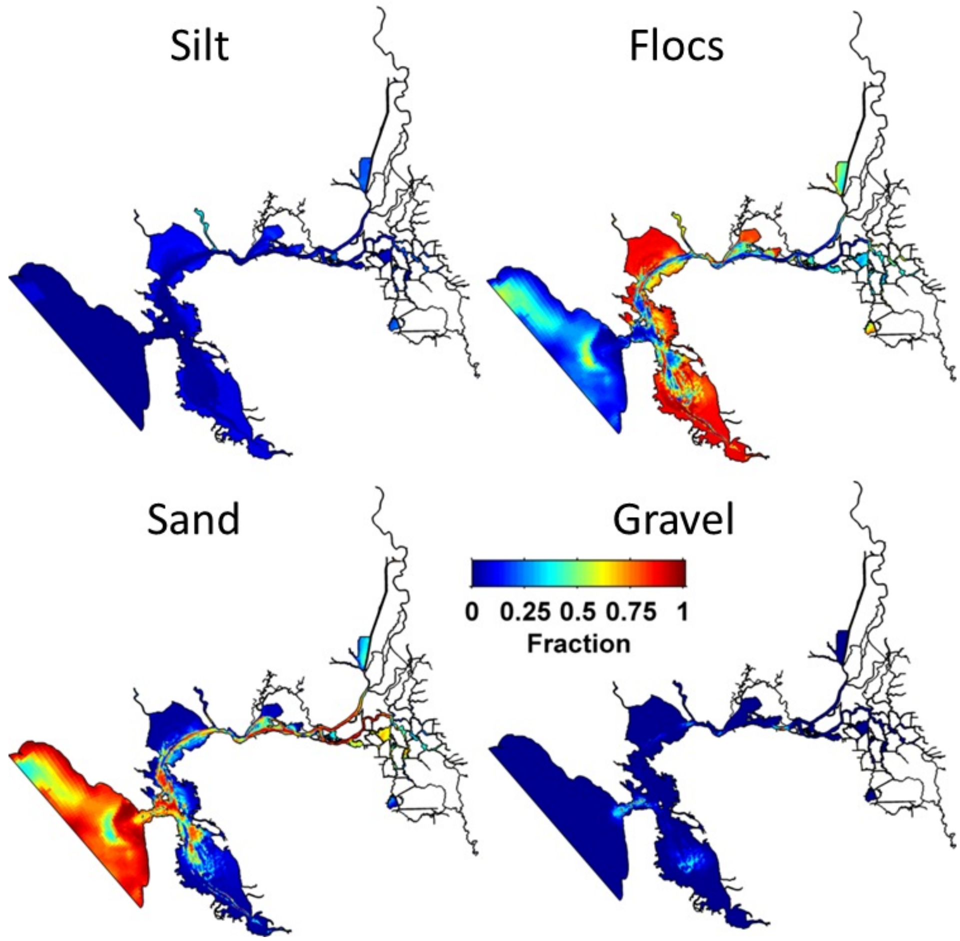


Figure 3-3
The fraction of each sediment class making up the initial sediment bed.

3.3.4 Previous Applications

The SediMorph model has been used for a wide range of applications at the BAW. Initial applications used in the validation of the SediMorph model are presented by BAW (2005). Weilbeer (2005) presents the simulation of sediment transport processes in the Ems-Dollard estuary using UnTRIM-SediMorph. Kahlfeld and Schüttrumpf (2006) apply the UnTRIM-SediMorph model to evaluate the potential morphodynamic impacts of the proposed construction of a container port in the Jade-Weser estuary. Sohrmann and Weilbeer (2006) use the UnTRIM-SediMorph model to evaluate the effect of channel deepening on sediment transport in the Elbe estuary using data from repeated bathymetric surveys spanning 30 years of channel deepening. Additional applications at BAW include the simulation of dredged material placement. SediMorph has also been used with UnTRIM and SWAN to simulate dredged material dispersal in North San Francisco Bay (MacWilliams et al. 2012a) and sediment fluxes between the channel and shoals in San Pablo Bay (Bever and MacWilliams 2013). Bever and MacWilliams (2014) used the UnTRIM-SWAN-SediMorph modeling system to evaluate the fate of dredged material following in-Bay open-water placements and investigated if open-water placements can potentially be used to augment mudflat and marsh sedimentation. Delta Modeling Associates (2015) used the model to predict sedimentation rates in the Oakland Harbor Channel under different water year types and project depths. These applications demonstrate the suitability of the SediMorph model for the types of applications conducted as part of this study.

4 ANALYSIS OF HYDROGRAPHIC SURVEY DATA

USACE conducts regular hydrographic surveys of navigation channels in San Francisco Bay to determine minimum water depths for navigation and estimate dredging requirements. Bathymetric data from the Redwood City Harbor Channel and the San Bruno Shoal Channel were used in this study to estimate the rate of shoaling of these two channels through time. The data also highlighted areas within the Redwood City Harbor Channel that are prone to high rates of sediment accumulation relative to the rest of the channel, indicating areas where channel realignment can potentially reduce dredging needs or advanced maintenance dredging can potentially reduce the occurrence of above grade shoaling. The sediment volume change within the two channels was also used to validate the predicted sediment deposition from the numerical modeling.

4.1 Navigation Channel Sediment Volume Change Overview

Hydrographic survey data from USACE was used to estimate the change in sediment volume within the Redwood City Harbor Channel and the San Bruno Shoal Channel through time. This rate of sediment accretion appears to be relatively uniform near 183,000 $yd^3\ yr^{-1}$ since January of 2004 for the Redwood City Harbor Channel. The data also show the channel southeast of Bair Island frequently accretes to an above grade condition and is the region with the highest sediment accumulation rates. Data from the San Bruno Shoal Channel suggest the channel does not undergo consistent sediment accretion, but rather both periods of sediment accretion and erosion.

4.2 Hydrographic Survey Bathymetric Data

Hydrographic surveys of the Redwood City Harbor Channel and the San Bruno Shoal Channel were obtained from USACE (Lisa Andes, Pers. Comm., 2012; Patrick Sing, Pers. Comm., 2013). The survey data provide locations in State Plane feet and the depth of the seabed below mean lower low water (MLLW) in and around the channels as individual location and depth soundings. The survey data were further processed onto a 10-meter Digital Elevation Model (DEM) in MLLW and Universal Transverse Mercator (UTM) to allow for the direct comparison of each hydrographic survey during analysis. During the conversion to a DEM, any depths of the seabed greater than 50 feet below MLLW were deemed bad data and were removed. Also, all bathymetric data outside of the federally authorized navigation channels were disregarded to prevent sediment erosion or deposition outside of the channels from influencing the channel shoaling analysis. Some surveys included nearly the entire channel while others were only partial surveys (Tables 4.2-1 and 4.2-2). Although the partial surveys are referenced in Tables 4.2-1 and 4.2-2, only the full surveys were used in the analysis presented here. The date of the survey used in the analysis (Table 4.2-1) was set as the first day the surveys were conducted because some hydrographic surveys spanned multiple days.

Table 4.2-1
Dates and extent of the hydrographic surveys for the Redwood City Harbor Channel. The Survey Notes are the USACE designation of Before Dredging, After Dredging, or Condition surveys.

Navigation Channel	Survey Date	Extent of Survey	Survey Notes
Redwood City Harbor	01/08/2004	Full	Condition
	06/07/2004	Partial	Condition
	06/16/2004	Partial	After Dredging
	09/08/2004	Partial	Before Dredging
	10/20/2004	Partial	Before Dredging
	11/09/2004	Full	Condition
	03/23/2005	Full	Condition
	09/13/2005	Full	Before Dredging
	11/16/2005	Full	Before Dredging
	12/15/2005	Partial	After Dredging
	12/24/2005	Full	After Dredging
	11/19/2006	Full	Condition
	04/13/2007	Full	Condition
	02/05/2008	Full	Condition
	10/28/2008	Full	Before Dredging
	08/30/2009	Full	Before Dredging
	10/14/2009	Full	Before Dredging
	11/03/2009	Full	After Dredging
	07/22/2010	Full	Condition
	05/26/2011	Full	Condition
	01/04/2012	Full	After Dredging
	03/19/2012	Partial	Condition
	06/28/2012	Full	Condition
	09/06/2012	Full	After Dredging
	11/25/2013	Full	Condition
	05/06/2014	Full	Condition
	08/04/2014	Full	Condition

Table 4.2-2
Dates and extent of the hydrographic surveys for the San Bruno Shoal Channel. The Survey Notes are the USACE designation of Before Dredging, After Dredging or Condition surveys.

Navigation Channel	Survey Date	Extent of Survey	Survey Notes
San Bruno Shoal	06/18/2002	Full	Condition
	04/15/2004	Full	Condition
	03/17/2005	Full	Condition
	10/15/2005	Full	Before Dredging
	11/21/2005	Partial	After Dredging
	11/20/2006	Full	Condition
	02/08/2008	Full	Condition
	06/21/2010	Full	Condition
	06/07/2011	Full	Condition
	04/15/2014	Full	Condition

4.3 Sediment Volume Change in the Navigation Channels

4.3.1 Calculations of Channel Area above Project Depth, Sediment Volume Above Project Depth and Sediment Volume Change

The USACE hydrographic surveys in the Redwood City Harbor Channel and the San Bruno Shoal Channel were used to calculate the area of the channels above the authorized project depth (30 feet MLLW), the volume of sediment in the channels above the project depth and the change in the sediment volume in the channels through time. These calculations used the processed USACE bathymetric data in MLLW which were converted into a 10-meter DEM as described in Section 4.2. The area above the project depth for each full survey was calculated by a summation of the area of each DEM grid cell in which the seabed depth was above the project depth. The volume of sediment above the project depth was also calculated by summing the sediment volume in each DEM grid cell that was above the project depth for each survey. These area and volume calculations were also performed for seabed depths of 1 foot above the project depth, 2 feet above the project depth, and 3 feet above the project depth. These calculations provide the area and volume at multiple elevations above the project depth for each of the full surveys, but no direct information on any time varying rate of sedimentation in the channel between the surveys. Because the data do not provide information on the channel between surveys, all plots of the area and volume above the project depth assume a linear trend between each survey.

The relative sediment volume change in the channels through time was calculated from the hydrosurvey data to estimate the volumetric sediment accumulation rate in each channel. Using periodic hydrosurveys to calculate the sediment volume change was suggested by Trawle (1981) to be a relatively accurate way of estimating the shoaling rate within dredged channels. The depth of the seabed below MLLW from each full survey of the channels was compared to the first full survey to estimate the sediment volume change between the surveys. This sediment volume change shows whether there was a net increase or a net decrease in the sediment volume in the channel between any two surveys or from one date to another. A linear trend is assumed between the surveys. An increase in the sediment volume indicates accretion, and a decrease indicates erosion or dredging. The volume of sediment in the channel was set to zero when the channel depth was the deepest, essentially making the sediment volumes relative to when the channel was the most dredged. This zeroing of the sediment volumes when the channel was the most dredged is arbitrary, but allows for an evaluation of the change in sediment volume in the channel through time and avoids negative sediment volumes. Using this approach, the change in sediment volume is not referenced to the project depth. However, the change in sediment volume relative to the project depth is better evaluated as the sediment volume above project depth as discussed above. Instead, these relative sediment volumes in the channel highlight the total sediment volume change in the channel, including both above the project depth and in any dredged overdepth that might be present. Figures of deposition volumes and shoaling rates are presented as $1x10^5$ yd^3, hundreds of thousands of cubic yards, which is the same order of magnitude as has historically been dredged from the Redwood City Harbor Channel. Uncertainty in the sediment volume within each channel was estimated by assuming a maximum potential measurement error in the seabed depth below MLLW of 6 inches over the surveyed area of each channel (Kilmon 2010). This gives error estimates of about ±137,000 yd^3 for Redwood City Harbor and ±276,000 yd^3 for San Bruno Shoal. These error estimates are considered very high estimates of the uncertainty in the sediment volume in the channels; the real error in the estimates is probably much smaller.

The hydrographic surveys were also used to identify areas that had higher sedimentation rates than the rest of the channel, termed “hot spots.” The total sediment deposition in each DEM grid cell was used as a basic metric for the relative magnitude of sediment deposition through time. To estimate the relative total deposition throughout the channel the positive (accretion) seabed elevation change from one hydrosurvey to the next was summed for each DEM grid cell between all successive surveys. In this way, only sediment deposition is summed and periods of negative seabed change (predominantly dredging) are not considered, providing an indication of areas that experienced relatively high rates of sedimentation compared to the rest of the channel. As such, the relative total deposition from all of the hydrosurveys gives a simple metric that highlights the hot spots in the channel that experienced repeated sediment accretion/shoaling and is relatively insensitive to variations in dredging depths or times and changing project depths. The hot spots stand out as having high relative deposition compared to other parts of the channel.

4.3.2 Redwood City Harbor Channel

The hydrographic surveys show the Redwood City Harbor Channel frequently aggraded above the project depth and was then dredged to either return the channel to the project depth or remove highly shoaled regions. Figures 4.3-1 through 4.3-11 highlight the thickness and the area of the seabed that was above project depth for each of the hydrographic surveys. Shoaling of the channel is shown by the continual increase in the area and thickness of the channel above the project depth, for example, from November 19, 2006, through October 28, 2008 (Figures 4.3-4 and 4.3-5). Conversely, dredging between September 13, 2005, and December 24, 2005, resulted in a reduction in the area and thickness above the project depth (Figures 4.3-2 and 4.3-3). Two sections of the Redwood City Harbor Channel consistently shoaled to above project depth. The regions that have historically been most prone to shoaling are on the western side of the channel southeast of Bair Island and in the north/south trending portion of the channel. These regions are most evident on Figures 4.3-5 and 4.3-6. Figure 4.3-12 shows that these regions have the greatest cumulative sediment deposition, indicating that they are hot spots undergoing a higher amount of shoaling than the rest of the channel. A possible effect of shipping traffic on sedimentation in the channel is highlighted by a generally narrow and deep region within the Redwood City Harbor Channel that remains even as the channel infills. Presumably, shipping traffic resuspends sediment from the center of the channel and the sediment is then deposited along the sides of the channel. This possible influence of shipping traffic on sedimentation is clearly seen in Figures 4.3-5, 4.3-10, and 4.3-11, where there is a relatively narrow and deep sub-channel inside the Redwood City Harbor Channel.

Each hydrographic survey was compared to the authorized project depth to estimate both the area of the channel above the project depth and the volume of sediment above the project depth. The hydrographic surveys show that both the area of the channel above the project depth and the sediment volume above the project depth increase as sediment is deposited within the channel (Figures 4.3-13 and 4.3-14). Dredging then reduces the area and volume above project depth. This dredging is highlighted on the figures by a break in the assumed linear trends between the surveys (dashed lines) and a reduction in the areas and volumes. The hydrosurveys indicate that a knockdown is effective at reducing the area and volume of the regions that are far above the project depth. For example, the surveys suggest a knockdown event in late 2009 when the volume from 0 to 1 foot above project depth increases while the volume greater than 1 foot above the project depth decreases (Figure 4.3-14). Even though the volume of sediment from 0 to 2 feet above project depth was decreased by this knockdown, the area of the channel in the same range was increased (Figure 4.3-13, light blue markers). The effects of the knockdown on the height of the seabed above the project depth throughout the channel can be seen on Figure 4.3-6.

The relative change in sediment volume in the Redwood City Harbor Channel can give insight into the rate of sediment accretion in the channel through time and the amount of dredging required. Figure 4.3-15 highlights six repeated episodes of sediment accretion followed by dredging within the Redwood City Harbor Channel. The fall 2005 and fall 2009 dredging episodes completely deepened the channel to the authorized project depth (30 feet MLLW).

The change in sediment volume in the channel was used to estimate the average rate of sediment accretion in the Redwood City Harbor Channel. Five periods of variable duration were available that had both an after dredging survey to give a starting sediment volume in the channel and then a before dredging survey giving an ending sediment volume (Figure 4.3-15). These after dredging and before dredging surveys provided changes in the sediment volume in the channel over discrete lengths of time and were used for calculating rates of sediment accretion within the channel. A simple weighted average based on the duration and magnitude of the five individual accretion rates was also calculated to estimate a longer term sediment accretion rate from about 8 years of data.

By using only the after dredging and before dredging surveys, the average sedimentation rate from one dredging episode to the next can be estimated (Figure 4.3-16). The average sedimentation rate between dredging episodes was estimated by calculating the change in sediment volume in the channel from the after dredging surveys to the before dredging surveys and dividing by the length of time between the surveys. The hydrosurvey data in the Redwood City Harbor Channel allowed for the estimation of five individual sedimentation rates ranging from about 159,000 yd^3 yr^{-1} to about 291,000 yd^3 yr^{-1}. The five episodes of sediment accretion followed by dredging were used to calculate an average rate of sediment accretion of about 183,000 yd^3 yr^{-1} using about 8 years of data. The estimated sediment deposition within the channel from one dredging episode to the next was greater than the maximum uncertainty in the sediment volumes (described in Section 3.1), highlighting that the calculated rate of sediment accretion is robust with regard to uncertainty in the calculated channel sediment volumes (Figure 4.3-17). The short 176-day accretion rate calculated in 2012 during a winter to spring time period potentially indicates the sediment deposition in the Redwood City Harbor Channel is not constant throughout the year, but rather experiences periods of relatively higher sedimentation either seasonally or in response to storm events. The estimated 183,000 yd^3 yr^{-1} sedimentation rate based on the hydrosurvey data agreed with an independent estimate of 180,000 yd^3 yr^{-1} that was made using dredging information from 1993 through 2009 provided by USACE.

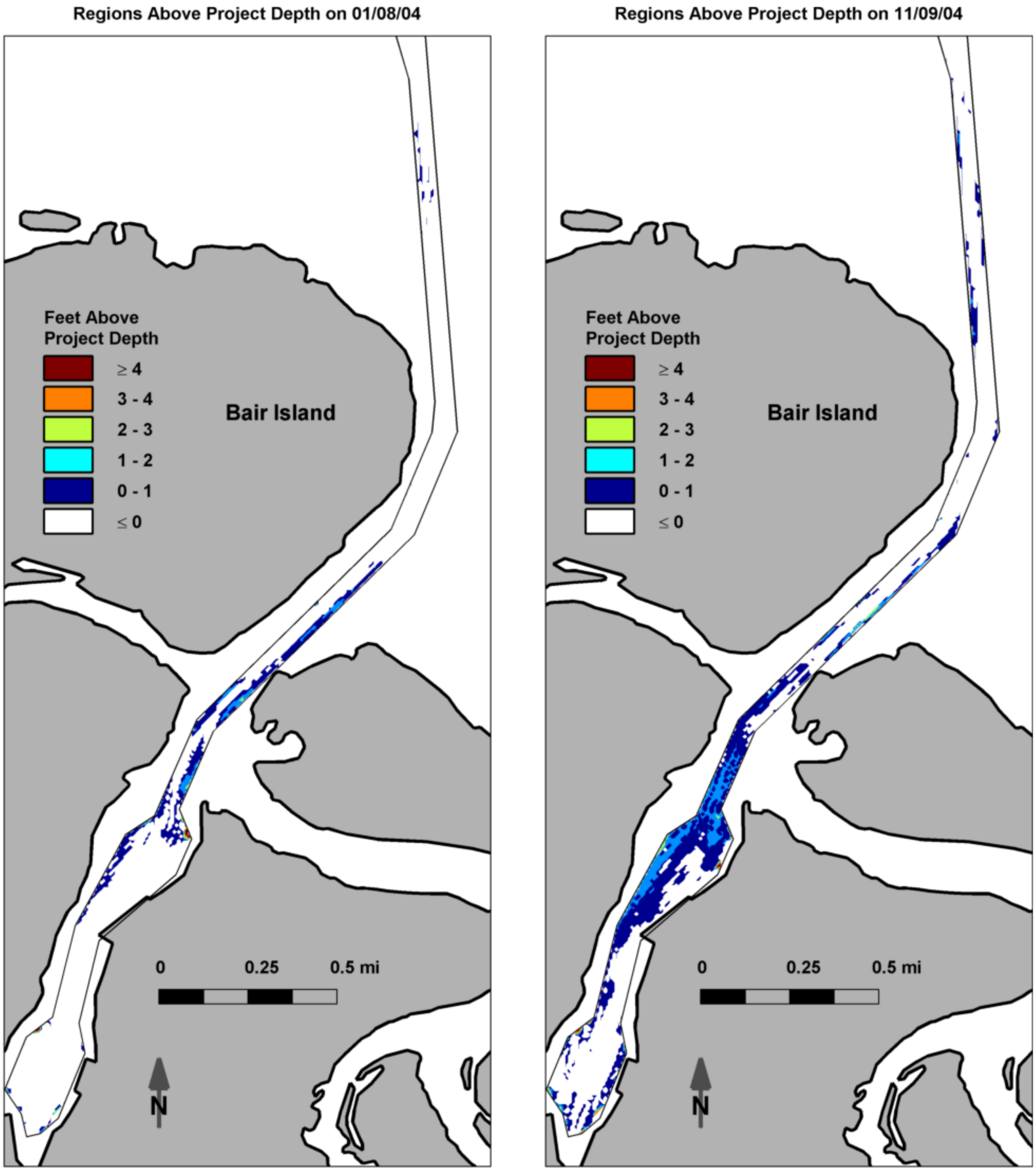


Figure 4.3-1
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on January 8, 2004, and November 9, 2004. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

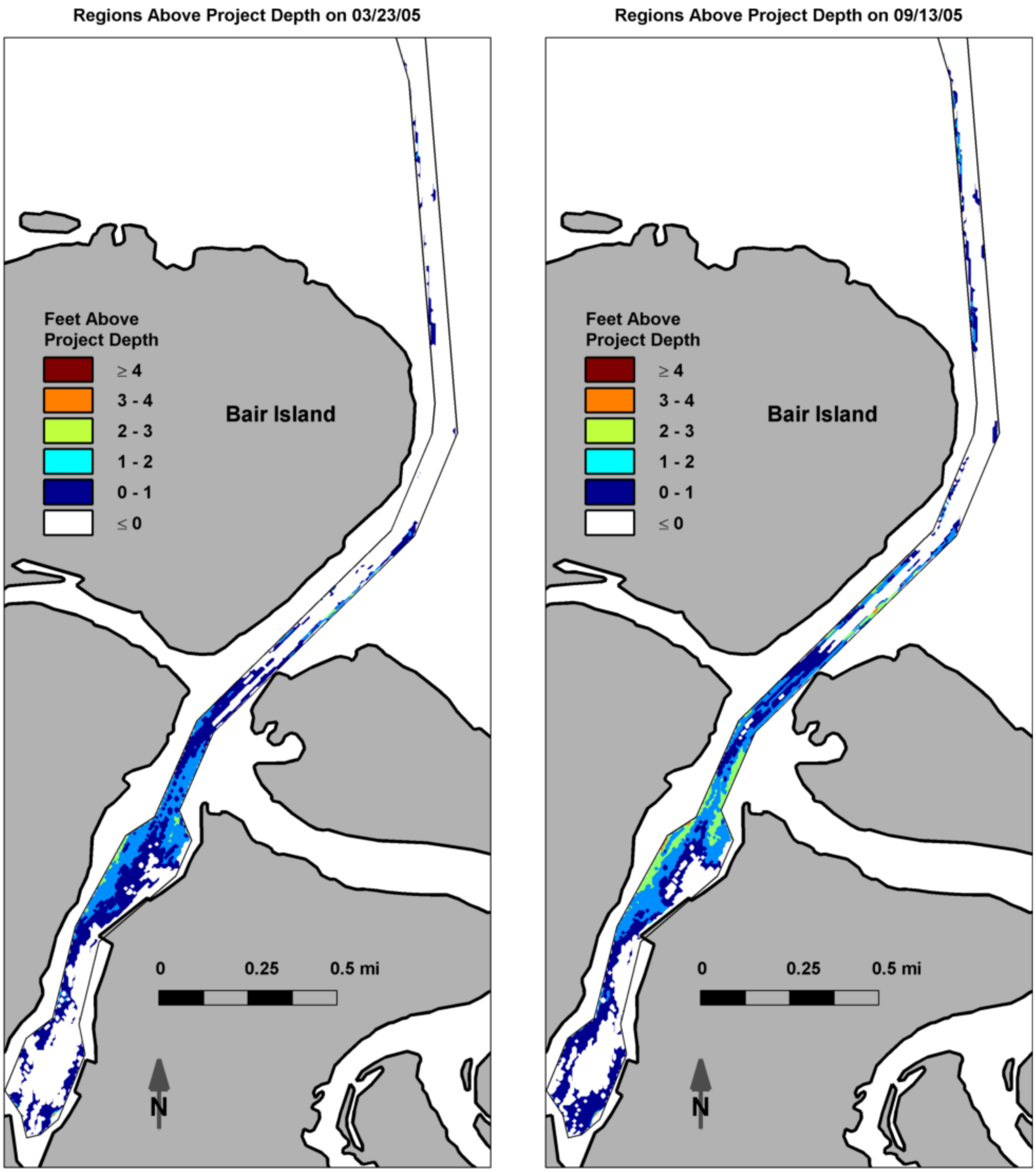


Figure 4.3-2
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on March 23, 2005, and September, 13 2005. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

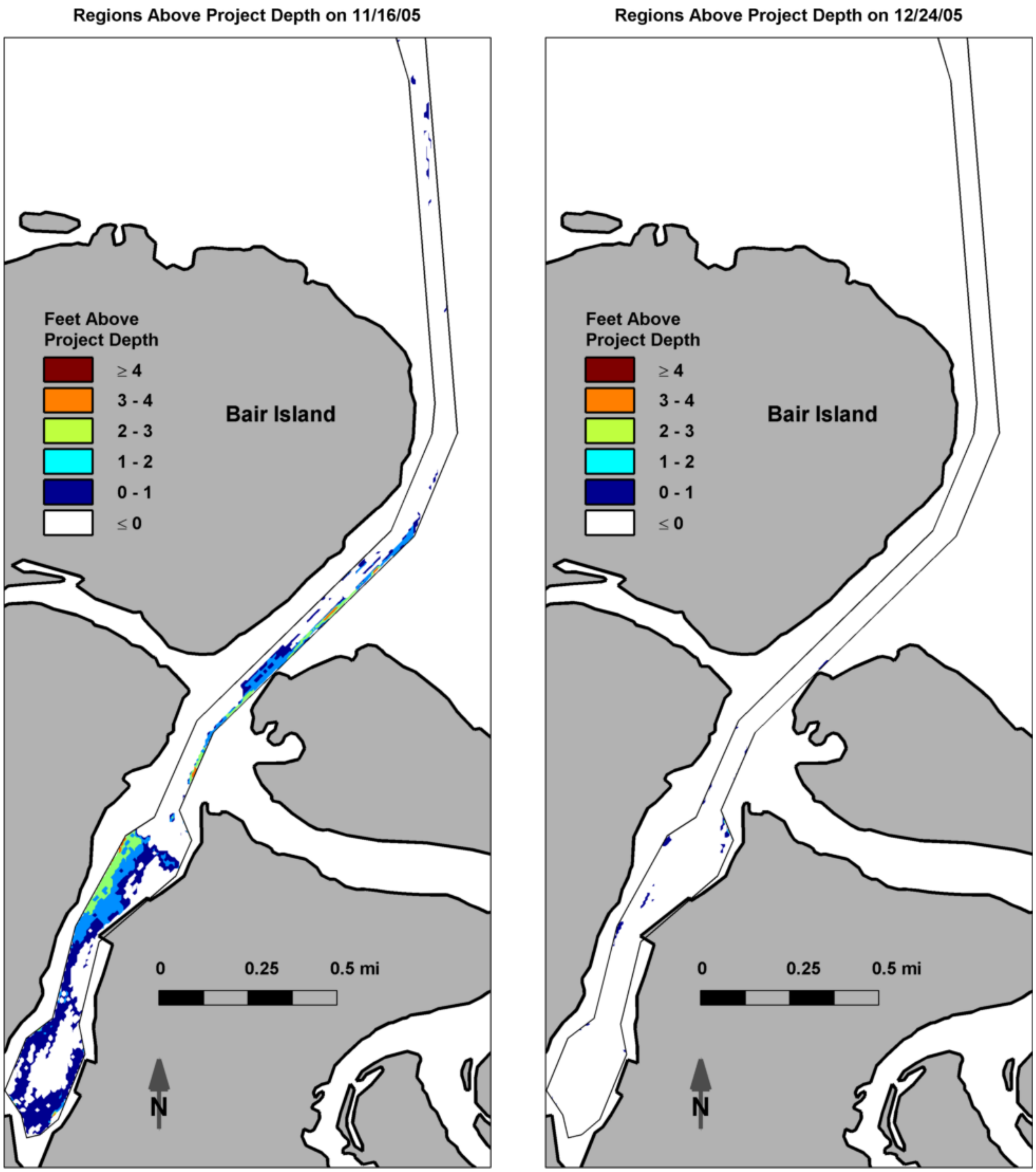


Figure 4.3-3
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on November 16, 2005 and December 24, 2005. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

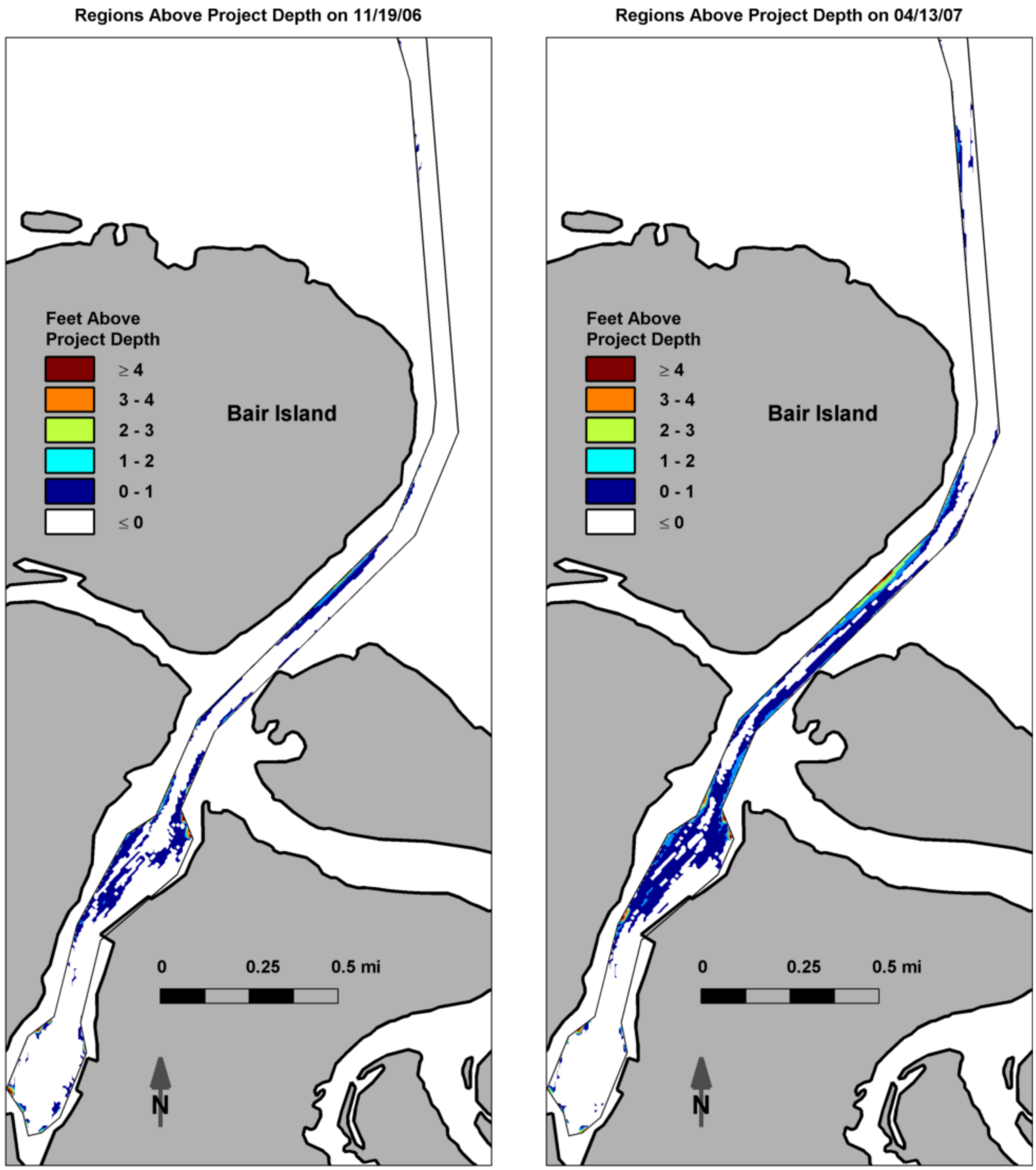


Figure 4.3-4
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on November 19, 2006, and April 13, 2007. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

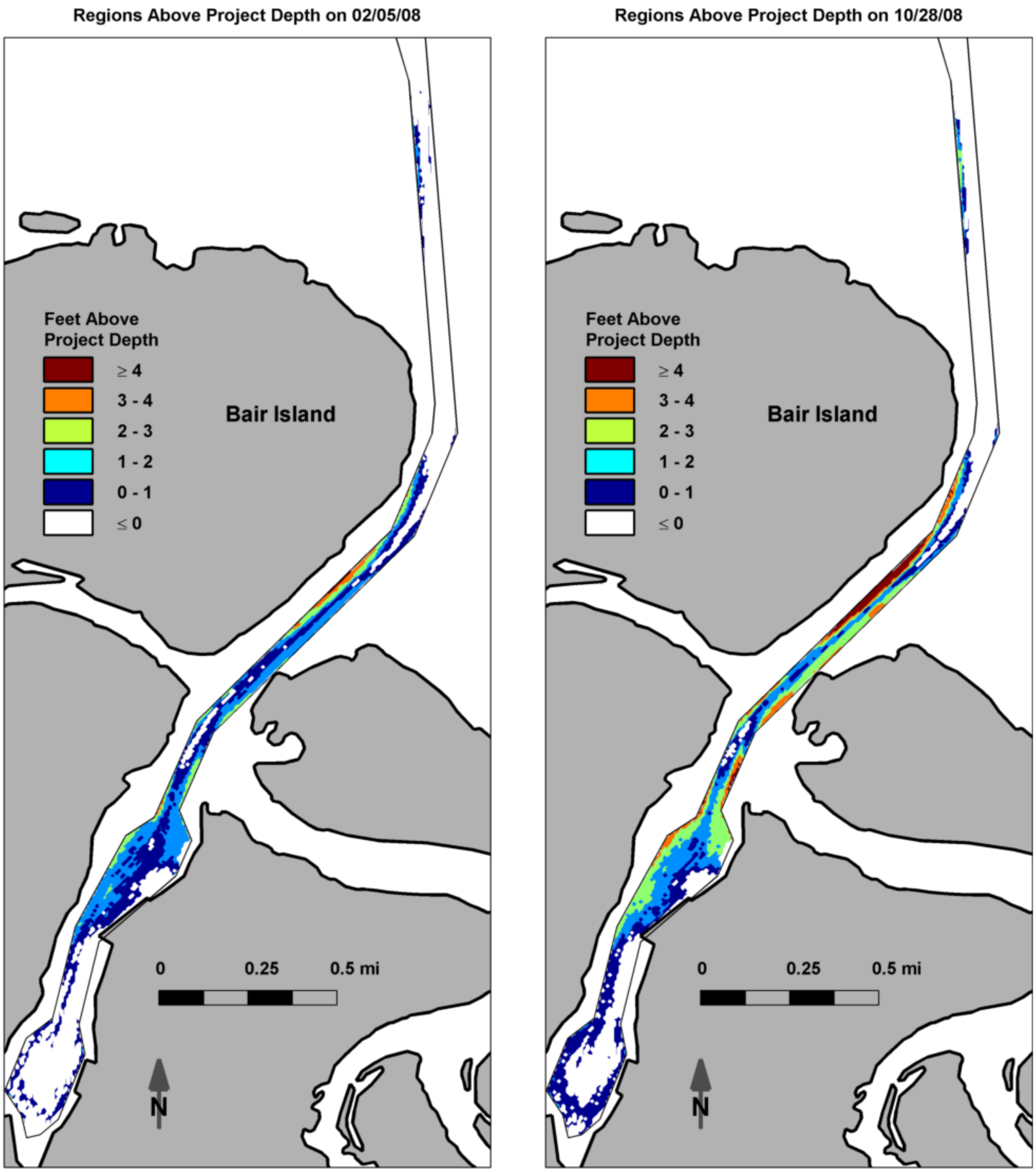


Figure 4.3-5
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on February 5, 2008, and October 28, 2008. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

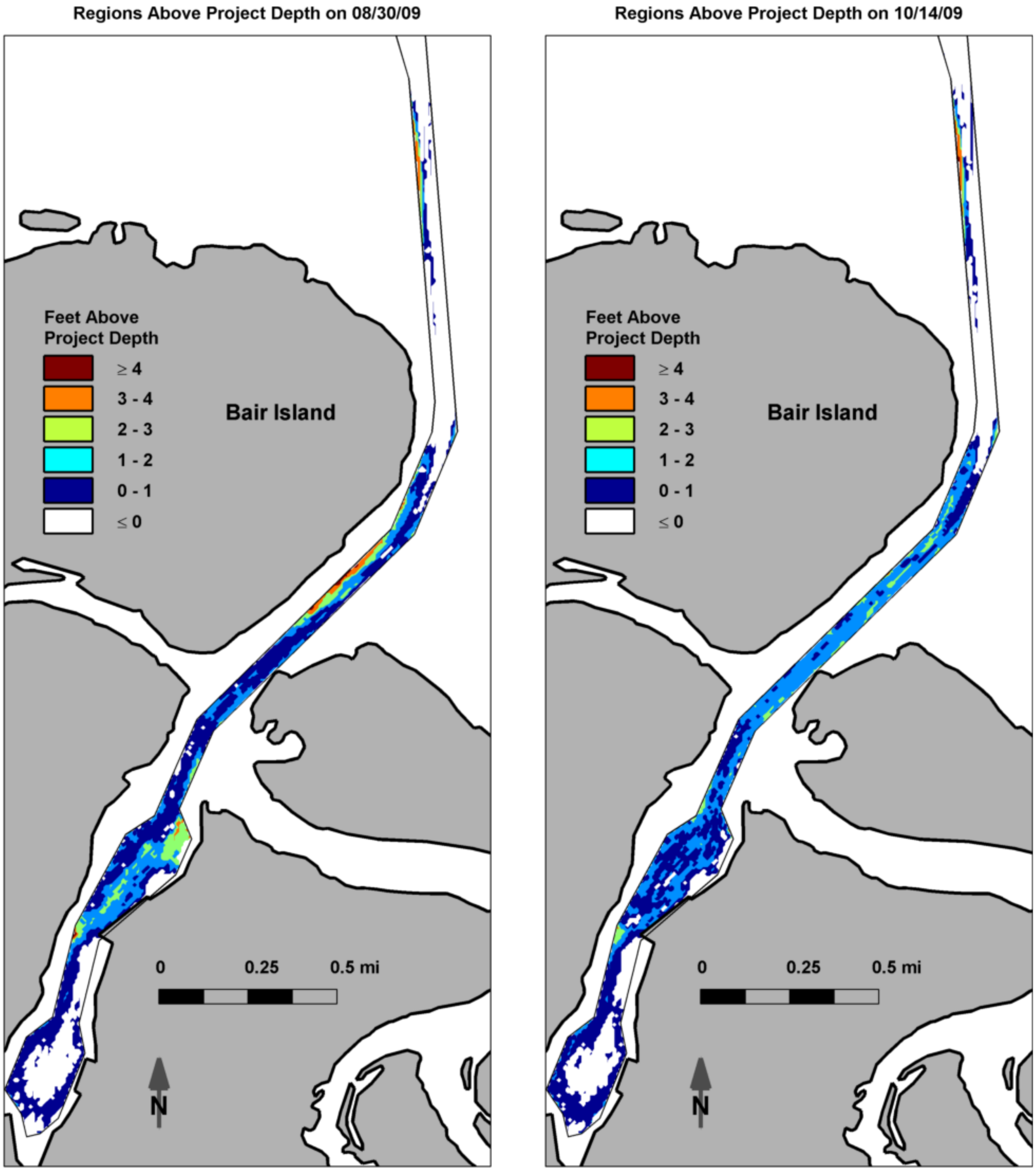


Figure 4.3-6
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on August 30, 2009, and October 14, 2009. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

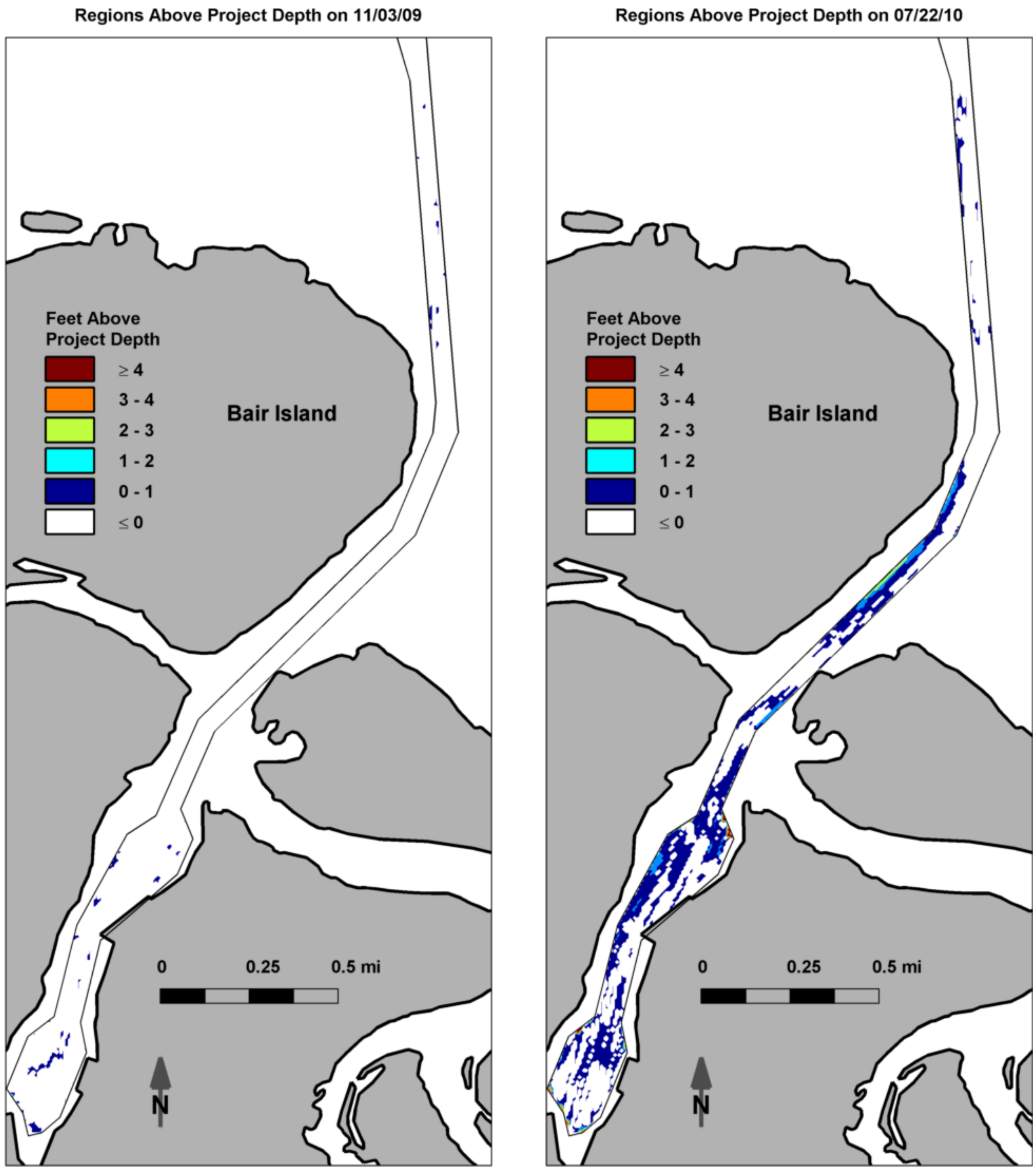


Figure 4.3-7
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on November 3, 2009 and July 22, 2010. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

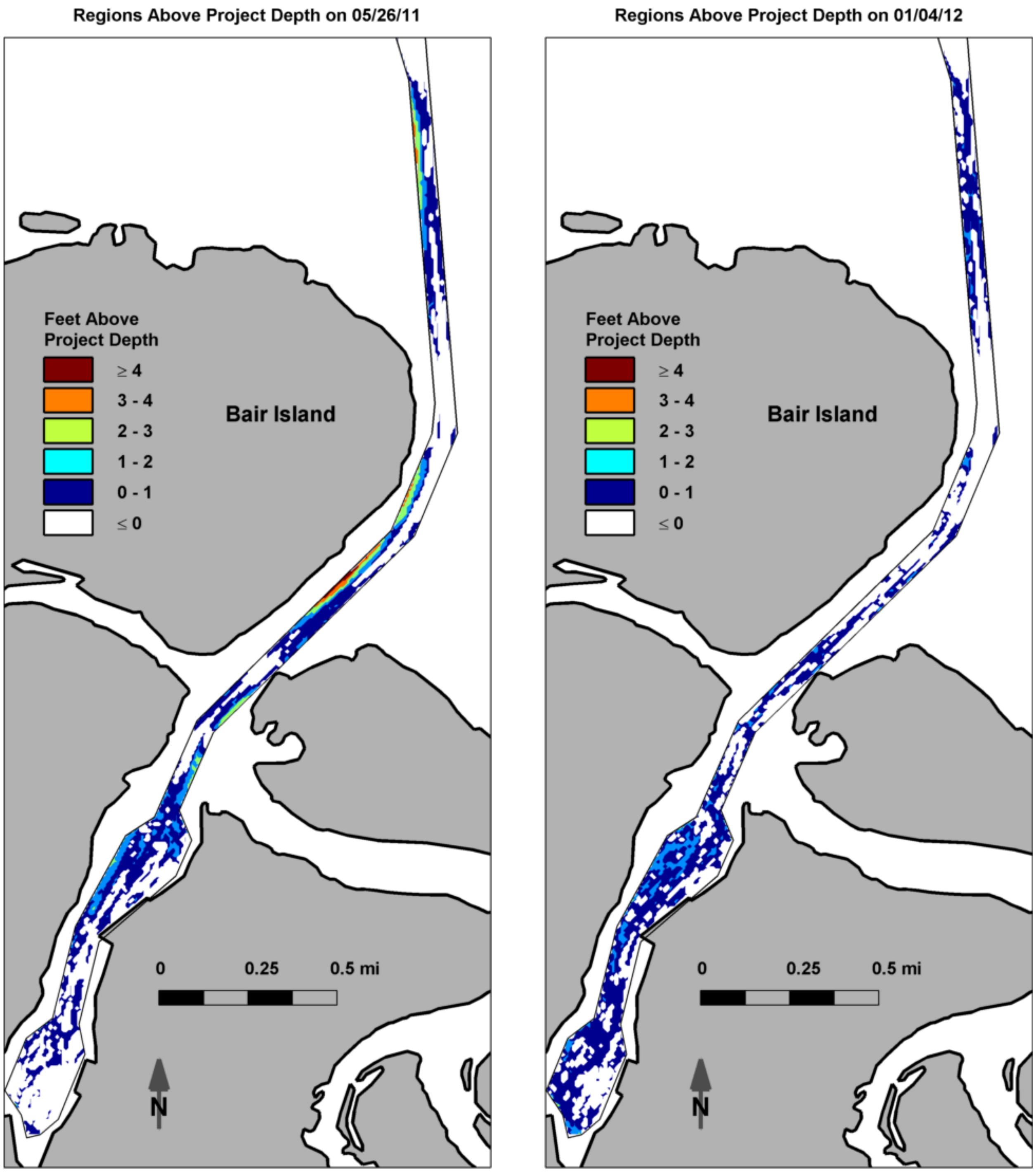


Figure 4.3-8.
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on May 26, 2011, and January 4, 2012. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

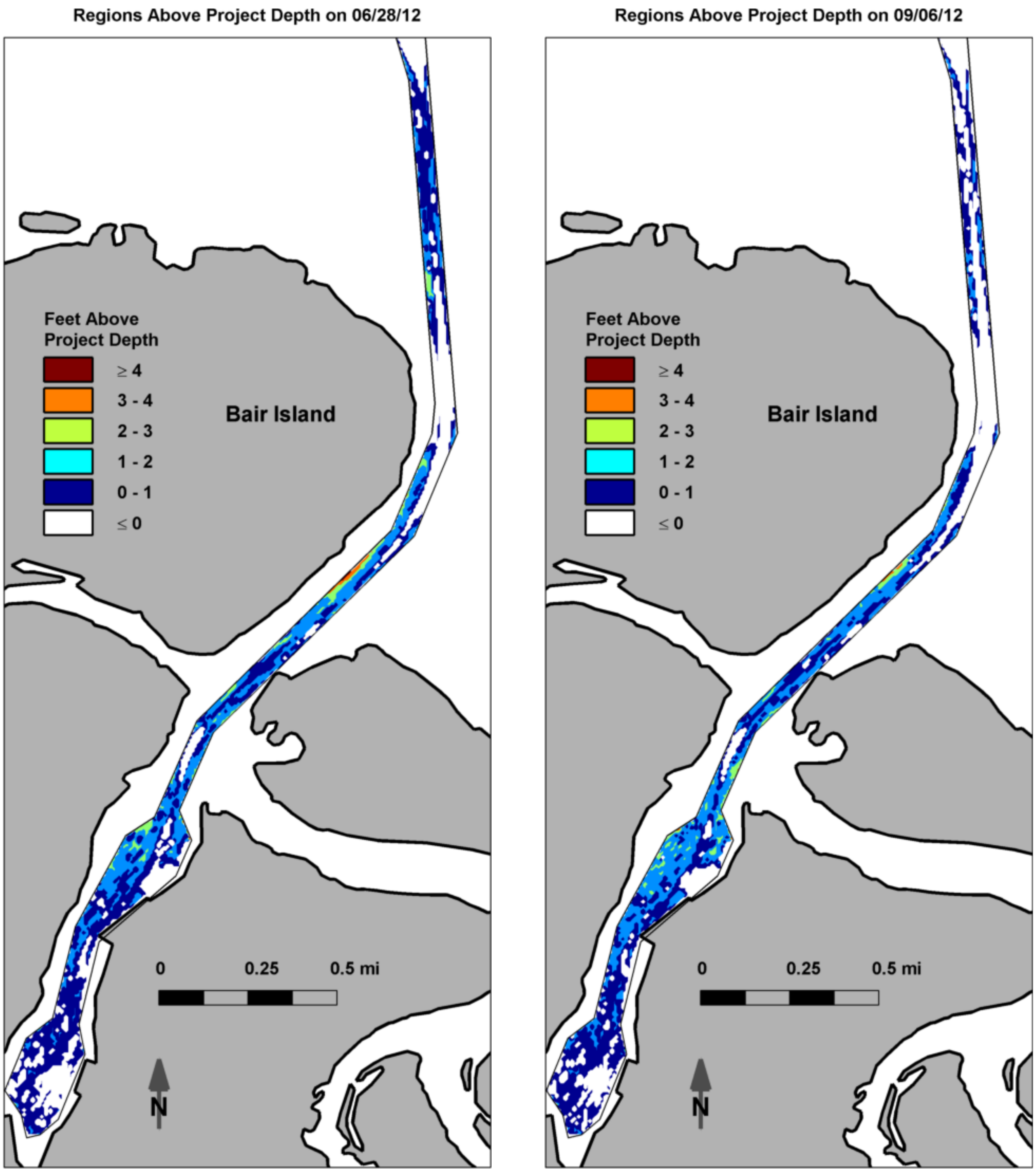


Figure 4.3-9
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on July 28, 2012, and September 6, 2012. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

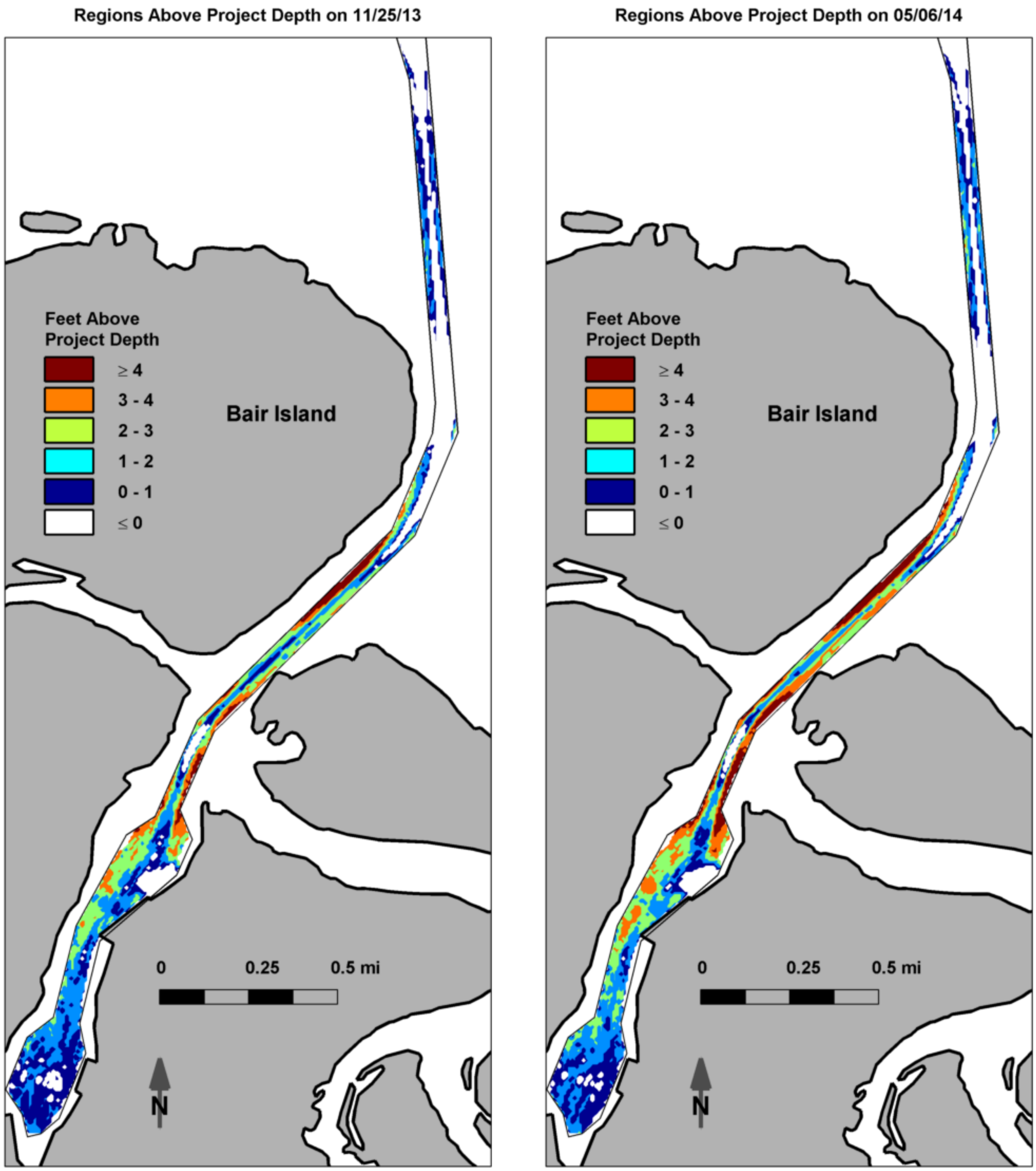


Figure 4.3-10
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on November 25, 2013, and May 6, 2014. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

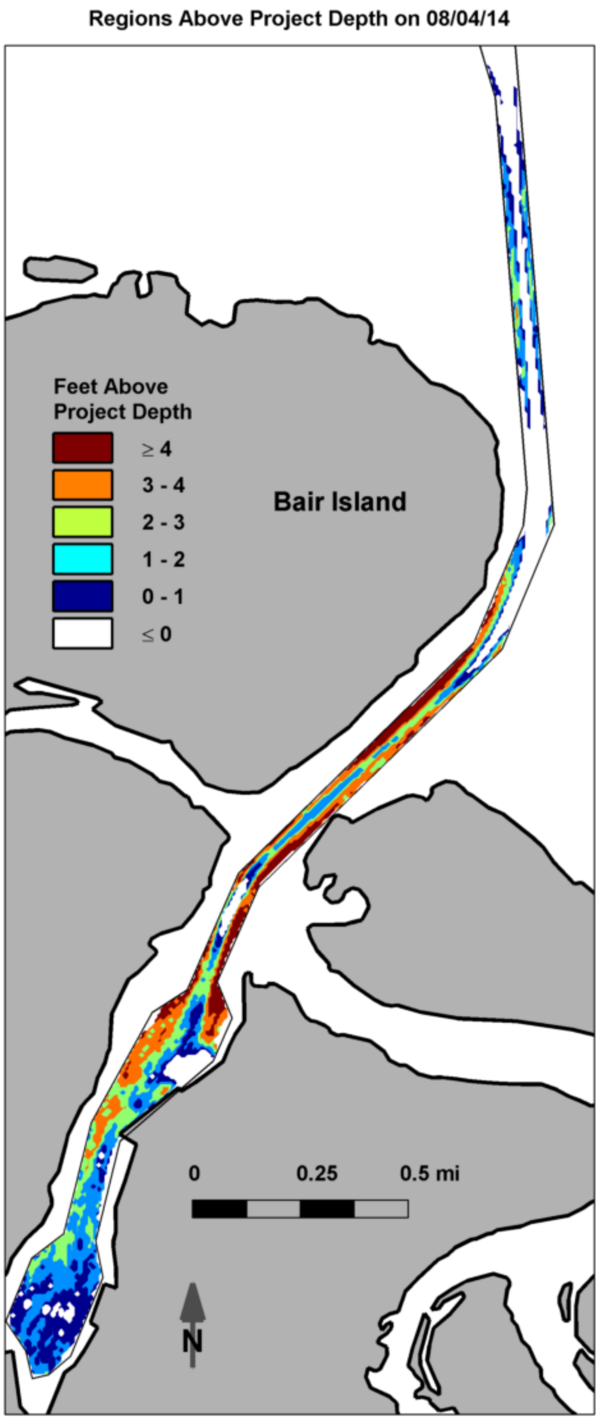


Figure 4.3-11
The regions above the Redwood City Harbor Channel project depth for five different heights above the project depth on August 4, 2014. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white.

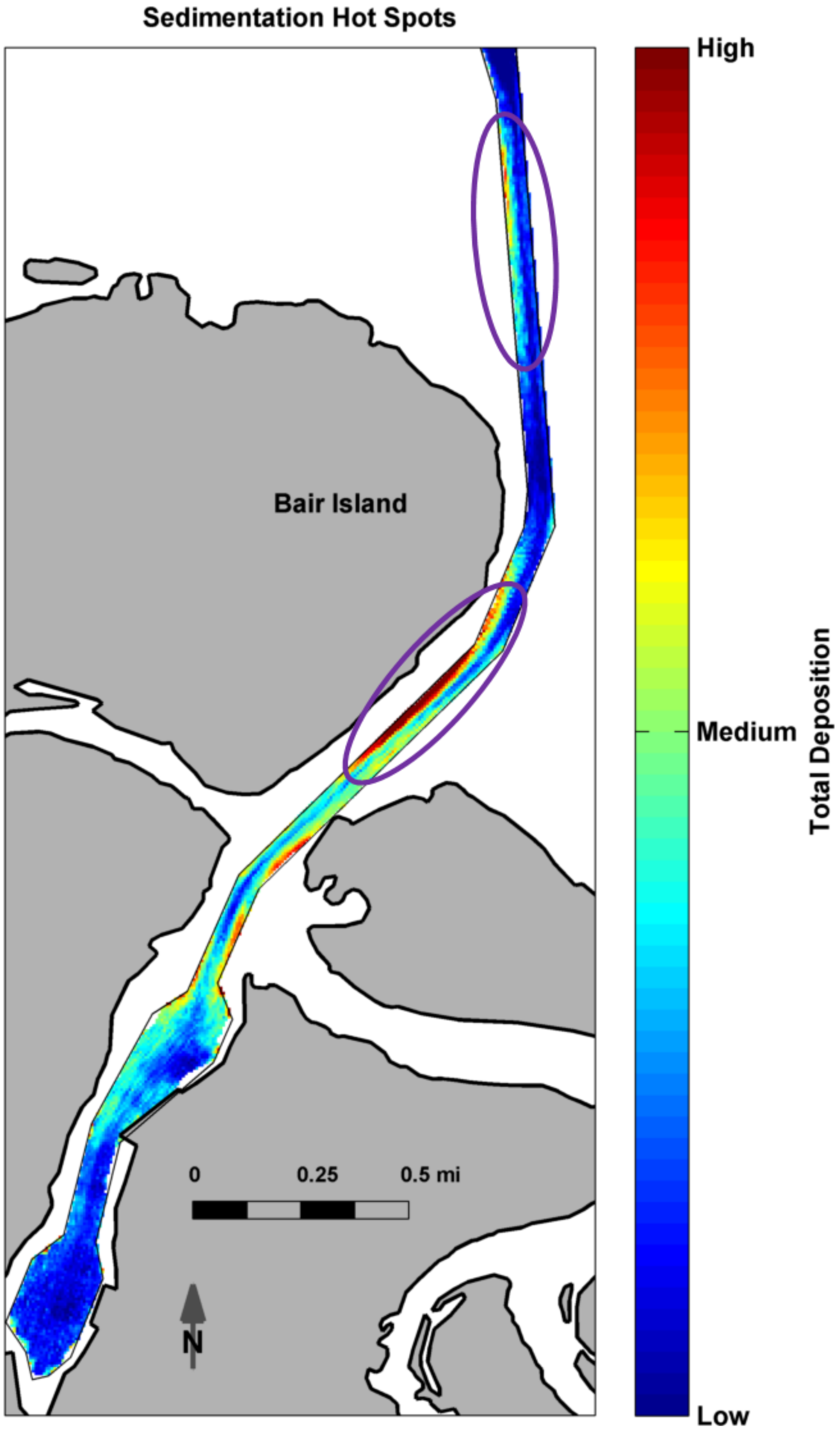


Figure 4.3-12
The relative sedimentation throughout the Redwood City Harbor Channel. Regions of relatively high sedimentation are indicative of areas experiencing a relatively high amount of shoaling. The predicted hot spots for sediment deposition in the channel are circled.

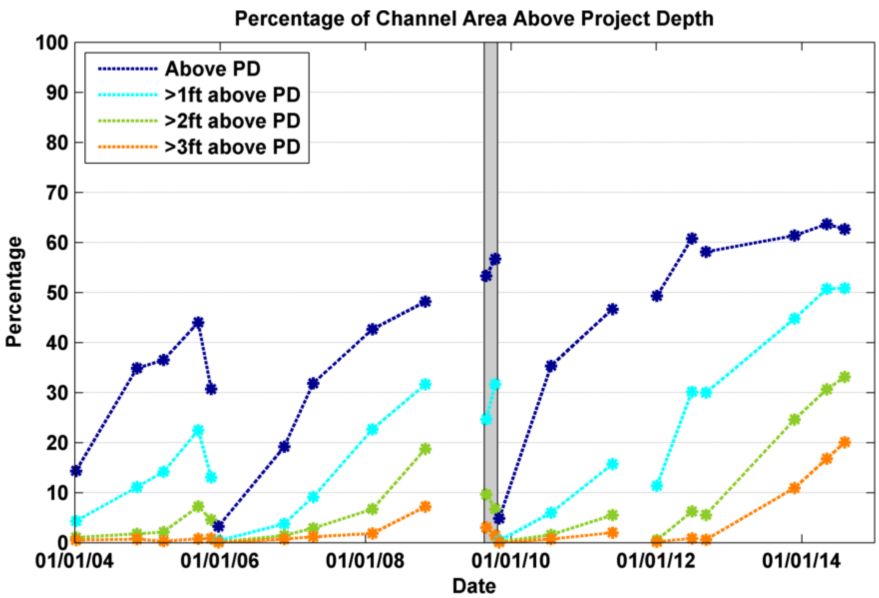


Figure 4.3-13
The percentage of the Redwood City Harbor Channel above the project depth for four different height ranges (stars). Dashed lines show an assumed linear trend between the surveys. Breaks in the lines are due to periods of dredging. The large reduction in area above project depth in late 2005 is shown because a full survey was conducted midway through dredging. Shading highlights a knockdown event.

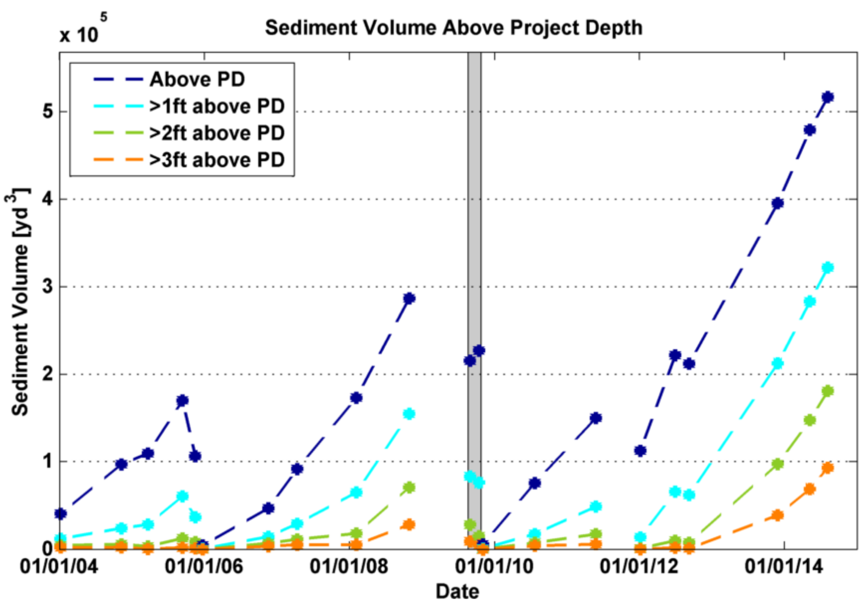


Figure 4.3-14
The volume of sediment above the Redwood City Harbor Channel project depth for four different height ranges (stars). Dashed lines show an assumed linear trend between the surveys. Breaks in the lines are due to periods of dredging. The large reduction in volume above project depth in late 2005 is shown because a full survey was conducted midway through dredging. Shading highlights a knockdown event.

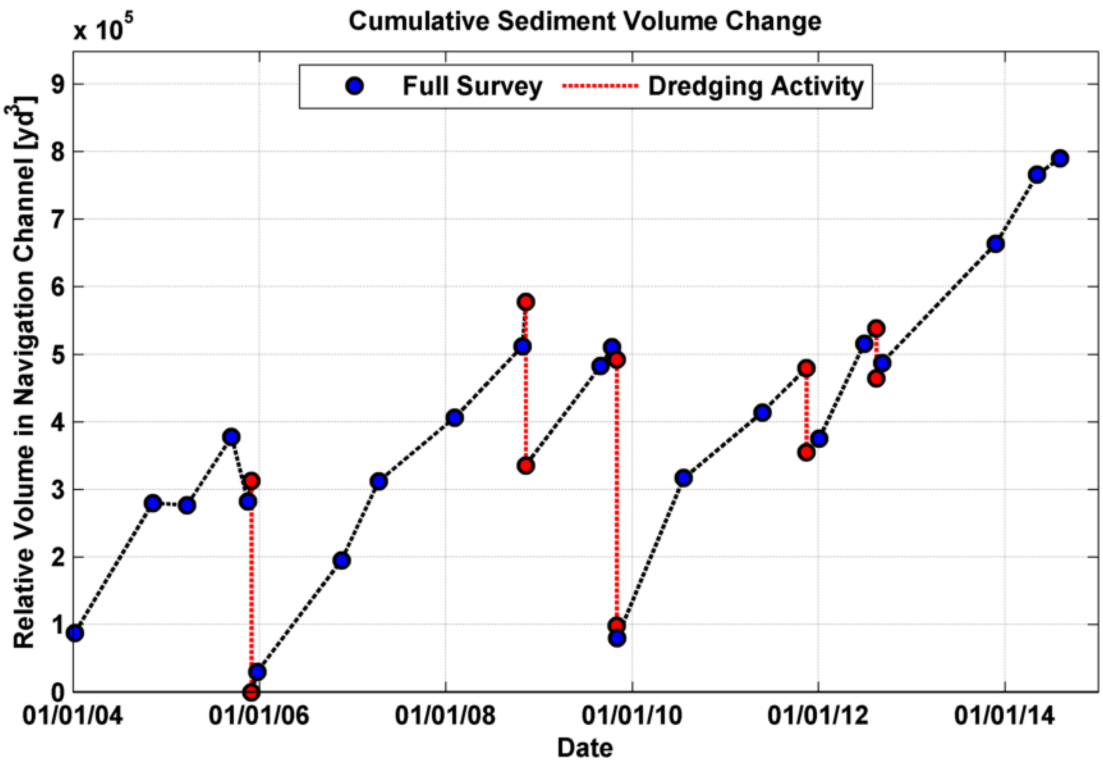


Figure 4.3-15
Relative sediment volume through time in the Redwood City Harbor Channel highlighting the change in the sediment volume through time due to accretion and dredging. Sediment volume in the channel is zeroed at the lowest sediment volume and is calculated using only the full surveys. As such the sediment volume in the channel is relative to after dredging in the late fall of 2005. Dark blue dots show the relative sediment volume in the channel calculated from the full surveys of the channel and are connected by an assumed linear sediment deposition trend between surveys (black dotted lines). Red dots show inferred approximate sediment volumes before and after dredging. The vertical red lines are the reported dredge volumes.

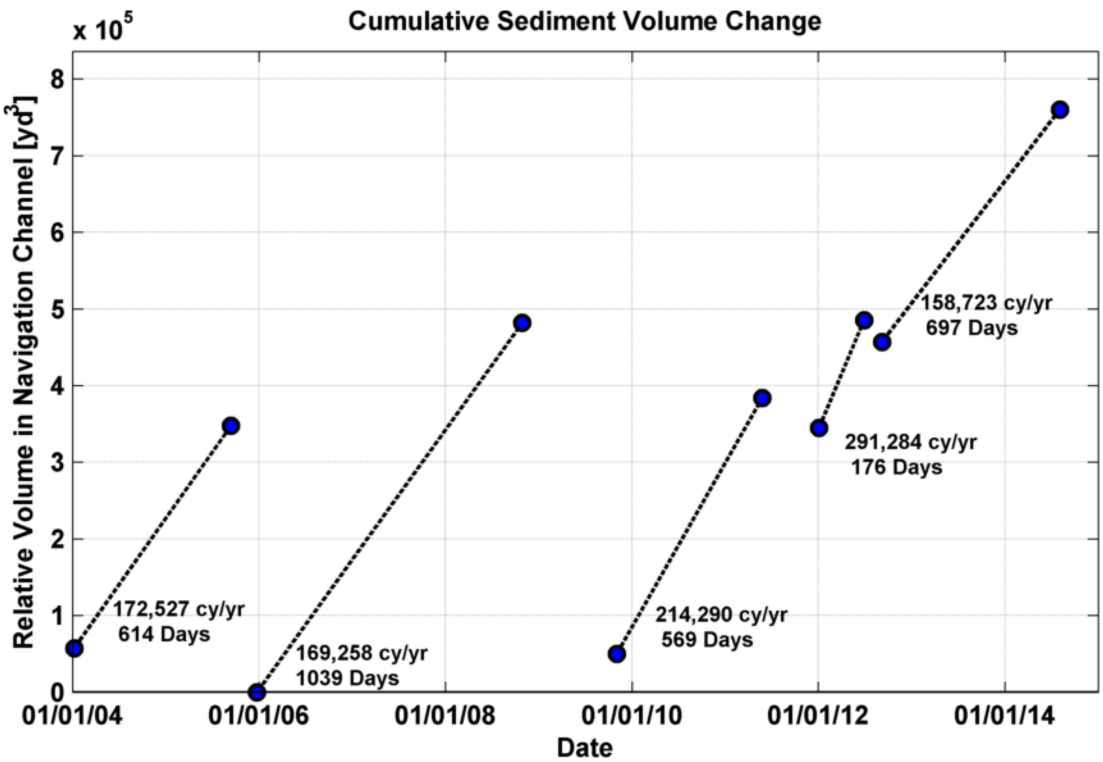


Figure 4.3-16.
Relative sediment volume through time in the Redwood City Harbor Channel highlighting the change in the sediment volume through time due to accretion and dredging. Sediment volume in the channel is zeroed at the lowest sediment volume and is calculated using only the full surveys. As such, the sediment volume in the channel is relative to post dredging in the late fall of 2005. Dark blue dots show the relative sediment volume in the channel calculated from the full surveys of the channel and are connected by an assumed linear sediment deposition trend (black dotted lines). Only time periods with surveys following and then preceding dredging are shown. The text labels show the average sedimentation rates and the length of time of each depositional episode.

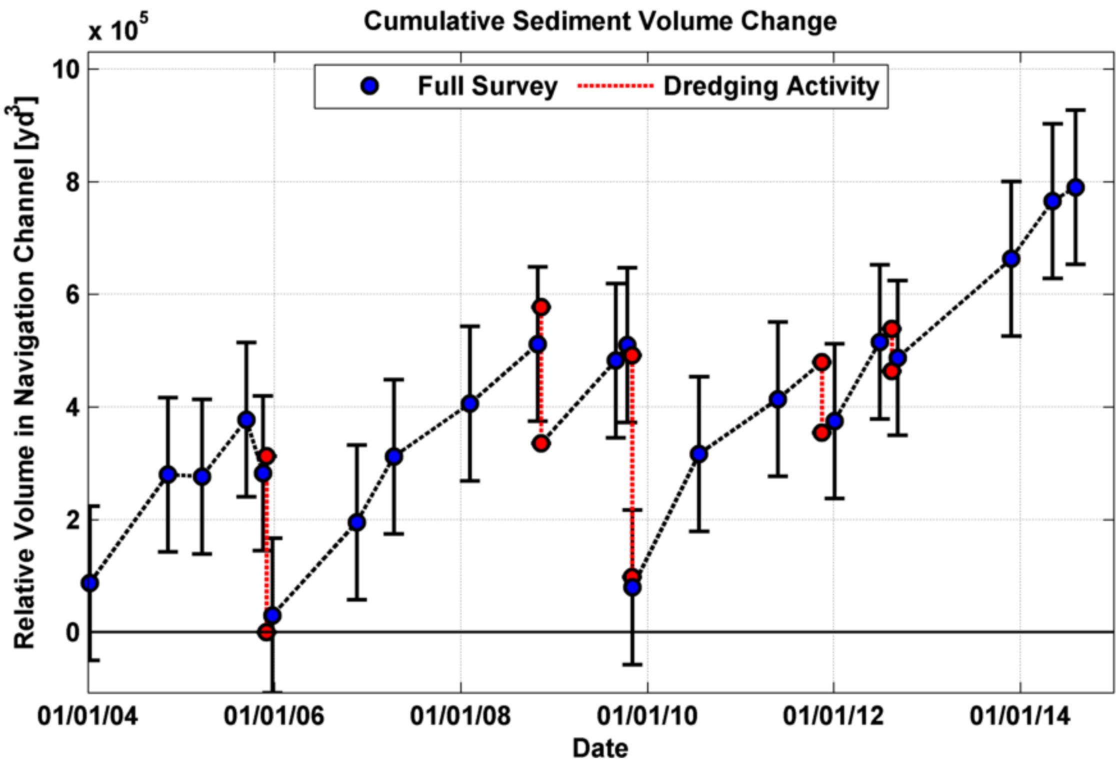


Figure 4.3-17
Relative sediment volume through time in the Redwood City Harbor Channel highlighting the change in the sediment volume through time due to accretion and dredging. Sediment volume in the channel is zeroed at the lowest sediment volume and is calculated using only the full surveys. As such, the sediment volume in the channel is relative to after dredging in the late fall of 2005. Dark blue dots show the relative sediment volume in the channel calculated from the full surveys of the channel and are connected by an assumed linear sediment deposition trend between surveys (black dotted lines). Red dots show inferred approximate sediment volumes before and after dredging. The vertical red lines are the reported dredge volumes. Error bars denote the maximum estimate of uncertainty in the sediment volume calculations from the hydrographic surveys (about ±137,000 yd^3, Section 4.3.1).

4.3.3 San Bruno Shoal Channel

The hydrographic surveys show the San Bruno Shoal Channel rarely aggraded above the project depth over the period when hydrosurvey data were available between July 2002 and April 2014. Figure 4.3-18 highlights surveys on October 15, 2005, when the largest volume of sediment was above the project depth (30 feet MLLW) and November 20, 2006, following a targeted dredging episode that returned the channel to below the project depth. Less than 3.5% of the channel area was above the authorized project depth during the analysis period

(Figure 4.3-19), and less than 16,000 yd^3 of sediment was above the project depth (Figure 4.3-20).

Figure 4.3-21 highlights the sediment volume change in the San Bruno Shoal Channel from July 2002 to April 2014. Only a single and relatively small dredging episode occurred during this time period (Patrick Sing, USACE, Pers. Comm., 2013). The 2002 through 2014 time period shows both periods of net erosion from the channel and periods of sediment accretion. All of the sediment volumes within the channel are within the maximum potential error of nearly every other survey, limiting the applicability of calculating net sediment accretion or erosion rates. Because of this, and the lack of a clear trend in the relative sediment volume in the channel, accretion rates have not been calculated for the San Bruno Shoal Channel.

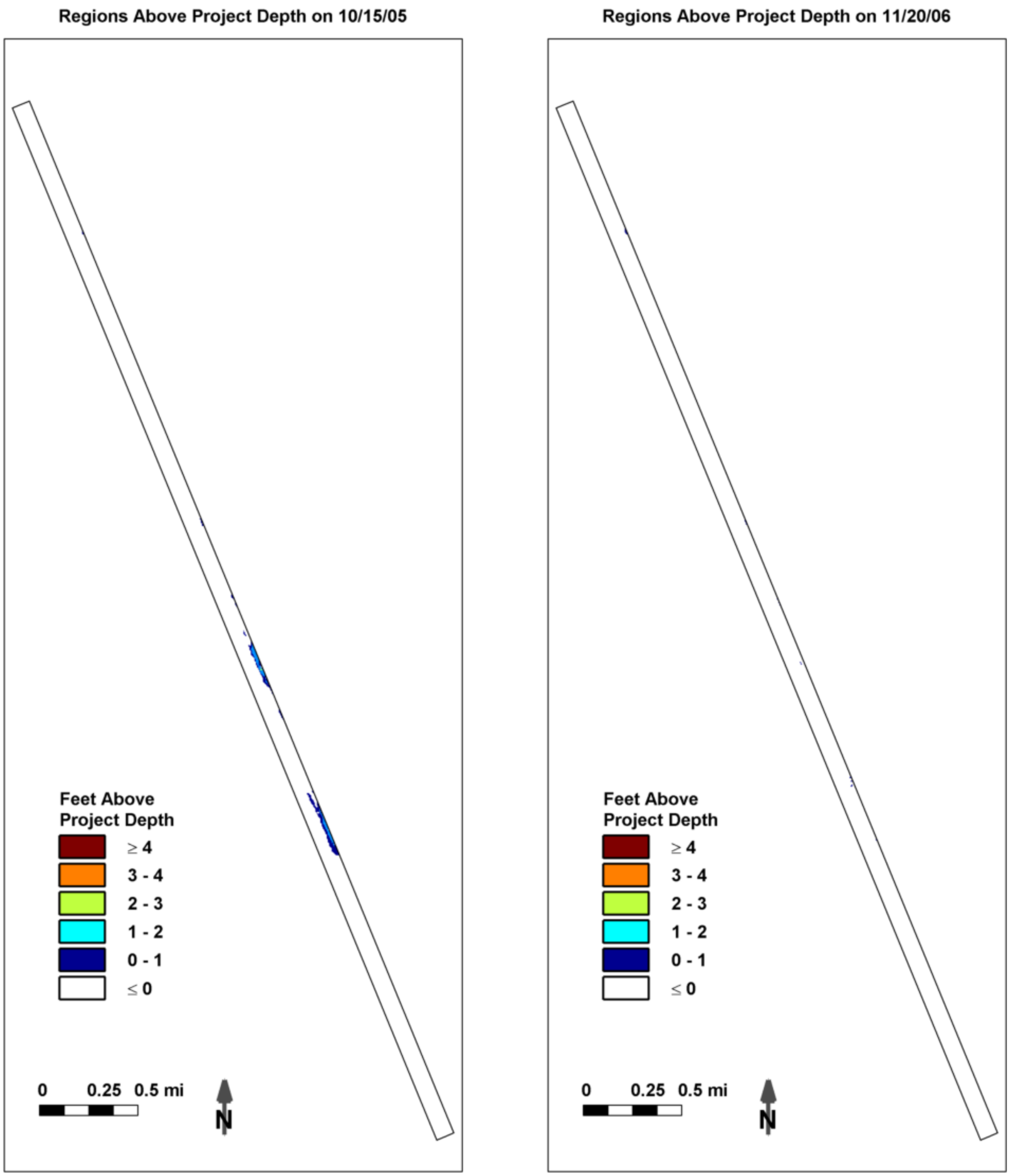


Figure 4.3-18
The regions above the San Bruno Shoal Channel project depth for five different heights above the project depth on about November 15 2005, and November 20, 2006. The outline of the authorized navigation channel is shown as the thin black line. Regions in the channel below project depth are colored white. Dredging was conducted between the dates of these surveys.

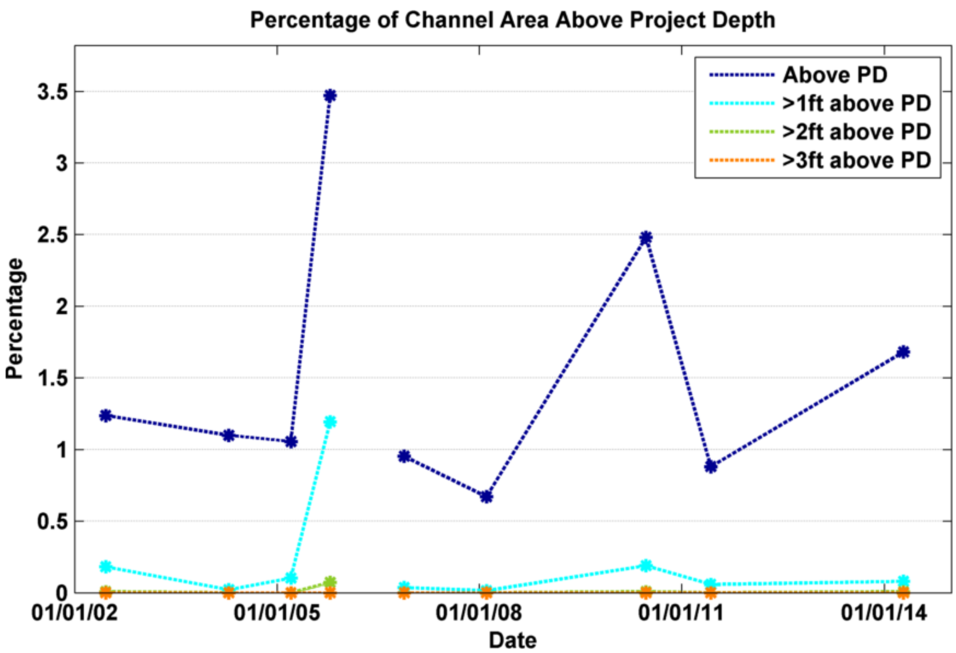


Figure 4.3-19
The percentage of the area of the San Bruno Shoal Channel above the authorized project depth for four different height ranges (stars). Dashed lines show an assumed linear trend between the surveys. The break in the lines is due to a dredging episode.

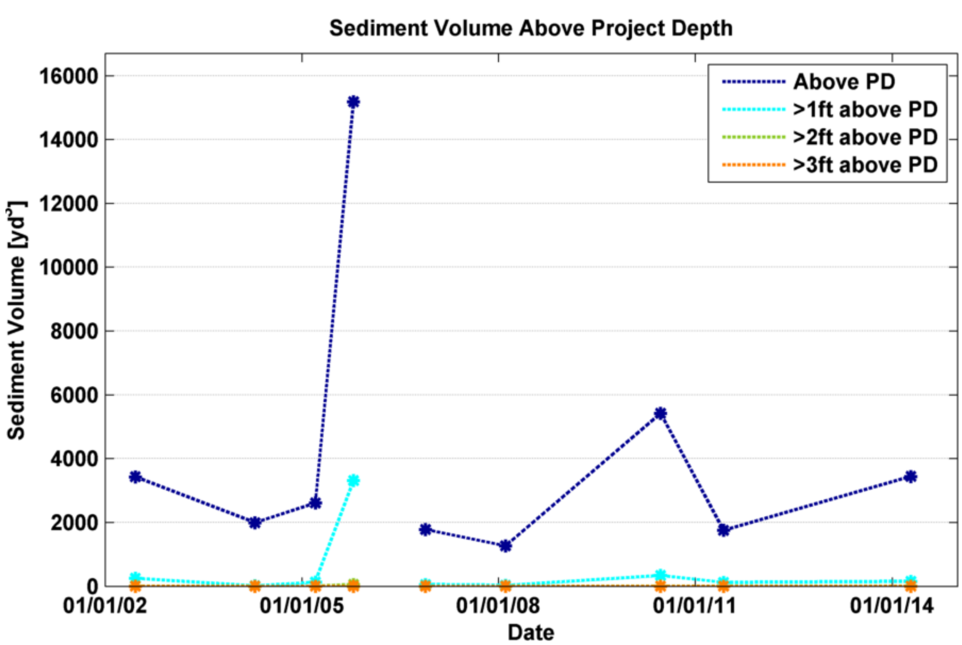


Figure 4.3-20
The volume of sediment above the San Bruno Shoal Channel authorized project depth for four different height ranges (stars). Dashed lines show an assumed linear trend between the surveys. The break in the lines is due to a dredging episode.

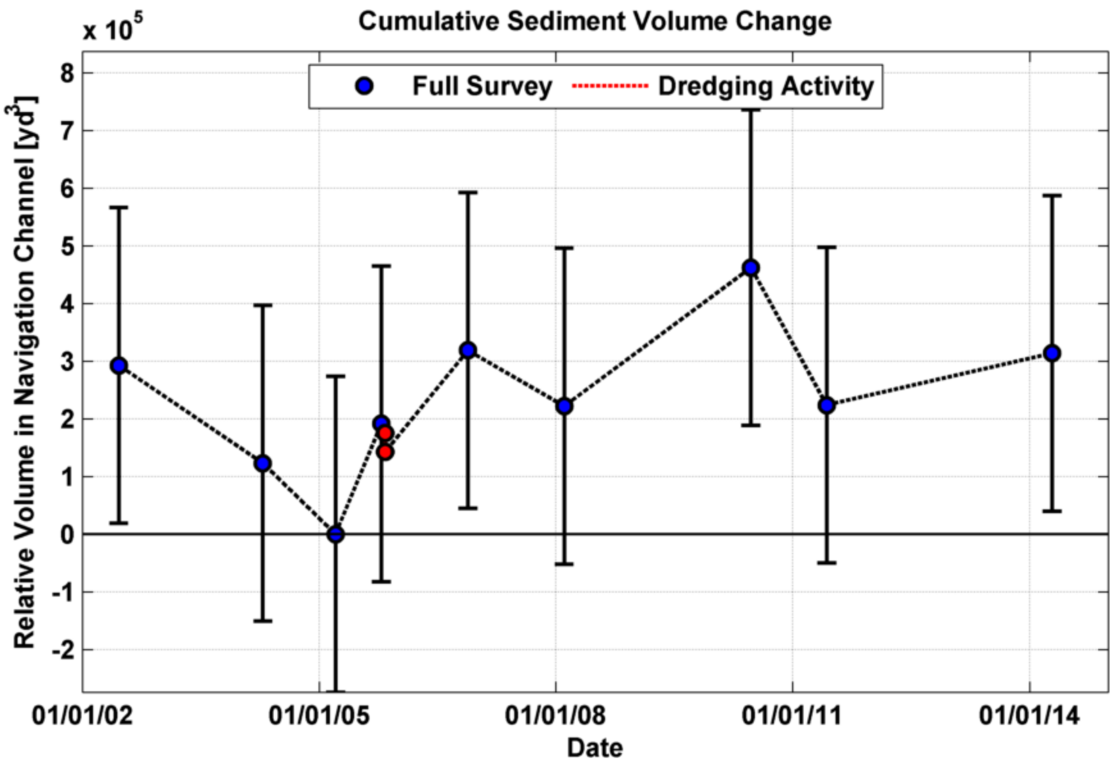


Figure 4.3-21
Relative sediment volume through time in the San Bruno Shoal Channel highlighting the change in the sediment volume through time due to accretion, erosion and dredging. Sediment volume in the channel is zeroed at the lowest sediment volume and is calculated using only the full surveys. As such the sediment volume in the channel is relative to March 17, 2005. Dark blue dots show the relative sediment volume in the channel calculated from the full surveys of the channel and are connected by an assumed linear sediment deposition trend (black dotted lines). Red dots show inferred approximate sediment volumes before and after dredging. Error bars denote the maximum estimate of uncertainty in the sediment volume calculations from the hydrographic surveys (about ±276,000 yd^3, Section 4.3.1).

4.4 Hydrographic Survey Data Conclusions

Regular bathymetric surveys of the Redwood City Harbor Channel were used to calculate an average sediment accretion rate of about 183,000 yd^3 yr^{-1} using 8 years of data. The short 176 day accretion rate calculated in 2012 during a winter to spring time period potentially indicates the sediment deposition in the Redwood City Harbor Channel is not constant throughout the year, but rather experiences periods of relatively higher sedimentation either seasonally or in response to storm events. The estimated 183,000 yd^3 yr^{-1} sedimentation rate based on the hydrosurvey data agreed with an independent estimate of 180,000 yd^3 yr^{-1} made using dredging information from 1993 through 2009 provided by USACE. Two hot spots within the channel were identified, both on the western side of the channel, one southeast of Bair Island and another on the north/south section of the channel. These hot spots are potential candidates for advanced maintenance dredging or channel realignment to reduce the above grade shoaling problems in those areas.

The hydrographic surveys of the San Bruno Shoal Channel suggested that historically the channel has not had a consistent rate of sediment accretion, but rather both periods of sediment accretion and erosion that have led to relatively little long-term net change of sediment volume in the channel.

5 VALIDATION OF THE MODELED SEDIMENT TRANSPORT IN CENTRAL BAY AND SOUTH BAY

The model predictions of sediment transport in Central Bay and South Bay surrounding the study region were validated using observed suspended sediment concentration, sediment deposition volume in the Redwood City Harbor Channel and San Bruno Shoal Channel derived from hydrosurvey data (Section 4), sediment deposition thickness in the channels, and the area of the channel above project depth. Validation of the suspended sediment concentration throughout Central Bay and South Bay was used to show that the model generally predicted the regional suspended sediment concentrations around the study area, while the deposition in the Redwood City Harbor Channel was used to demonstrate that the model was suitable for predicting sediment deposition volumes in the channel and general locations where the deposition occurred. Previous studies have compared suspended sediment concentration predicted by the UnTRIM Bay Delta model to data throughout the San Francisco Bay-Delta system (Bever and MacWilliams 2013, 2014; Delta Modeling Associates 2015), and as such this section is limited to an abbreviated suspended sediment validation. Validation of the water level in the Central Bay and South Bay is presented in Appendix C. In this report, the term "validation" is used to mean determining if the model satisfactorily reproduced observed data, while a model calibration refers to the parameters within the model and the act of improving the model predictions through changing the parameters within the model or the boundary conditions. For example, if a model validation showed that the model was not satisfactorily predicting a set of observations, the model could be calibrated by adjusting the boundary conditions or sediment characteristics until the predictions were within a threshold that indicated the predictions were satisfactory.

Because the calibration and validation of the UnTRIM Bay-Delta model has already been well-documented in previous studies (e.g., MacWilliams et al. 2007, 2008, 2009, 2015; Bever and MacWilliams 2014; Delta Modeling Associates 2015) only a short validation of the model predictions of suspended sediment concentration at the two closest continuous monitoring stations to the focus region and of sediment deposition within the Redwood City Harbor Channel and the San Bruno Shoal Channel are included in this report (Section 5).

5.1 Validation Simulations

5.1.1 Grid Refinement in the Vicinity of the Navigation Channels

The Redwood City Harbor and San Bruno Shoal regions of the UnTRIM Bay-Delta model grid were refined to directly resolve the two navigation channels (Figure 5.1-1). With the grid refinement the grid cells in the Central Bay are about 200 by 250 meters, the cells in the San Bruno Shoal Channel were about 150 by 400 meters, and the cells in the Redwood City Harbor Channel near the Redwood City Harbor were refined to about 25 by 40 meters. The model grid included the eastern portion of Bair Island that was open to tidal flow and Corkscrew, Steinberger, Smith, and Westpoint Sloughs. The model grid also encompassed Outer, Middle, and Inner Bair Island, however these areas were not breached in either the 2006 or 2008 validation simulations.

5.1.2 Redwood Creek Inflow

Inflow data for Redwood Creek were available from a USGS gauging station (11162800) for the period from 1959 through 1997 (USGS 2014). However, flow data were not available for either 2006 or 2008. To estimate Redwood Creek inflows for 2006 and 2008, a scaling relationship was developed to relate the flow in Redwood Creek to the flow in San Francisquito Creek using the data available for the period between 1957 and 1997. The simple derived relationship indicated that the flow in Redwood Creek was 0.0487 times the flow in San Francisquito Creek (Figure 5.1-2). For the period from 1997 through 2014, an inflow hydrograph for Redwood Creek was developed using this scaling relationship and the observed flows in San Francisquito Creek (Figure 5.1-3). Measurements of sediment inflow from Redwood Creek were not available for any time periods, so it was not possible to develop a flow-based sediment rating for Redwood Creek. Because the magnitude of the sediment inflow was assumed to be small compared to the sediment supply to the Redwood City Harbor Channel from the South Bay, sediment inflow from Redwood Creek was not included in the simulations.

5.1.3 Validation Simulation Time Periods

Simulations of water years 2006 and 2008 were used to validate the sediment transport around the Redwood City Harbor Channel and San Bruno Shoal Channel. Water year 2006 was classified as a wet water year, and water year 2008 was classified as critical water year

(CDEC 2014). Thus the simulation of these two years allowed for model validation of sediment concentrations and shoaling rates for both wet and dry conditions.

5.1.4 Navigation Channel Bathymetry

The initial bathymetry in the Redwood City Harbor Channel for the 2006 simulation was set using hydrosurvey data from December 24, 2005 (Figure 5.1-4). The initial bathymetry in the Redwood City Harbor Channel for the 2008 simulation were set using hydrosurvey data from February 5, 2008 (Figure 5.1-4). The initial San Bruno Shoal Channel bathymetry for the 2006 simulation was set using hydrosurvey data from October 15, 2005, and the initial San Bruno Shoal Channel bathymetry for the 2008 simulation was set using hydrosurvey data from February 8, 2008 (Figure 5.1-5). The hydrosurvey data were converted from MLLW to the North American Vertical Datum of 1988 (NAVD88) for use in the UnTRIM Bay-Delta model using constant offsets of 1.13 feet provided by USACE for the Redwood City Harbor Channel and 0.46 foot for the San Bruno Shoal Channel.

5.1.5 Validation of Sedimentation in the Navigation Channels

Validation of the suspended sediment concentration spanned the 2006 and 2008 water years, from October 1 through September 30. Validation of sediment deposition in the Redwood City Harbor Channel spanned consecutive full hydrosurveys, with the predicted deposition during the 2006 simulation validated using the observed deposition between the hydrosurvey on December 24, 2005 and the subsequent hydrosurvey on November 19, 2006. Validation of the sediment deposition in the Redwood City Harbor Channel for the 2008 simulation spanned from the hydrosurvey on February 5, 2008, through the hydrosurvey on October 28, 2008. Predicted sediment deposition in the San Bruno Shoal Channel from the 2006 simulation was compared to the deposition derived for the period between the hydrosurveys on October 15, 2005, and November 20, 2006. A more qualitative sediment deposition comparison was performed for the 2008 simulation because consecutive hydrosurveys of the San Bruno Shoal Channel were not available for the 2008 period.

The model setup including the initial sediment bed, seabed grain fractions, and porosity were nearly identical to that used in previous modeling of sediment deposition in the Oakland Harbor Channel (Delta Modeling Associates 2015). Only the sediment bed fractions near

Dumbarton Bridge and in the far South Bay were modified from the previous modeling application. Maintaining the consistency of the model applications facilitates the comparison of results between the two projects and further demonstrates that the model is sufficiently accurate for predicting the relative change in sediment deposition in navigation channels under a wide range of channel and environmental conditions.

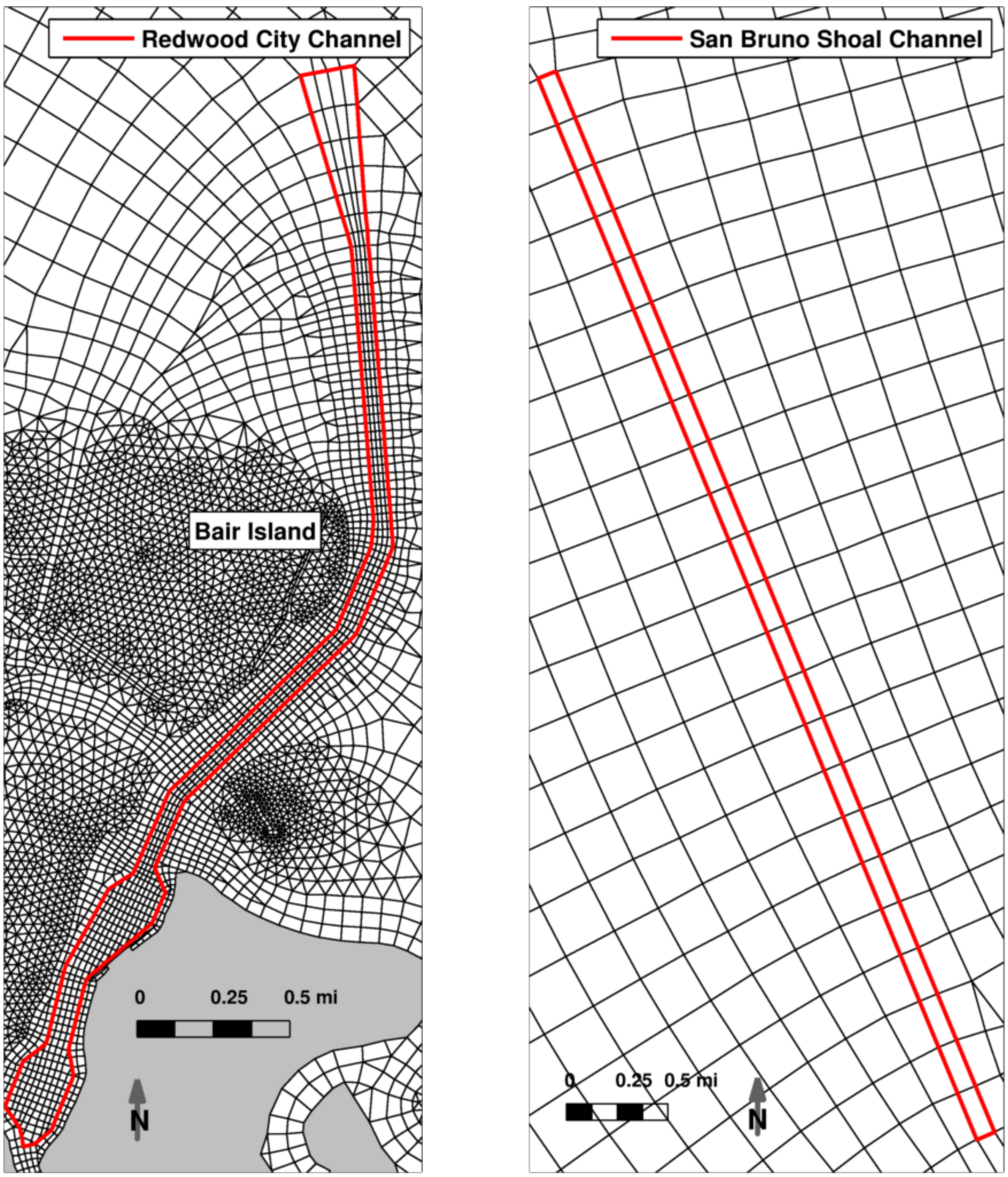


Figure 5.1-1
The model grid around Redwood City Harbor (left) and San Bruno Shoal Channel (right). The designated navigation channels are outlined in red.

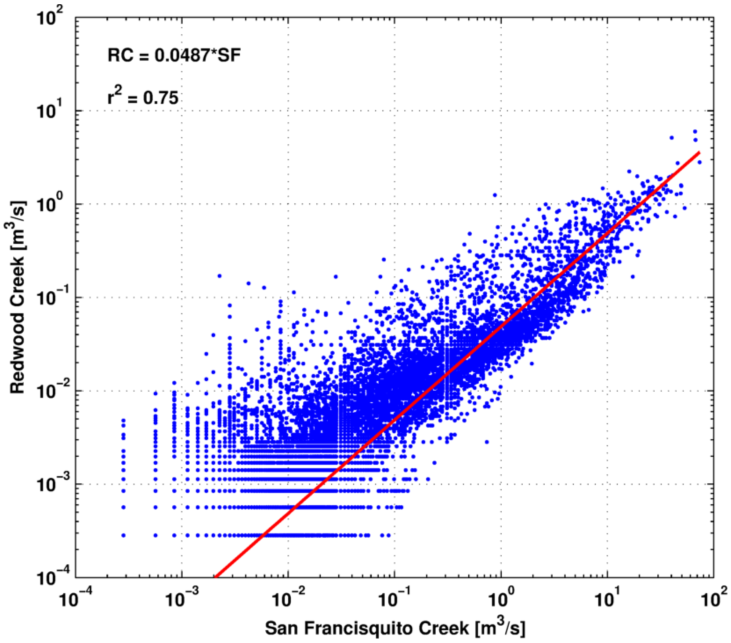


Figure 5.1-2
Scatter plot and best fit line between the flows in San Francisquito Creek and Redwood Creek from 1959 through 1997. RC stands for Redwood Creek and SF stands for San Francisquito Creek.

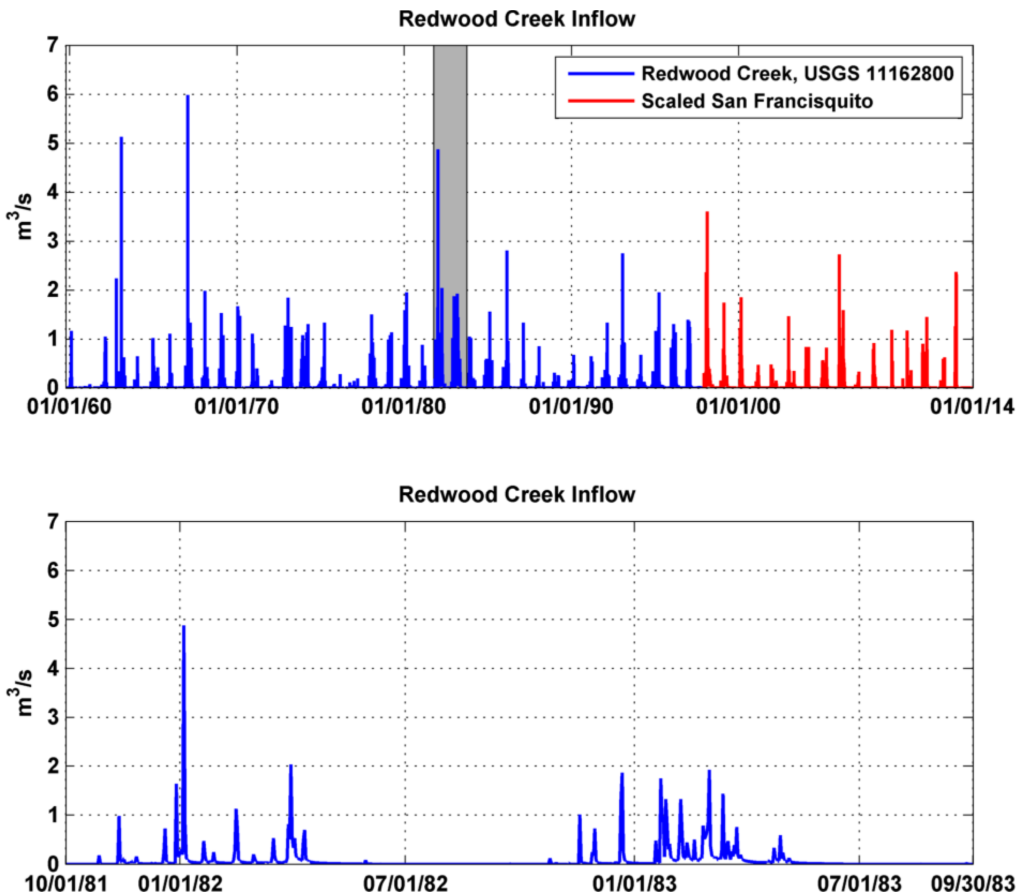


Figure 5.1-3
Redwood Creek inflow measured by USGS and based on the scaling relationship with San Francisquito Creek. The shaded portion of the top panel is highlighted in the bottom panel.

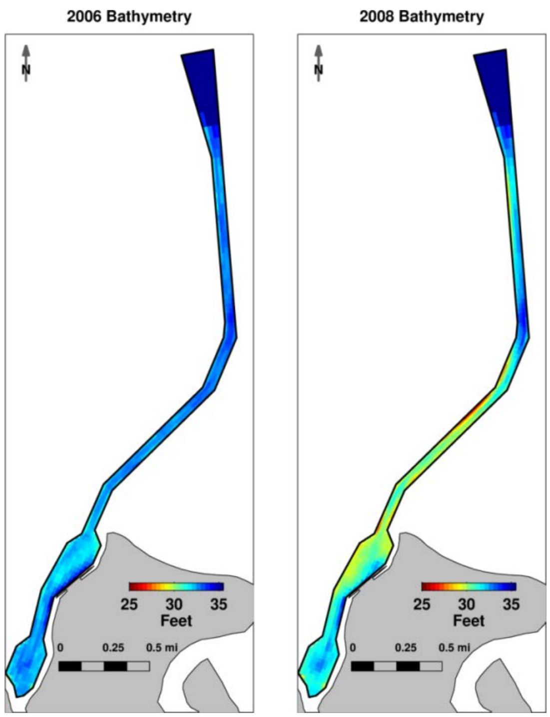


Figure 5.1-4
Model bathymetry in the Redwood City Harbor Channel for the 2006 (left) and 2008 (right) simulations.

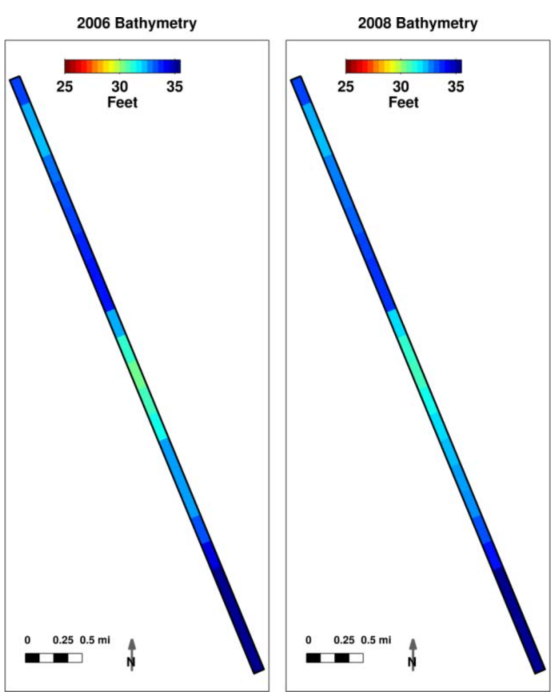


Figure 5.1-5
Model bathymetry in the San Bruno Shoal Channel for the 2006 (left) and 2008 (right) simulations.

5.2 Validation of Central Bay and South Bay Suspended Sediment Concentrations

Predicted suspended sediment concentrations were validated using USGS time series observations of suspended sediment concentrations at the Alcatraz station in the Central Bay and at Dumbarton Bridge in the South Bay for the 2006 and 2008 simulations (Figure 5.2-1). At Dumbarton Bridge, observation data was available at both the upper and lower sensors. The time series suspended sediment concentrations were validated in the same manner as in Bever and MacWilliams (2014) and MacWilliams et al. (2015), which give detailed descriptions of the model validation methods and the statistics used. In short, the model validation statistics included the observed and predicted means, the amplitude ratio, lag time in minutes, coefficient of determination (r^2), model skill between the observed and predicted values based on Willmott (1981), and target diagram statistics (Jolliff et al. 2009; Hofmann et al. 2011). The assessment of model accuracy focused on the model skill based on Willmott (1981) and the target diagram statistics. The model skill gives a quantitative metric that varies from zero to one, with zero indicating no model skill and one indicating a perfect prediction of the observations. The target diagram statistics give information about whether the model predictions were on average too high or too low (bias) and whether the modeled variability in the values was higher, positive unbiased root-mean-square difference (ubRMSD) or lower, negative ubRMSD, than from the observations. The target diagram statistics were normalized by the observed standard deviation, as discussed in Bever and MacWilliams (2014), MacWilliams et al. (2015), and Jolliff et al. (2009).

The accuracy of the predicted instantaneous time series of suspended sediment concentration was assessed using a combination of thresholds for model skill similar to those used in MacWilliams et al. (2015), with model skill values of 0.4 to 0.5 indicating the predictions could benefit from more calibration, 0.5 to 0.65 indicating the model acceptably predicted the observations and 0.65 to 1.0 indicating the model accurately predicted the observations. A second metric used the length of a vector composed of the two target diagram statistics, with values greater than one indicating the model predictions would benefit from increased calibration, 1.0 to 0.5 indicated the model acceptably predicted the observations, 0.5 to 0.25 indicated accurate model predictions and less than 0.25 indicated very accurate model predictions. These accuracy classification thresholds were identical to those used for validating suspended sediment concentration in simulations predicting sediment deposition in the Oakland Harbor Channel (Delta Modeling Associates 2015).

During 2006 water year the suspended sediment concentration was acceptably to accurately predicted at the Alcatraz station, with the mean concentration very well predicted (Figure 5.2-2, Tables 5.2-1 and 5.2-2). The model also accurately predicted the spring to neap signal seen in the observed suspended sediment concentration at the Alcatraz station (Figure 5.2-2). The model predicted a higher mean suspended sediment concentration yet lower peak concentrations than the observations at both the upper and lower Dumbarton Bridge sensors during the 2006 simulation (Figures 5.2-3 and 5.2-4). During the 2008 simulation the suspended sediment concentration at the Alcatraz station was acceptably predicted, but the model predicted higher concentrations than observed in the later 3 months of the simulation (Figure 5.2-5, Tables 5.2-1 and 5.2-2). The mean concentrations at the Dumbarton Bridge station were better predicted by the model in the 2008 simulation than for 2006, but the 2008 predictions had lower suspended sediment concentration peaks and less variability in the concentrations than the observations (Figures 5.2-6 and 5.2-7, Tables 5.2-1 and 5.2-2).

The horizontal and vertical structure of the predicted suspended sediment concentration were also validated for the 2006 simulation using vertical profiles of suspended sediment concentration measured by USGS along a transect spanning from the far South Bay to Rio Vista (Figures 5.2-8 and 5.2-9). Analysis of the suspended sediment concentration transects showed the model predicted the correct horizontal and vertical structure in the suspended sediment concentrations, but tended to predict higher concentrations in the South Bay than were observed. Both the predictions and the observations showed generally higher concentration near Dumbarton Bridge than were observed either near San Mateo Bridge or in the Central Bay. The predictions and observations also showed higher concentrations between Point San Pablo and Carquinez Bridge than the surrounding area in the North Bay. The model predicted the suspended sediment concentration better near San Mateo Bridge than near Dumbarton Bridge, indicating that the predicted suspended sediment concentration near the Redwood City Harbor Channel was likely better predicted than at Dumbarton Bridge but not as well as at the Alcatraz station. The model also predicted the correct vertical structure to the suspended sediment concentration, with generally higher concentrations near the seabed than near the water surface.

Table 5.2-1
Predicted and observed suspended sediment concentrations, cross-correlation statistics, model skills, and target diagram statistics for suspended sediment concentration continuous monitoring stations in the Central Bay and South Bay. The ubRMSD is the unbiased root-mean-square difference. The bias and ubRMSD have both been normalized by the observed standard deviation. Station locations are shown on Figure 5.2-1.

Station Location	Data Source	Figure Number	Mean Concentration		Cross Correlation		r^2	Skill	Target Diagram	
			Observed (mg L^{-1})	Predicted (mg L^{-1})	Amp Ratio	Lag (min)			Bias	ubRMSD
2006 Suspended Sediment Concentration Stations										
Alcatraz	USGS	5.2-2	19.90	22.77	0.584	-7	0.578	0.845	0.147	-0.655
Dumbarton Bridge Upper	USGS	5.2-3	40.65	55.02	0.148	6	0.061	0.474	0.375	-1.032
Dumbarton Bridge Lower	USGS	5.2-4	47.45	84.66	0.160	0	0.023	0.397	1.001	1.346
2008 Suspended Sediment Concentration Stations										
Alcatraz	USGS	5.2-5	20.81	20.42	0.599	-55	0.303	0.738	-0.037	1.061
Dumbarton Bridge Upper	USGS	5.2-6	55.98	44.66	0.103	9	0.188	0.377	-0.207	-0.922
Dumbarton Bridge Lower	USGS	5.2-7	83.75	68.00	0.081	58	0.097	0.346	-0.176	-0.964

Table 5.2-2
The standard deviation of the observed and predicted suspended sediment concentrations and the number of individual data points used in the time series analysis.

Station Location	Data Source	Figure Number	Standard Deviation		Number of Data Points
			Observed (mg L^{-1})	Predicted (mg L^{-1})	
2006 Suspended Sediment Concentration Stations					
Alcatraz	USGS	5.2-2	19.57	15.13	22443
Dumbarton Bridge Upper	USGS	5.2-3	38.27	23.05	29138
Dumbarton Bridge Lower	USGS	5.2-4	37.18	39.54	25934
2008 Suspended Sediment Concentration Stations					
Alcatraz	USGS	5.2-5	10.42	11.42	28775
Dumbarton Bridge Upper	USGS	5.2-6	54.52	13.02	21275
Dumbarton Bridge Lower	USGS	5.2-7	89.82	23.42	23690

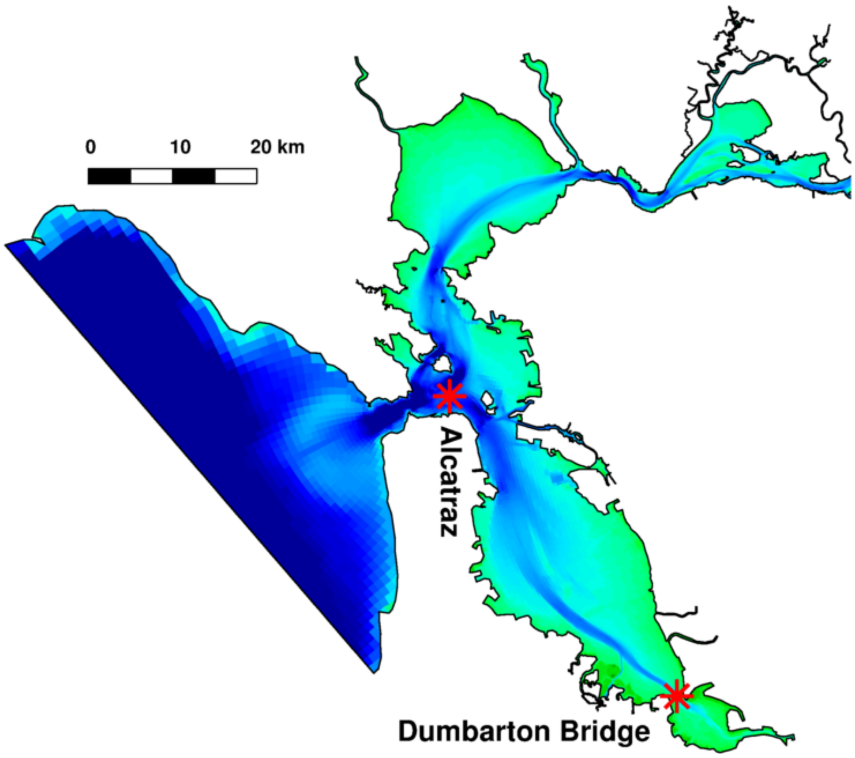


Figure 5.2-1
Location of USGS suspended sediment concentration monitoring stations in Central Bay and South Bay used for model validation.

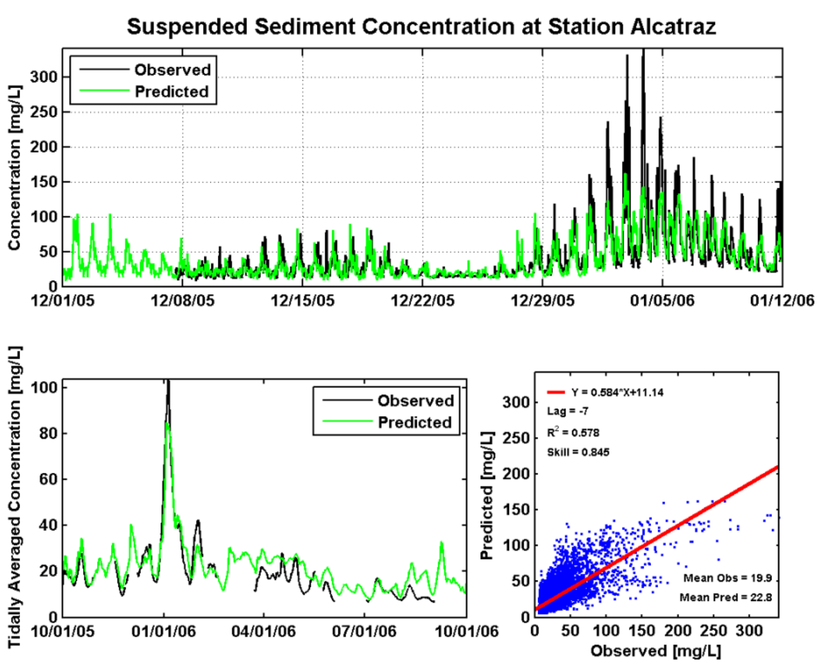


Figure 5.2-2
Observed and predicted suspended sediment concentration at Alcatraz during the 2006 simulation period.

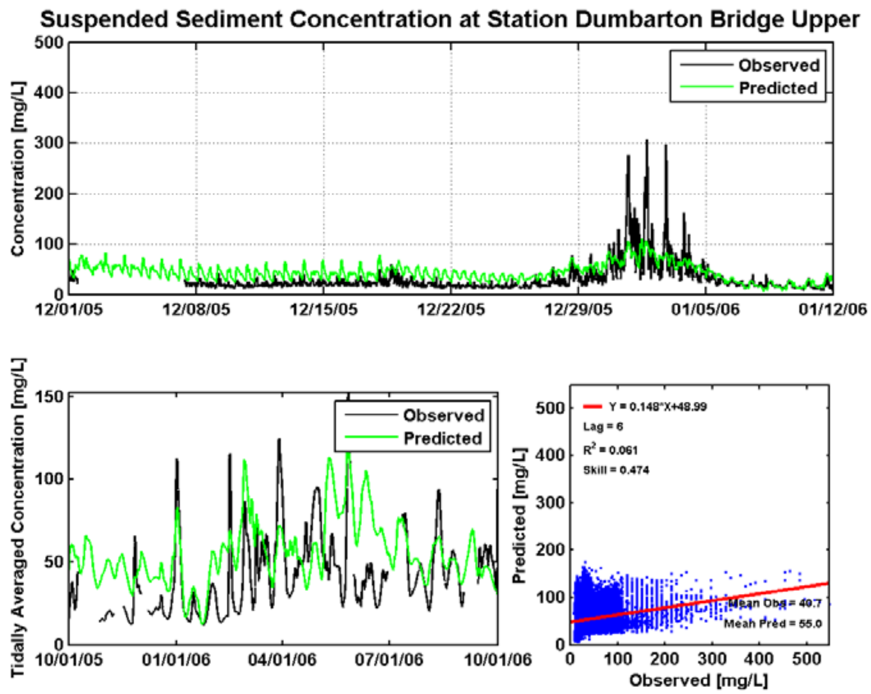


Figure 5.2-3
Observed and predicted suspended sediment concentration at Dumbarton Bridge (upper sensor) during the 2006 simulation period.

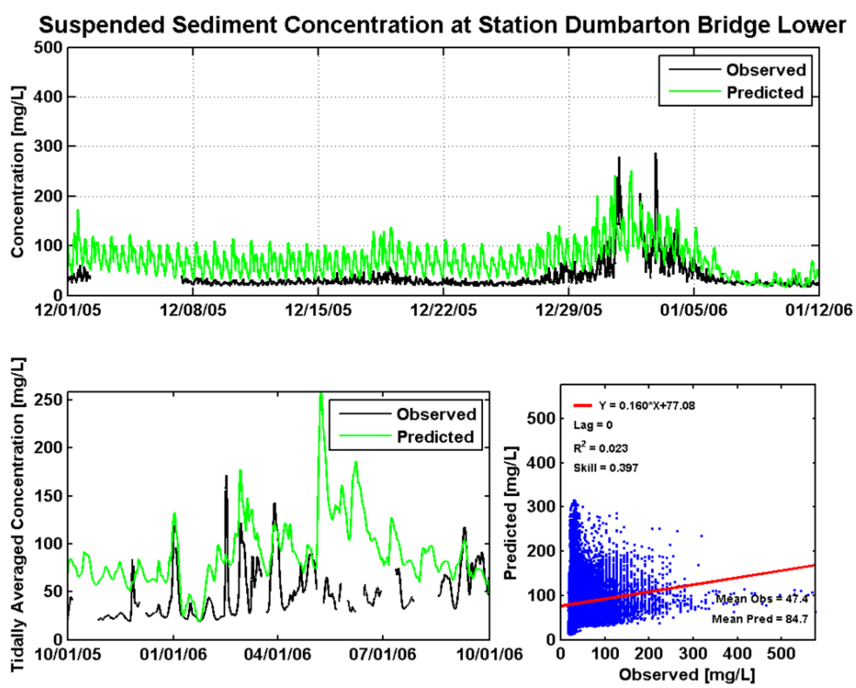


Figure 5.2-4
Observed and predicted suspended sediment concentration at Dumbarton Bridge (lower sensor) during the 2006 simulation period.

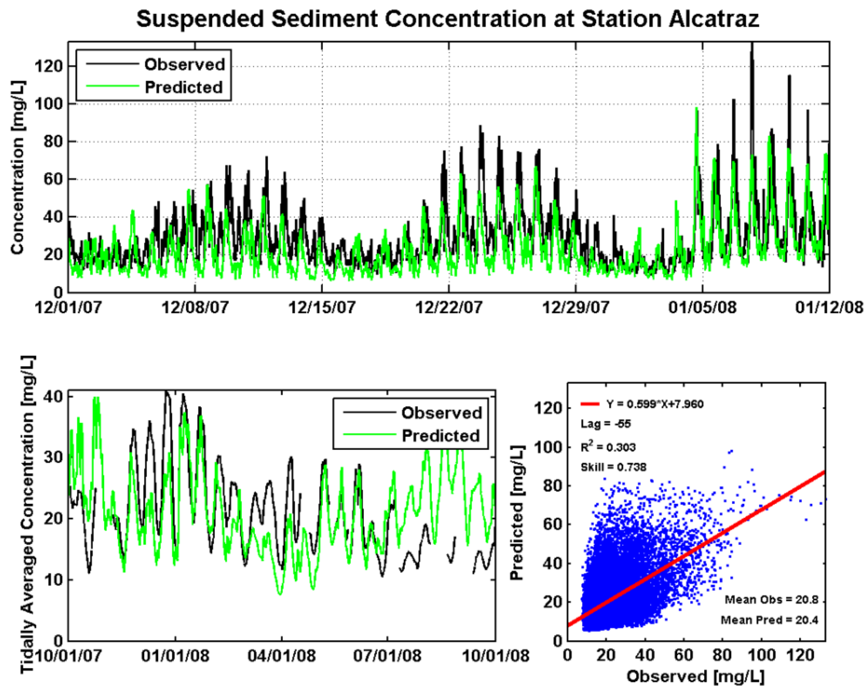


Figure 5.2-5
Observed and predicted suspended sediment concentration at Alcatraz during the 2008 simulation period.

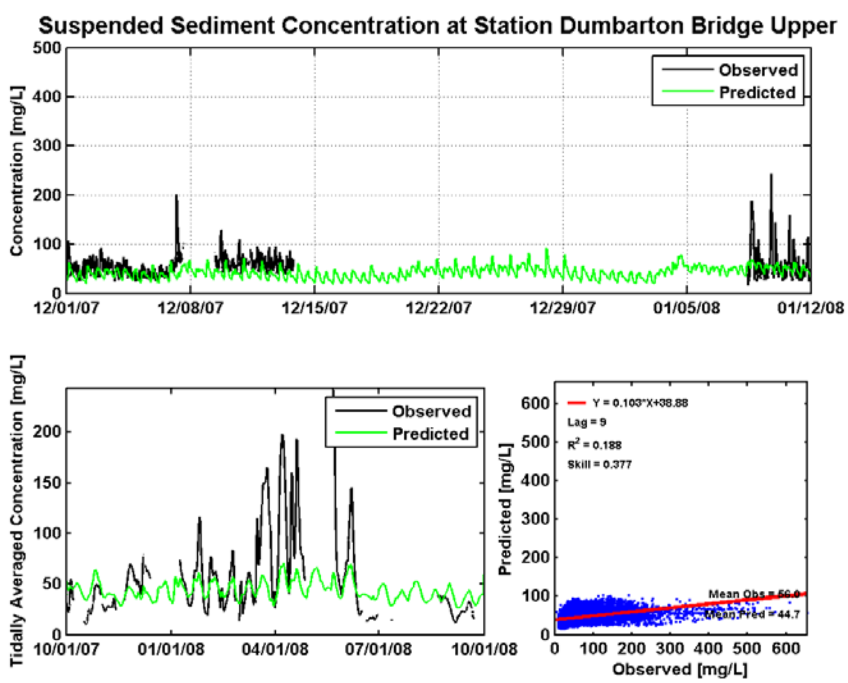


Figure 5.2-6
Observed and predicted suspended sediment concentration at Dumbarton Bridge (upper sensor) during the 2008 simulation period.

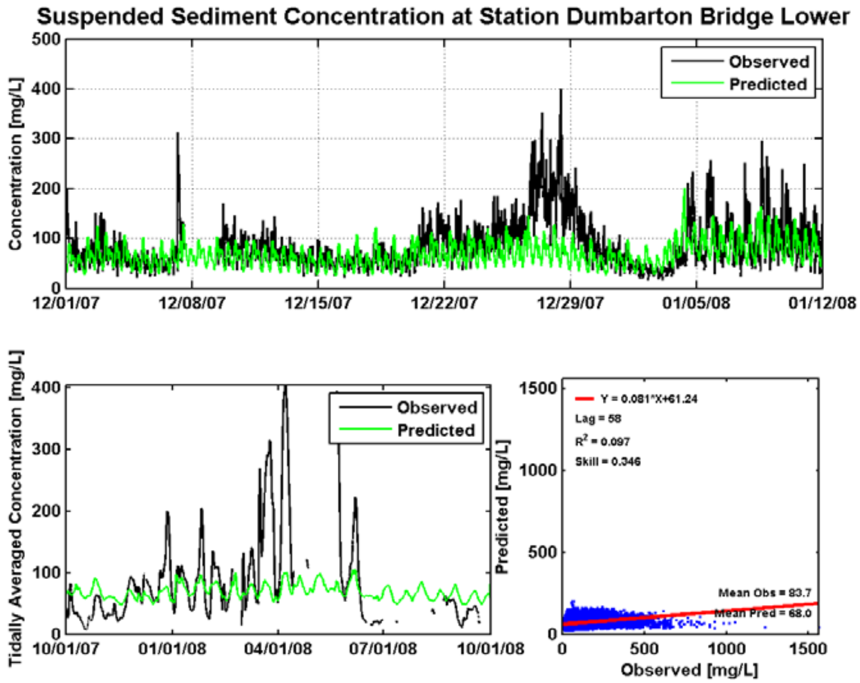


Figure 5.2-7
Observed and predicted suspended sediment concentration at Dumbarton Bridge (lower sensor) during the 2008 simulation period.

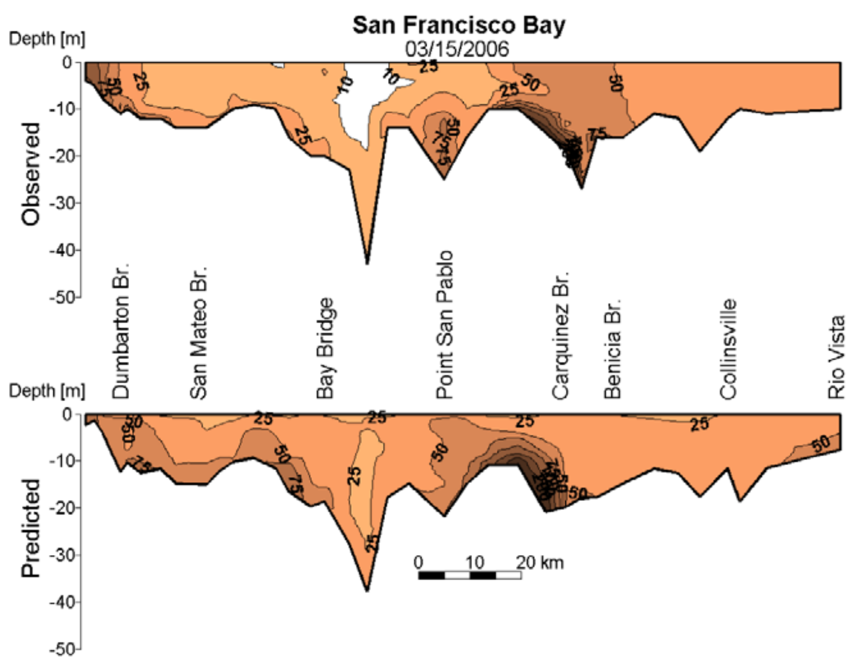


Figure 5.2-8
Observed and predicted suspended sediment concentration profiles for San Francisco Bay, interpolated to a transect from the far South Bay to Rio Vista on March 15, 2006.

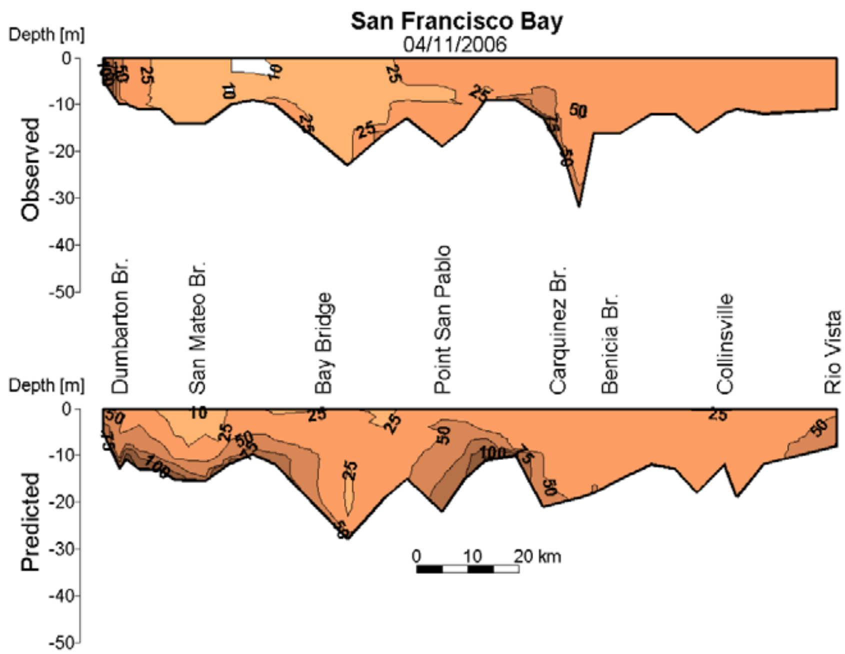


Figure 5.2-9
Observed and predicted suspended sediment concentration profiles for San Francisco Bay, interpolated to a transect from the far South Bay to Rio Vista on April 11, 2006.

5.3 Validation of Sediment Deposition in the Redwood City Harbor Channel

The hydrosurvey data presented in Section 4 were used to validate the predicted sedimentation rate, area above project depth, deposition thickness, and deposition location in the Redwood City Harbor Channel. When comparing the predicted deposition to the sediment deposition estimated from the hydrosurvey data, the deposition predicted by the model over the period between two hydrosurveys was compared to the change in volume derived from the consecutive hydrosurveys. This approach allowed for a comparison of observed and predicted deposition over identical time periods. The model predicted a sedimentation rate 48% lower than that estimated from the hydrosurvey data in the 2006 simulation and 49% lower in the 2008 simulation (Figure 5.3-1, Table 5.3-1). However, the model predictions of deposition for both the simulations were well within the error bars on the deposition derived from the hydrosurvey data, indicating the model acceptably predicted the sediment deposition volumes. The model predicted a decrease of 23% in the sedimentation rate in the Redwood City Harbor Channel from the 2006 to the 2008 simulations. This decrease of 23% matched very well with the hydrosurvey derived decrease in the sedimentation rate of 21% from the 2006 to the 2008 simulations, indicating that the model very accurately predicted the relative change in the sedimentation rate due to different channel depths and environmental conditions.

When comparing predicted area above the project depth to the observed area above the project depth, it was not necessary to limit the evaluation only to the time between the hydrosurveys. However, some uncertainty is introduced in this type of comparison because the initial bathymetry for each simulation was derived using a hydrosurvey from a day that was not identical to the start date of each simulation. The model predicted the percentage of the Redwood City Harbor Channel that shoaled above the project depth sufficiently well for both simulations (Figure 5.3-2). The model predicted a larger change in the percent of the channel that shoaled to above project depth in the 2006 simulation than in the 2008 simulation, as also seen in the hydrosurvey data. Both the model predictions and the hydrosurvey data suggest regions of relatively higher sediment deposition just south of Bair Island and toward the northern end of the channel, although the model predicted less deposition thickness near Bair Island and more deposition thickness near the northern end of the channel than was estimated from the hydrosurvey data (Figures 5.3-3 and 5.3-4). In 2006 the model correctly predicted the increased depositional thicknesses to be primarily toward the northwest side the channel south of Bair Island and toward the western side of the channel near the northern end of the channel.

Table 5.3-1
Estimated and predicted sedimentation rate in the Redwood City Harbor Channel for the 2006 and 2008 simulations. The volume percent is the model predictions divided by the hydrosurvey deposition volume times 100 and the duration is the length of time from one survey to the next. The change from 2006 to 2008 is the percentage change in the sedimentation rate between the 2006 and 2008 estimates.

Year	Hydrosurvey or Predicted	Deposition Volume ($1x10^5$ yd^3)	Sedimentation Rate ($1x10^5$ yd^3 yr^{-1})	Volume Percent	Duration (days)	Change From 2006 to 2008
2006	Hydrosurvey	1.65	1.83	52	330	not applicable
	Predicted	0.86	0.96			
2008	Hydrosurvey	1.06	1.45	51	266	-21%
	Predicted	0.54	0.74			-23%

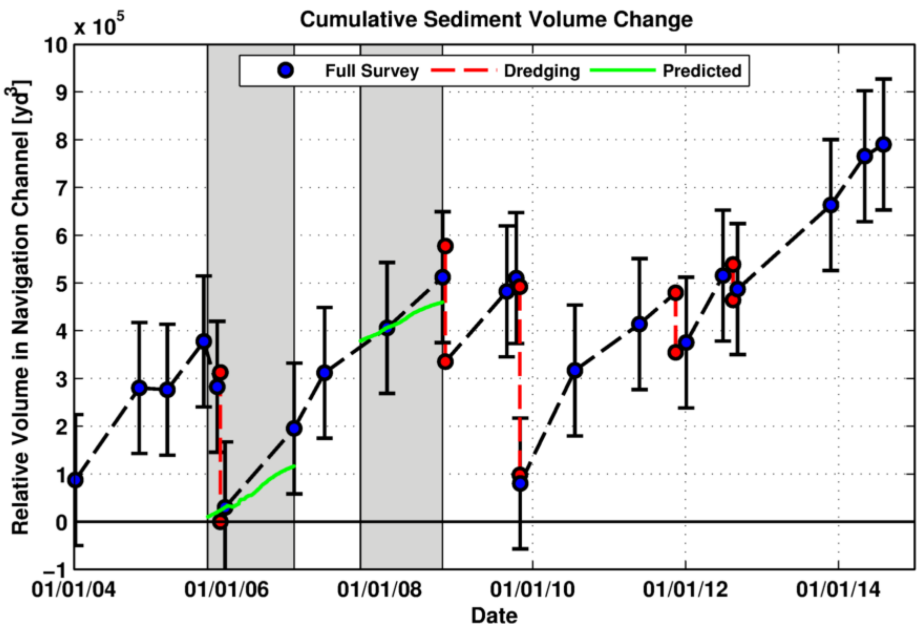


Figure 5.3-1
Relative sediment volume in the Redwood City Harbor Channel through time. The hydrosurvey data is shown as explained in Section 4 and the model predictions are represented by the thick green lines. The model predictions are shown for the entire simulation period (grey shading).

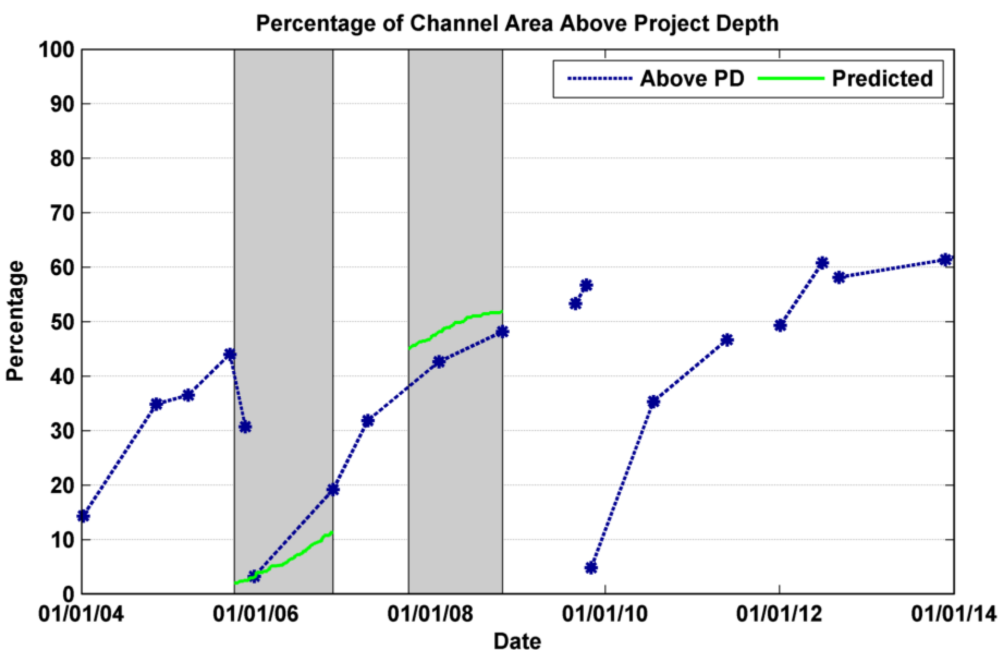


Figure 5.3-2
The percentage of the Redwood City Harbor Channel that is shallower than the project depth estimated from the hydrosurvey data (blue) and predicted by the model (green). The model predictions are shown for the entire simulation period (grey shading).

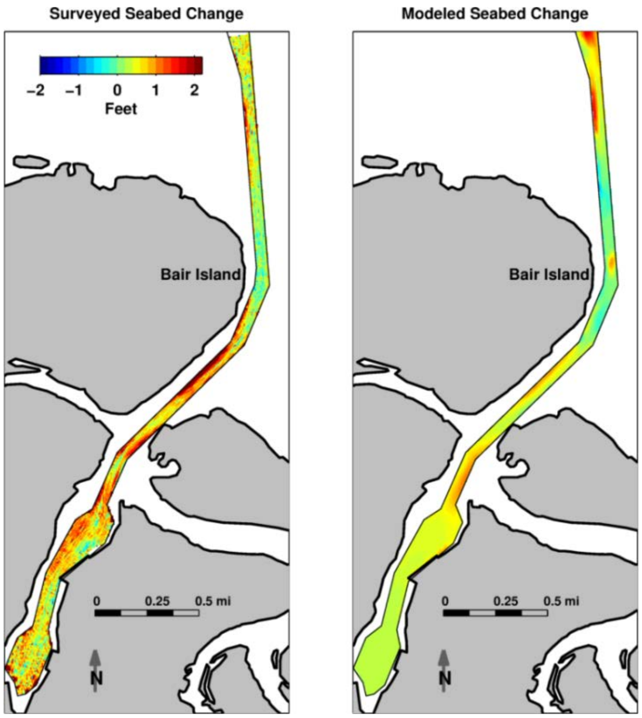


Figure 5.3-3
Sediment deposition thicknesses in the Redwood City Harbor Channel estimated from the hydrosurvey data and predicted by the model for the 2006 simulation.

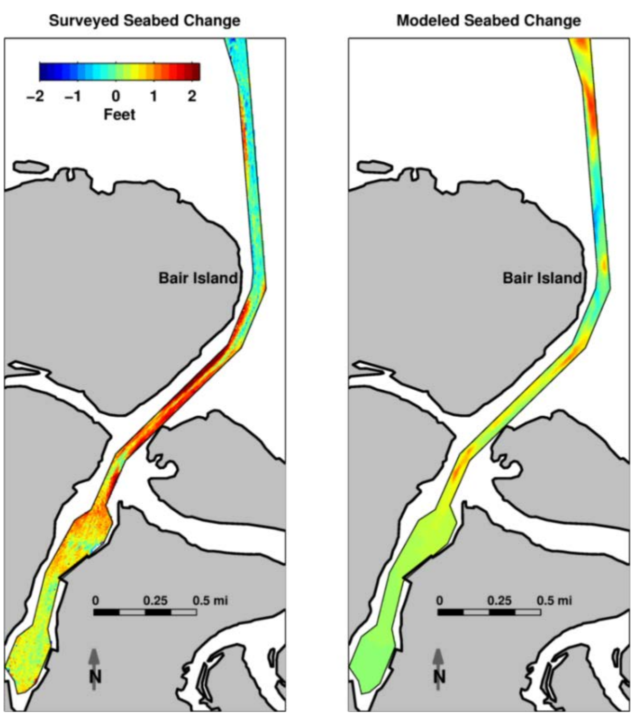


Figure 5.3-4
Sediment deposition thicknesses in the Redwood City Harbor Channel estimated from the hydrosurvey data and predicted by the model for the 2008 simulation.

5.4 Validation of Sediment Deposition in the San Bruno Shoal Channel

The hydrosurvey data presented in Section 4 were used to validate the predicted sedimentation rate, deposition thickness, and deposition location in the San Bruno Shoal Channel. Consecutive full surveys of the San Bruno Shoal Channel without dredging between the surveys were not available during either the period simulated for 2006 or 2008. As a result, only a qualitative assessment of model predictions of sediment deposition volume in San Bruno Shoal Channel was possible from the data available. For comparison purposes, the relative volume in the navigation channel was set to zero at the start of each simulation. Based on this, it appears that the model predicted higher than observed deposition in the San Bruno Shoal Channel for both the 2006 and 2008 simulation periods (Figure 5.4-1). However, sediment deposition volumes were predicted to the correct order of magnitude, and the ending sediment volume in the channel for each simulation is within the error bars of the volume derived from the subsequent survey for which hydrosurvey data were available.

Even though the model predicted higher sedimentation in the San Bruno Shoal Channel than suggested by the hydrosurvey data, the available data do not allow for an examination of how shorter time scale variability may influence the deposition in the San Bruno Shoal Channel and the validation of the modeled sedimentation rates. For example, the observed sedimentation rate immediately prior to the 2006 simulation seems too much better match the predicted sedimentation rate than the observed data over the simulation period, indicating that the model predicted sedimentation rate is reasonable. Also, as the time between consecutive surveys in the San Bruno Shoal Channel increases the rate of change (slope of the connecting line) generally decreases. The hydrosurveys during and after the 2008 simulation spanned a large length of time (about 865 days), which may lead to the overall sedimentation rate between those surveys not being representative of the sedimentation rate over the shorter 2008 simulation period.

Predicted deposition thicknesses for the period from October 15, 2005, to November 20, 2006, were compared to the observed deposition for the same period (Figure 5.4-2). However, dredging occurred between these two hydrosurveys. The location of the thickest predicted deposition matched with a location of deposition in the hydrosurvey data. Sharp transitions between depositional and erosional areas in the hydrosurvey data (Figure 5.4-2, left panel) were caused by dredging between the October 2005 and November 2006 hydrosurveys. Consecutive hydrosurveys of the San Bruno Shoal Channel within the simulated date range were not available to compare the deposition thicknesses for the 2008 simulation.

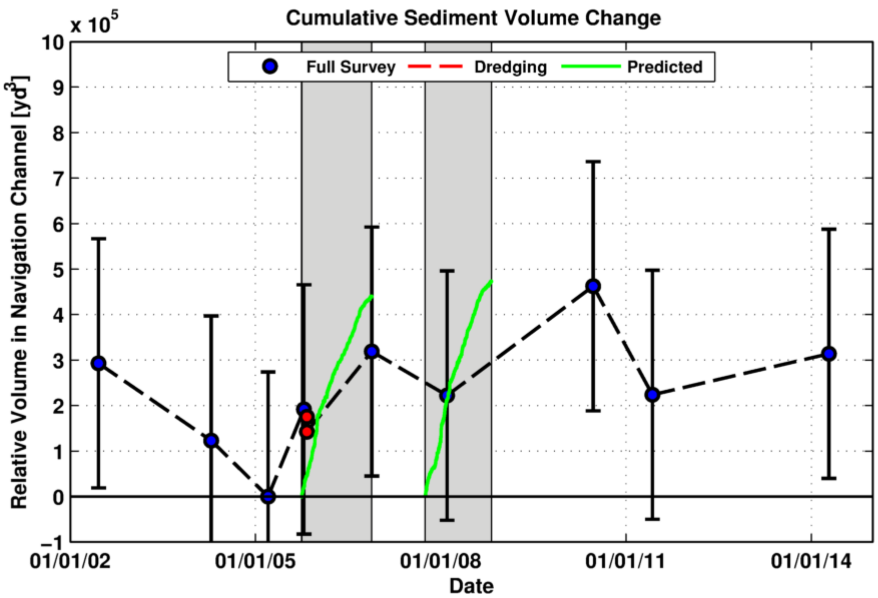


Figure 5.4-1
Relative sediment volume in the San Bruno Shoal Channel through time. The hydrosurvey data is shown as explained in Section 4 and the model predictions are represented by the thick green lines. The model predictions are shown for the entire simulation period (grey shading).

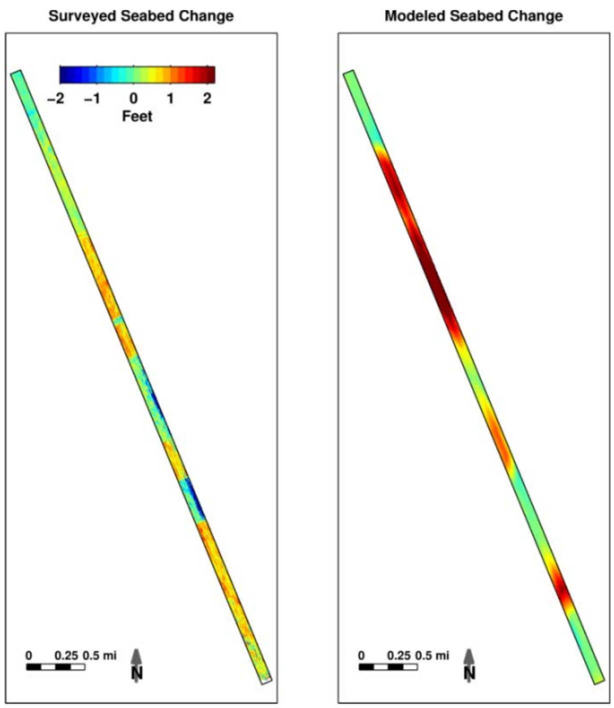


Figure 5.4-2
Sediment deposition thickness in the San Bruno Shoal Channel estimated from the hydrosurvey data and predicted by the model for the 2006 simulation.

5.5 Model Validation Conclusions

The model predictions of sediment transport were validated using observations of suspended sediment concentration, sediment deposition volume and thickness in the Redwood City Harbor Channel and San Bruno Shoal Channel, and the percentage of the channels that shoaled to above project depth. The model accurately predicted the suspended sediment concentration at the Alcatraz station in the Central Bay for the 2006 simulation and acceptably for the 2008 simulation. Predicted suspended sediment concentrations were higher than observed at the South Bay Dumbarton Bridge station in 2006 and slightly lower than observed in the 2008 simulation, while the peak concentrations were lower than observed in both simulations. The thresholds of model skill indicated the model could benefit from further calibration if the focus region were situated at Dumbarton Bridge. However, analysis of along-Bay transects suggested the model more accurately predicted the suspended sediment concentration near the Redwood City Harbor Channel and the San Bruno Shoal Channel than at Dumbarton Bridge, but less accurately than at the Alcatraz station. The model predicted a lower total volume of sediment deposited in the Redwood

City Harbor Channel than was estimated from the hydrosurvey data. The model correctly predicted the locations of both the hot spot south of Bair Island and near the northern end of the channel identified in the hydrosurvey analysis. The model also predicted the correct across-channel location of the hot spots on the western side of the channel in the 2006 simulation. The predicted reduction in the sedimentation rate in the Redwood City Harbor Channel from the 2006 to the 2008 simulations agreed very well with the hydrosurvey derived reduction (23% vs. 21%), indicating that the model very accurately predicted the relative change in the sedimentation rate due to different channel depths and environmental conditions. The model predicted the same order of magnitude change in the area of the channel that shoaled to above project depth as the hydrosurvey data. It is likely that model overpredicted the sediment deposition in the San Bruno Shoal Channel relative to the hydrosurvey data but the model did predict the correct order of magnitude deposition volume and was within the error bars of the hydrosurvey derived deposition volumes. A quantified assessment of deposition volumes for the San Bruno Shoal was not possible based on the hydrosurvey data available for the periods simulated.

The validation indicated that the model was sufficiently accurate for investigating relative changes in the sediment deposition volumes due to channel deepening of the Redwood City Harbor Channel. The validation also showed the model did not predict the sediment deposition in the San Bruno Shoal Channel as well as in the Redwood City Harbor Channel. However, even in the San Bruno Shoal Channel, the model predicted the correct order of magnitude for the sediment deposition volume in the channel and was within the error bars of the hydrosurvey derived deposition volumes, indicating that it is suitable for investigating the relative difference between scenarios.

6 INFLUENCE OF PROJECT DEPTH ON SHOALING

The application of the UnTRIM Bay-Delta model (MacWilliams et al. 2007, 2008, 2009, 2015) coupled with the SWAN wave model (SWAN Team 2009a) and the SediMorph sediment transport model (BAW 2005) was used to investigate the effects of deepening the project depth of the Redwood City Harbor Channel and the San Bruno Shoal Channel on shoaling rates. Six scenarios were used to estimate how the sedimentation rate in the channels would be changed by deepening the project depth from 30 feet MLLW to either 32 feet MLLW or to 37 feet MLLW. This analysis showed that increasing the project depth increased sedimentation in both of the channels.

The influence of the project depths on shoaling rates was evaluated for base year conditions. The base year conditions are defined based on the expected bathymetric, hydrologic, and operating conditions in year 2018 for the Redwood City Harbor Channel and the San Bruno Shoal Channel. The base year scenario represents the "Year 0" conditions, which are an estimate of possible conditions that may exist at the approximate time that the project is completed. Because the exact weather, hydrology, and operating conditions cannot be predicted in advance, representative conditions for 2018 were developed using 2006 hydrology, and modified to account for both sea level rise and to include changes to the Bair Island Restoration Project that are expected to occur prior to 2018. A projected sea level rise of 0.09 foot from the model forcing year (2006) to the project start year (2018) was applied based on the NRC curve 1 (USACE 2014). The model grid was refined to include all of Bair Island and levee breaches, channel blocks, flow constrictors, and flooded areas based on the current configuration and the planned future restoration of the system which is likely to occur prior to 2018 (Figure 6.1-1). The planned changes to the Bair Island Restoration Project were included based on information provided by the U.S. Fish and Wildlife Service (E. Mruz pers. comm. 2014; A. Payne pers. comm. 2014).

6.1 Project Depth Scenarios Overview

The analysis evaluated three project depths, which were combined to produce a set of scenarios in which only a single variable was changed within the scenario set. Varying only a single variable (project depth) within the set of scenarios allowed for an assessment of how the project depth affected the shoaling rate in the Redwood City Harbor Channel and the

San Bruno Shoal Channel. Thus, to evaluate how the depth of the Redwood City Harbor Channel and the San Bruno Shoal Channel influences the sedimentation rate, nearly identical model simulations were conducted using identical hydrological forcing, such that only the bathymetry in the navigation channels was changed between scenarios. These scenarios then allowed for the examination of how changing the Redwood City Harbor Channel and San Bruno Shoal Channel project depths influenced the sedimentation rates, because all variables were consistent between the scenarios except the project depth. Thus, any predicted differences in the sedimentation rate in the channel can be attributed solely to differences in the project depth.

Six scenarios were used to evaluate the influence of the project depth on the sedimentation rate in the Redwood City Harbor Channel and the San Bruno Shoal Channel (Table 6.1-1). All six scenarios used identical model boundary conditions for the base year (2018) conditions but had different project depths and were evaluated over different seasonal time periods (Table 6.1-1). The scenarios were based on project depths of 30 feet MLLW, 32 feet MLLW and 37 feet MLLW. All scenarios included 2 feet of overdepth and assumed 3:1 side slopes. These scenarios were used to estimate a relative change in the sedimentation rate after the Redwood City Harbor Channel and the San Bruno Shoal Channel were deepened from the current project depth (30 feet MLLW) to either 32 feet MLLW or to 37 feet MLLW.

The existing conditions bathymetry in the Redwood City Harbor Channel and the San Bruno Shoal Channel for the scenarios was derived using the most recent available hydrosurveys for each channel. The existing conditions bathymetry for the Redwood City Harbor Channel was derived using hydrosurvey data from August 2014 and June 2012. The June 2012 hydrosurvey data was primarily used for the channel sides because the August survey only covered the navigation channel and not the adjacent shoals. The existing condition for the San Bruno Shoal Channel was set based on hydrosurvey data from April 2014. The existing conditions bathymetry was used as the starting point for developing the channel bathymetry for each of the scenarios.

For the baseline conditions, the bathymetry in the Redwood City Harbor Channel and the San Bruno Shoal Channel was set as the deeper of the exiting conditions bathymetry or the elevation corresponding to 30 feet MLLW plus 2 feet of overdepth in each channel grid cell.

The overdepth was applied as a box-cut and did not affect the channel side slopes. Channel side slopes of 3:1 were applied from the edge of the channel and any areas shallower than the design side slopes were also deepened based on the distance from the channel. This approach ensured that all cells were at least as deep as the currently authorized project depth plus overdepth, but did not fill in any areas that are already deeper than the project depth plus overdepth.

The channel bathymetry for the two deepening scenarios were set using the same approach used to develop the baseline conditions. For the 32 feet MLLW deepening scenario, the bathymetry in the Redwood City Harbor Channel and the San Bruno Shoal Channel was set as the deeper of the exiting conditions bathymetry or the elevation corresponding to 32 feet MLLW plus 2 feet of overdepth in each channel grid cell. For the 37 feet MLLW deepening scenario, the bathymetry in the Redwood City Harbor Channel and the San Bruno Shoal Channel was set as the deeper of the exiting conditions bathymetry or the elevation corresponding to 37 feet MLLW plus 2 feet of overdepth in each channel grid cell. The overdepth and side slopes for the deepening scenarios were set using the same approach used for the baseline conditions grid. About 65% of the Redwood City Harbor Channel was deepened by more than 2 feet to develop the 30 feet MLLW scenario bathymetry from the existing conditions, indicating that a significant portion of the channel was shallower than the authorized depth plus 2 feet of overdepth under existing conditions. Deepening of 12 feet to 15 feet was necessary in some locations to develop the 37 feet MLLW scenario bathymetry including overdepth (Figure 6.1-2). The San Bruno Shoal Channel required less deepening relative to the existing conditions than the Redwood City Harbor Channel, because the majority of the San Bruno Shoal Channel was already deeper than the 30 feet MLLW project depth plus 2 feet of overdepth (Figure 6.1-3). With the exception of the navigation channel project depths, the model bathymetry, boundary conditions, and all other parameters were identical between the baseline scenario and each of the deepening scenarios.

Table 6.1-1
The scenario matrix used to estimate how the project depth influences the sedimentation rate in the Redwood City Harbor Channel and San Bruno Shoal Channel.

Scenario	Channel Project Depth (feet MLLW)	Seasonal Period	Water Year	Notes
1	30	Fall – Winter	2006	Bathymetry set as deeper of existing conditions or project depth plus 2 feet of overdepth.
2	32			
3	37			
4	30	Spring - Summer		
5	32			
6	37			

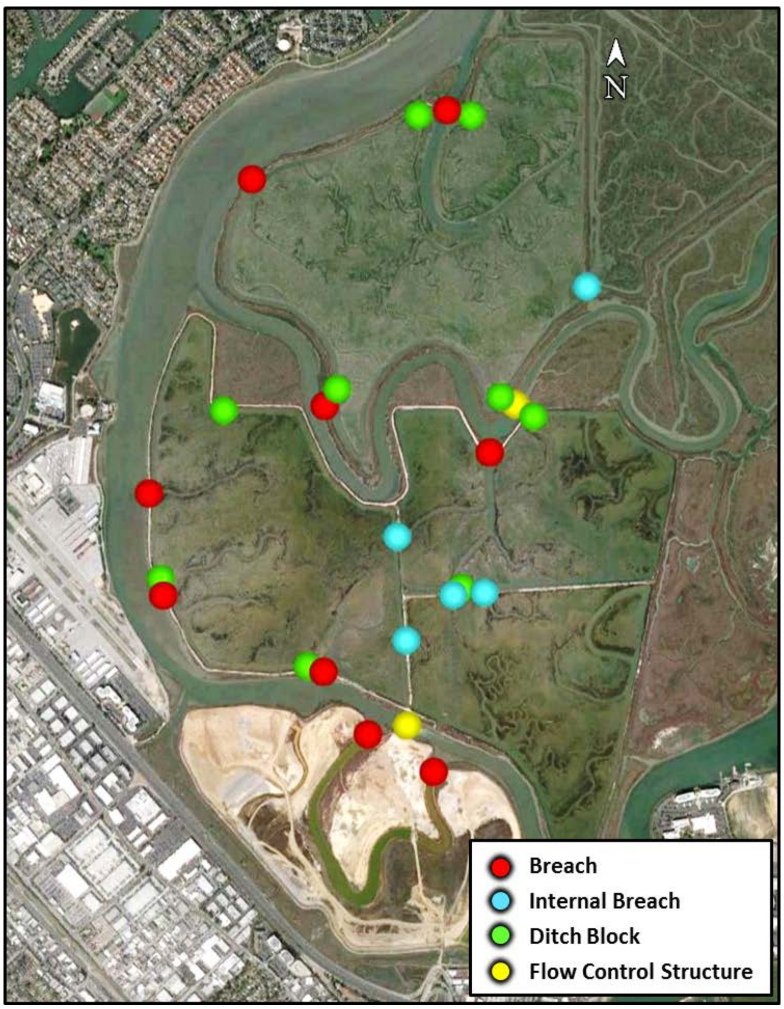


Figure 6.1-1
The levee breaches, channel blocks, and flow constrictors in Bair Island included in the numerical model.

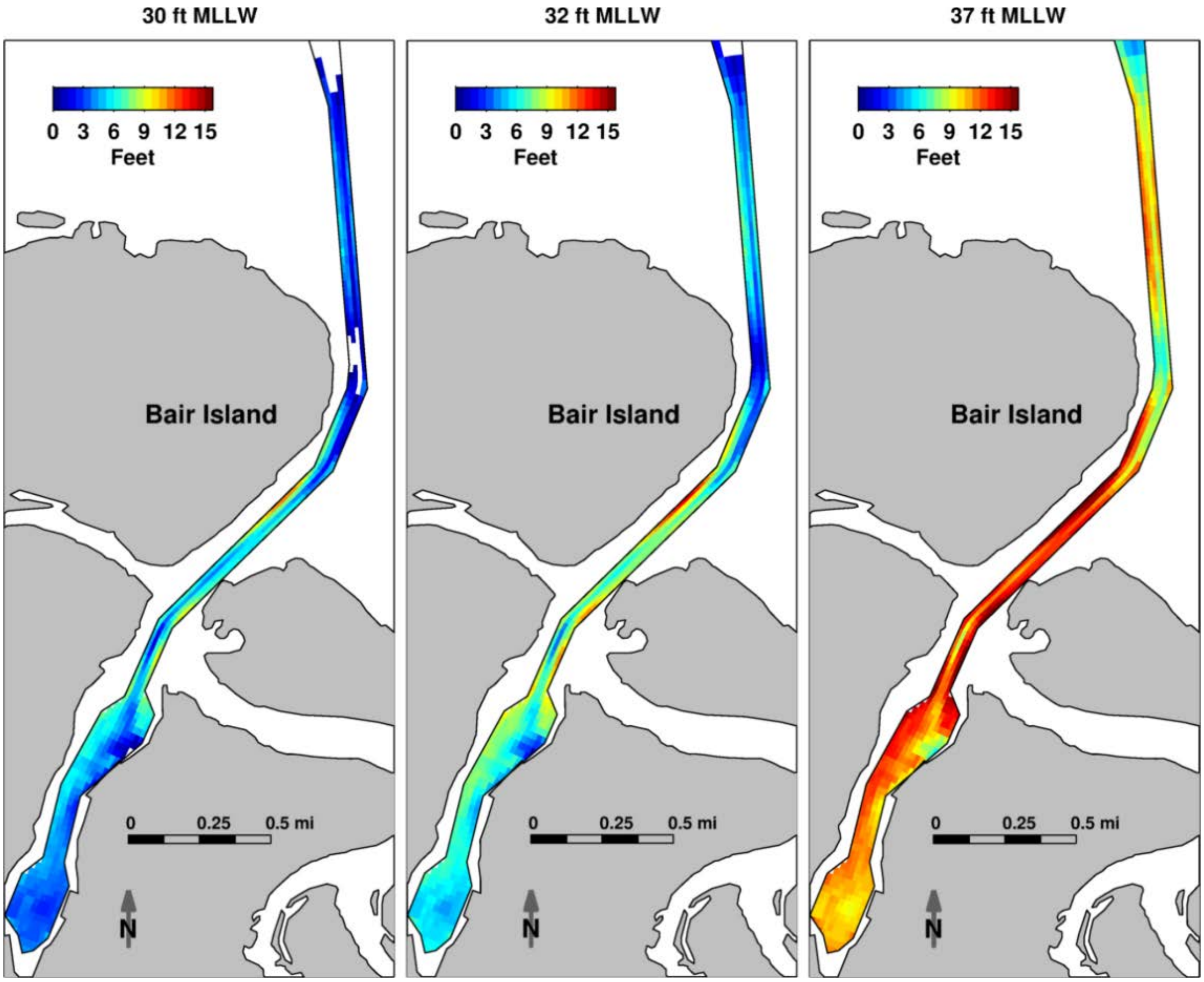


Figure 6.1-2
The amount the Redwood City Harbor Channel was deepened relative to existing conditions required to develop the 30 feet MLLW, 32 feet MLLW, and 37 feet MLLW scenarios (including 2 feet of overdepth). White areas inside the channel represent no deepening.

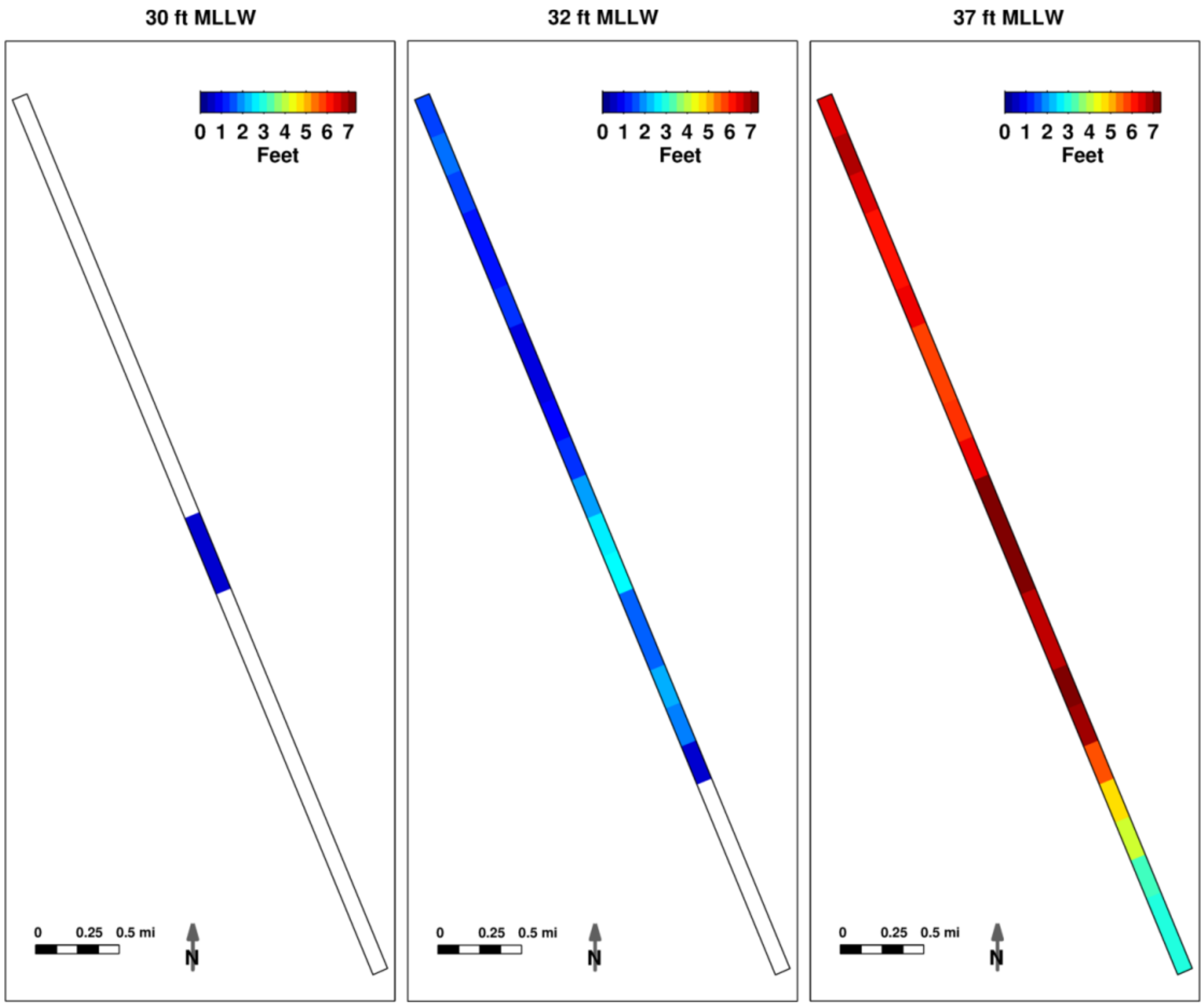


Figure 6.1-3
The amount the San Bruno Shoal Channel was deepened relative to existing conditions to develop the 30 feet MLLW, 32 feet MLLW, and 37 feet MLLW scenarios (including 2 feet of overdepth). White areas inside the channel represent no deepening.

6.2 Overview of Scenario Analysis

The relative change in sediment deposition between scenarios was used to evaluate the influence of increasing the project depth on the sedimentation rate within the Redwood City Harbor Channel and the San Bruno Shoal Channel. Because the model acceptably predicted the sediment deposition volume, deposition thickness, depositional locations, and area of the channel above project depth, yet very accurately predicted the relative change in deposition between two different years, the model is best suited to examine the percentage differences in the sedimentation rate between the scenarios rather than quantify exact differences in deposition volume. That is, the predicted percentage difference in the sedimentation rate caused by different project depths will have less uncertainty than the corresponding absolute differences in deposition volumes between scenarios. As such, this analysis focuses more on the relative difference between scenarios and less on the absolute differences between the scenarios.

Six scenarios were used to estimate the relative change in the sedimentation rate. The simulations were analyzed over three time periods to assess whether seasonal changes in sediment transport influence the sediment deposition in the Redwood City Harbor Channel. The three time periods consisted of the fall and winter period of September 1 through February 28, the spring and summer period of March 1 through August 31, and the complete base year from September 1 through August 31. The analysis periods were shifted by one month from a water year start and end to better align with the fall/winter and spring/summer seasons. The fall through winter period is generally characterized as being composed of winter storms, the first flush from the Delta, and relatively high tributary sediment input to the Bay compared to the spring through summer period. The spring through summer period would be generally characterized as consistently having elevated daily winds that drive wind waves and local sediment resuspension but relatively low tributary sediment supply to the Bay relative to the fall through winter period.

6.3 Influence of Project Depth on Sedimentation Rate

6.3.1 Redwood City Harbor Channel

Increasing the project depth from 30 feet MLLW to either 32 feet MLLW or to 37 feet MLLW was predicted to increase the sedimentation rate in the Redwood City Harbor Channel (Figure 6.3-1, Table 6.3-1). During the fall through winter time period the sedimentation rate was predicted to increase relative to the 30 feet MLLW project depth by 5% with the 32 feet MLLW project depth and by 50% with the 37 feet MLLW project depth. During the spring through summer period, the sedimentation rate was predicted to increase relative to the 30 feet MLLW project depth by 22% with the 32 feet MLLW project depth and by 51% with the 37 feet MLLW project depth.

Over the complete year the sedimentation rate was predicted to increase relative to the 30 feet MLLW project depth by 13% with the 32 feet MLLW project depth and by 51% with the 37 feet MLLW project depth (Figure 6.3-1, Table 6.3-1). The model predicted the sediment deposition thicknesses to generally increase from the 30 feet MLLW to the 32 feet MLLW to the 37 feet MLLW project depths (Figure 6.3-2). The two hot spots located south of Bair Island and near the northern end of the channel were both predicted to thicken in both the 32 feet MLLW and 37 feet MLLW scenarios relative to the 30 feet MLLW scenario. The model also consistently predicted an area of no deposition east of Bair Island; however, this region of no deposition was smaller in the 37 feet MLLW project depth than in the 30 feet MLLW and 32 feet MLLW project depth scenarios. This area of no deposition is also seen in the hydrosurvey data as a region that both rarely shoals above project depth (Figures 4.3-1 through 4.3-11) and has a very small relative sediment deposition compared to the rest of the channel (Figure 4.3-12), indicating that the model correctly predicted this location of reduced sediment deposition.

The model predicted a relatively small difference in the sedimentation rate between the fall through winter and the spring through summer time periods in the Redwood City Harbor Channel. For example, with the 30 feet MLLW project depth the model predicted a sedimentation rate of 139,000 yd^3 yr^{-1} for the fall through winter and 129,000 yd^3 yr^{-1} for the spring through summer. The sediment transport and deposition in the Redwood City Channel during the fall-winter is influenced by winter storms and potentially any large sediment supply events from the Delta, while the sediment transport in the spring through summer is more strongly influenced by sediment resuspension driven by daily wind waves. During the period simulated, which is representative of wet 2018 conditions, the model predicted the influence of the fall through winter and spring through summer sediment transport processes to lead to a similar sedimentation rate within the Redwood City Harbor Channel for all three project depths.

Table 6.3-1
The predicted sedimentation rate in the Redwood City Harbor Channel for fall through winter, spring through summer, and a complete year.

Date Range	Project Depth (feet MLLW)	Channel Sedimentation Rate ($yd^3\ yr^{-1}$)	Percent Increase Relative To 30 feet MLLW Project Depth
Fall-Winter	30	139,000	n/a
	32	147,000	5
	37	209,000	50
Spring-Summer	30	129,000	n/a
	32	157,000	22
	37	195,000	51
Complete Year	30	134,000	n/a
	32	152,000	13
	37	202,000	51

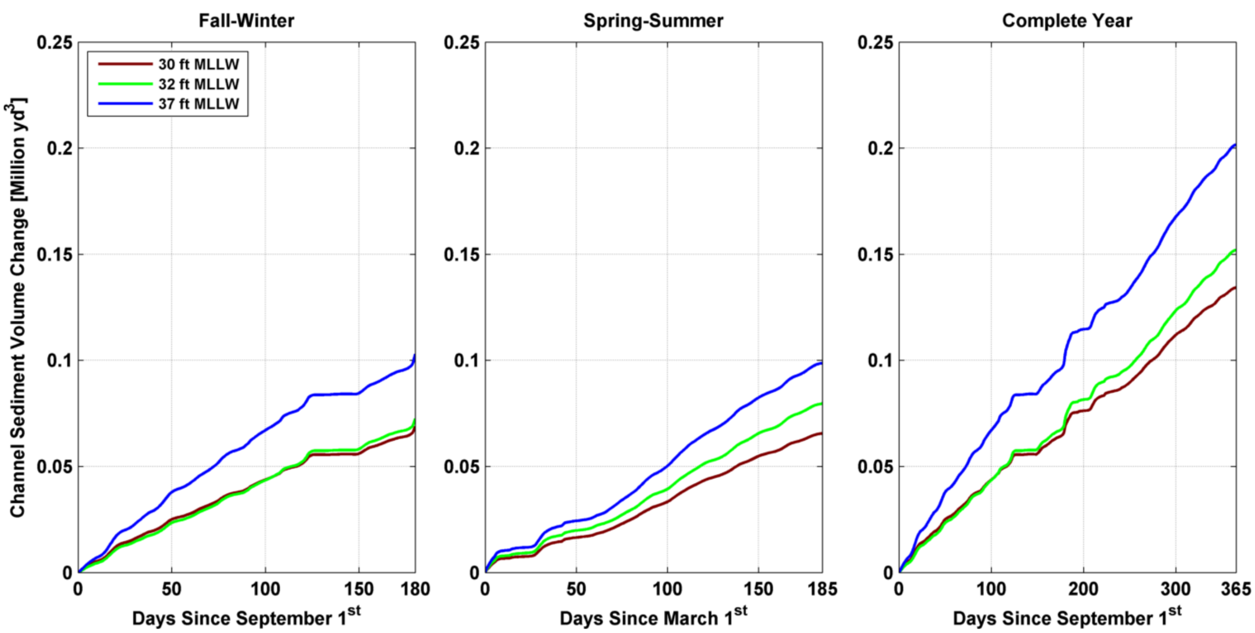


Figure 6.3-1
The predicted volume of sediment deposited in the Redwood City Harbor Channel for 30 feet MLLW, 32 feet MLLW, and 37 feet MLLW project depths.

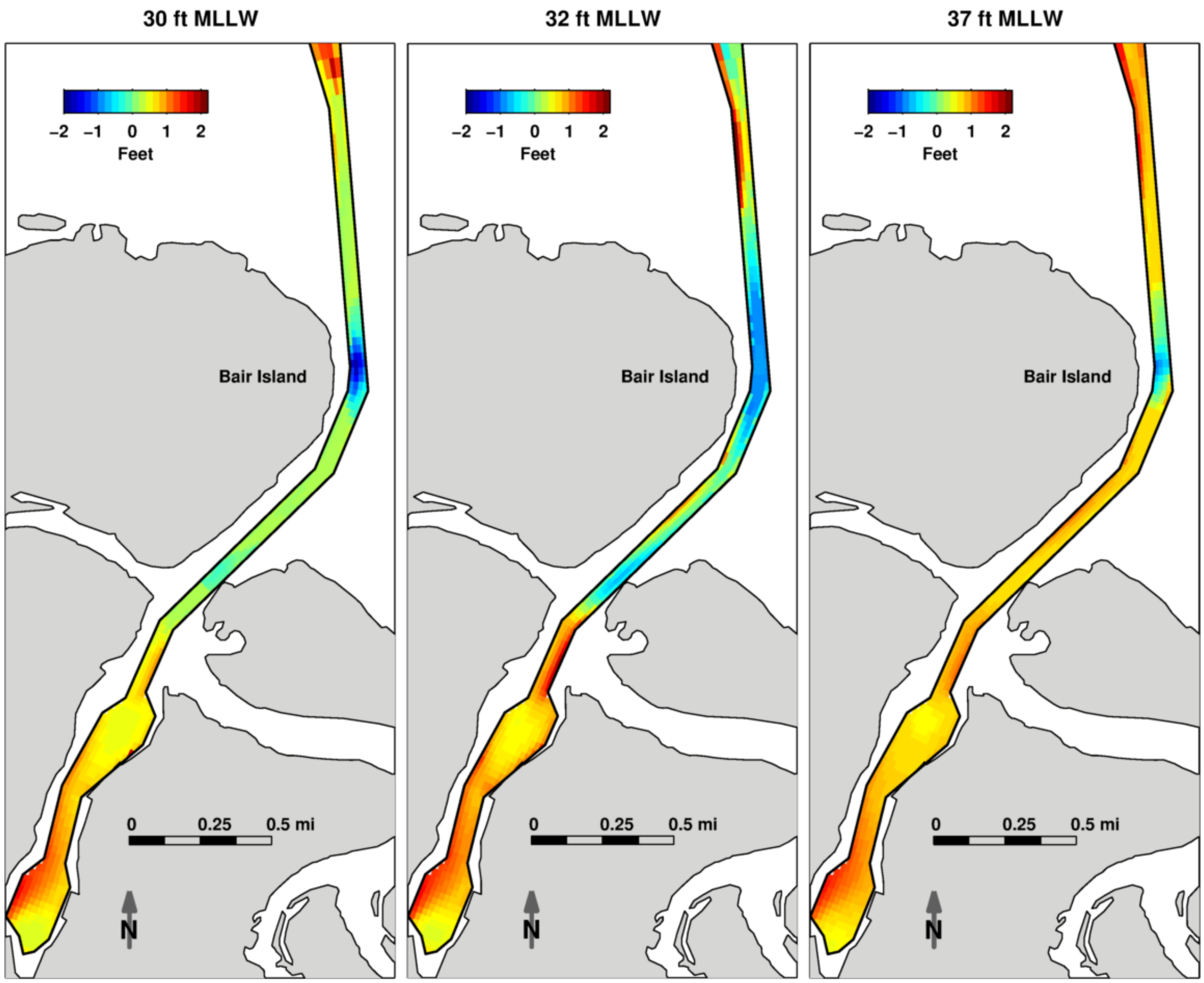


Figure 6.3-2
The predicted sediment deposit thickness in the Redwood City Harbor Channel over the complete year for 30 feet MLLW, 32 feet MLLW, and 37 feet MLLW project depths.

6.3.2 San Bruno Shoal Channel

Increasing the project depth from 30 feet MLLW to either 32 feet MLLW or to 37 feet MLLW was predicted to increase the sedimentation rate in the San Bruno Shoal Channel (Figure 6.3-3, Table 6.3-2). During the fall through winter time period the sedimentation rate was predicted to increase relative to the 30 feet MLLW project depth by 95% for the 32 feet MLLW project depth and by 79% for the 37 feet MLLW project depth (Figure 6.3-3). During the spring through summer time period the sedimentation rate was predicted to increase relative to the 30 feet MLLW project depth by 1% with the 32 feet MLLW project depth and by 94% with the 37 feet MLLW project depth (Figure 6.3-3).

Over the full year, the sedimentation rate in the San Bruno Shoal Channel was predicted to increase relative to the 30 feet MLLW project depth by 54% for the 32 feet MLLW project depth and by 86% for the 37 feet MLLW project depth (Figure 6.3-3, Table 6.3-2). The depositional thickness was also predicted to increase from the 30 feet MLLW to the 32 feet MLLW and to the 37 feet MLLW project depths, especially near the northern and southern ends of the channel (Figure 6.3-4).

The model predicted higher sedimentation rates in the San Bruno Shoal Channel during the fall through winter period than during the spring through summer period. For example, the model predicted a sedimentation rate of 569,000 $yd^3\ yr^{-1}$ during the fall through winter and 427,000 $yd^3\ yr^{-1}$ during the spring through summer periods with the 30 feet MLLW project depth. This increase in sedimentation in the fall through winter period relative to the spring through summer period is likely a result of the close proximity of the San Bruno Shoal Channel to the Central Bay. As the distance to the Central Bay is reduced, there will likely be a corresponding increase in the influence of the first flush and sediment supply from the Delta and North Bay tributaries on sedimentation in the channel. The period simulated is representative of a wet year with a large first flush, and thus the prediction of more sediment deposition in the fall through winter period than in the spring through summer is not surprising, especially considering sedimentation in the Oakland Harbor Channel was predicted to varying strongly with water year type with much higher sediment deposition predicted during wet water years (Delta Modeling Associates 2015).

The potential increase in dredging requirements in the San Bruno Shoal Channel due to increasing the project depth may be greater than the percentage increases in the sedimentation rate developed for the entire San Bruno Shoal Channel. The San Bruno Shoal Channel is currently only infrequently dredged and the majority of the channel is below the existing 30 feet MLLW project depth. Thus some of the deposition which currently occurs within the channel does not require dredging if the existing depth is below the project depth. However, both the 32 feet MLLW and the 37 feet MLLW project depths necessitated the deepening of a large percentage of the channel (Figure 6.1-3), such that deposition in regions that are naturally deeper than 30 feet MLLW but not naturally deeper than 37 feet MLLW would result in a larger maintenance dredging footprint in the deepened channel. A large portion of the deposition in the 30 feet MLLW scenario was predicted to occur in portions of the channel where the existing depth is below the project depth plus 2 feet of overdepth and thus would not generally be dredged. This highlights that the necessary increase in dredging after deepening from the 30 feet MLLW to either the 32 feet MLLW or to the 37 feet MLLW project depths may be greater than the predicted relative increase in the sedimentation rate in the San Bruno Shoals Channel estimated in the analysis presented in this section.

Table 6.3-2
The predicted sedimentation rate in the San Bruno Shoal Channel for fall through winter, spring through summer, and a complete year.

Date Range	Project Depth (feet MLLW)	Channel Sedimentation Rate ($yd^3\ yr^{-1}$)	Percent Increase Relative To 30 feet MLLW Project Depth
Fall-Winter	30	569,000	N/A
	32	1,112,000	95
	37	1,019,000	79
Spring-Summer	30	427,000	N/A
	32	429,000	1
	37	828,000	94
Complete Year	30	497,000	N/A
	32	766,000	54
	37	922,000	86

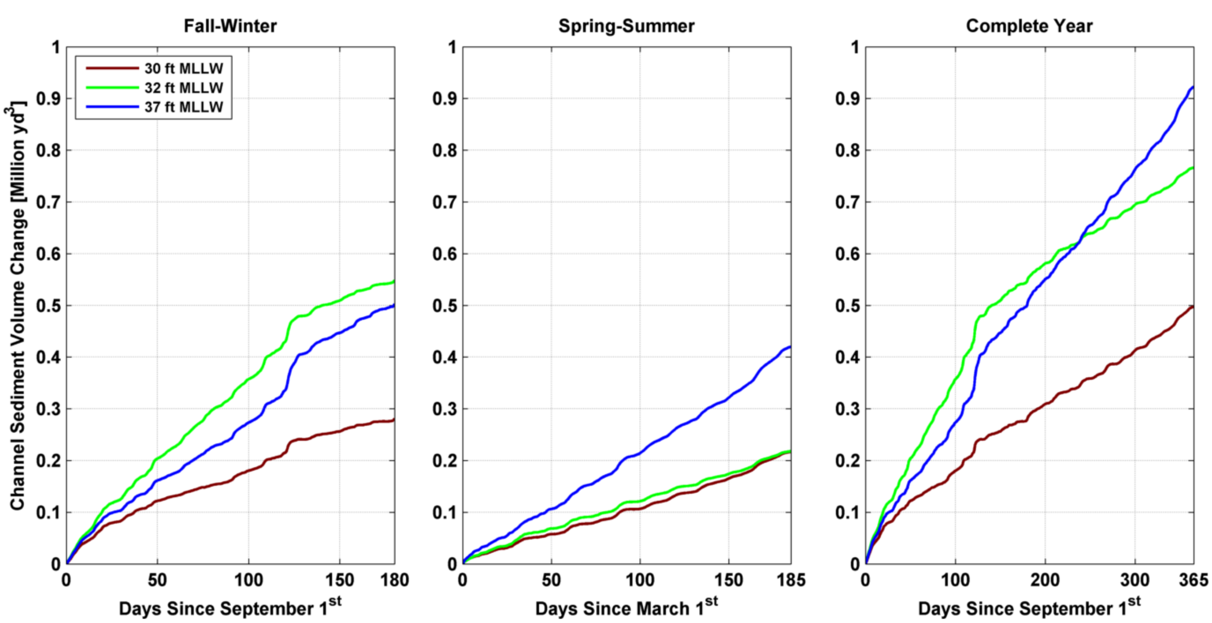


Figure 6.3-3
The predicted volume of sediment deposited in the San Bruno Shoal Channel for 30 feet MLLW, 32 feet MLLW, and 37 feet MLLW project depths.

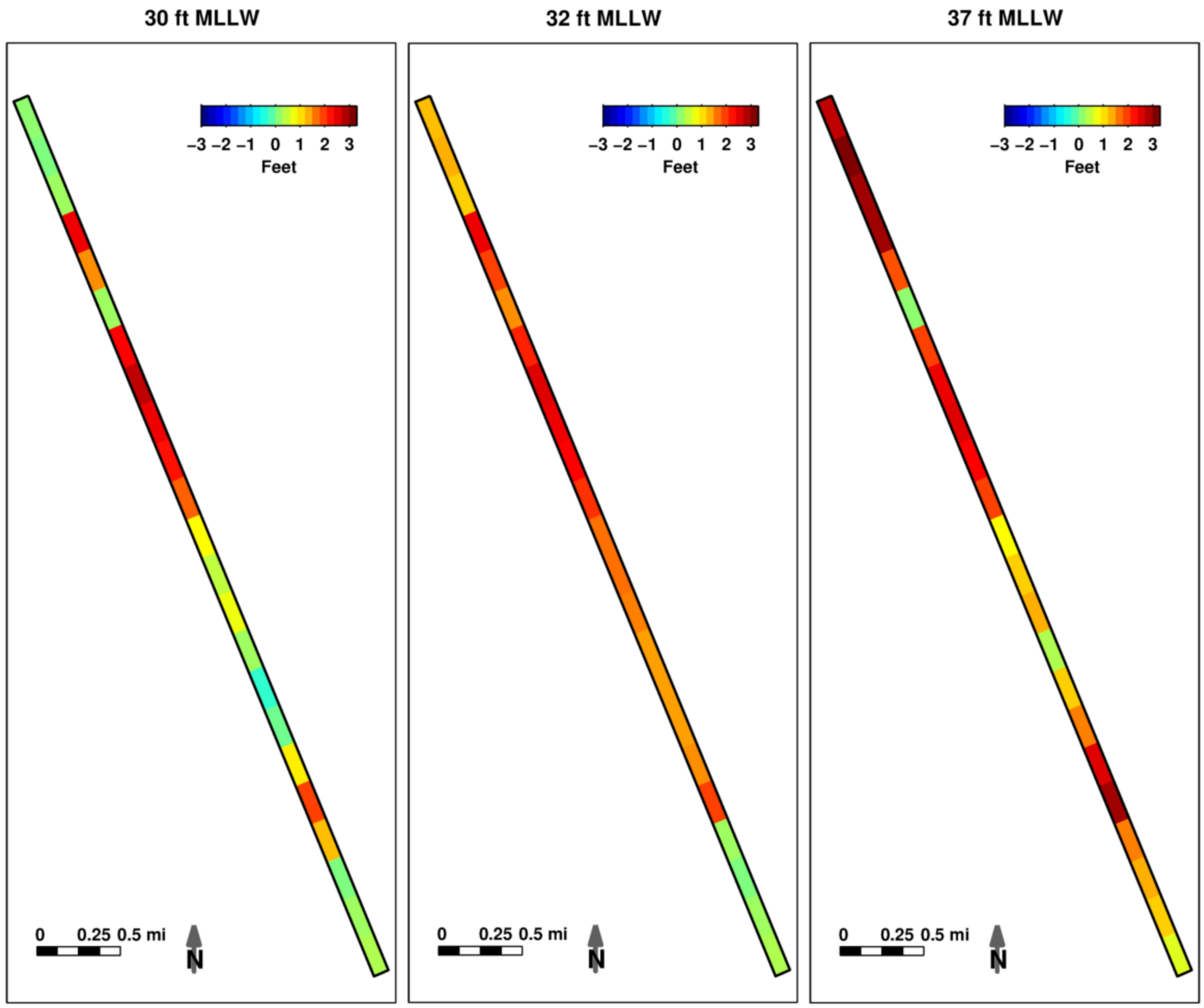


Figure 6.3-4
The predicted sediment deposit thickness in the San Bruno Shoal Channel over the complete year for 30 feet MLLW, 32 feet MLLW, and 37 feet MLLW project depths.

6.4 Project Depth Conclusions

Increasing the project depth from 30 feet MLLW to either 32 feet MLLW or to 37 feet MLLW was predicted to increase sedimentation rates in the Redwood City Harbor Channel and the San Bruno Shoal Channel. This suggests that the proposed channel deepening would result in an increase in annual maintenance dredging in both the Redwood City Harbor Channel and the San Bruno Shoal Channel. The annual sedimentation rate in the Redwood City Harbor Channel was predicted to increase relative to the 30 feet MLLW project depth by 13% with the 32 feet MLLW project depth and by 51% with the 37 feet MLLW project depth for the full year evaluated. The annual sedimentation rate in the San Bruno Shoal Channel was predicted to increase relative to the 30 feet MLLW project depth by 54% with the 32 feet MLLW project depth and by 86% with the 37 feet MLLW project depth for the full year evaluated. The increases in the sedimentation rate with increasing project depth are consistent with results from Oakland Harbor, where the sedimentation rate was predicted to increase by 34% after deepening from 42 feet MLLW to 46 feet MLLW and by 55% after deepening from 42 feet MLLW to 50 feet MLLW (Delta Modeling Associates 2015). The relative increase in the sedimentation rate caused by deepening project depths is expected to remain relatively constant regardless of the water year type, even if the total deposition volume changes between different years, based on analysis of Oakland Harbor sedimentation rates (Delta Modeling Associates 2015).

The analysis of sedimentation rate over different seasonal time periods suggested the sedimentation rate in the Redwood City Harbor Channel is less sensitive to seasonal influences than the San Bruno Shoal Channel. This is potentially caused by the Redwood City Harbor Channel being located farther from the Central Bay than the San Bruno Shoal Channel. The influence of large sediment supply events from the Delta and North Bay are likely to be lower in the Redwood City Harbor Channel than in the San Bruno Shoal Channel.

Because of the acceptable validation of the modeled sediment deposition volumes in the two channels, yet a very accurate validation of the relative difference in sedimentation between two different years, the model analysis focused on the percentage difference in the sedimentation rate between the scenarios rather than the exact differences in deposition volume. That is, the predicted percentage difference in the sedimentation rate resulting from different project depths will have less uncertainty than the corresponding absolute differences in deposition volumes between scenarios. However, these percentages can be combined with the average observed shoaling rate derived from the hydrosurvey analysis (Section 4) to provide rough estimates of the potential shoaling rates associated with the 32 feet MLLW and 37 feet MLLW project depths. Based on the annual average shoaling rate within the Redwood City Harbor Channel of approximately 183,000 $yd^3\ yr^{-1}$ and the percent increase predicted by the model, this would suggest that annual maintenance dredging for the 32 feet MLLW project depth would average 207,000 $yd^3\ yr^{-1}$, and annual maintenance dredging for the 37 feet MLLW project depth would average 276,000 yd^3 yr^{-1}. However, these should be treated as approximations due to uncertainty in the model predictions, and potential variations due to interannual variability or future changes to sediment supply in the Bay.

The change in the sedimentation rate predicted for the San Bruno Shoal Channel may underestimate the increase in dredging requirements resulting from deepening the San Bruno Shoal Channel relative to the existing 30 feet MLLW project depth. This is because the results suggest that a larger portion of the channel may begin to experience above grade shoaling and require dredging for both the 32 feet MLLW and 37 feet MLLW project depths than currently occurs for the 30 feet MLLW project depth. After deepening below the existing depths any buffer that currently exists between the existing conditions and the project depth will have been removed and sediment deposition that may not have caused above grade shoaling with the 30 feet MLLW project depth may cause above grade shoaling for both the 32 feet MLLW and the 37 feet MLLW project depths.

7 INFLUENCE OF CHANNEL ALIGNMENT ON SHOALING

The application of the UnTRIM Bay-Delta model (MacWilliams et al. 2007, 2008, 2009, 2015) coupled with the SWAN wave model (SWAN Team 2009a) and the SediMorph sediment transport model (BAW 2005) was used to investigate the effects of a potential realignment of the Redwood City Harbor Channel on shoaling rates and sediment deposition in the hot spot south of Bair Island. Two scenarios were used to estimate how the sedimentation rate in the channels would be changed by a potential realignment using the 37 feet MLLW project depth. This analysis predicted the proposed channel realignment would not decrease the sedimentation rate in the Redwood City Harbor Channel nor alleviate the above grade shoaling south of Bair Island.

7.1 Channel Alignment Overview

Two scenarios were used to evaluate the influence of a proposed realignment of the Redwood City Harbor Channel on sedimentation in the channel. The proposed realignment was designed to increase the distance between the channel and the southeastern side of Bair Island while still considering the ease of navigation. The scenarios evaluated whether this increased distance between the channel and Bair Island could potentially reduce the sediment deposition in the hot spot south of Bair Island.

The two scenarios used in this analysis were based on a 37 feet MLLW project depth and used the same boundary conditions for the base year (2018) described in Section 6. The 37 feet MLLW scenario described in Section 6 was used as the existing channel alignment scenario and a new model grid was created that included a more eastward alignment of the Redwood City Harbor Channel in the vicinity of Bair Island (Figure 7.1-1). The channel realignment was provided by USACE and developed by the Project Delivery Team based on feedback from the San Francisco Bar Pilots (Captain Tonny Coppo) to ensure the alignment would be navigable by vessels entering and exiting Redwood City Harbor. The bathymetry for the realignment grid was based on the most current hydrosurvey data, as explained in Section 6. The area within the realigned channel was set as the deeper of the hydrosurvey data or 37 feet MLLW plus 2 feet of overdepth. A 3:1 side slope was used outside of the channel. The region of the existing channel alignment that did not overlap with the realigned channel was not infilled to the surrounding mudflat elevation, but was rather left as the relatively deep existing channel conditions. This method produced a realigned channel that only differed from the 37 feet MLLW scenario in the region around the channel realignment, with the remainder of the Redwood City Harbor Channel identical between the two scenarios.

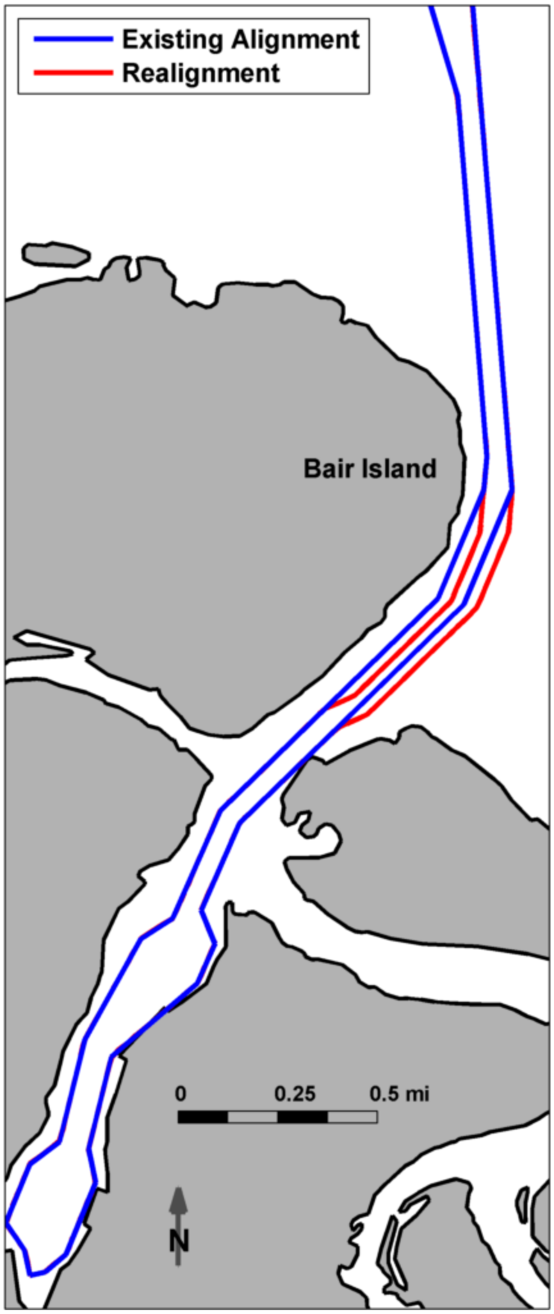


Figure 7.1-1
The existing alignment and proposed future alignment of the Redwood City Harbor Channel.

7.2 Influence of Channel Alignment on Sedimentation

The realignment of the Redwood City Harbor Channel was predicted to slightly increase the sedimentation rate in the channel. The sedimentation rate was predicted to increase in the realignment scenario relative to the 37 feet MLLW scenario by 3% over the fall through winter period, by 3% over the spring through summer period, and by 3% over the complete year (Figure 7.2-1, Table 7.2-1). Although the predicted sediment deposition thickness was very similar throughout the channel for the two scenarios, the realignment scenario did predict an increase in the deposition thickness of about 0.25 foot around the hot spot south of Bair Island over the one year simulation period (Figure 7.2-2). In the realignment scenario, the model predicted some erosion of the seabed in the portion of the existing channel that was excluded from the realignment channel, some of which likely deposited in the realigned channel and partially contributed to the predicted increase in sediment deposition south of Bair Island.

Table 7.2-1
The predicted sedimentation rate in the Redwood City Harbor Channel for fall through winter, spring through summer, and a complete year with the 37 feet MLLW project depth.

Date Range	Channel Alignment	Channel Sedimentation Rate [$yd^3\ yr^{-1}$]	Percent Increase Relative To Current Alignment
Fall-Winter	Existing	209,000	N/A
	Realignment	215,000	3
Spring-Summer	Existing	195,000	N/A
	Realignment	201,000	3
Complete Year	Existing	202,000	N/A
	Realignment	208,000	3

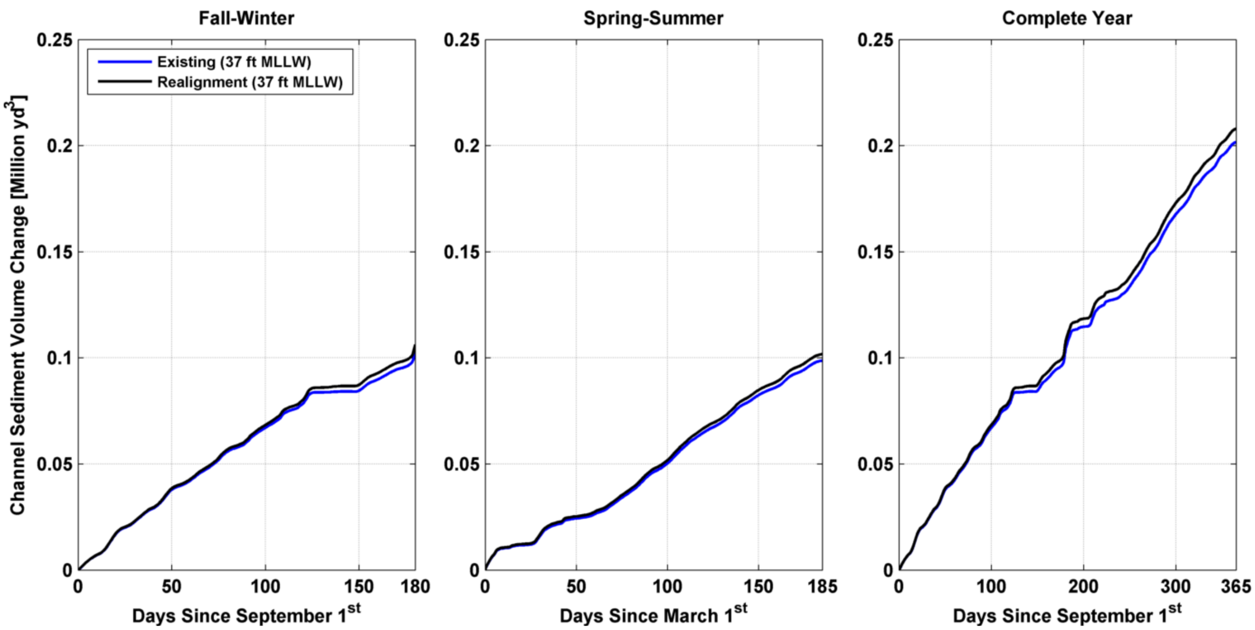


Figure 7.2-1
The predicted volume of sediment deposited in the Redwood City Harbor Channel for the existing alignment and proposed realignment scenarios.

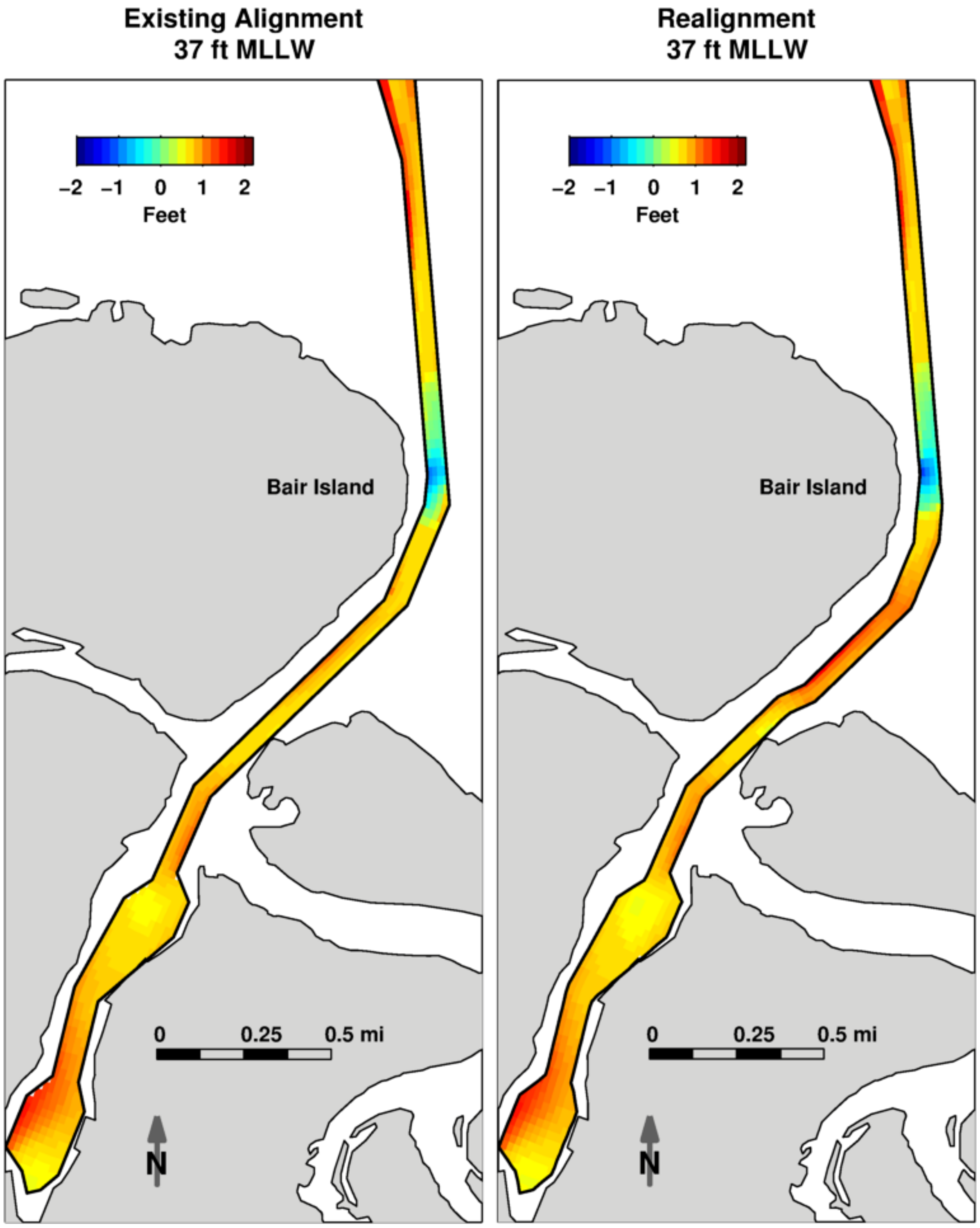


Figure 7.2-2
The predicted depositional thickness in the Redwood City Harbor Channel for the existing alignment and proposed realignment scenarios.

7.3 Channel Alignment Conclusions

The proposed realignment of the Redwood City Harbor Channel was predicted to have a minimal effect on the sedimentation in the channel with a 37 feet MLLW project depth, and thus the realignment was predicted to not likely decrease shoaling south of Bair Island with project depths from 30 feet MLLW to 37 feet MLLW. The sedimentation rate was predicted to increase by 3% in the realignment scenario compared to the existing alignment. The thickness of the hot spot south of Bair Island was also predicted to increase in the realignment scenario relative to the existing alignment scenario.

The 37 feet MLLW project depth was used for the realignment scenarios because it had a higher predicted sedimentation rate in the Redwood City Harbor Channel than either the 30 feet MLLW or the 32 feet MLLW scenarios. Because there was more sediment deposition predicted for the 37 feet MLLW scenario, it is also likely that the scenario would show more sensitivity to the proposed channel realignment than the 30 feet MLLW and the 32 feet MLLW simulations. Because the proposed realignment did not result in a significant decrease in the sedimentation south of Bair Island for the 37 feet MLLW project depth, it is not expected that the realignment would significantly change the shoaling rate for either the 30 feet MLLW or the 32 feet MLLW project depths.

8 INFLUENCE OF PROJECT DEPTH ON HYDRODYNAMICS AND SEDIMENT DEPOSITION IN THE VICINITY OF THE REDWOOD CITY HARBOR CHANNEL

The UnTRIM Bay-Delta model was applied to evaluate potential effects on hydrodynamics and sediment deposition in the vicinity of the Redwood City Harbor Channel and Bair Island resulting from deepening the project depth from 30 feet MLLW to 32 feet MLLW. Without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions were evaluated for effects on the hydrodynamics under both Year 0 and Year 50 conditions over a 2-week period that included elevated outflow from Redwood Creek, high winds, and spring tides, resulting in a total of four scenarios. The influence of deepening the project depth on the hydrodynamics was determined by examining the water level, tidal flows, salinity, and shear stress in the vicinity of the Redwood City Harbor Channel and Bair Island. Without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions were evaluated for effects on sediment deposition outside of the Redwood City Harbor Channel under Year 0 conditions over the one year simulations detailed in Section 6.

Five additional scenarios were used to assess the effects of the channel deepening on peak water levels and storm surge in the Redwood City Harbor during a large storm event. One simulation was used to validate the peak water levels during the December 1983 storm, which had the second highest recorded water level at San Francisco at Fort Point and highest recorded water level at the NOAA Redwood City tide gauge (MacWilliams et al. 2012b). This storm event was then simulated under without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions for both Year 0 and Year 50 conditions which included sea level rise. These four scenarios were used to determine the effect of increasing the project depth on water level resonance in Redwood City by examining the peak water levels in each scenario.

8.1 Model Scenarios Overview

8.1.1 Effect of Increased Project Depth on Hydrodynamics

Because the exact weather, hydrology, and operating conditions cannot be predicted in advance, representative conditions for 2018 (Year 0) and 2068 (Year 50) were developed for the hydrodynamic simulations using 2005 hydrology, and modified to account for both sea level rise and to include changes to the Bair Island Restoration Project that are expected to occur prior to 2018. The period from December 25 through January 8 was used for the evaluation of the effects of deepening the project depth on the water surface elevation, water flow, salinity, and bed shear stress in the vicinity of the Redwood City Harbor Channel and Bair Island. This period includes a historic storm that provided the necessary combination of Redwood Creek inflow, tides, and winds to examine how deepening the project depth will affect the hydrodynamics during a large storm event. Validation of the water level and salinity in the Central Bay and the South Bay during this analysis period under historic conditions is included in the validation period used for the sediment transport simulations (Appendix C).

The first set of four scenarios simulated without-project and with-project conditions from December 25 through January 8 under both Year 0 and Year 50 conditions. These scenarios were used to determine the effects of increasing the project depth on water levels, flows, salinity, and shear stress in the vicinity of the Redwood City Harbor Channel and Bair Island (Table 8.1-1). The four modeled scenarios included without-project and with-project conditions and included both a restored Bair Island (Figure 6.1-1) and sea level rise (Table 8.1-1). For the without-project conditions, the bathymetry inside the Redwood City Harbor Channel was set as the deeper of the existing conditions or 30 feet MLLW plus 2 feet of overdepth, for a total minimum depth of 32 feet MLLW. For the with-project conditions, the bathymetry inside the Redwood City Harbor Channel was set as the deeper of the existing conditions or 32 feet MLLW plus 2 feet of overdepth, for a total minimum depth of 34 feet MLLW. Channel side slopes of 3:1 were applied from the edge of the channel and any areas shallower than the design side slopes were also deepened based on the distance from the channel.

Sea level rise was included in the without-project and with-project scenarios by adjusting the San Francisco at Fort Point (NOAA 9414290) water level from the model forcing year of 2005 for the projected sea level rise from 2005 to the project start year (Year 0, 2018) and from 2005 to 50 years after the project start year (Year 50, 2068). A projected sea level rise of 0.09 foot from the model forcing year (2005) to Year 0 was applied based on the NRC curve 1 (USACE 2014). The NRC curve 1 was used to adjust for sea level rise from 2005 to 2018 because the sea level rise in the San Francisco Bay over the last 30 years has been below the historic trend. Using the NRC curve 3 for the relatively near-term project start year of 2018 would largely overpredict the sea level rise between the model forcing year and the project base year (Year 0). A projected sea level rise of 2.51 feet from the model forcing year to Year 50 was applied based on the NRC curve 3 (USACE 2014).

8.1.2 Effect of Increased Project Depth on Water Level Resonance in Redwood City Harbor

Five scenarios were used to evaluate the effects of the channel deepening on peak water levels and storm surge in the Redwood City Harbor during a large storm event (Table 8.1-2). One simulation was used to validate the predicted peak water levels during the December 1983 storm under historic conditions. This scenario used the Redwood City Harbor Channel bathymetry based on hydrosurvey data from December 24, 2005, as explained in Section 5.1.4. The model validation focused on the period between November 26 and December 8, 1983. This time period included the highest water level ever recorded at the NOAA Redwood City station and the second highest water level on record at the NOAA San Francisco tide gauge (MacWilliams et al. 2012b).

Without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions were then simulated for both Year 0 and Year 50 conditions which included sea level rise (Table 8.1-2). For each of these scenarios, the Bair Island configuration and bathymetry of the without-project and with-project Redwood City Harbor Channel were specified for the Year 0 and Year 50 scenarios as explained in Section 8.1.1. These four scenarios were used to determine the effect of increasing the project depth on water level resonance in the Redwood City Harbor by examining the peak water levels in each scenario. For each of these scenarios, the period between November 26 and December 8 was evaluated.

Sea level rise was included in the Year 0 and Year 50 scenarios by adjusting the San Francisco at Fort Point (NOAA 9414290) water level from the model forcing year of 1983 for the projected sea level rise from 1983 to Year 0 (2018) and from 1983 to Year 50 (2068). The amount of projected sea level rise was determined in two steps because the USACE guidance started in 1992 (USACE 2014). First, the sea level rise from 1983 to 1992 was estimated and then the sea level rise from 1992 to 2018 and from 1992 to 2068 was calculated. The sea level rise from 1983 to 1992 was estimated to be 0.05 foot based on a eustatic sea level rise of

0.005577 ft yr^{-1} (1.7 mm yr^{-1}, USACE 2014). For the Year 0 scenarios, the NRC curve 1 was then used to determine a sea level rise from 1992 to 2018 of 0.18 feet. For the Year 0 scenarios, the water level at San Francisco at Fort Point (NOAA 9414290) was adjusted by a total of 0.23 foot to account for sea level rise between 1983 and 2018. The NRC curve 1 was used to adjust for sea level rise from 1992 to 2018. The NRC curve 3 was used to determine a sea level rise of 2.66 feet from 1992 to 2068 (USACE 2014). For the Year 50 scenarios the water level at San Francisco at Fort Point (NOAA 9414290) was adjusted by a total of 2.71 feet to account for sea level rise between 1983 and 2068.

Table 8.1-1
The scenario matrix used to determine how deepening the project depth will affect the hydrodynamics in the Redwood City Harbor Channel. These scenarios were also used for the ship simulation flow field output detailed in Section 9.

Scenario	Channel Project Depth (feet MLLW)	Project Year For Sea Level Rise	Model Forcing Year
1	30 (Without-Project)	Year 0 (2018)	2005
2	32 (With-Project)		
3	30 (Without-Project)	Year 50 (2068)	
4	32 (With-Project)		

Table 8.1-2
The scenario matrix used to determine how deepening the project depth will affect the water level resonance and the peak water level in the Redwood City Harbor Channel.

Scenario	Channel Project Depth (feet MLLW)	Project Year For Sea Level Rise	Model Forcing Year
1	2005 Hydrosurvey Data	No Sea Level Rise	1983
2	30 (Without-Project)	Year 0 (2018)	
3	32 (With-Project)		
4	30 (Without-Project)	Year 50 (2068)	
5	32 (With-Project)		

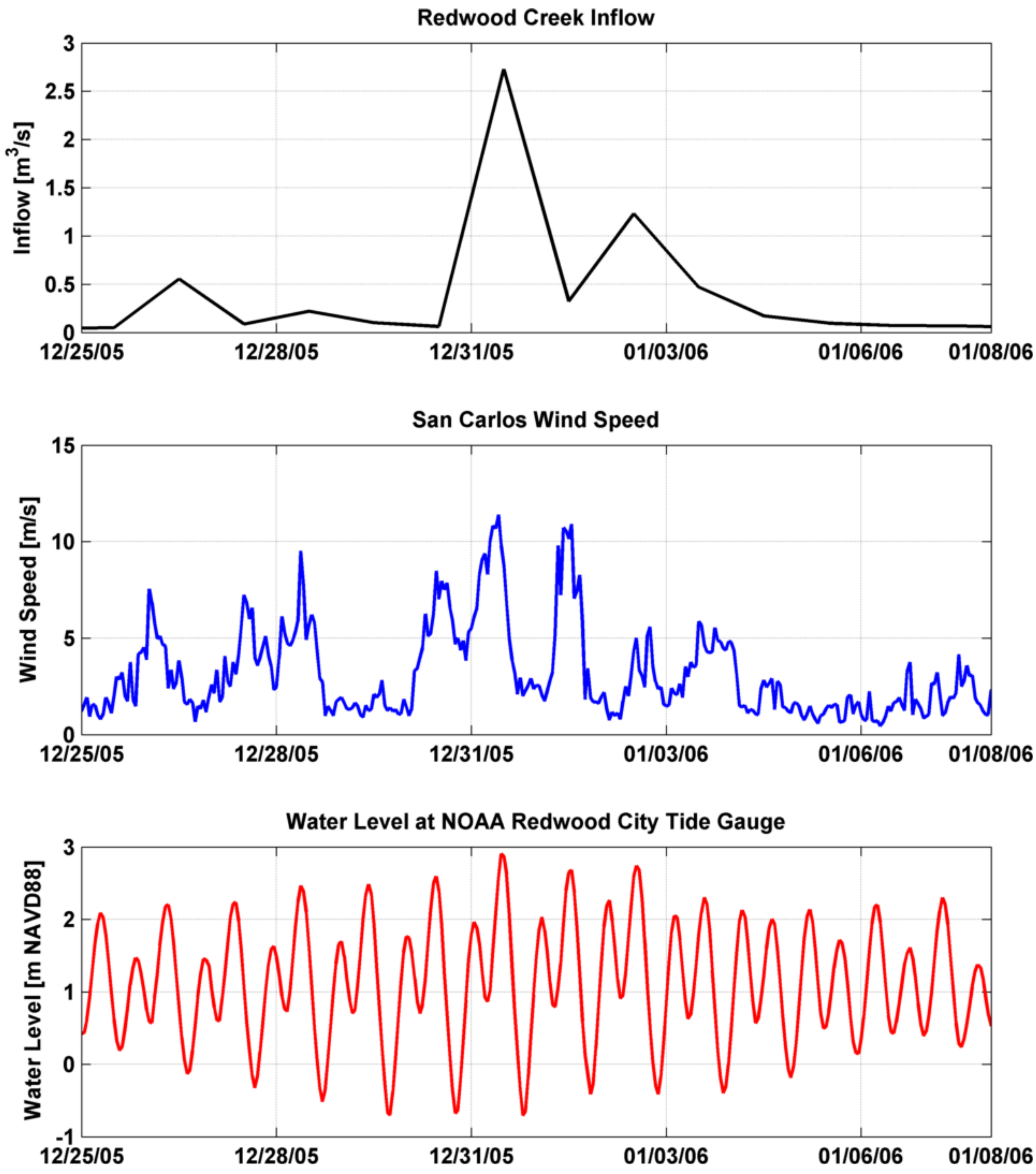


Figure 8.1-1
The Redwood Creek inflow, wind speed at San Carlos, and observed water level at the Redwood City NOAA tide gauge during the 2-week analysis period in December 2005 and January 2006 used to develop Year 0 and Year 50 conditions.

8.2 Effect of Increased Project Depth on Hydrodynamics

The model validation presented in Appendix C demonstrates that the model accurately predicted the water level and salinity at the Central Bay and South Bay validation stations, based on the thresholds for model accuracy detailed in MacWilliams et al. (2015).

The water levels in the vicinity of Bair Island, the water flow through channel cross sections in the vicinity of Bair Island, the salinity in the vicinity of Bair Island, and the bed shear stress were used to determine the effect of increasing the project depth on hydrodynamics in both the Year 0 and Year 50 scenarios. The model predictions were analyzed for the period between December 25 and January 8 detailed in Section 8.1.1 for both Year 0 (2018) and Year 50 (2068) conditions.

8.2.1 Effect of Increased Project Depth on Water Level, Flow, and Salinity

Water level (Figure 8.2-1), flow (Figure 8.2-2), and salinity (Figure 8.2-3), were examined at eight locations in the vicinity of Redwood City Harbor and Bair Island. Increasing the project depth from 30 feet MLLW to 32 feet MLLW was predicted to have essentially no effect on the water levels in the vicinity of Redwood City Harbor and Bair Island for both the Year 0 and the Year 50 scenarios. The model predicted nearly the same tidal phase, peak water level, mean water level, and tidal water level ranges throughout the Redwood City Harbor Channel and Bair Island in the without-project and with-project conditions for both the Year 0 (Figures 8.2-4 through 8.2-11, Table 8.2-1) and the Year 50 scenarios (Figures 8.2-12 through 8.2-19, Table 8.2-1).

The model also predicted increasing the project depth will have very little effect on the flow in the vicinity of Bair Island in both the Year 0 and the Year 50 scenarios. The model predicted nearly the same tidal phase, peak flow, mean flow magnitude, and tidal flow magnitude ranges throughout the Redwood City Harbor Channel and Bair Island for the without-project and with-project conditions in both the Year 0 (Figures 8.2-20 through 8.2-27, Table 8.2-2) and the Year 50 scenarios (Figures 8.2-28 through 8.2-35, Table 8.2-2).

Increasing the project depth from 30 feet MLLW to 32 feet MLLW was predicted to have very little effect on the salinity in the vicinity of Bair Island for both the Year 0 and the Year

50 scenarios. The model predicted nearly the same phasing of salinity and the same decrease in salinity over the duration of the scenarios at all eight analyzed locations in the without-project and with-project conditions for both the Year 0 (Figures 8.2-36 through 8.2-43) and the Year 50 scenarios (Figures 8.2-44 through 8.2-51). The mean difference in salinity between the without-project and with-project conditions was less than 0.1 PSU at all eight locations evaluations for both the Year 0 and Year 50 scenarios (Table 8.2-3).

8.2.2 Effect of Increased Project Depth on Shear Stress

The bed shear stress was examined spatially in the vicinity of the Redwood City Harbor Channel and Bair Island during slack water, peak flood velocity, and peak ebb velocity. Figure 8.2-52 highlights the timing of the peak velocities in the northern portion of the Redwood City Harbor Channel, centered around the elevated discharge from Redwood Creek, for the 30 feet MLLW project depth Year 0 scenario. For the Year 0 scenarios the shear stress was evaluated on December 31, 2018 at 06:00 (slack water), December 31, 2018 at 07:30 (peak flood), and December 31, 2018 at 15:45 (peak ebb). The timing of peak flood, slack water, and peak ebb were predicted to only change by up to 15 minutes (one output time step) in the Year 50 scenarios relative to the Year 0 scenarios. For the Year 50 scenarios the shear stress was evaluated on December 31, 2068 at 05:45 (slack water), December 31, 2068 at 07:15 (peak flood), and December 31, 2068 at 15:45 (peak ebb).

The shear stress maps were generated using the near-bed velocity predicted in the UnTRIM hydrodynamic simulations. Within each grid cell the bed shear stress was calculated as:

$$\tau = \rho C_d u_b^2$$

where ρ is the density of water, C_d is the drag coefficient, and u_b is the predicted velocity one meter above the bed. The drag coefficient applied was 0.0025 at one meter above the bed, as used in MacWilliams and Cheng (2008) and MacWilliams (2011). This value of the drag coefficient is consistent with the sediment transport analysis conducted as part of the Hamilton Wetlands Restoration Aquatic Transfer Facility technical study (Sea Engineering 2008).

Increasing the project depth from 30 feet MLLW to 32 feet MLLW was predicted to have a minimal effect on the bed shear stress in the vicinity of the Redwood City Harbor Channel and Bair Island near slack water (Figure 8.2-53), during peak flood tide (Figure 8.2-54), and during peak ebb tide (Figure 8.2-55) in the Year 0 scenarios. In the Year 50 scenarios, increasing the project depth from 30 feet MLLW to 32 feet MLLW was also predicted to have a minimal effect on the bed shear stress near slack water (Figure 8.2-56), during peak flood tide (Figure 8.2-57), and during peak ebb tide (Figure 8.2-58).

8.2.3 Effect of Increased Project Depth on Bair Island Sedimentation and the Mudflat Surrounding the Redwood City Harbor Channel

Analysis was conducted on the sedimentation in Bair Island and on the mudflat surrounding the Redwood City Harbor Channel to determine the effects of increasing the project depth on sedimentation in these two areas. This analysis used the without-project (30 feet MLLW) and with-project (32 feet MLLW) Year 0 simulations from Section 6 that were a full year long. The predicted sediment depositional volumes in five subregions of Bair Island were analyzed to determine if the deepening of the Redwood City Harbor Channel will influence the sediment transported into Bair Island. The five evaluated subregions were the three planned restoration areas of Inner Bair Island, Middle Bair Island, and Outer Bair Island, and the Middle Bair Island marsh and Outer Bair Island marsh (Figure 8.2-59). The change in sediment deposition thickness surrounding the Redwood City Harbor Channel was used to determine if the mudflats surrounding the channel are predicted to erode after deepening of the navigation channel.

The model predicted Bair Island to be net depositional during the simulated period, and that the increase in the project depth had a negligible effect on the amount of sediment predicted to accumulate in Bair Island. The average sediment depositional thickness in each Bair Island region was predicted to change by less than 0.001 feet after deepening from 30 feet MLLW to 32 feet MLLW (Table 8.2-4). The very small difference in the predicted sedimentation in Bair Island with increasing project depths indicates only a minimal predicted effect on the net sediment deposition in Bair Island from deepening the Redwood City Harbor Channel.

Figure 8.2-60 shows the difference in sedimentation between the 30 feet MLLW and the 32 feet MLLW scenarios over the full one-year simulation. Positive values indicate the seabed elevation in the deepened project depth scenario was predicted to be higher than in the 30 feet MLLW scenario, either due to increased deposition or decreased erosion in the deepened project depth scenario relative to the 30 feet MLLW scenario. Negative values indicate the seabed elevation in the deepened project depth scenario was predicted to be lower than the 30 feet MLLW scenario, either due to decreased deposition or increased erosion in the deepened project depth scenario relative to the 30 feet MLLW scenario.

Figure 8.2-60 highlights that the model predicted relatively little effect of deepening the Redwood City Harbor Channel project depth on sedimentation on the surrounding mudflat. The extent of differences in the seabed between the 30 feet MLLW and the 32 feet MLLW scenarios of more than 0.1 inch was generally limited to within one or two grid cells from the Redwood City Harbor Channel. Over the majority of the mudflats surrounding the Redwood City Harbor Channel the model predicted less than 0.1 inch of difference in the sediment deposition or erosion thicknesses from deepening the project depth. The deepening of the Redwood City Harbor Channel was predicted to have a negligible influence on the mudflats surrounding the channel because the model predicted relatively small changes to the deposition, erosion, and seabed elevation surrounding the Redwood City Harbor Channel between the 30 feet MLLW scenario and the scenarios with increased project depth. An exception to the predictions of negligible changes in the deposition or erosion thicknesses was seen on the side slopes and grid cells immediately adjacent to the channel. However, this region directly adjacent to the channel would be expected to show changes in the sedimentation between the scenarios because the depths of this region also increased with the increases in project depth.

Table 8.2-1
Predicted water levels in the vicinity of the Redwood City Harbor Channel and Bair Island under without-project and with-project conditions for the Year 0 and Year 50 scenarios during the two week analysis period.

Location	Project Year For Sea Level Rise	Channel Project Depth (feet MLLW)	Mean Water Level [m NAVD88]	Peak Water Level [m NAVD88]	RMS Difference in Tidally-Averaged Water Level (m)
Redwood City Harbor Channel	Year 0 (2018)	30 (Without-Project)	1.246	2.945	0.000
		32 (With-Project)	1.246	2.946	
	Year 50 (2068)	30 (Without-Project)	1.977	3.683	0.000
		32 (With-Project)	1.977	3.684	
Corkscrew Slough	Year 0 (2018)	30 (Without-Project)	1.268	2.952	0.000
		32 (With-Project)	1.268	2.953	
	Year 50 (2068)	30 (Without-Project)	1.979	3.686	0.000
		32 (With-Project)	1.979	3.687	
Redwood City Tide Gauge	Year 0 (2018)	30 (Without-Project)	1.250	2.966	0.001
		32 (With-Project)	1.250	2.965	
	Year 50 (2068)	30 (Without-Project)	1.981	3.692	0.000
		32 (With-Project)	1.981	3.693	
Steinberger Slough	Year 0 (2018)	30 (Without-Project)	1.331	2.911	0.000
		32 (With-Project)	1.331	2.912	
	Year 50 (2068)	30 (Without-Project)	1.997	3.662	0.000
		32 (With-Project)	1.997	3.662	
Bair Island Marsh	Year 0 (2018)	30 (Without-Project)	1.996	2.924	0.000
		32 (With-Project)	1.996	2.924	
	Year 50 (2068)	30 (Without-Project)	2.265	3.677	0.000
		32 (With-Project)	2.265	3.677	
Outer Bair Island	Year 0 (2018)	30 (Without-Project)	1.603	2.927	0.000
		32 (With-Project)	1.603	2.927	
	Year 50 (2068)	30 (Without-Project)	2.084	3.676	0.000
		32 (With-Project)	2.084	3.676	
Middle Bair Island	Year 0 (2018)	30 (Without-Project)	1.538	2.933	0.000
		32 (With-Project)	1.538	2.933	
	Year 50 (2068)	30 (Without-Project)	2.070	3.683	0.000
		32 (With-Project)	2.070	3.683	
Inner Bair Island	Year 0 (2018)	30 (Without-Project)	1.455	2.961	0.000
		32 (With-Project)	1.455	2.960	
	Year 50 (2068)	30 (Without-Project)	2.037	3.681	0.000
		32 (With-Project)	2.037	3.682	

Table 8.2-2
Predicted water flows in the vicinity of the Redwood City Harbor Channel and Bair Island under without-project and with-project conditions for the Year 0 and Year 50 scenarios during the two week analysis period.

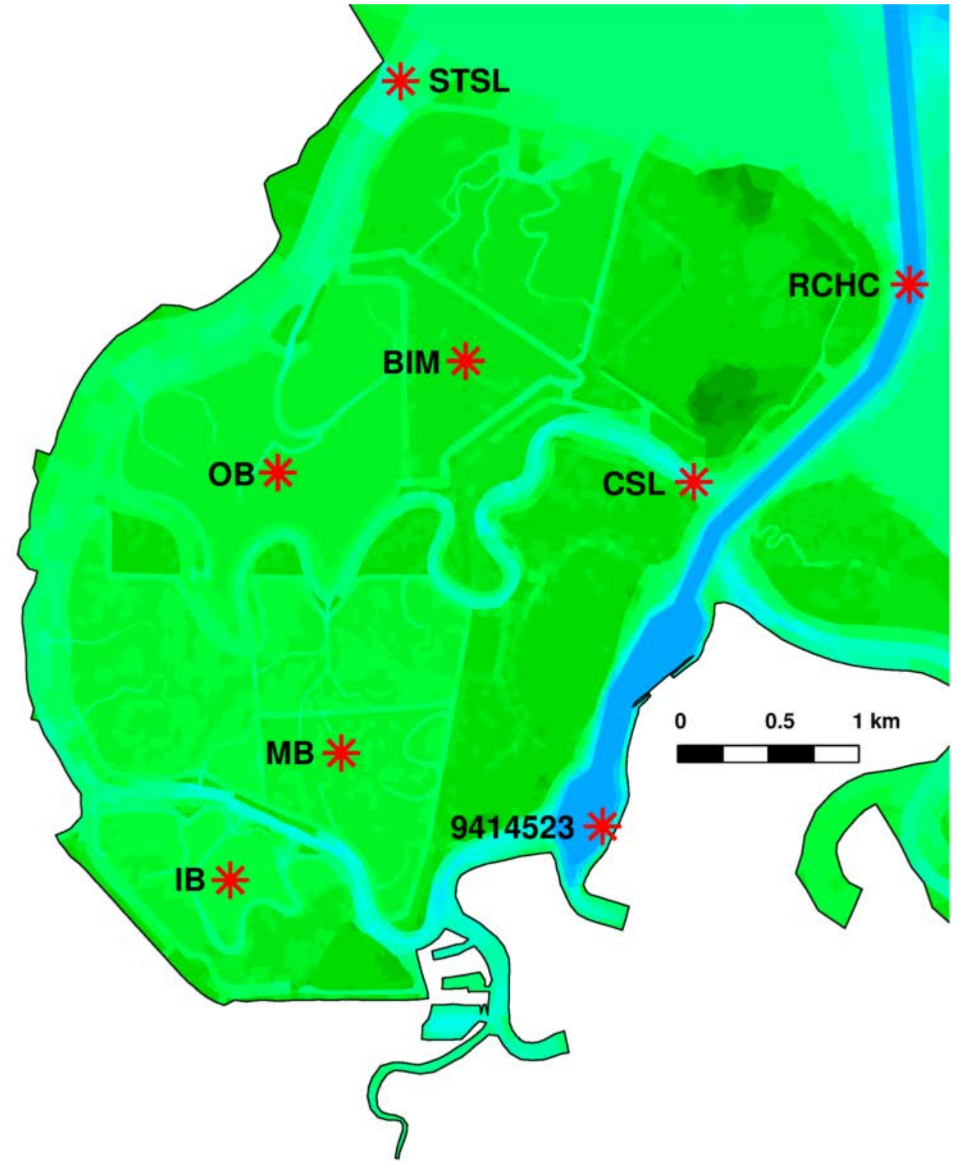
Location	Project Year For Sea Level Rise	Channel Project Depth (feet MLLW)	Mean Flow Magnitude (m^3/s)	Peak Flow Magnitude (m^3/s)	RMS Difference in Tidally-Averaged Flow (m^3/s)
Redwood City Harbor Channel (Northern)	Year 0 (2018)	30 (Without-Project)	4.390	14.160	0.003
		32 (With-Project)	4.394	14.384	
	Year 50 (2068)	30 (Without-Project)	5.803	15.086	0.019
		32 (With-Project)	5.830	15.142	
Corkscrew Slough	Year 0 (2018)	30 (Without-Project)	0.827	3.662	0.001
		32 (With-Project)	0.828	3.688	
	Year 50 (2068)	30 (Without-Project)	1.297	3.789	0.002
		32 (With-Project)	1.298	3.793	
Redwood City Harbor Channel (Southern)	Year 0 (2018)	30 (Without-Project)	1.612	4.561	0.001
		32 (With-Project)	1.612	4.617	
	Year 50 (2068)	30 (Without-Project)	2.084	5.276	0.004
		32 (With-Project)	2.086	5.271	
Steinberger Slough	Year 0 (2018)	30 (Without-Project)	2.065	6.899	0.001
		32 (With-Project)	2.064	6.913	
	Year 50 (2068)	30 (Without-Project)	3.181	7.191	0.002
		32 (With-Project)	3.177	7.162	
Corkscrew Slough Flow Constrictor	Year 0 (2018)	30 (Without-Project)	0.217	0.981	0.000
		32 (With-Project)	0.217	0.986	
	Year 50 (2068)	30 (Without-Project)	0.339	1.038	0.000
		32 (With-Project)	0.340	1.045	
Outer Bair Island Breach	Year 0 (2018)	30 (Without-Project)	0.402	1.775	0.000
		32 (With-Project)	0.402	1.784	
	Year 50 (2068)	30 (Without-Project)	0.697	1.860	0.001
		32 (With-Project)	0.696	1.840	
Middle Bair Island Breach	Year 0 (2018)	30 (Without-Project)	0.383	1.752	0.000
		32 (With-Project)	0.383	1.744	
	Year 50 (2068)	30 (Without-Project)	0.609	1.851	0.000
		32 (With-Project)	0.609	1.845	
Inner Bair Island Breach	Year 0 (2018)	30 (Without-Project)	0.173	0.500	0.001
		32 (With-Project)	0.173	0.493	
	Year 50 (2068)	30 (Without-Project)	0.203	0.501	0.001
		32 (With-Project)	0.204	0.508	

Table 8.2-3
Predicted differences in salinity in the vicinity of the Redwood City Harbor Channel and Bair Island between without-project and with-project conditions for the Year 0 and Year 50 scenarios during the two week analysis period.

Location	Project Year For Sea Level Rise	Mean Difference (PSU)	Maximum Difference in Daily-Average Salinity (PSU)
Redwood City Harbor Channel	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1
Corkscrew Slough	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1
Redwood City Tide Gauge	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1
Steinberger Slough	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1
Bair Island Marsh	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1
Outer Bair Island	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1
Middle Bair Island	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1
Inner Bair Island	Year 0 (2018)	<0.1	<0.1
	Year 50 (2068)	<0.1	<0.1

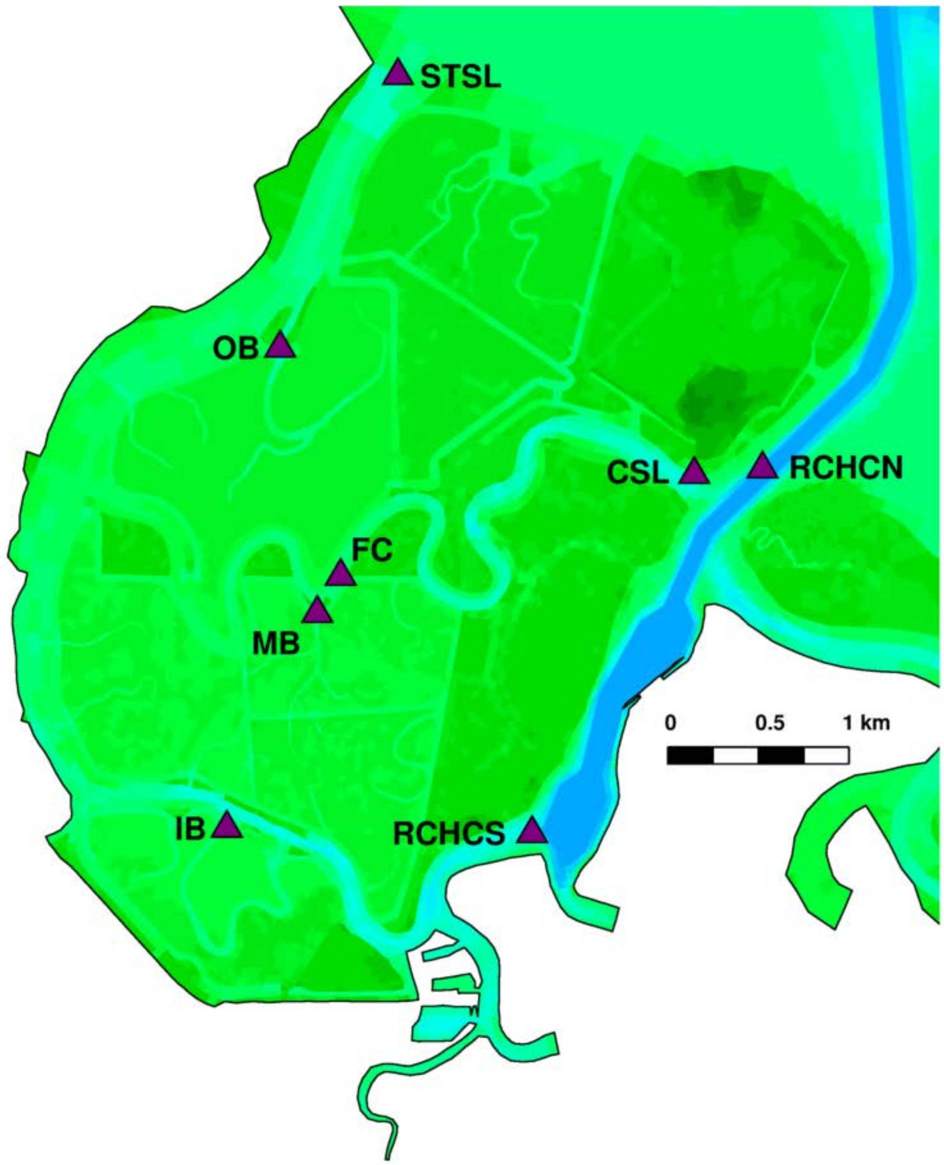
Table 8.2-4
Predicted change in the average deposition thickness in each subregion of Bair Island after deepening the Redwood City Harbor Channel from 30 feet MLLW to 32 feet MLLW.

Bair Island Subregion	Predicted Change in Depositional Thickness [feet]
Outer Bair Island	<0.001
Middle Bair Island	<0.001
Inner Bair Island	<0.001
Middle Bair Island Marsh	<0.001
Outer Bair Island Marsh	<0.001



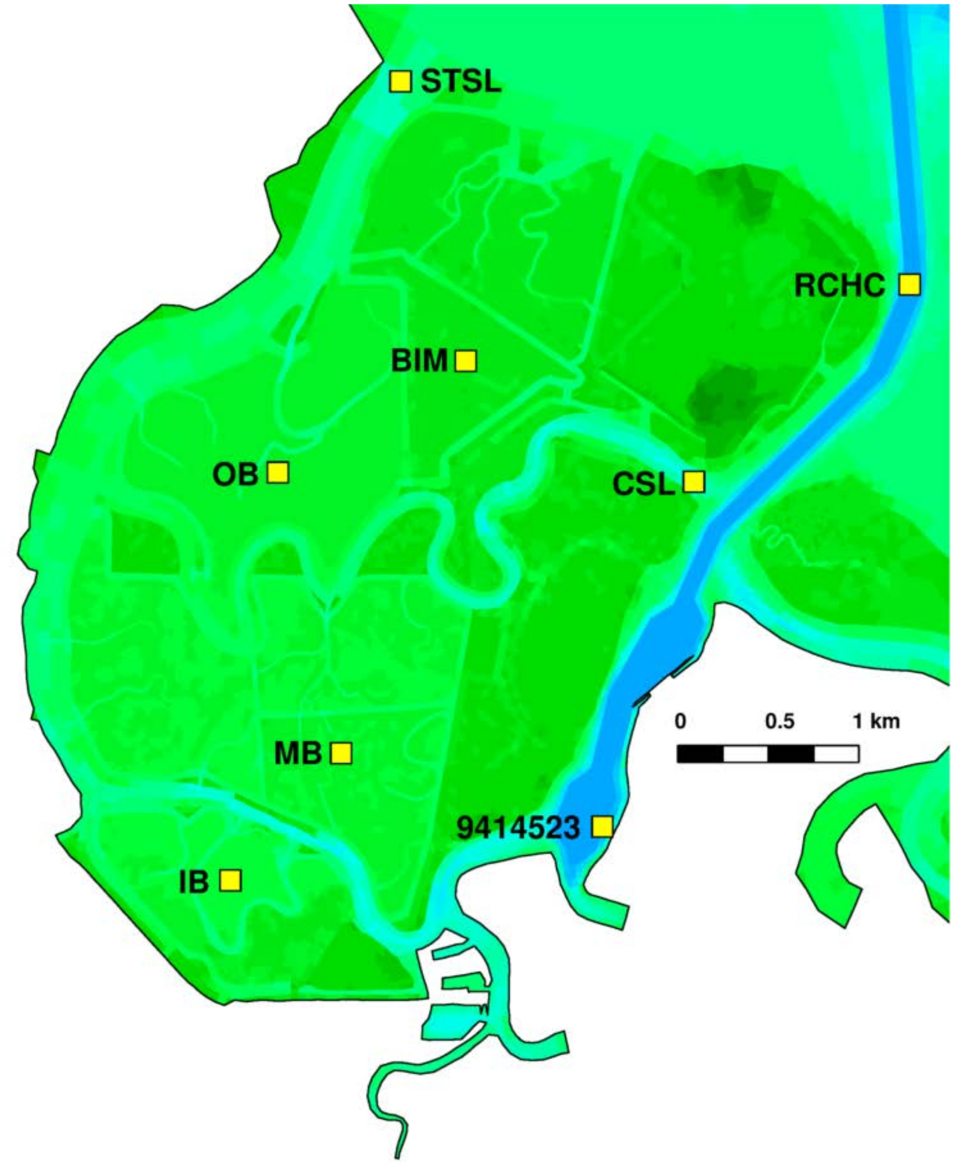
Redwood City Harbor Channel (RCHC)
Corkscrew Slough Near Redwood City Harbor Channel (CSL)
NOAA Redwood City Tide Gauge (9414523)
Steinberger Slough (STSL)
Bair Island Marsh (BIM)
Outer Bair Island (OB)
Middle Bair Island (MB)
Inner Bair Island (IB)

Figure 8.2-1
The locations used to determine the effects of deepening the Redwood City Harbor Channel project depth on water level in the vicinity of the Redwood City Harbor Channel and Bair Island.



Redwood City Harbor Channel North (RCHCN)
Corkscrew Slough Near Redwood City Harbor Channel (CSL)
Redwood City Harbor Channel South (RCHCS)
Steinberger Slough (STSL)
Corkscrew Slough Flow Constrictor (FC)
Outer Bair Island Breach (OB)
Middle Bair Island Breach (MB)
Inner Bair Island Breach (IB)

Figure 8.2-2
The locations used to determine the effects of deepening the Redwood City Harbor Channel project depth on water flow in the vicinity of the Redwood City Harbor Channel and Bair Island.



Redwood City Harbor Channel (RCHC)
Corkscrew Slough Near Redwood City Harbor Channel (CSL)
NOAA Redwood City Tide Gauge (9414523)
Steinberger Slough (STSL)
Bair Island Marsh (BIM)
Outer Bair Island (OB)
Middle Bair Island (MB)
Inner Bair Island (IB)

Figure 8.2-3
The locations used to determine the effects of deepening the Redwood City Harbor Channel project depth on salinity in the vicinity of the Redwood City Harbor Channel and Bair Island.

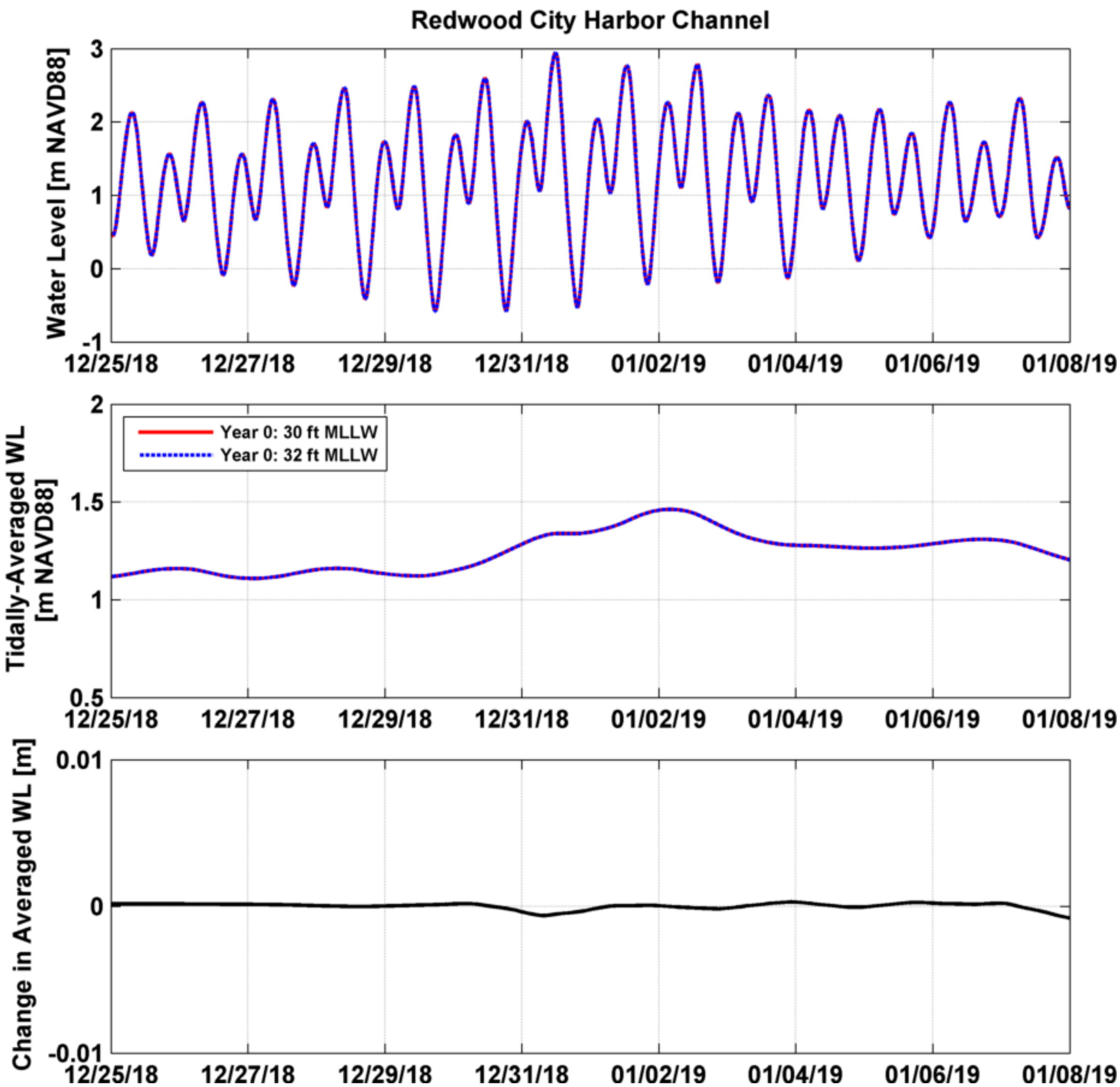


Figure 8.2-4

Predicted water levels in the Redwood City Harbor Channel (RCHC, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

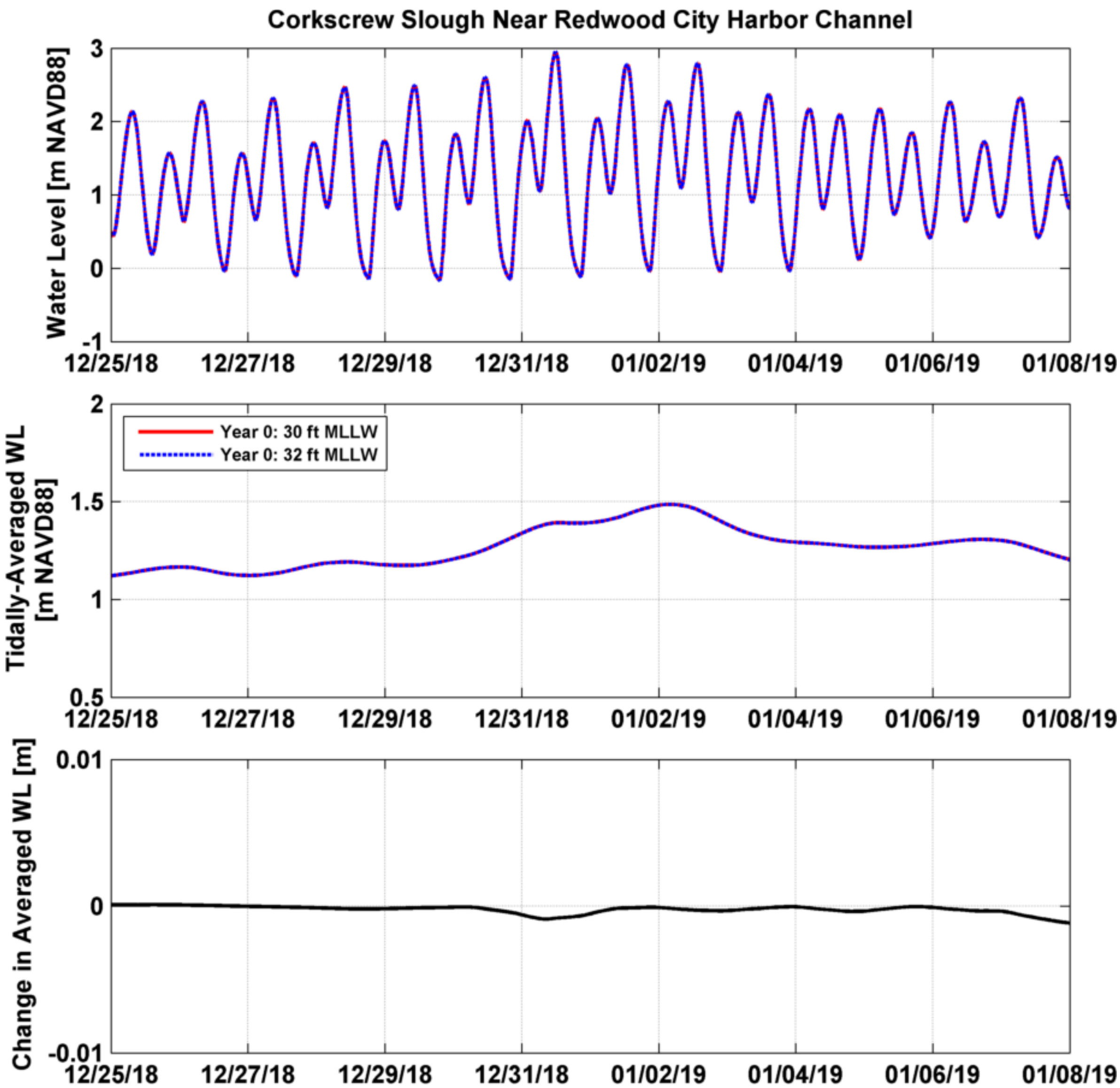


Figure 8.2-5
Predicted water levels in Corkscrew Slough near the Redwood City Harbor Channel (CSL, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

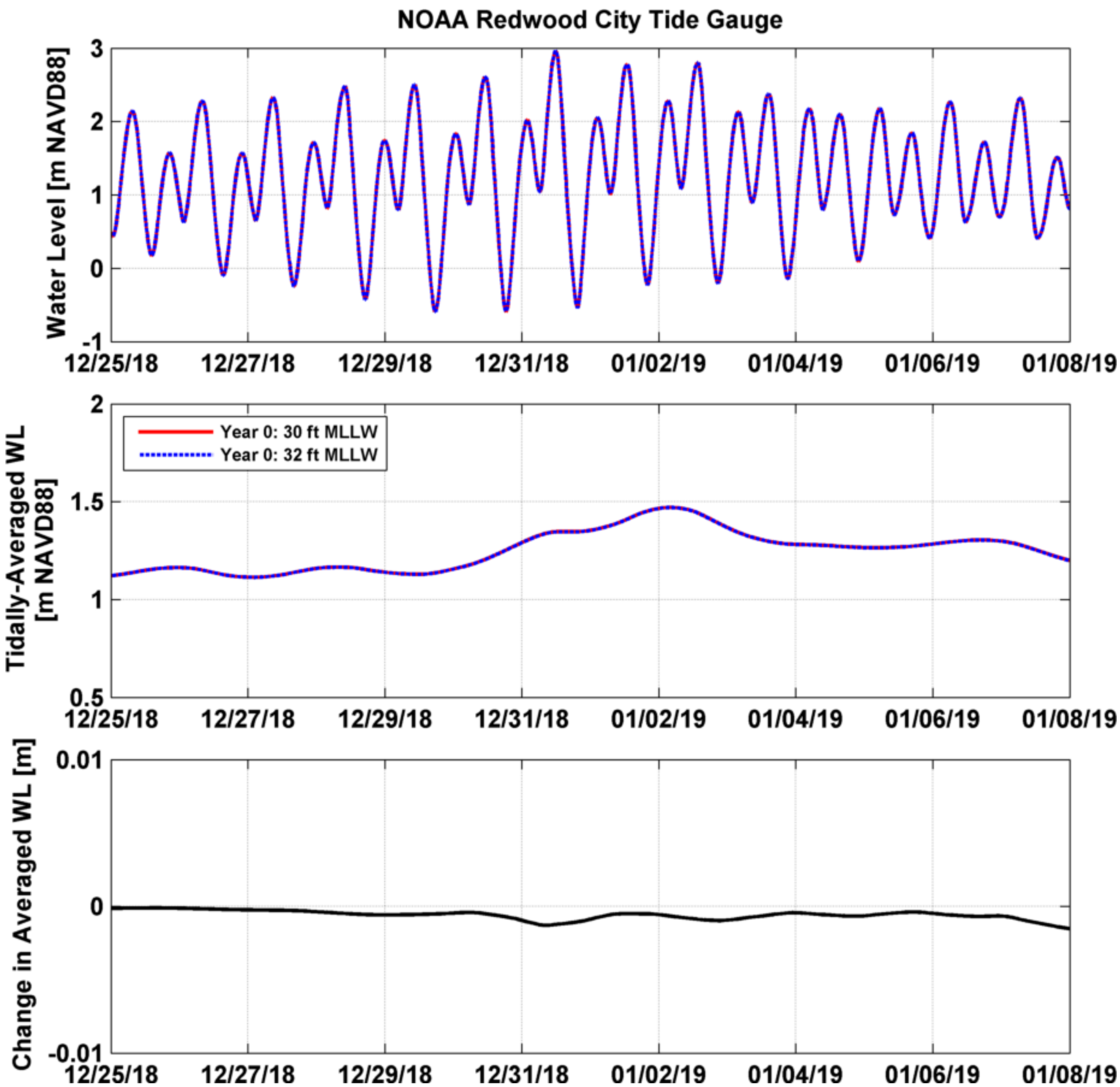


Figure 8.2-6
Predicted water levels at the NOAA Redwood City tide gauge (9414523, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

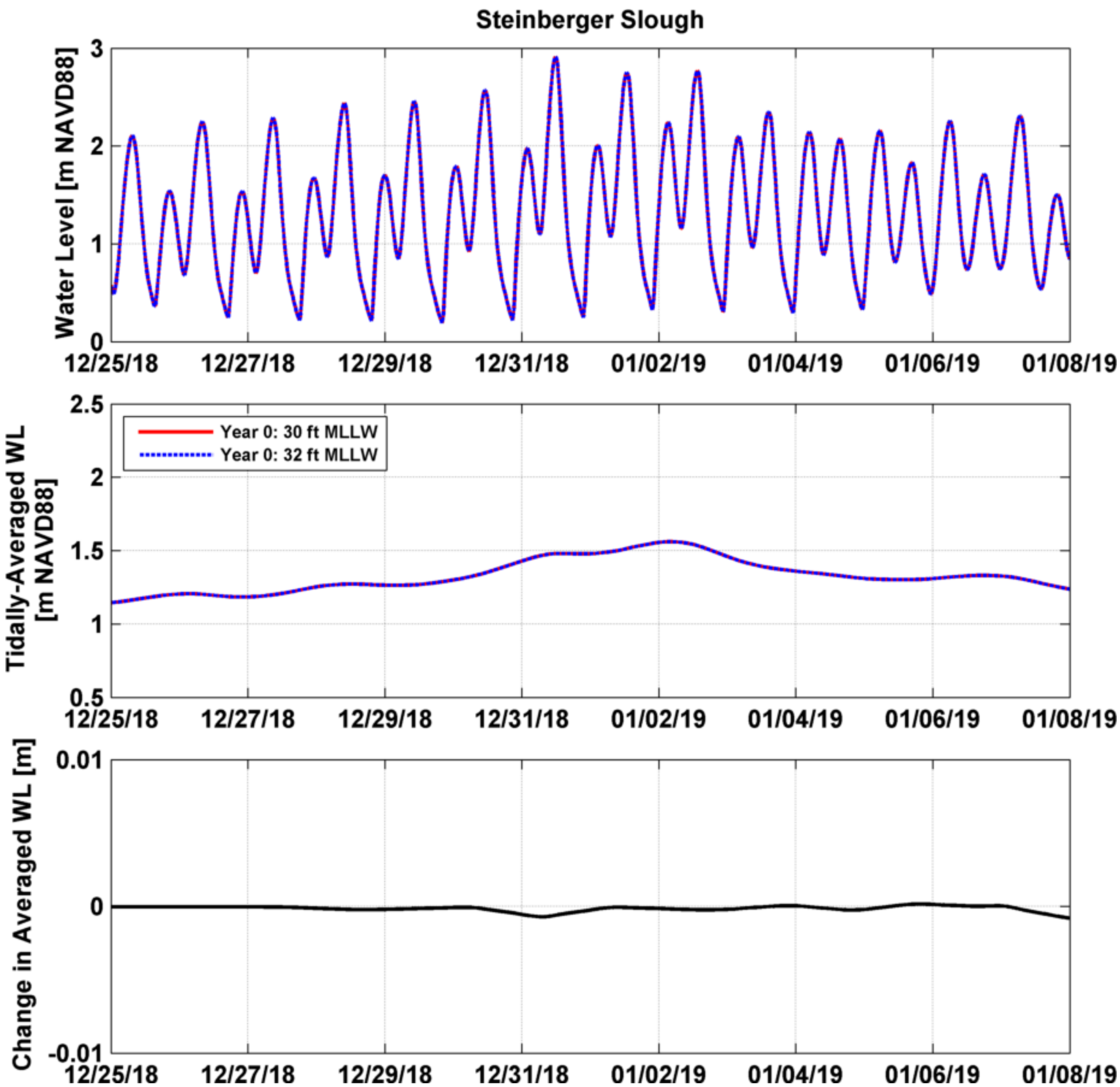


Figure 8.2-7
Predicted water levels in Steinberger Slough (STSL, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

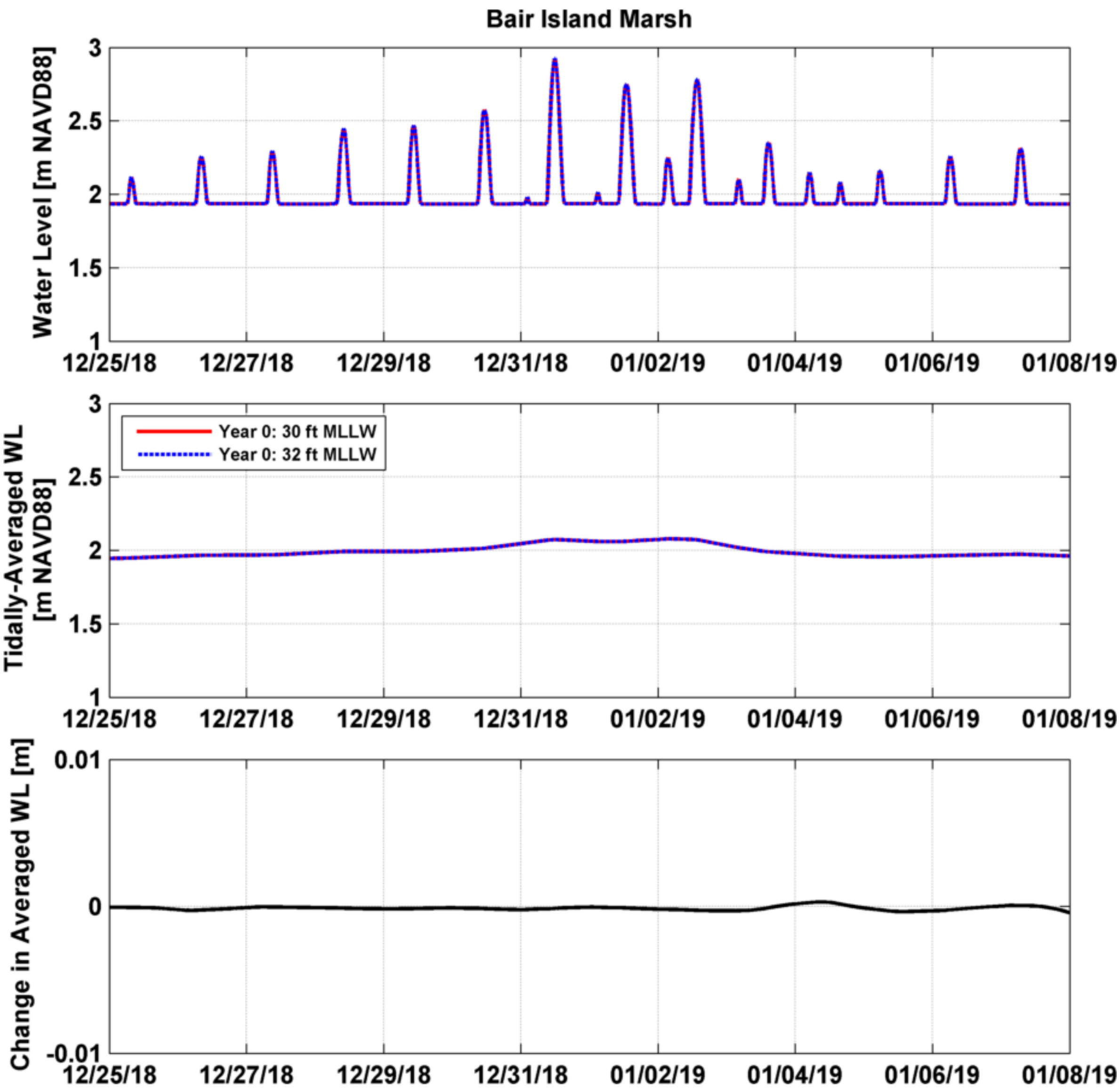


Figure 8.2-8
Predicted water levels in the Bair Island marsh (BIM, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

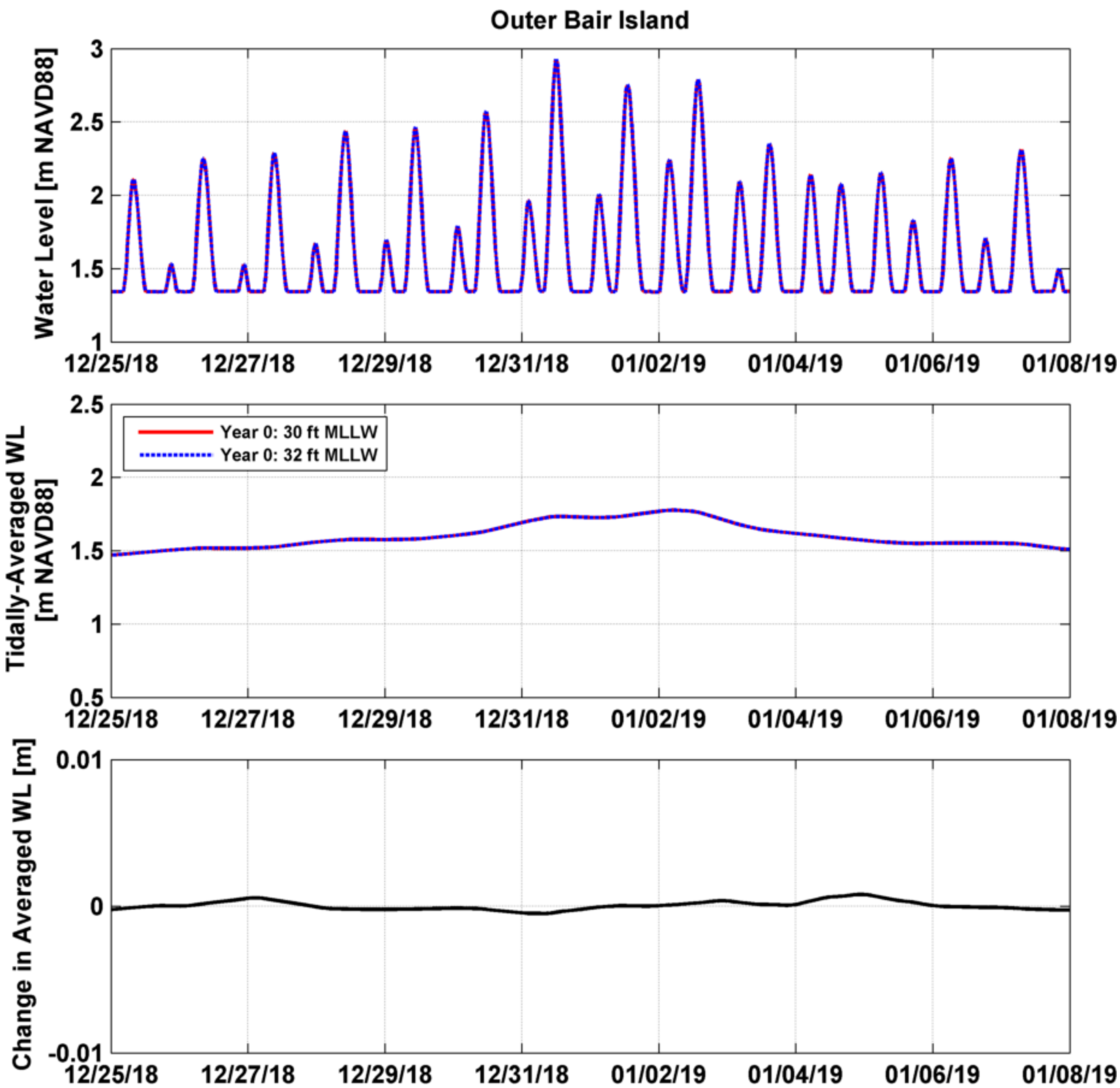


Figure 8.2-9
Predicted water levels in Outer Bair Island (OB, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

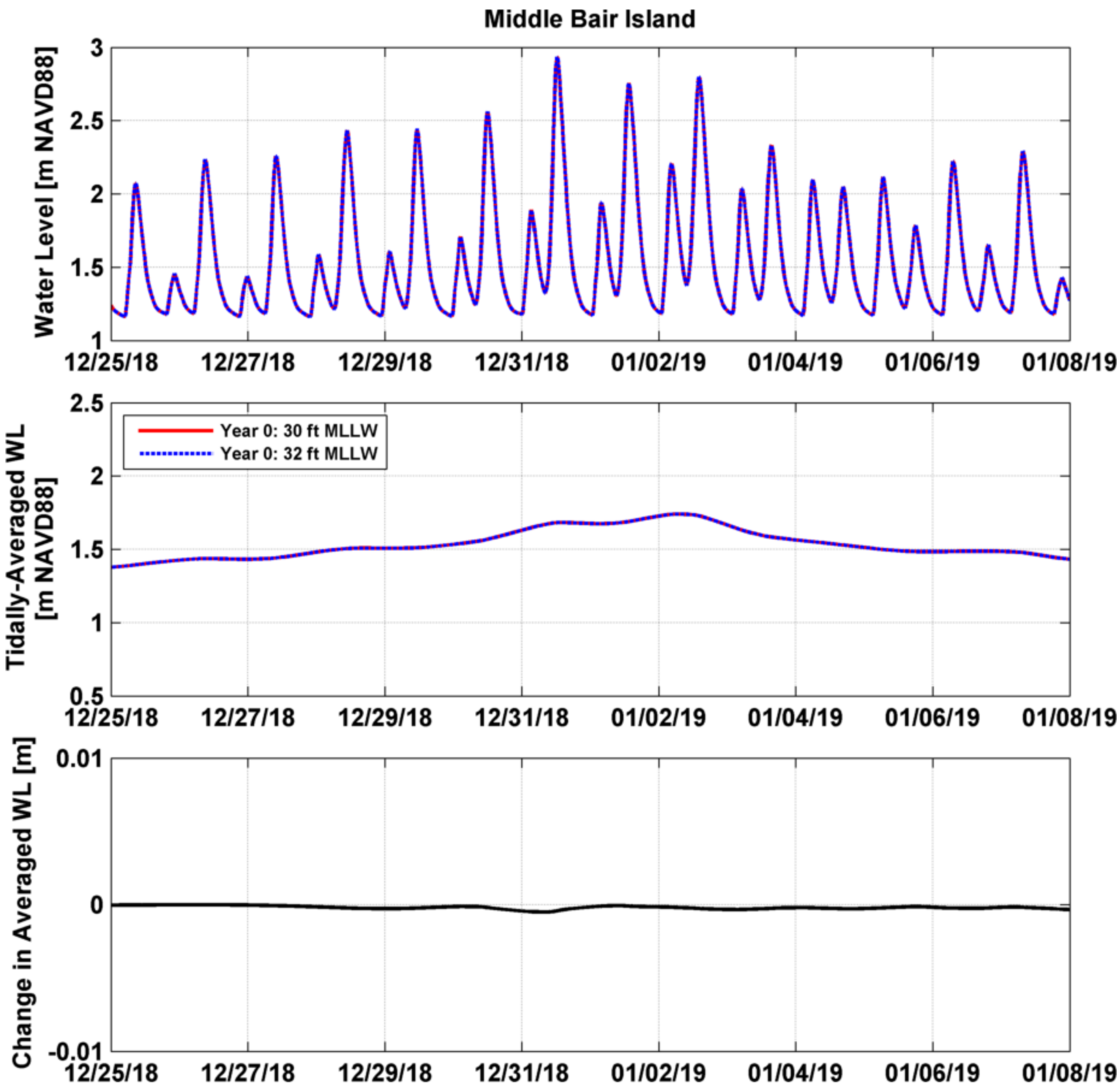


Figure 8.2-10
Predicted water levels in Middle Bair Island (MB, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

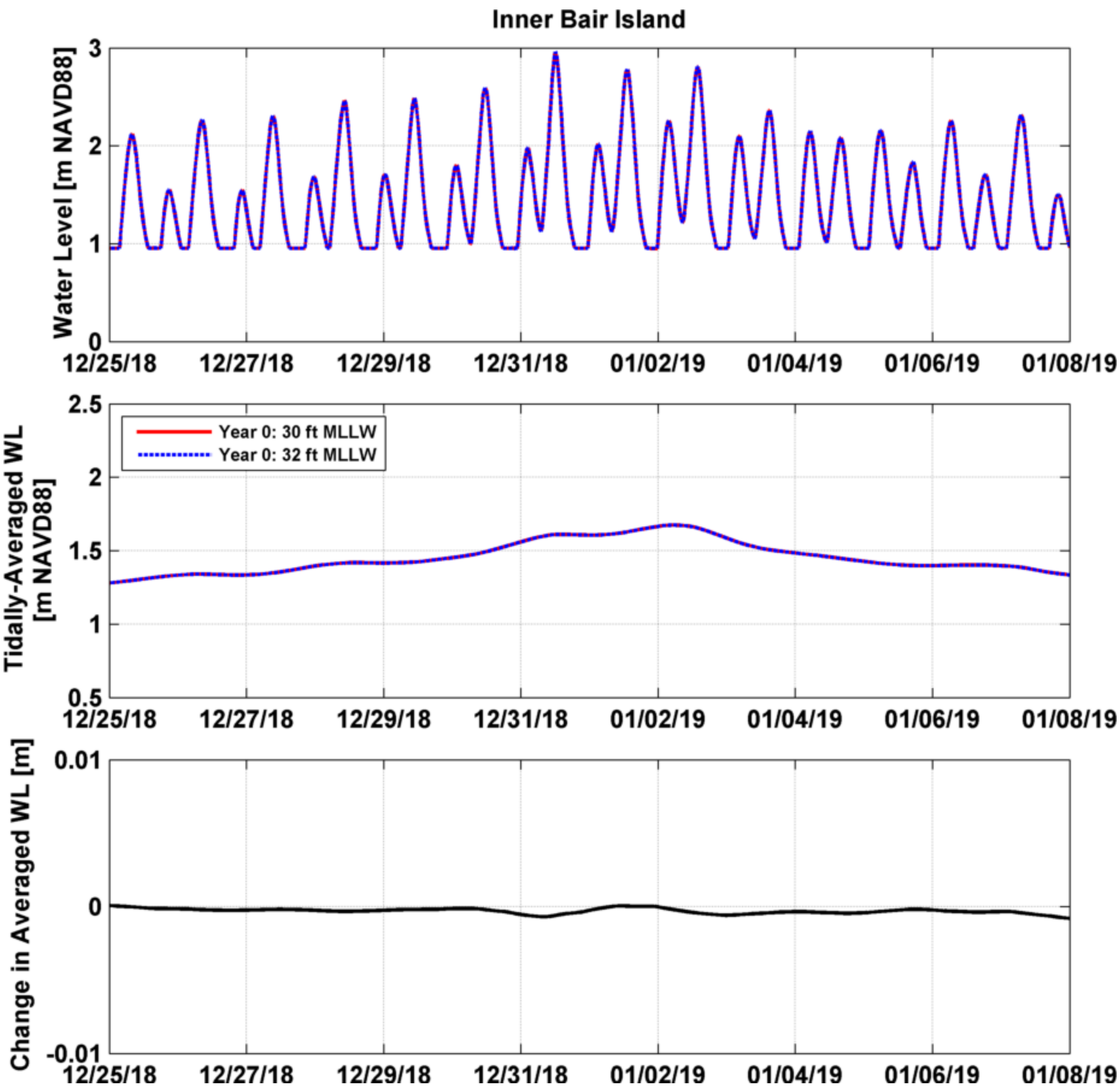


Figure 8.2-11
Predicted water levels in Inner Bair Island (IB, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

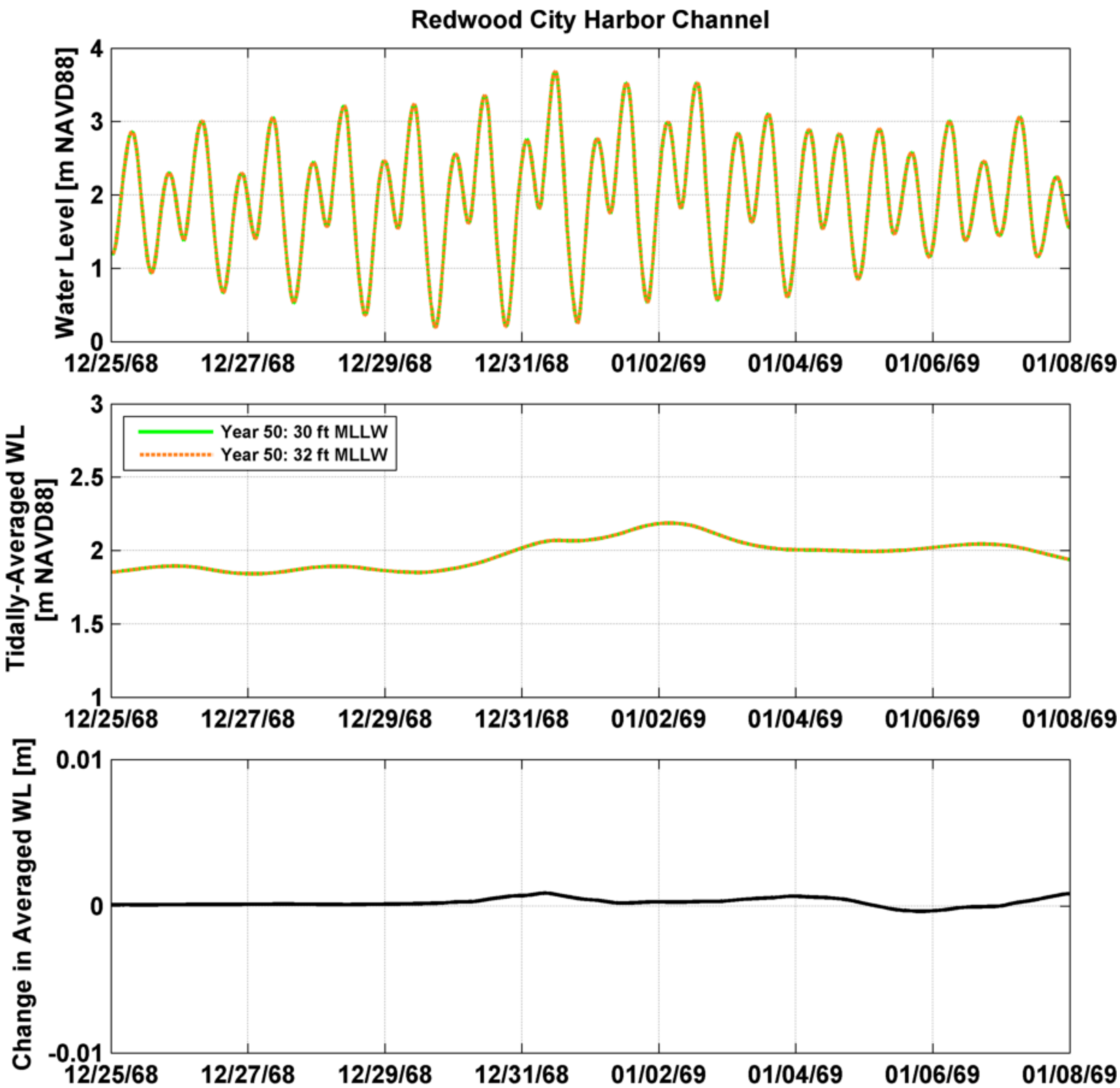


Figure 8.2-12
Predicted water levels in the Redwood City Harbor Channel (RCHC, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

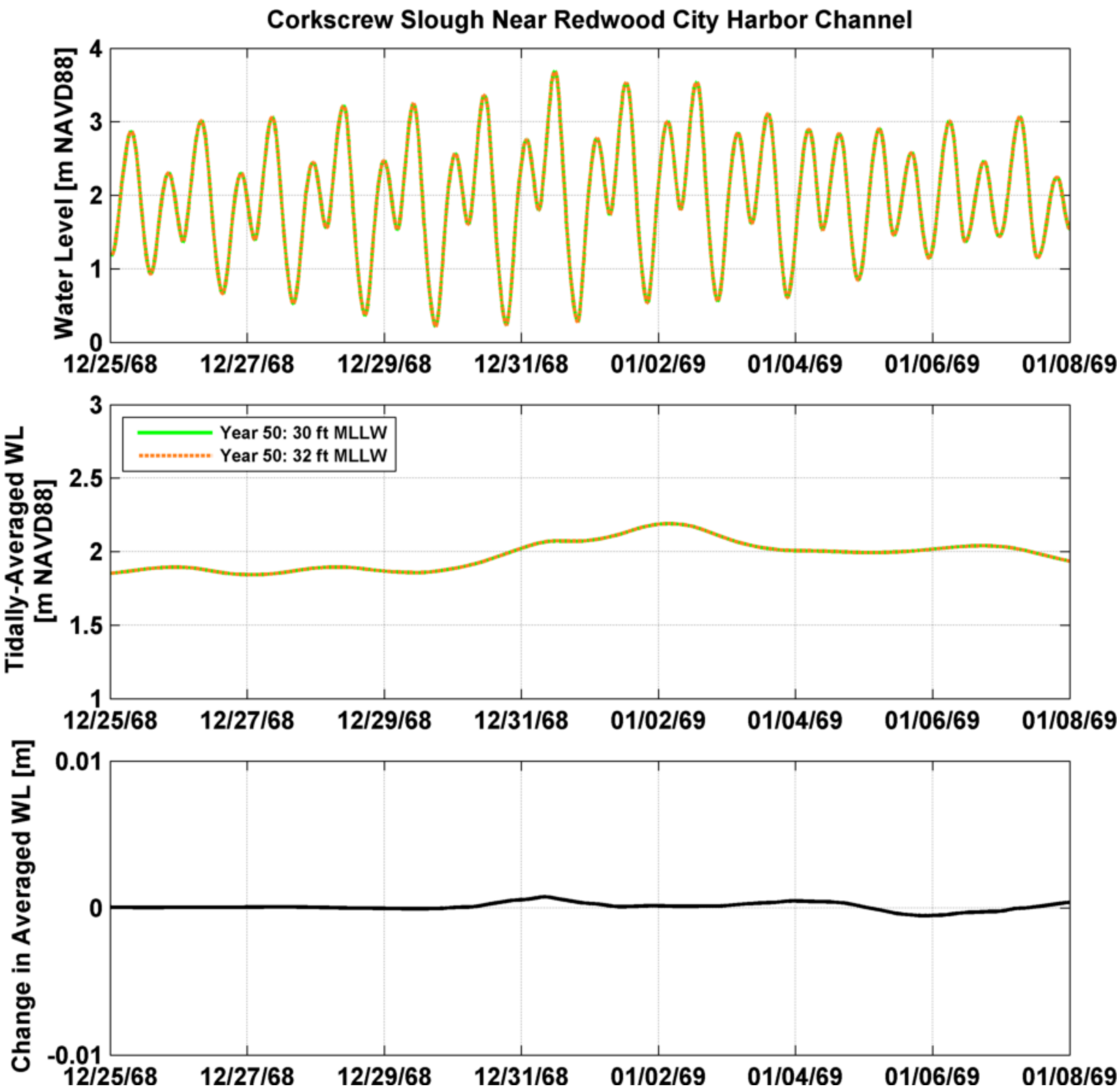


Figure 8.2-13
Predicted water levels in Corkscrew Slough near the Redwood City Harbor Channel (CSL, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

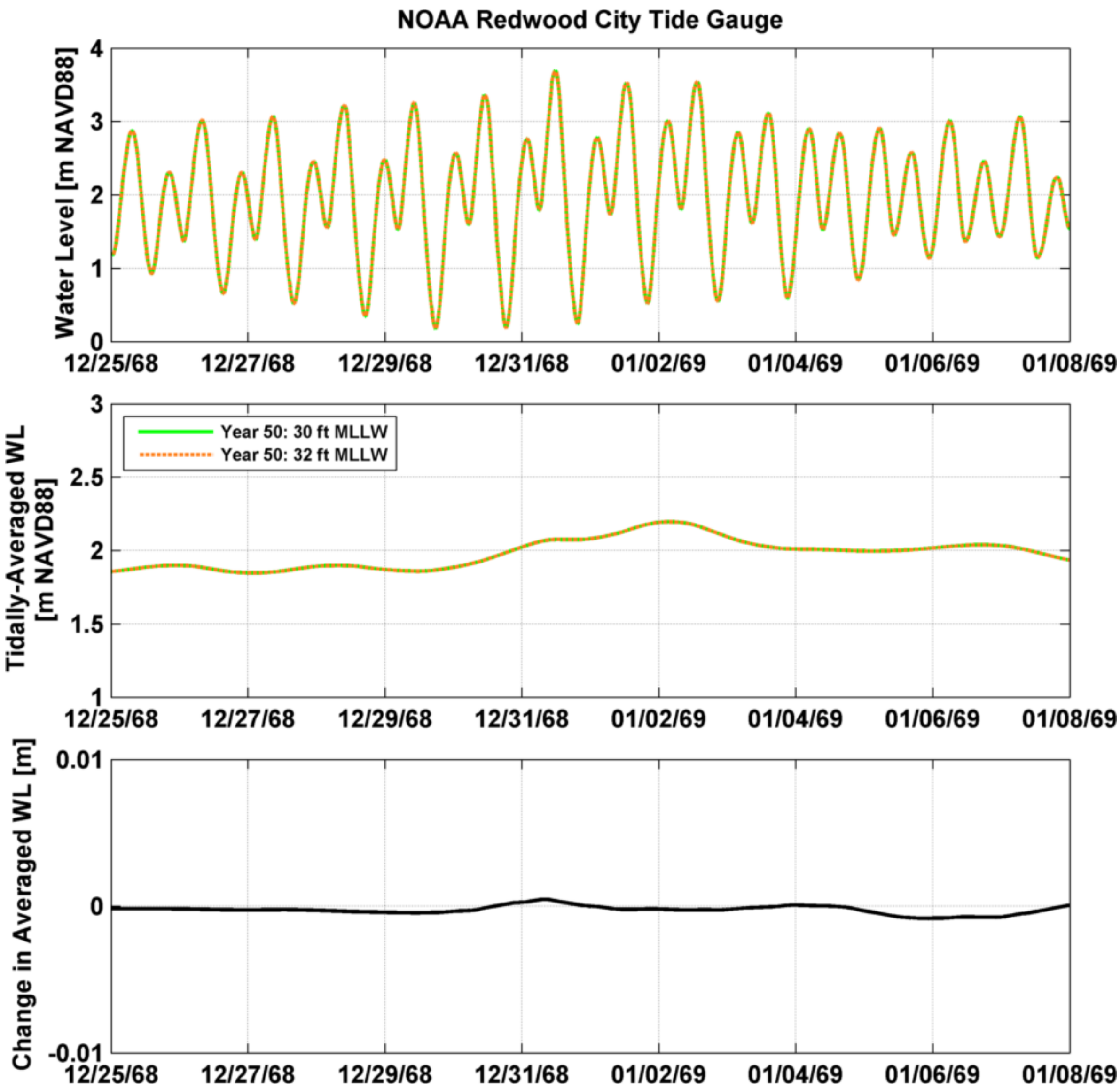


Figure 8.2-14
Predicted water levels at the NOAA Redwood City tide gauge (9414523, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

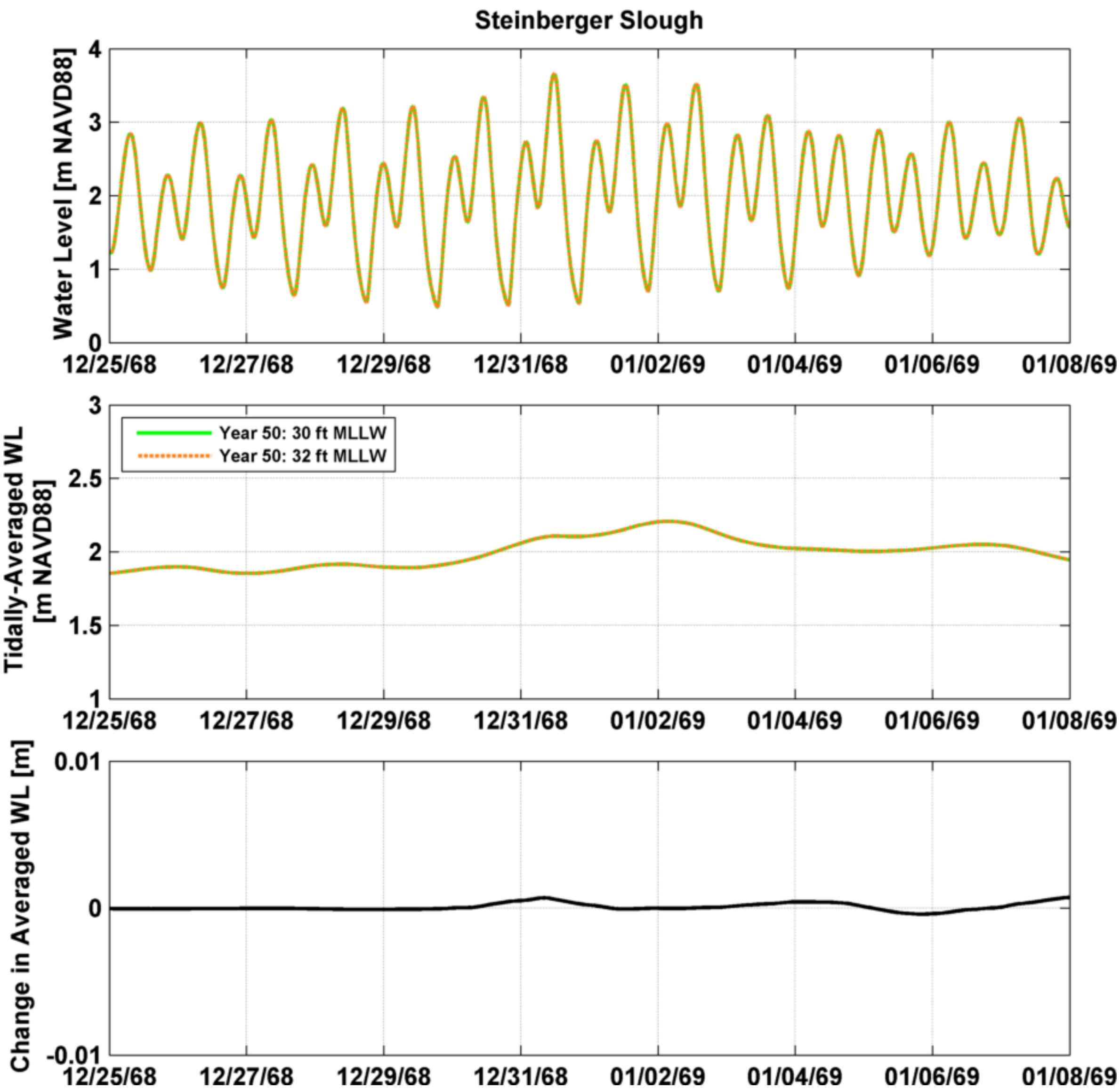


Figure 8.2-15
Predicted water levels in Steinberger Slough (STSL, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

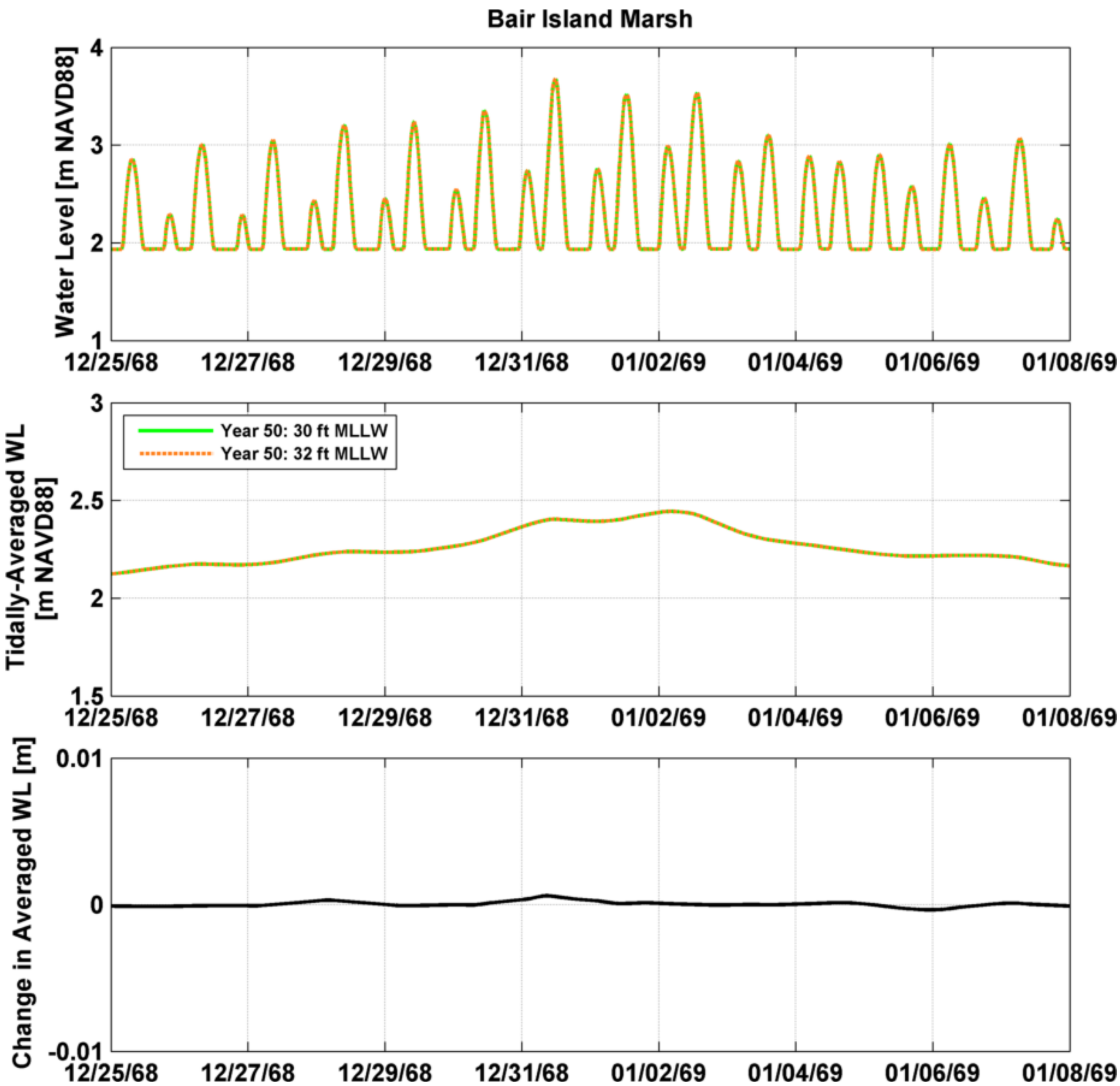


Figure 8.2-16
Predicted water levels in the Bair Island marsh (BIM, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

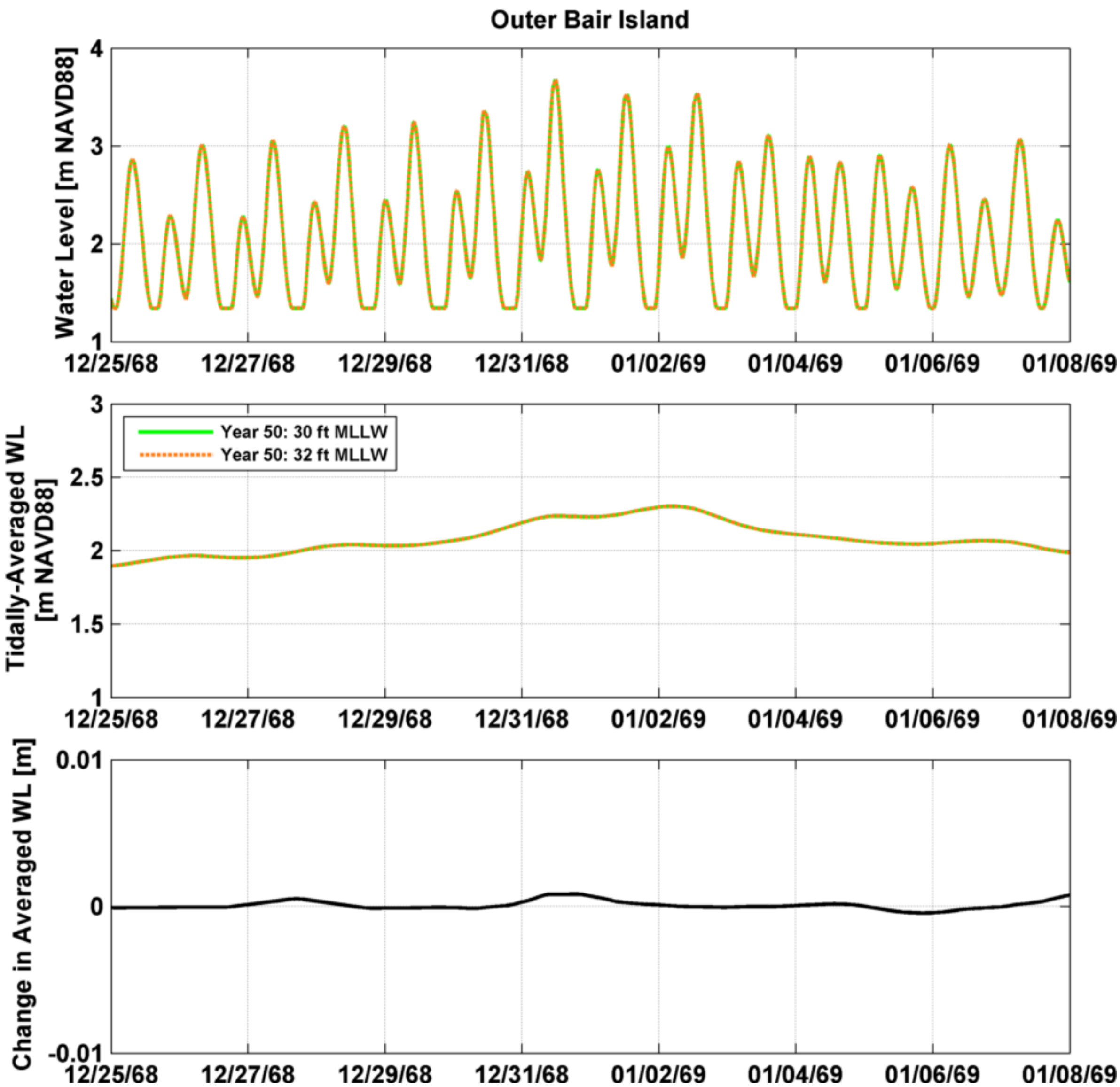


Figure 8.2-17
Predicted water levels in Outer Bair Island (OB, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

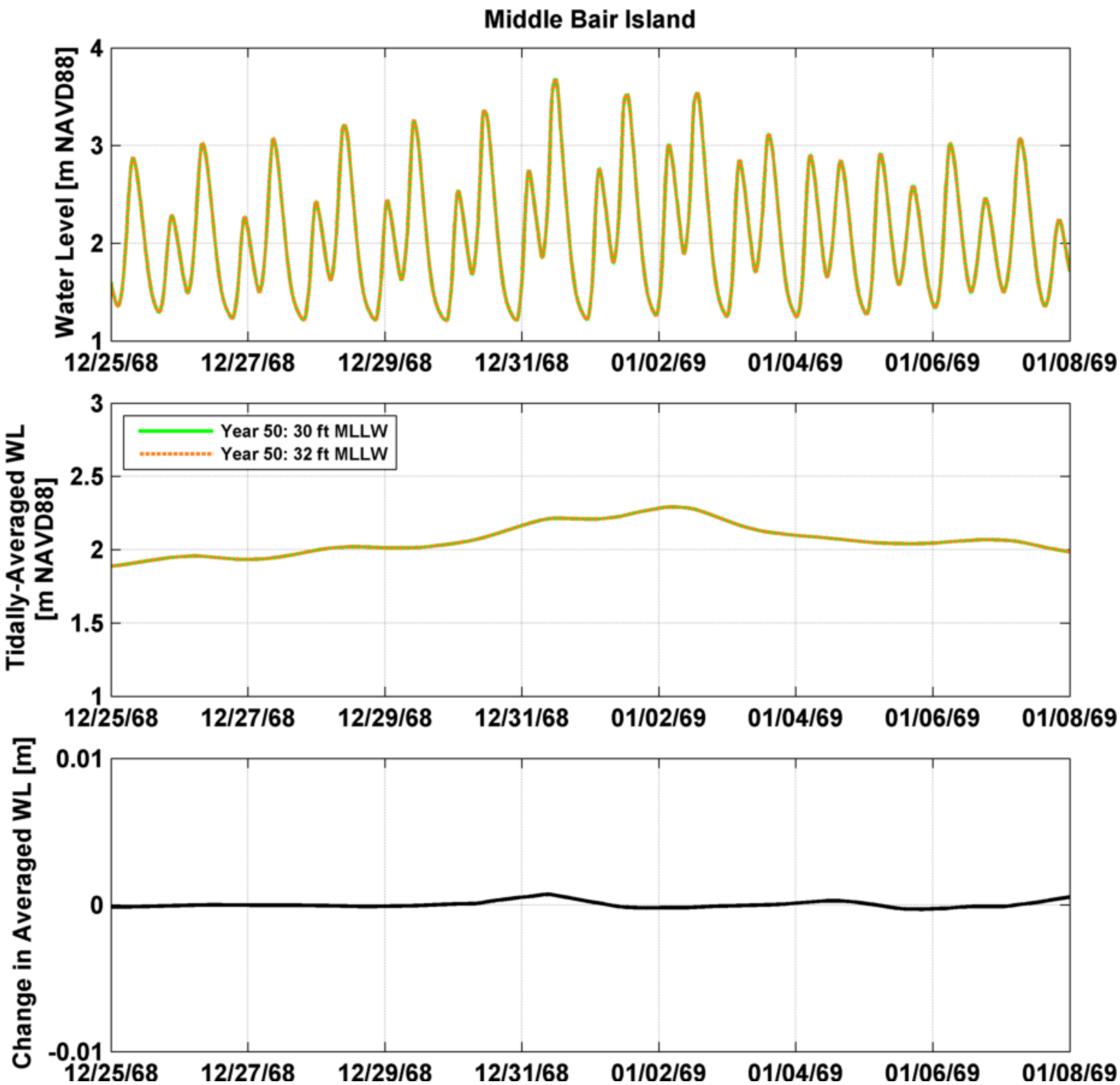


Figure 8.2-18
Predicted water levels in Middle Bair Island (MB, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

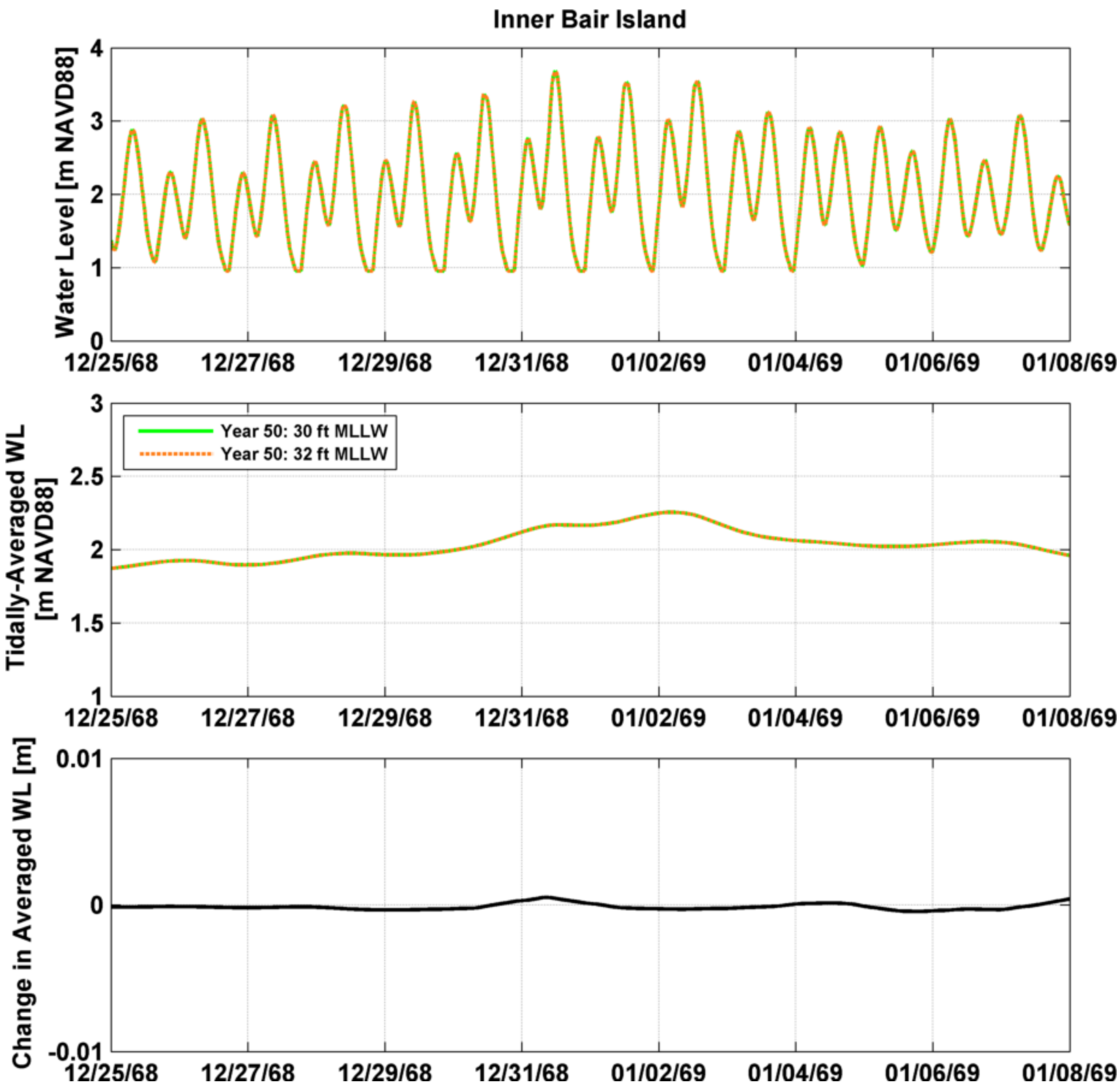


Figure 8.2-19
Predicted water levels in Inner Bair Island (IB, Figure 8.2-1) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

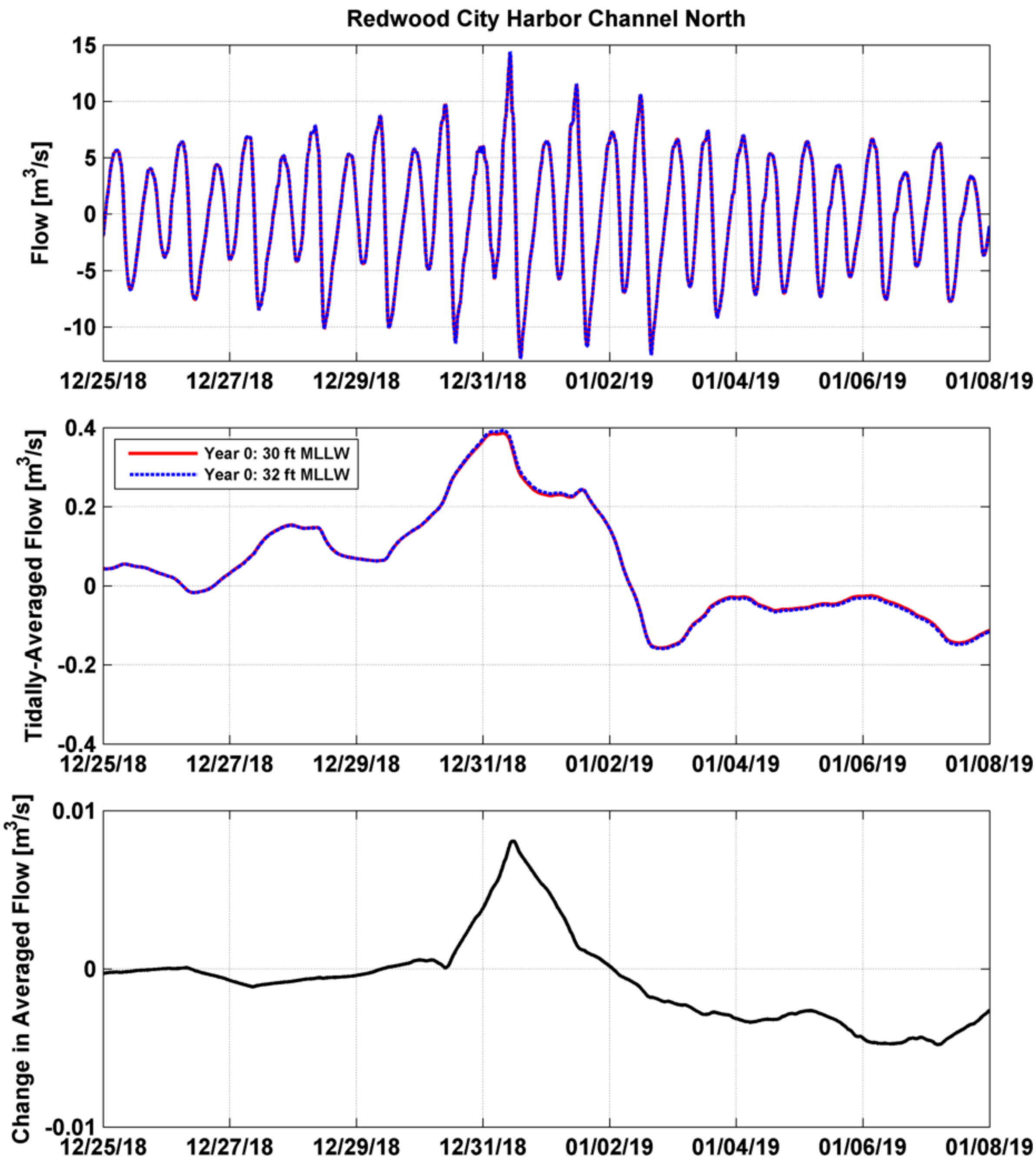


Figure 8.2-20
Predicted flow through the Redwood City Harbor Channel northern cross section (RCHCN, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

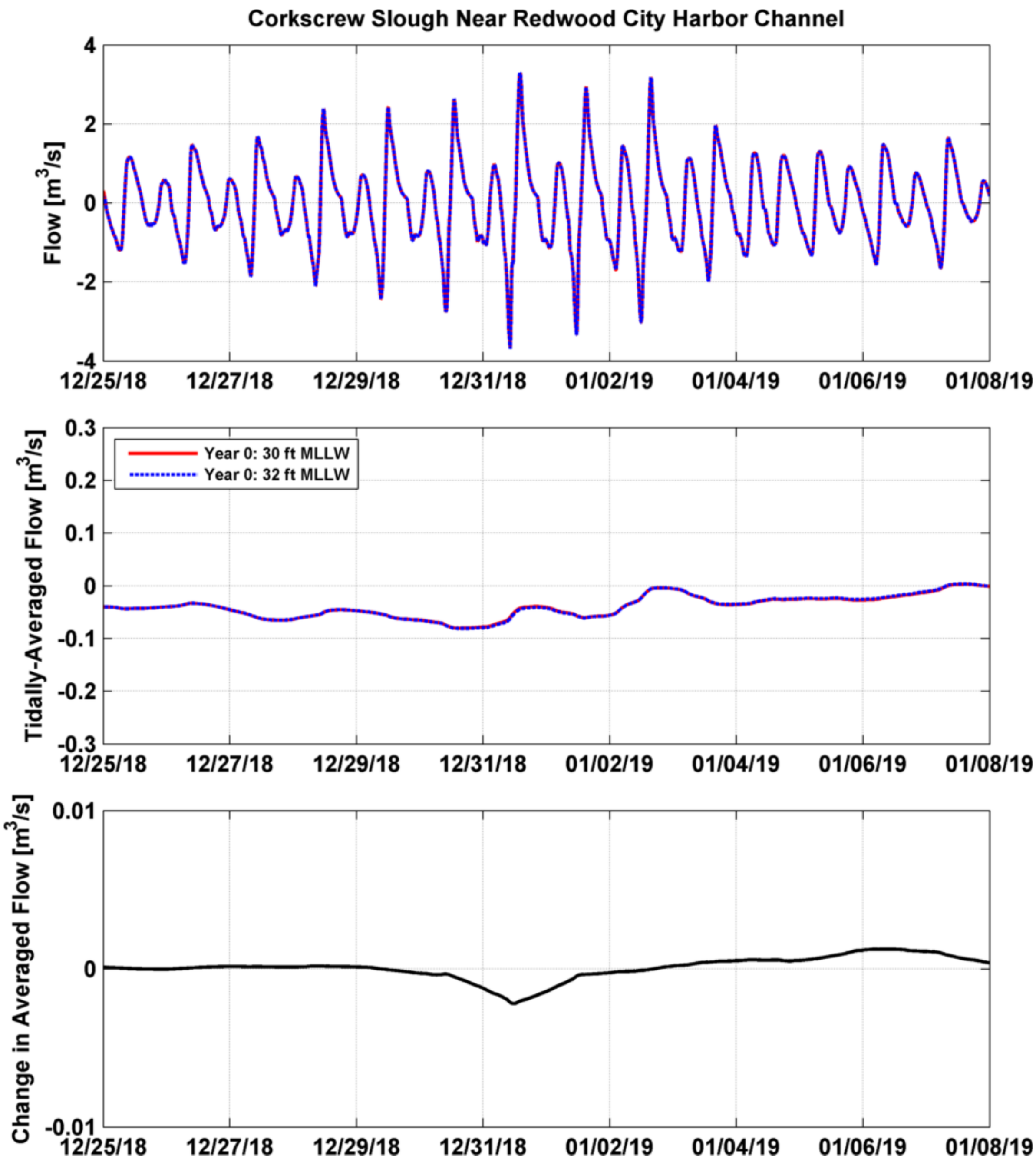


Figure 8.2-21
Predicted flow through Corkscrew Slough near the Redwood City Harbor Channel (CSL, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

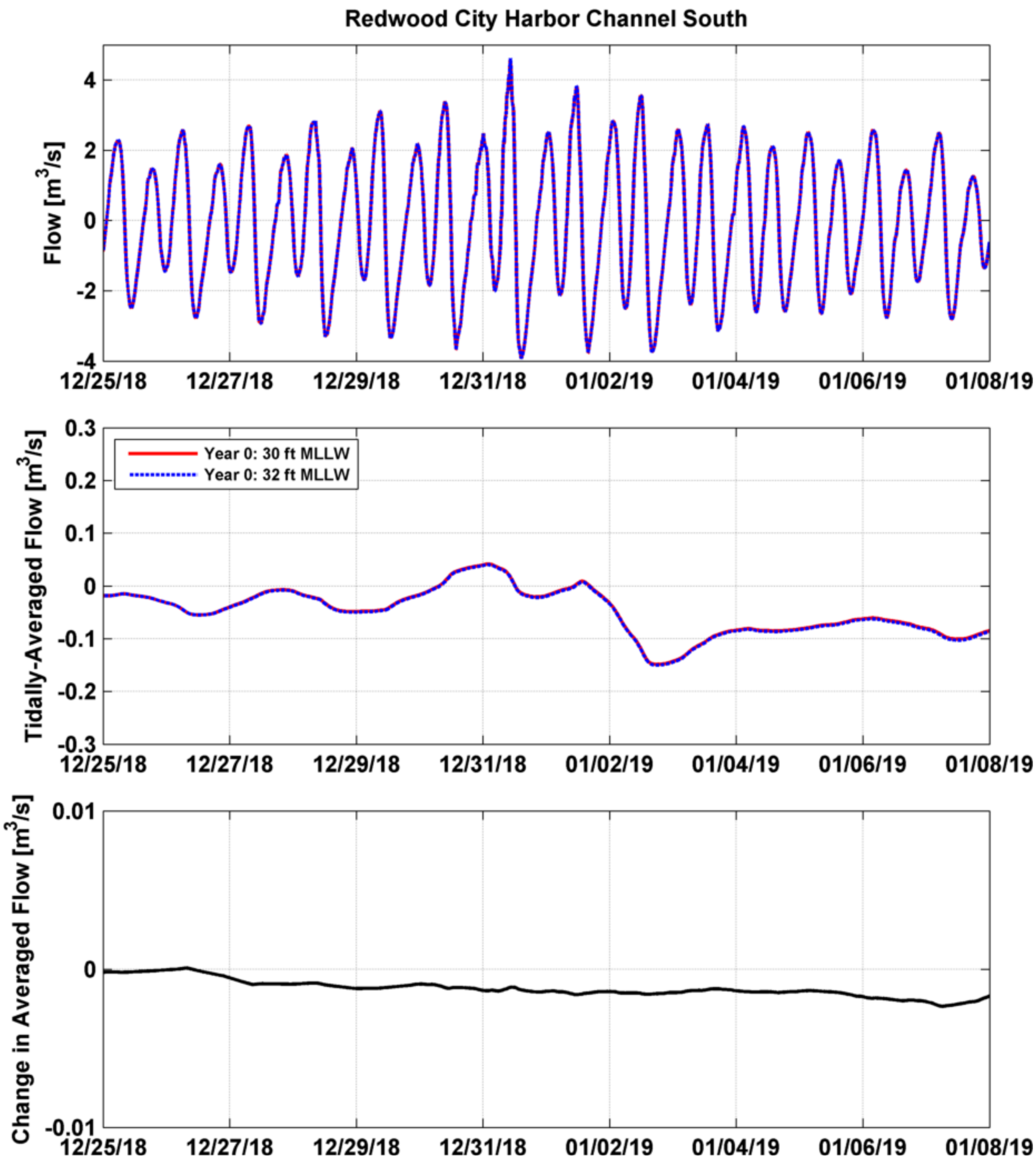


Figure 8.2-22
Predicted flow through the Redwood City Harbor Channel southern cross section (RCHCS, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

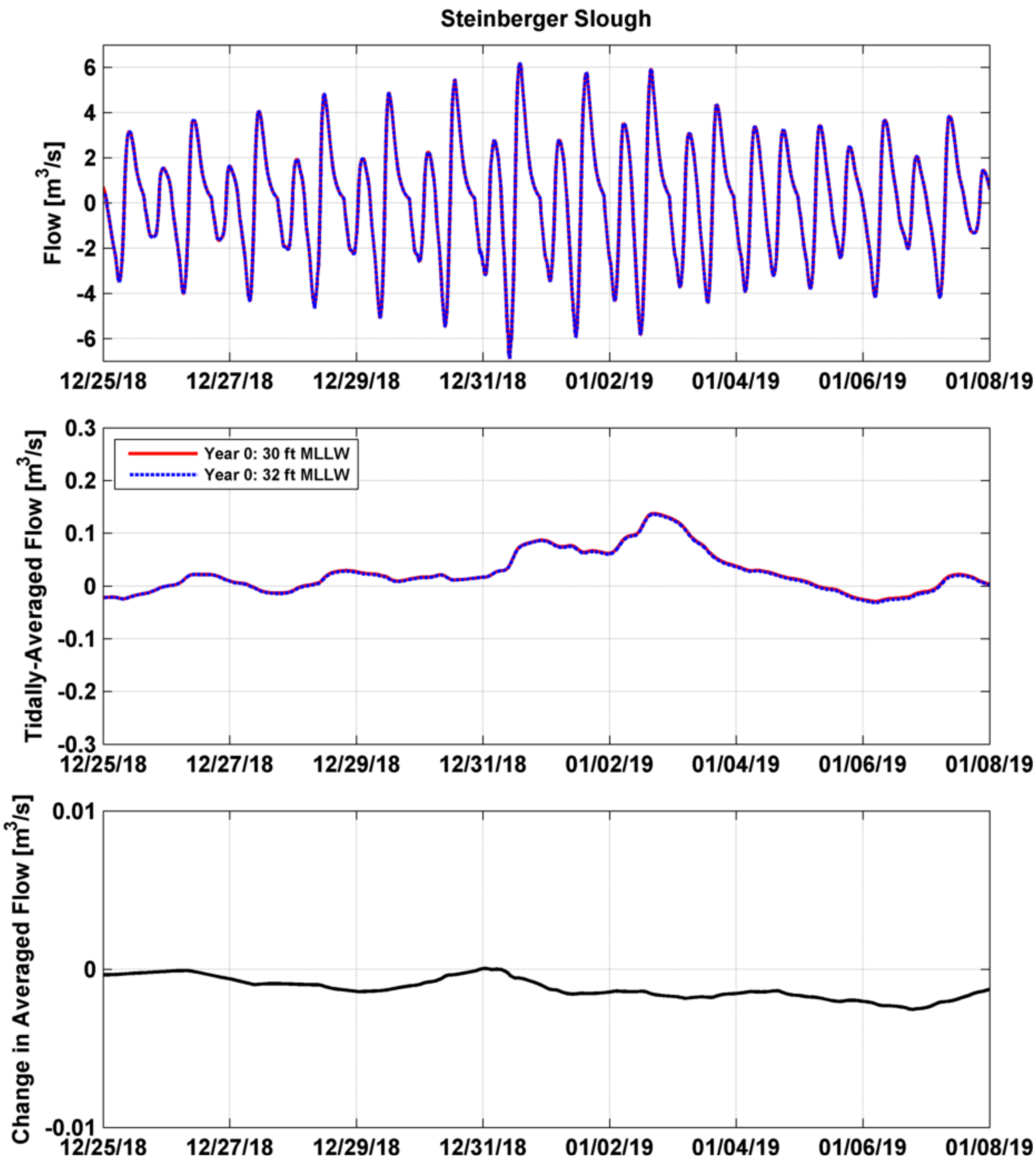


Figure 8.2-23
Predicted flow through Steinberger Slough (STSL, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

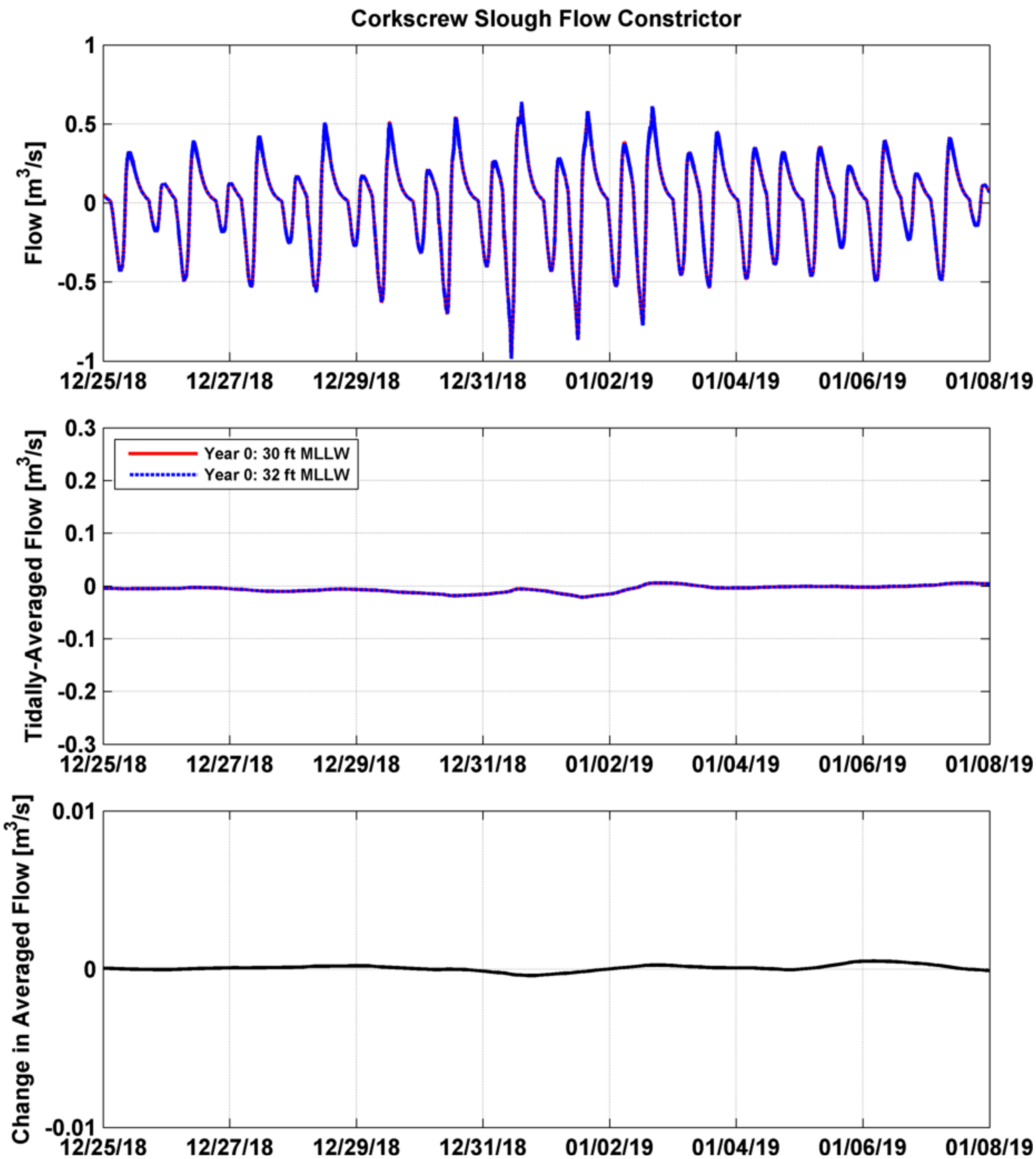


Figure 8.2-24
Predicted flow through the Corkscrew Slough flow constrictor (FC, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

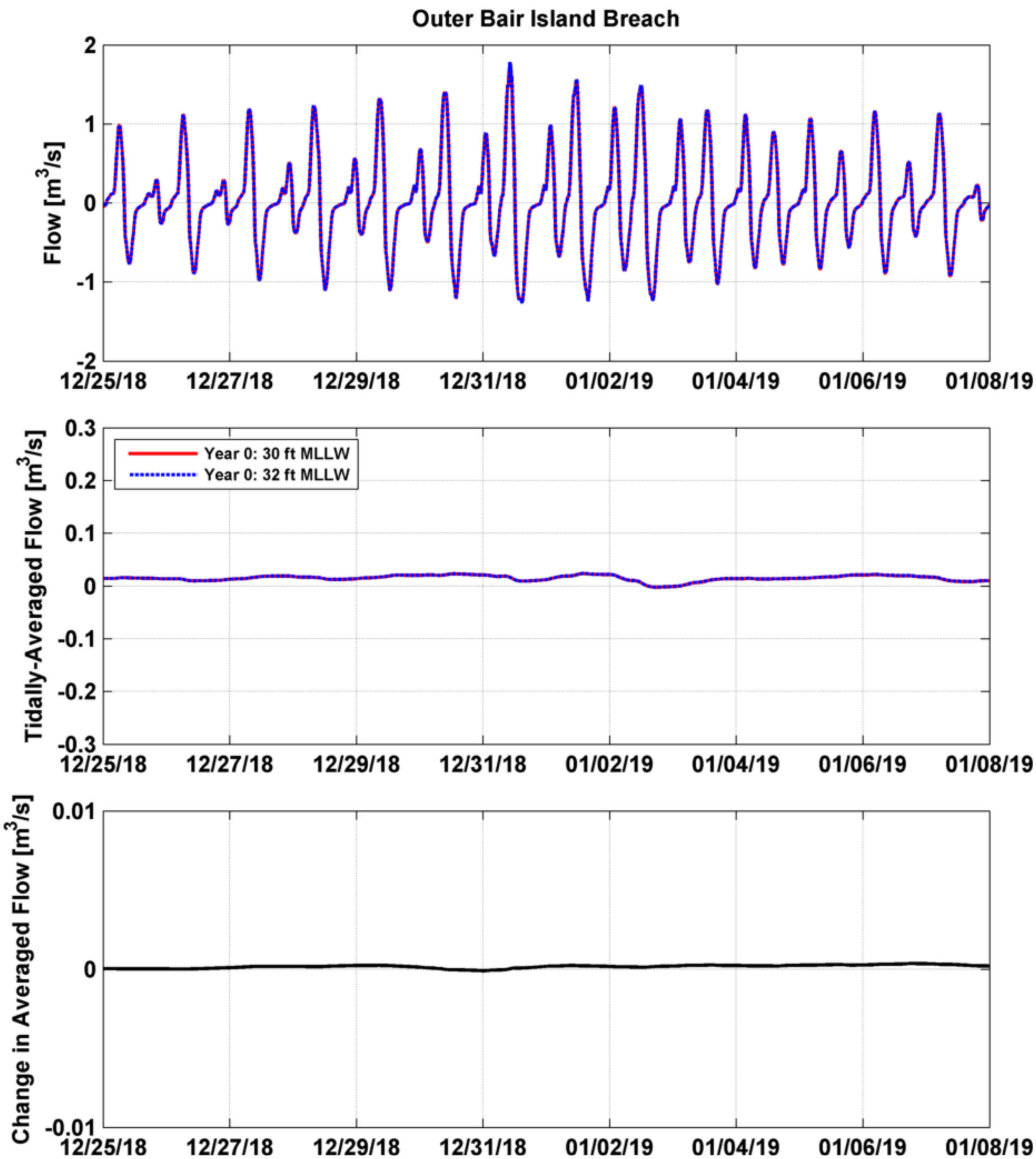


Figure 8.2-25
Predicted flow through a breach in Outer Bair Island (OB, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

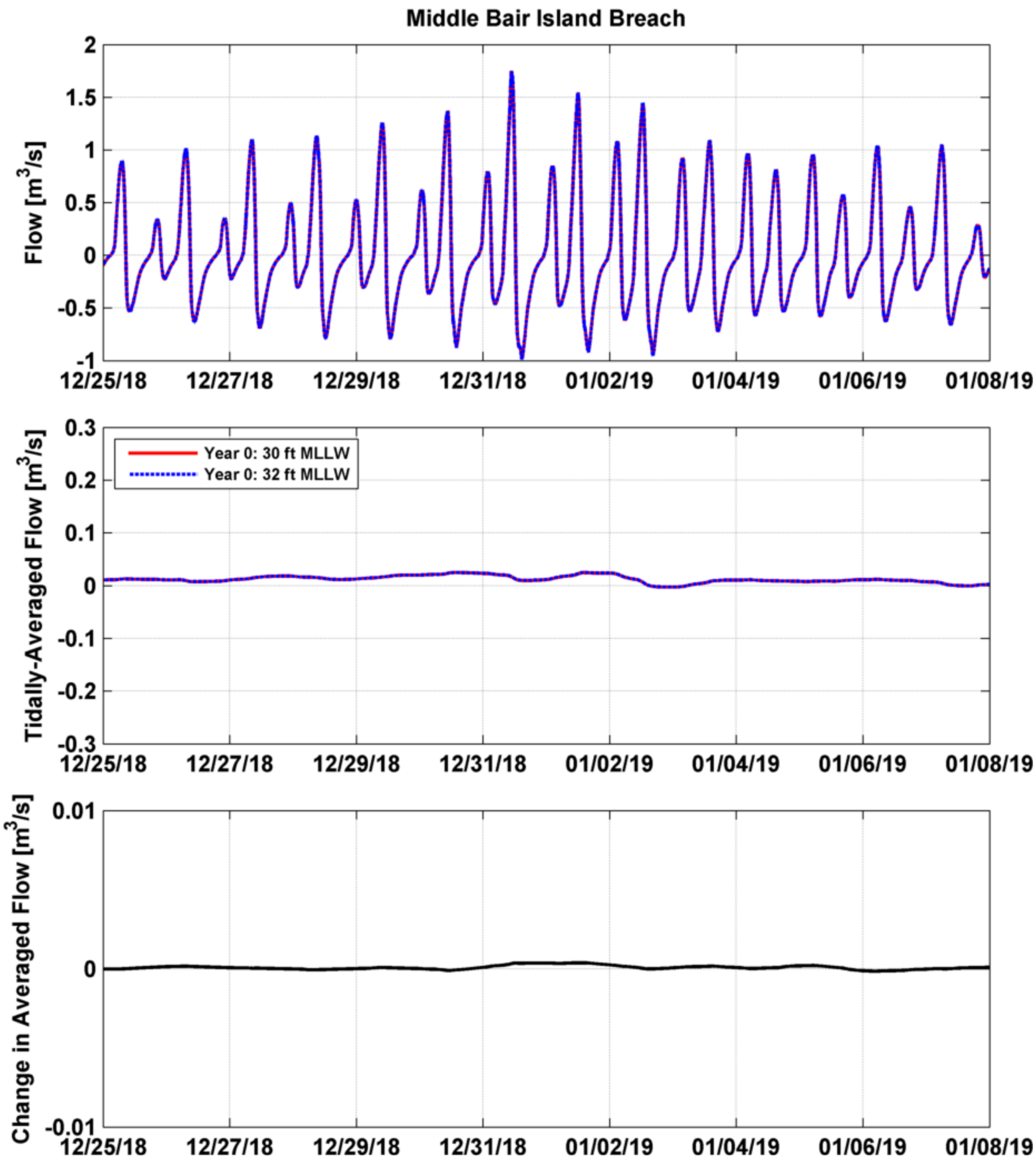


Figure 8.2-26
Predicted flow through a breach in Middle Bair Island (MB, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

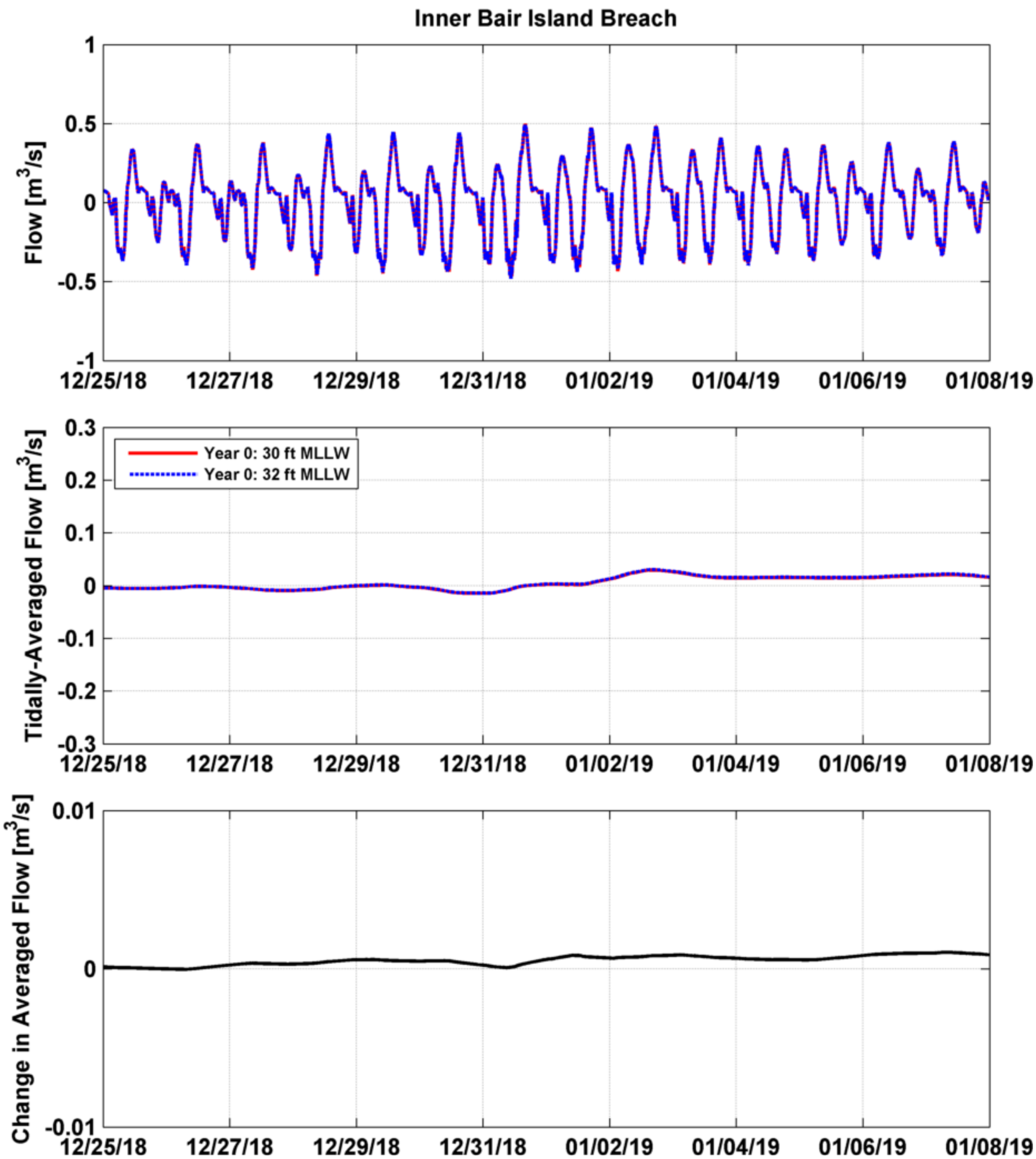


Figure 8.2-27
Predicted flow through a breach in Inner Bair Island (IB, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

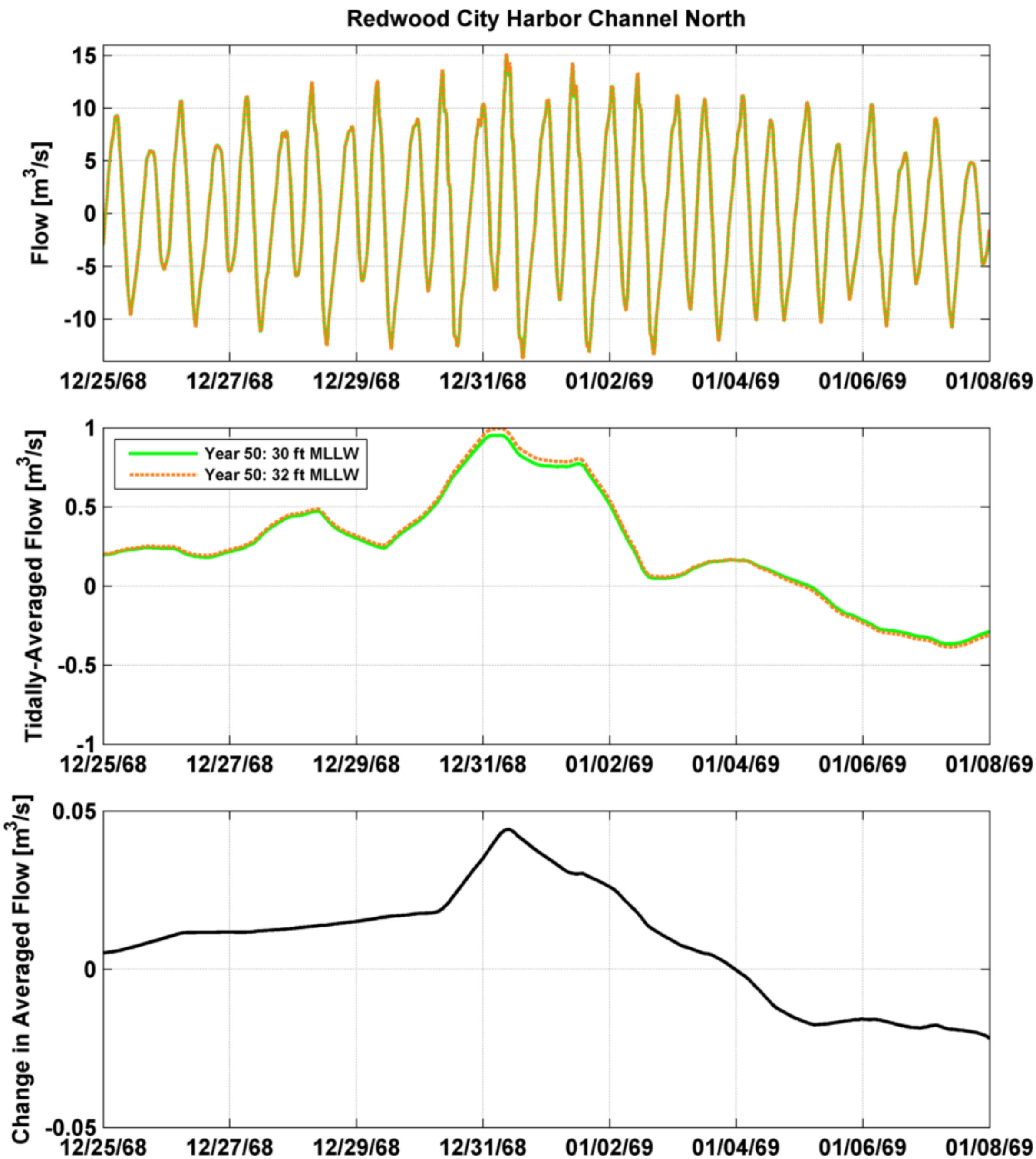


Figure 8.2-28
Predicted flow through the Redwood City Harbor Channel northern cross section (RCHCN, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

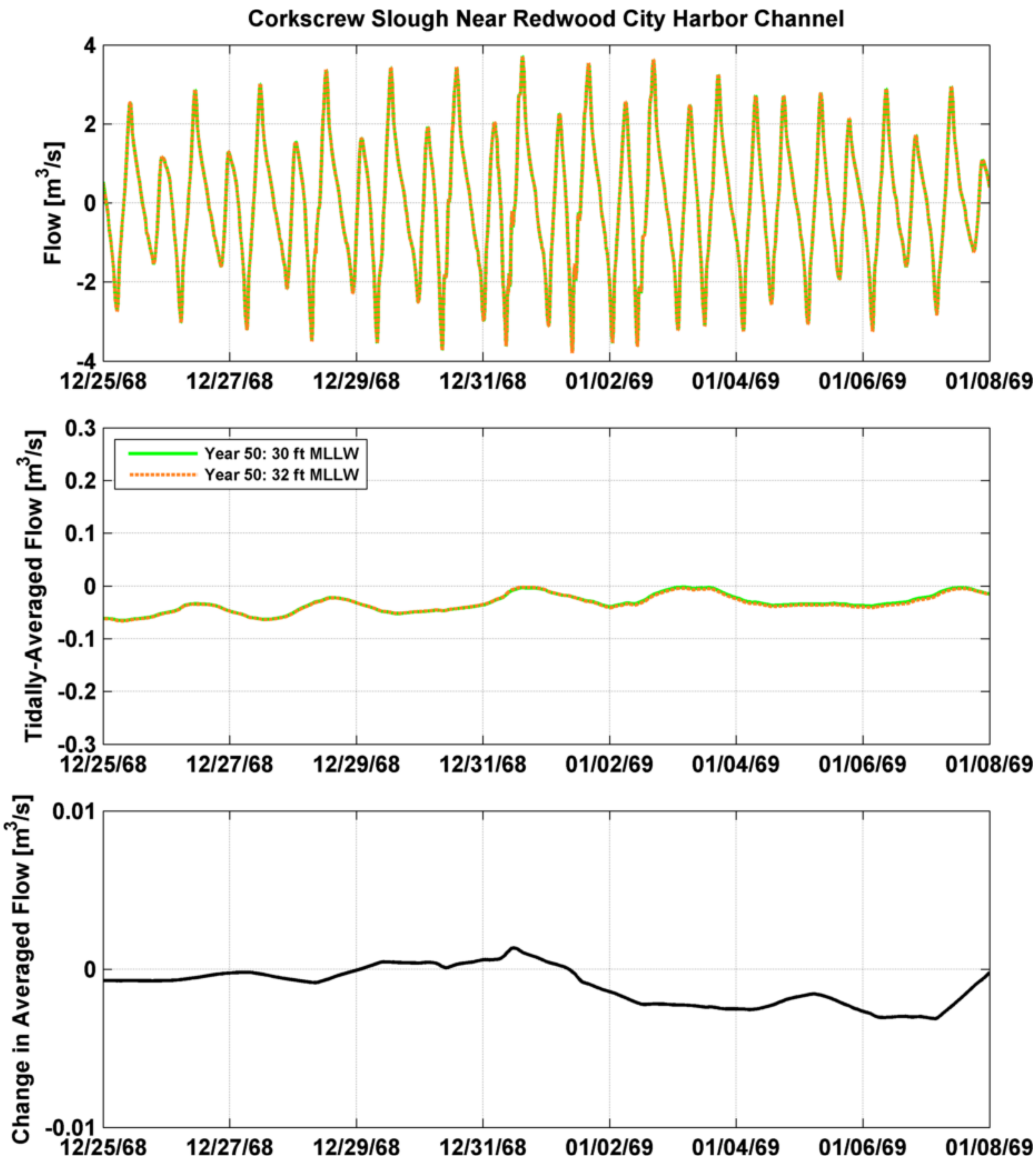


Figure 8.2-29

Predicted flow through Corkscrew Slough near the Redwood City Harbor Channel (CSL, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

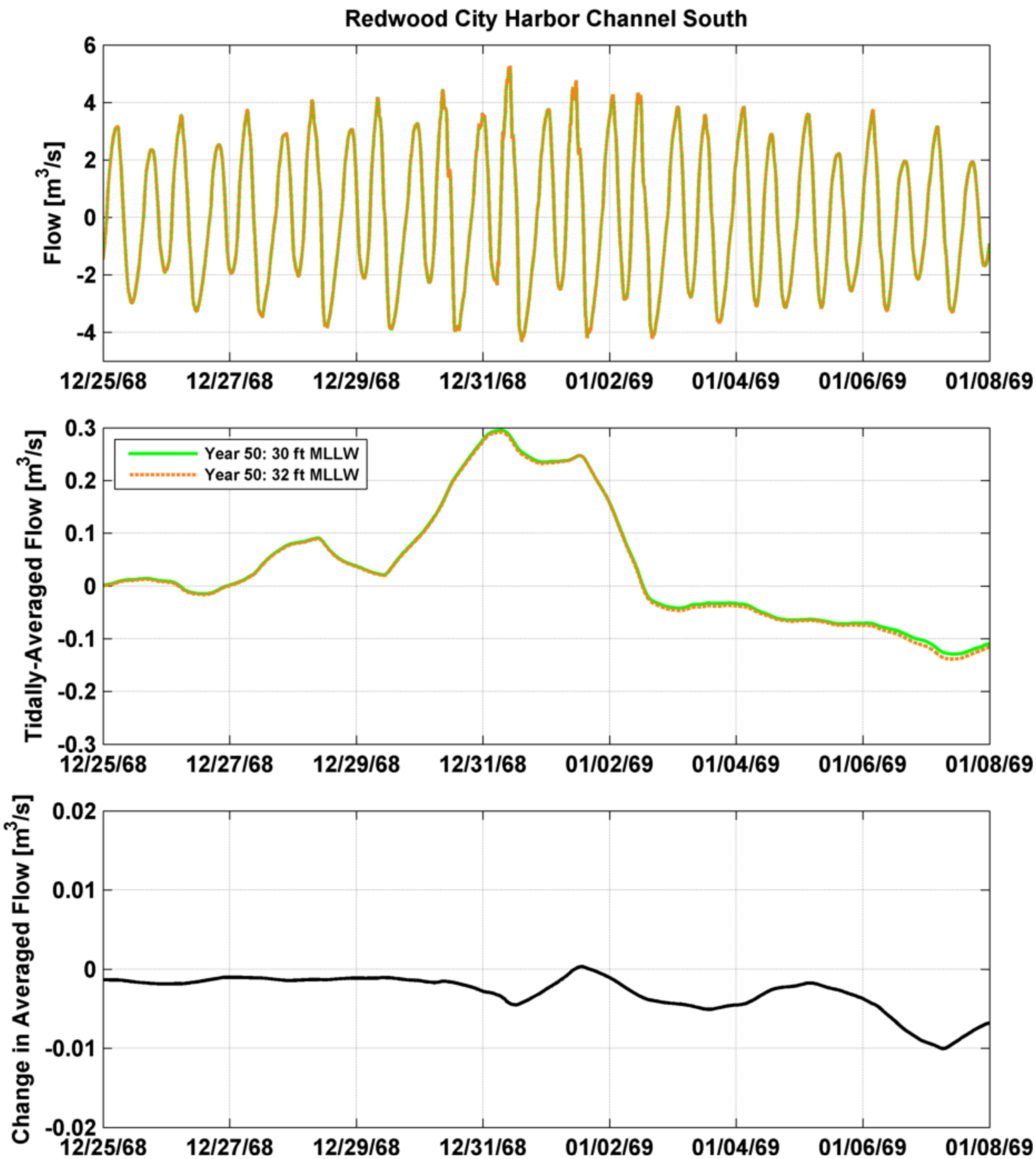


Figure 8.2-30
Predicted flow through the Redwood City Harbor Channel southern cross section (RCHCS, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

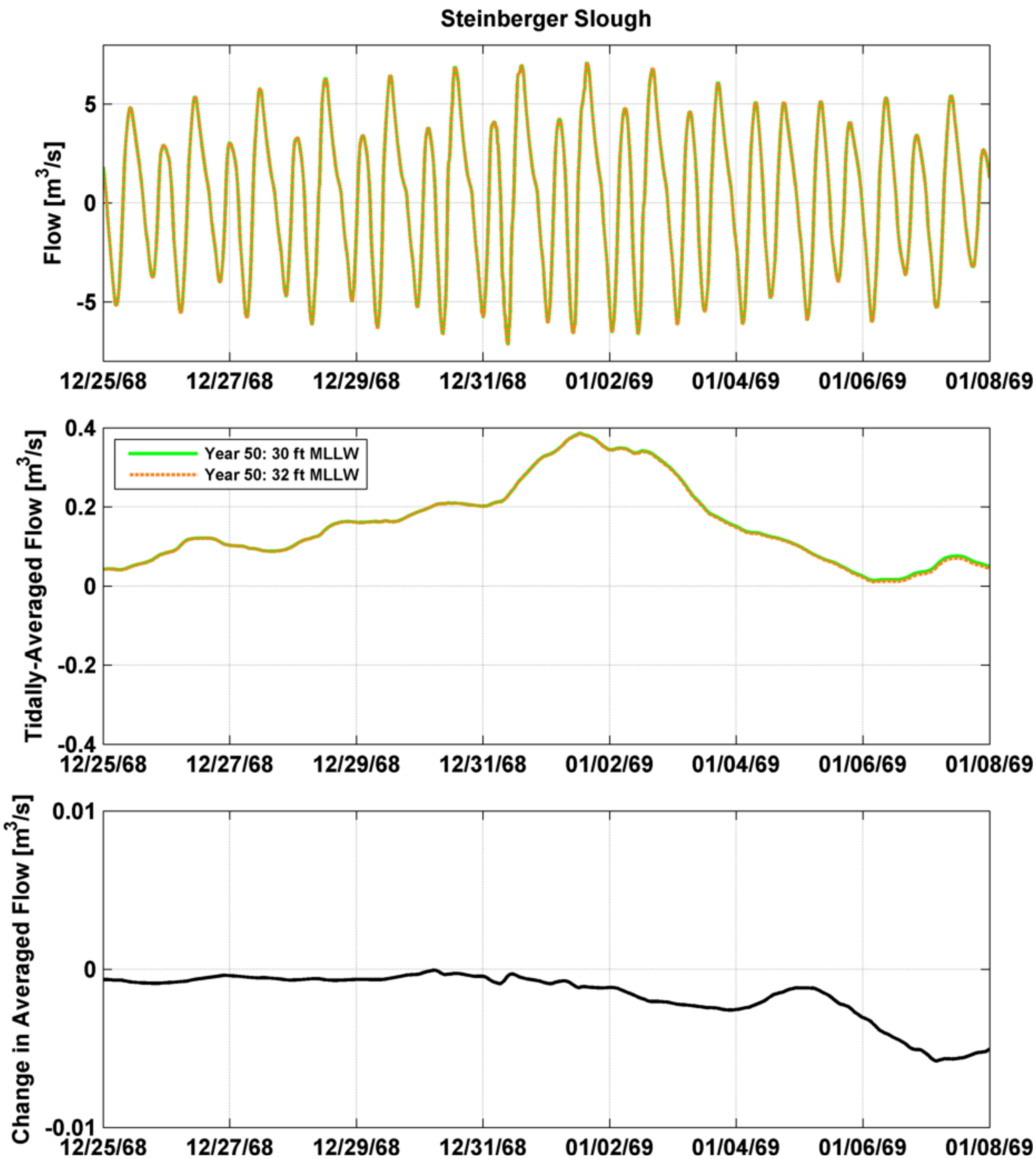


Figure 8.2-31
Predicted flow through Steinberger Slough (STSL, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

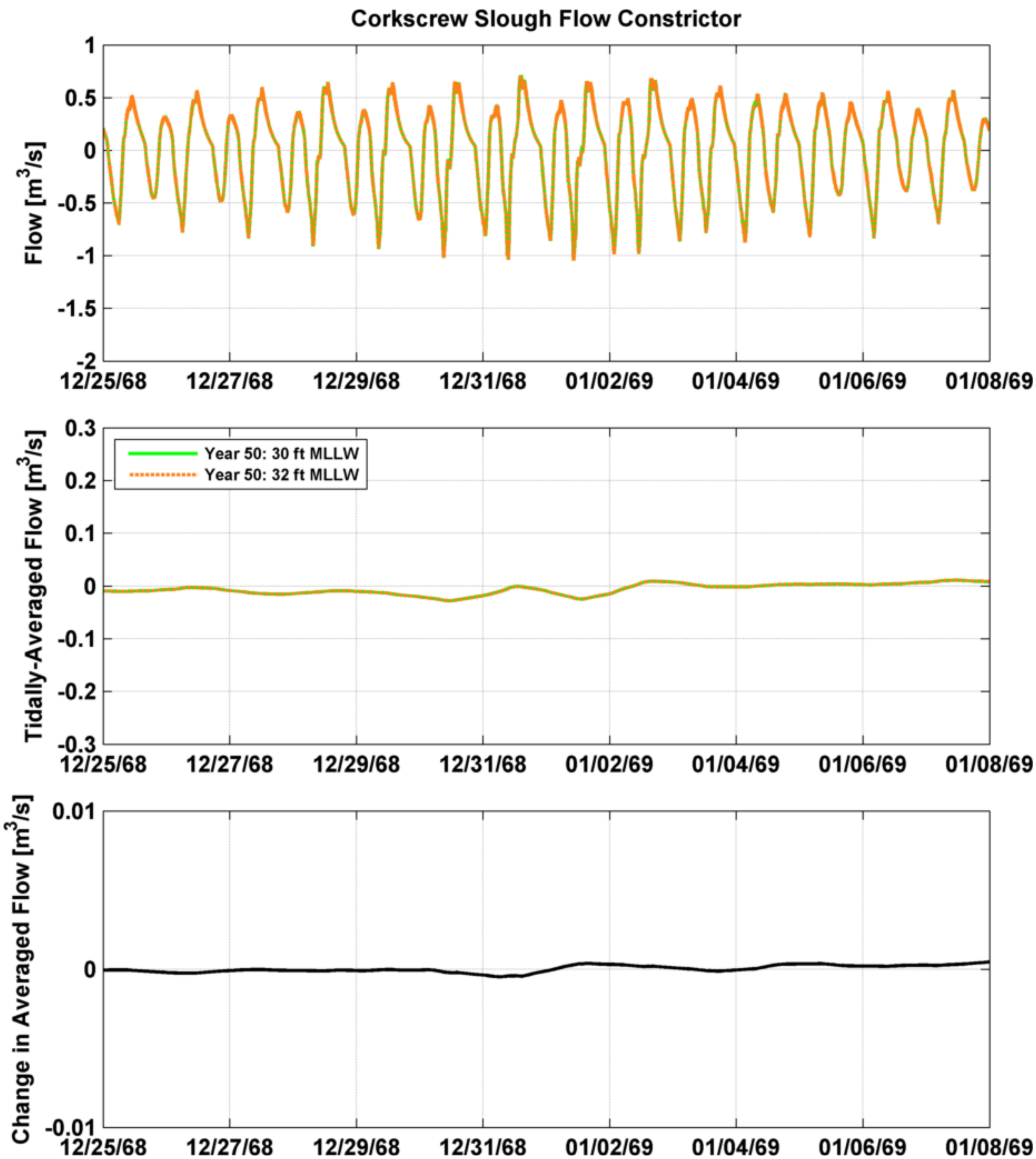


Figure 8.2-32

Predicted flow through the Corkscrew Slough flow constrictor (FC, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

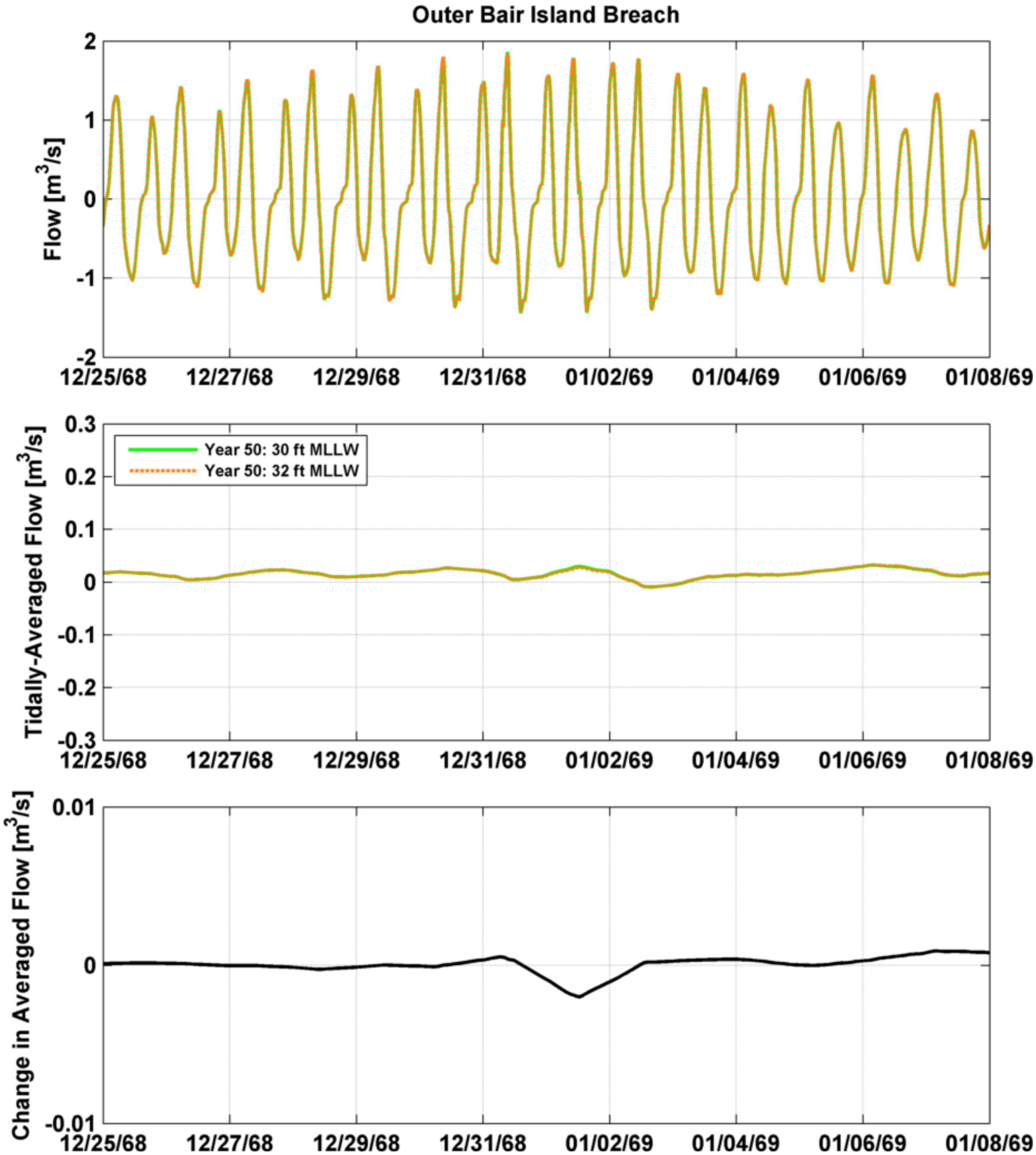


Figure 8.2-33

Predicted flow through a breach in Outer Bair Island (OB, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

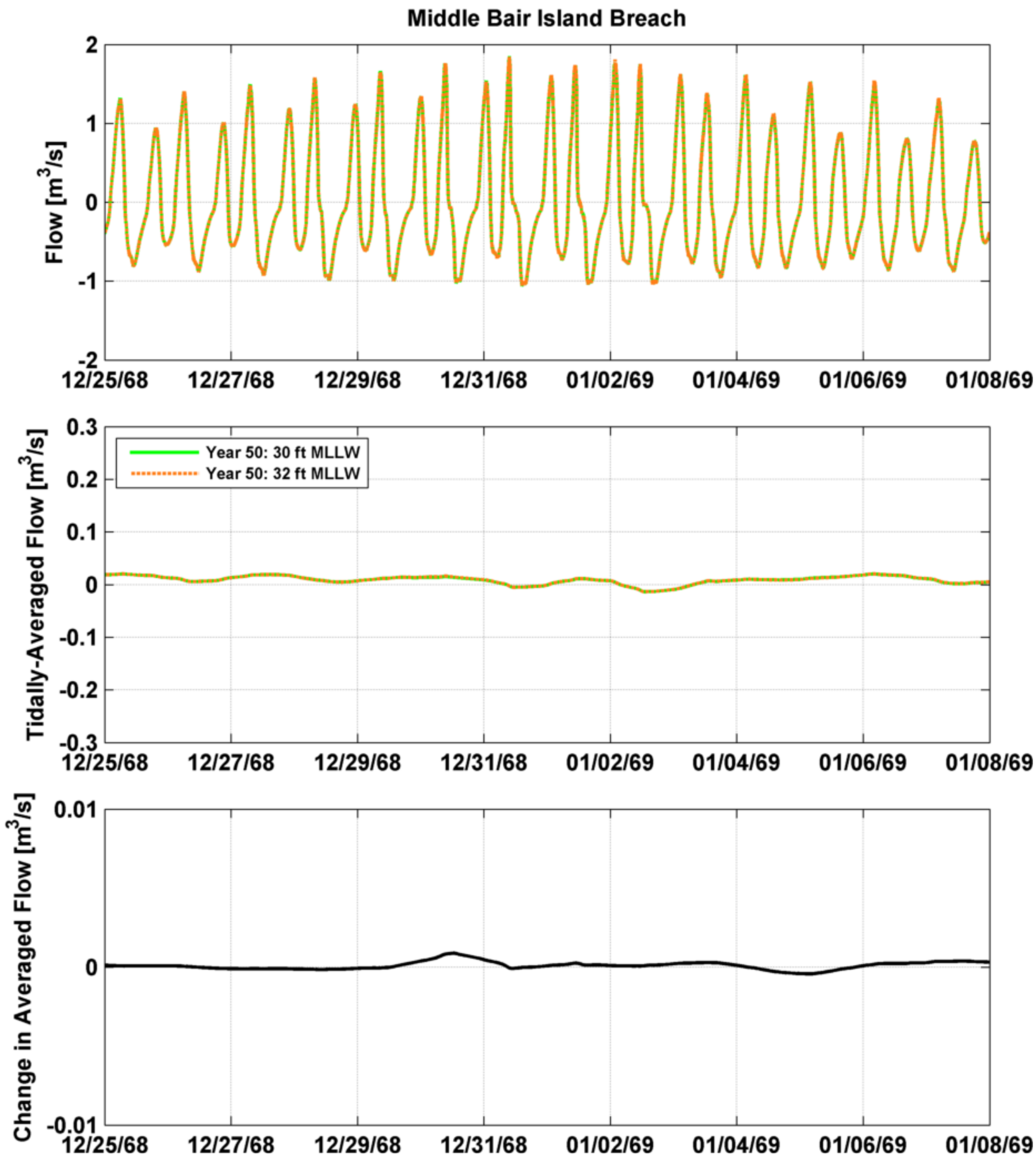


Figure 8.2-34
Predicted flow through a breach in Middle Bair Island (MB, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

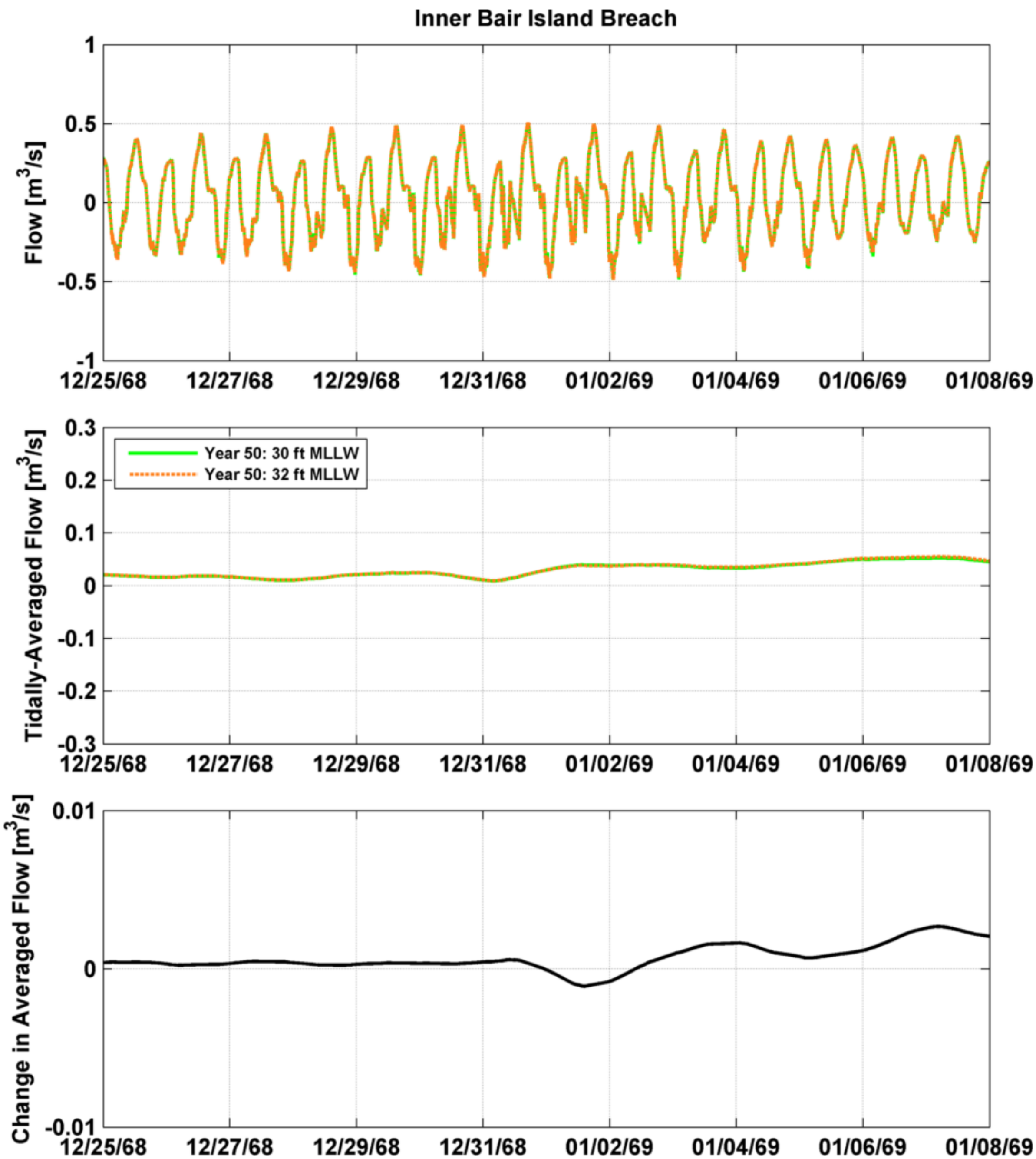


Figure 8.2-35
Predicted flow through a breach in Inner Bair Island (IB, Figure 8.2-2) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

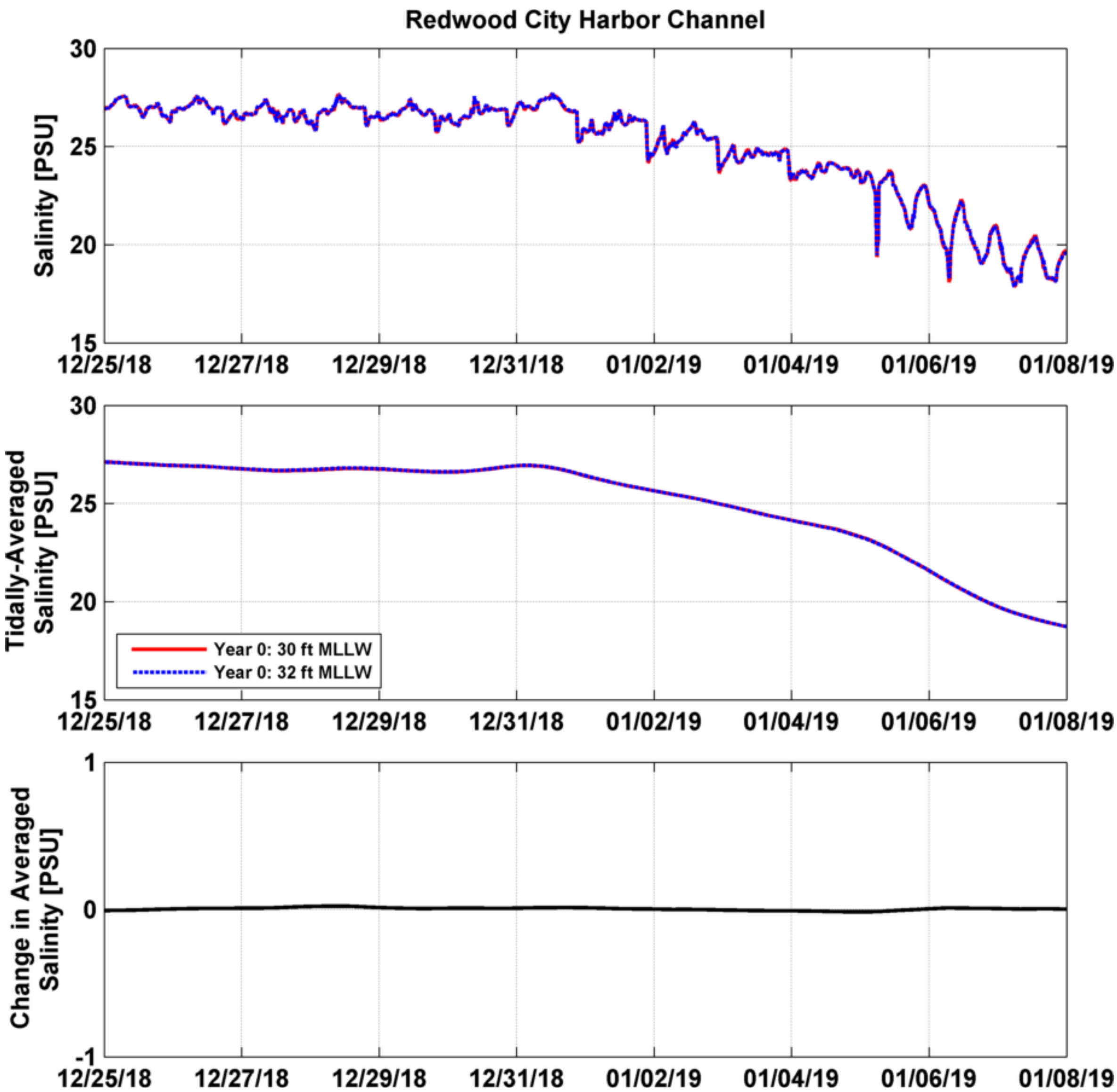


Figure 8.2-36
Predicted surface salinity in the Redwood City Harbor Channel (RCHC, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

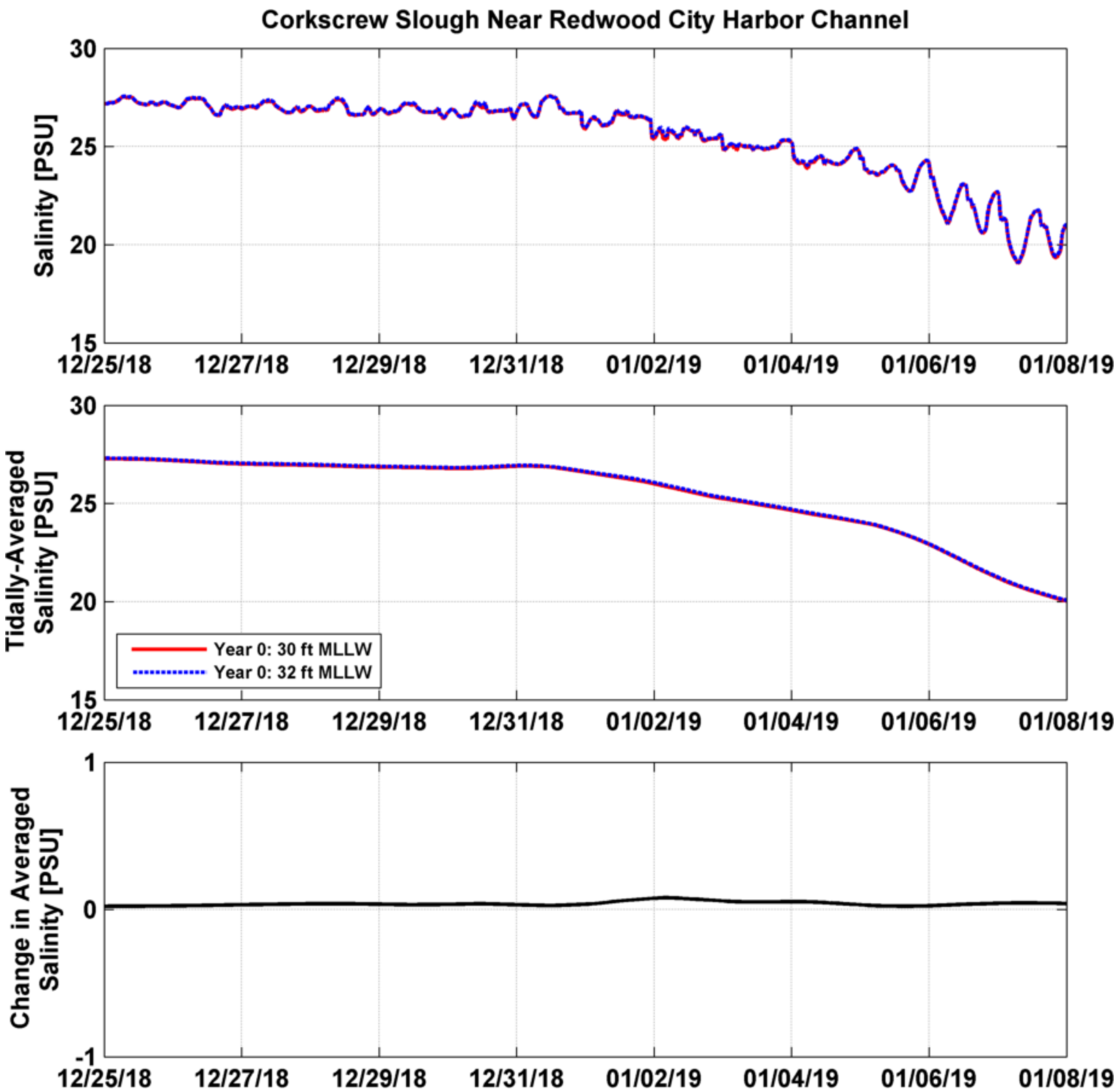


Figure 8.2-37
Predicted surface salinity in Corkscrew Slough near the Redwood City Harbor Channel (CSL, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

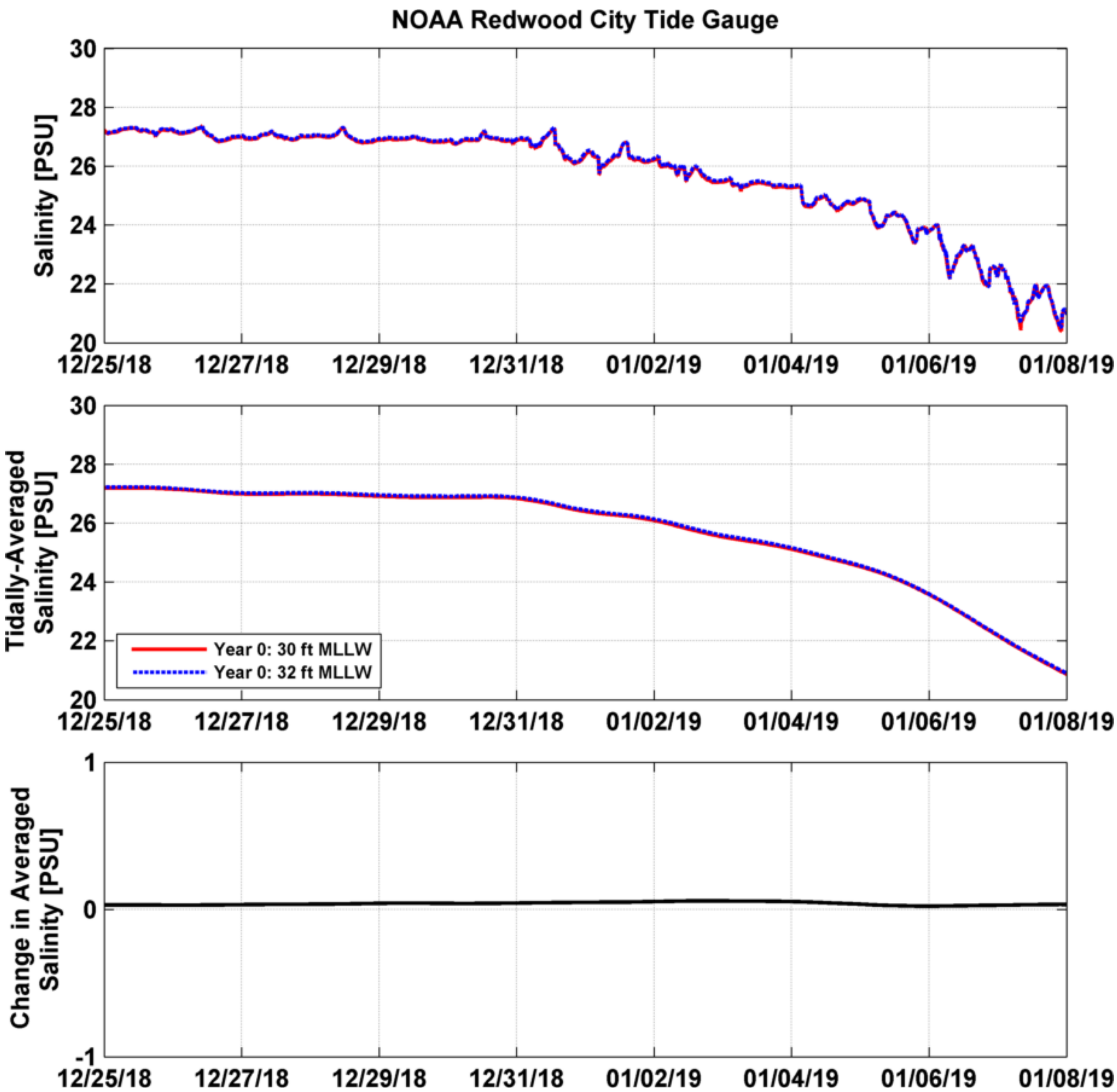


Figure 8.2-38
Predicted surface salinity at the NOAA Redwood City tide gauge (9414523, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

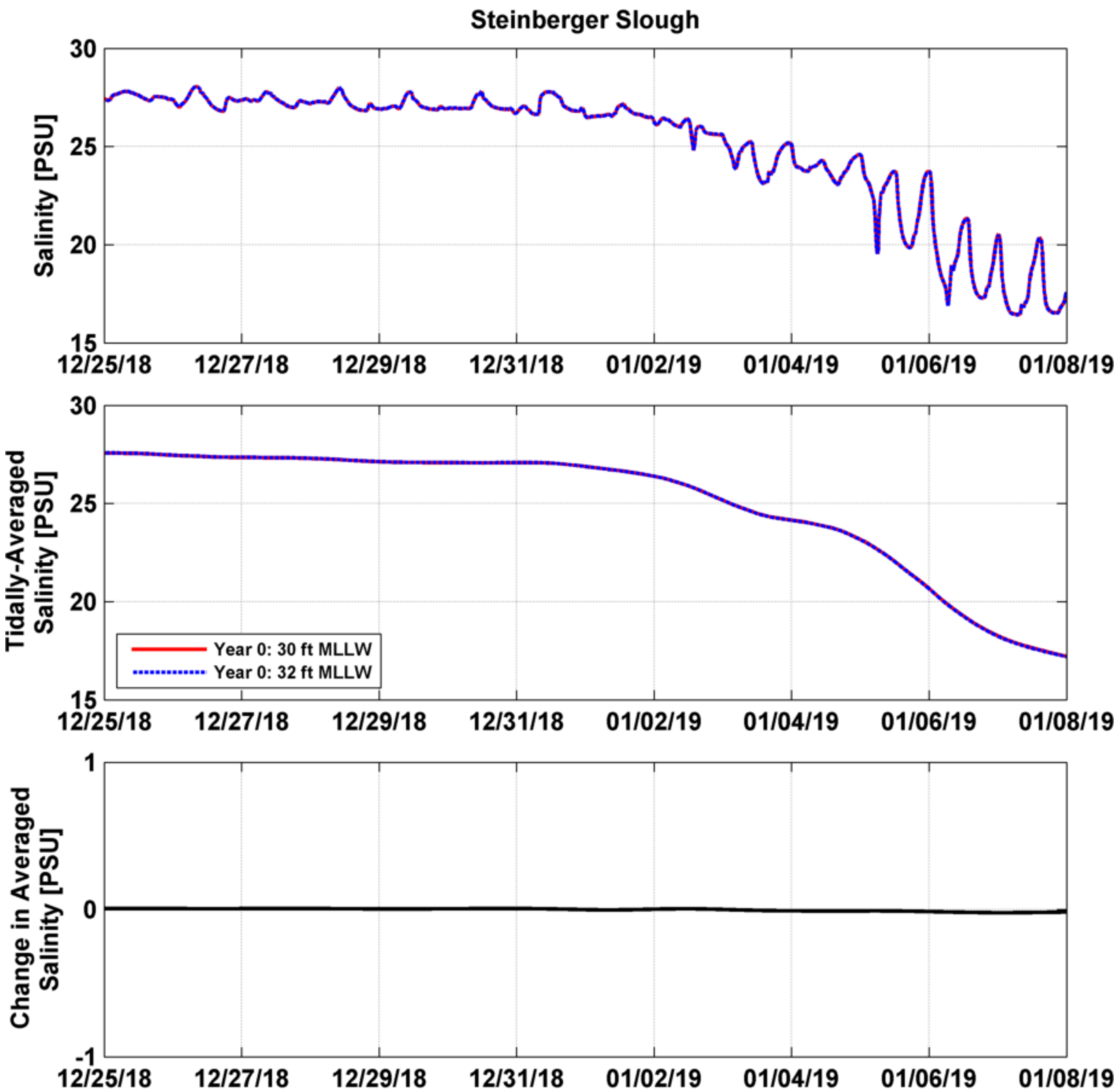


Figure 8.2-39

Predicted surface salinity in Steinberger Slough (STSL, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

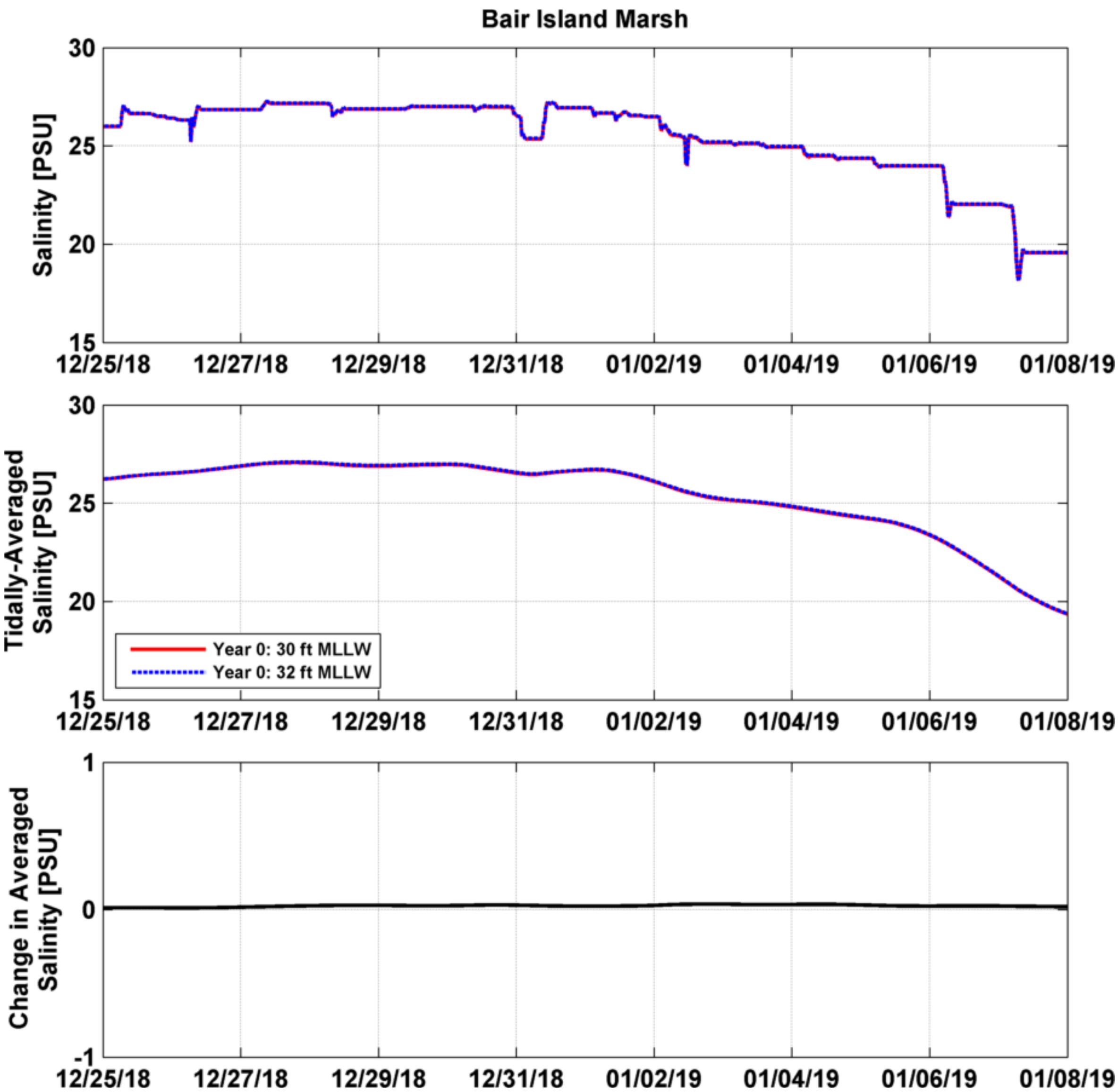


Figure 8.2-40
Predicted surface salinity in the Bair Island marsh (BIM, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

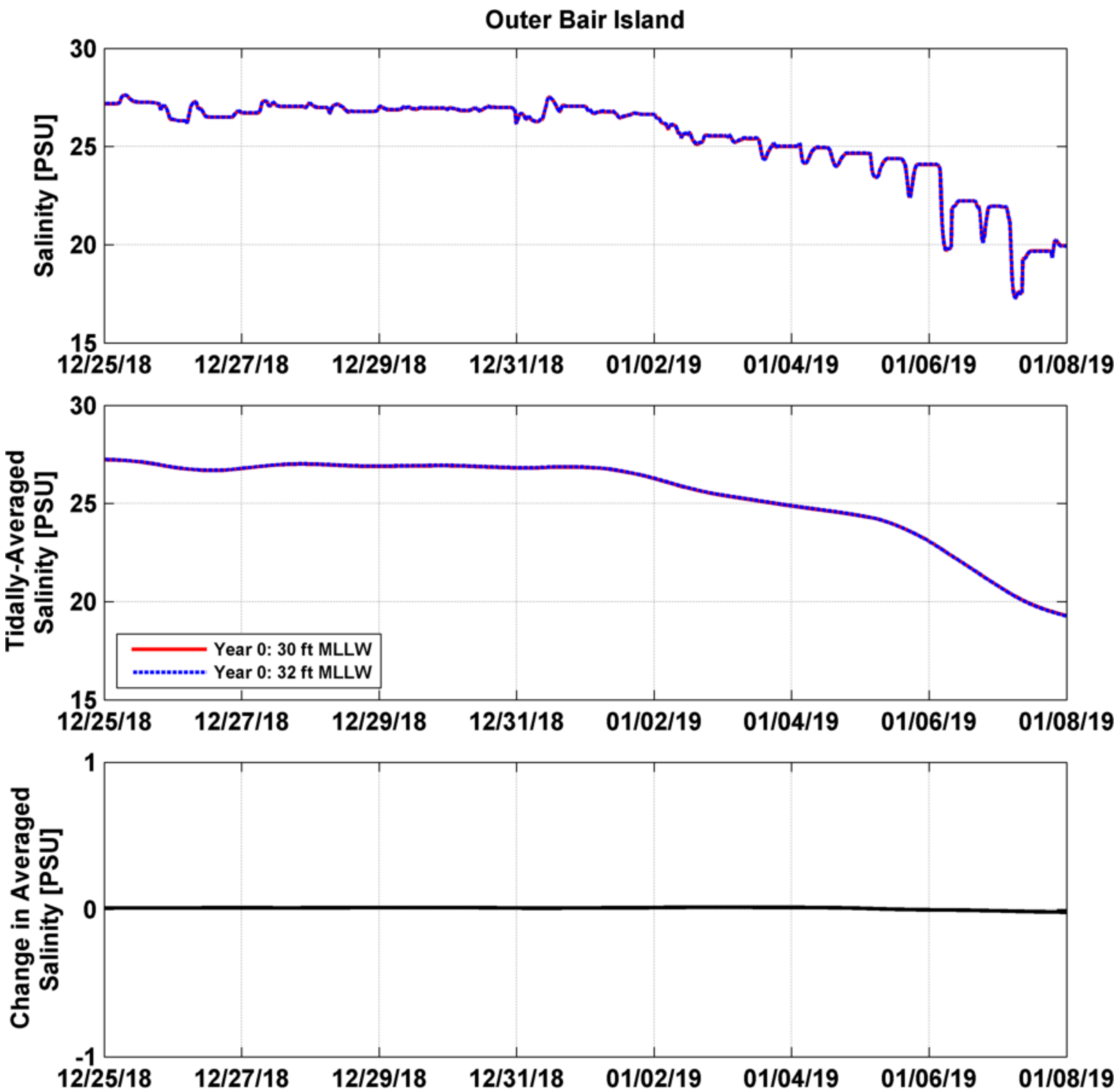


Figure 8.2-41

Predicted surface salinity in Outer Bair Island (OB, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

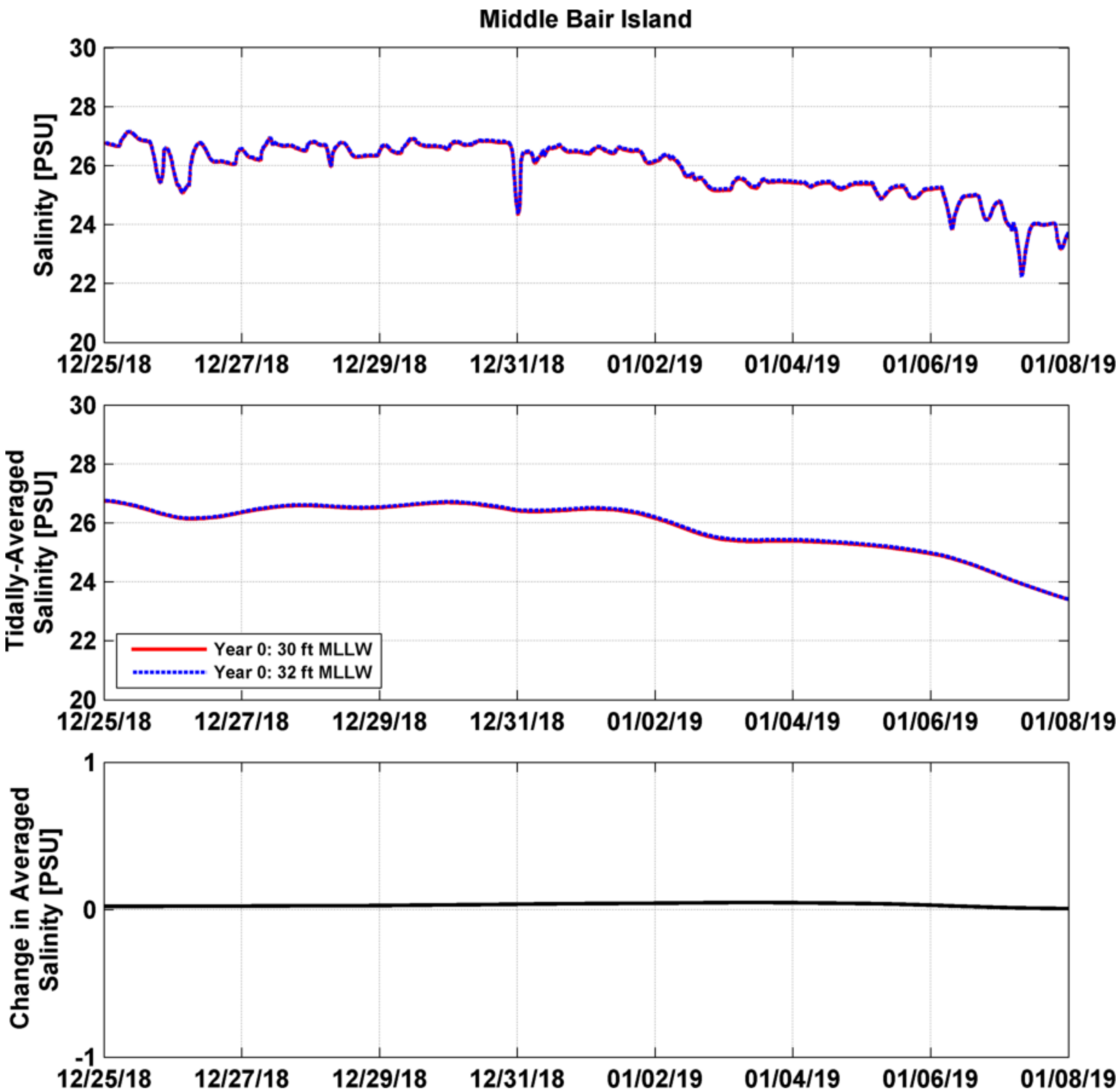


Figure 8.2-42
Predicted surface salinity in Middle Bair Island (MB, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

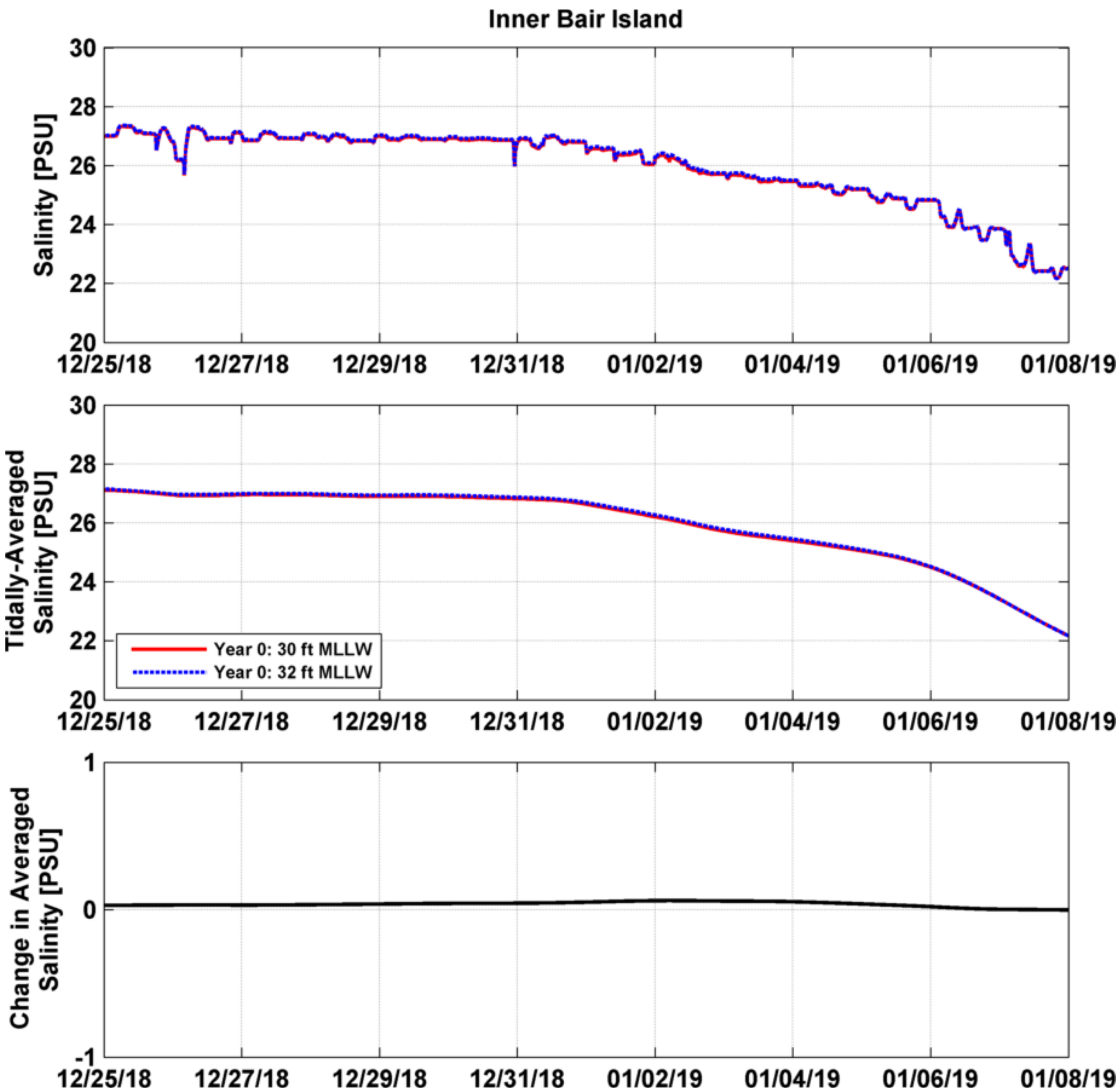


Figure 8.2-43 Predicted surface salinity in Inner Bair Island (IB, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 0 scenarios.

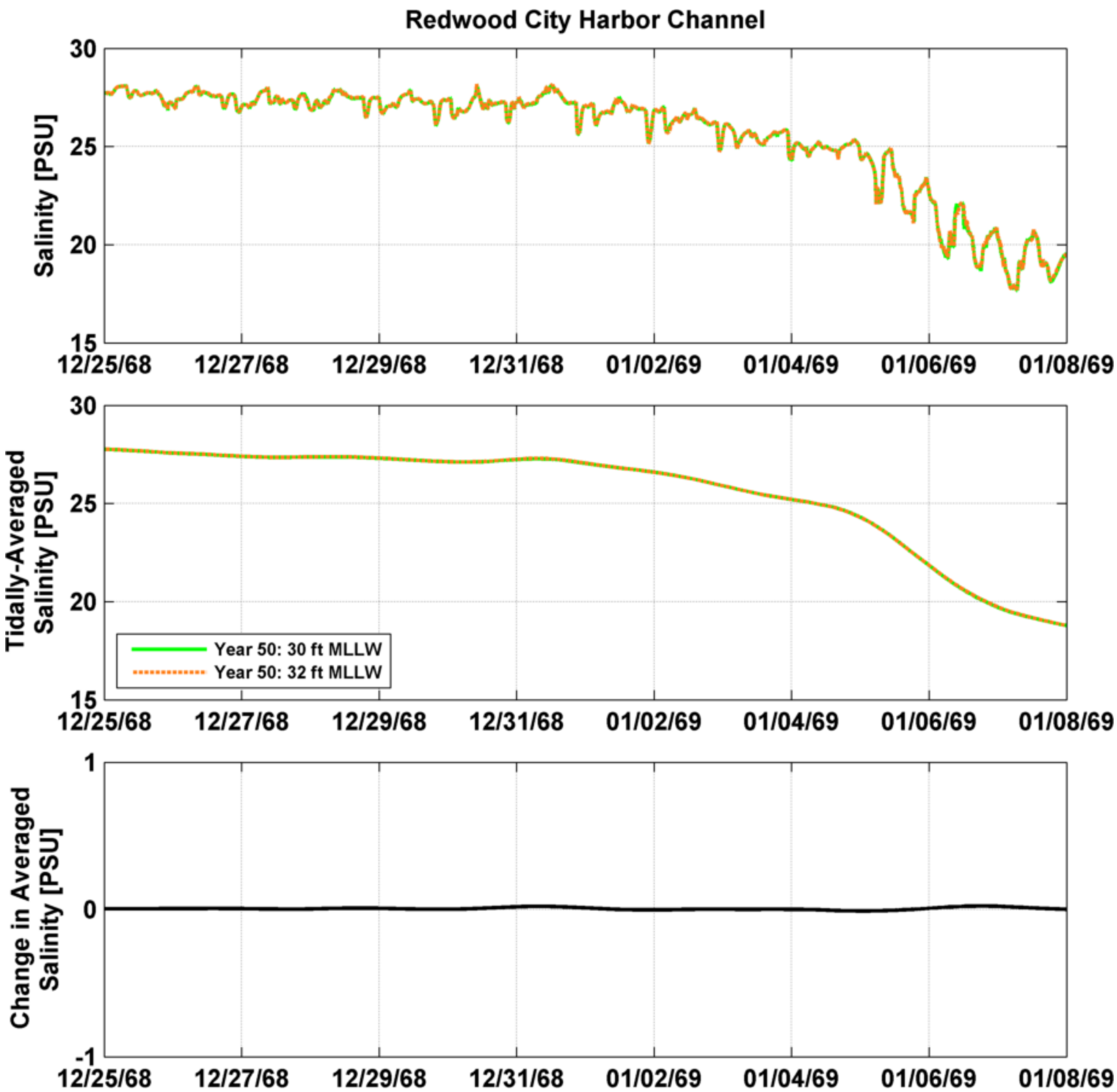


Figure 8.2-44

Predicted surface salinity in the Redwood City Harbor Channel (RCHC, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

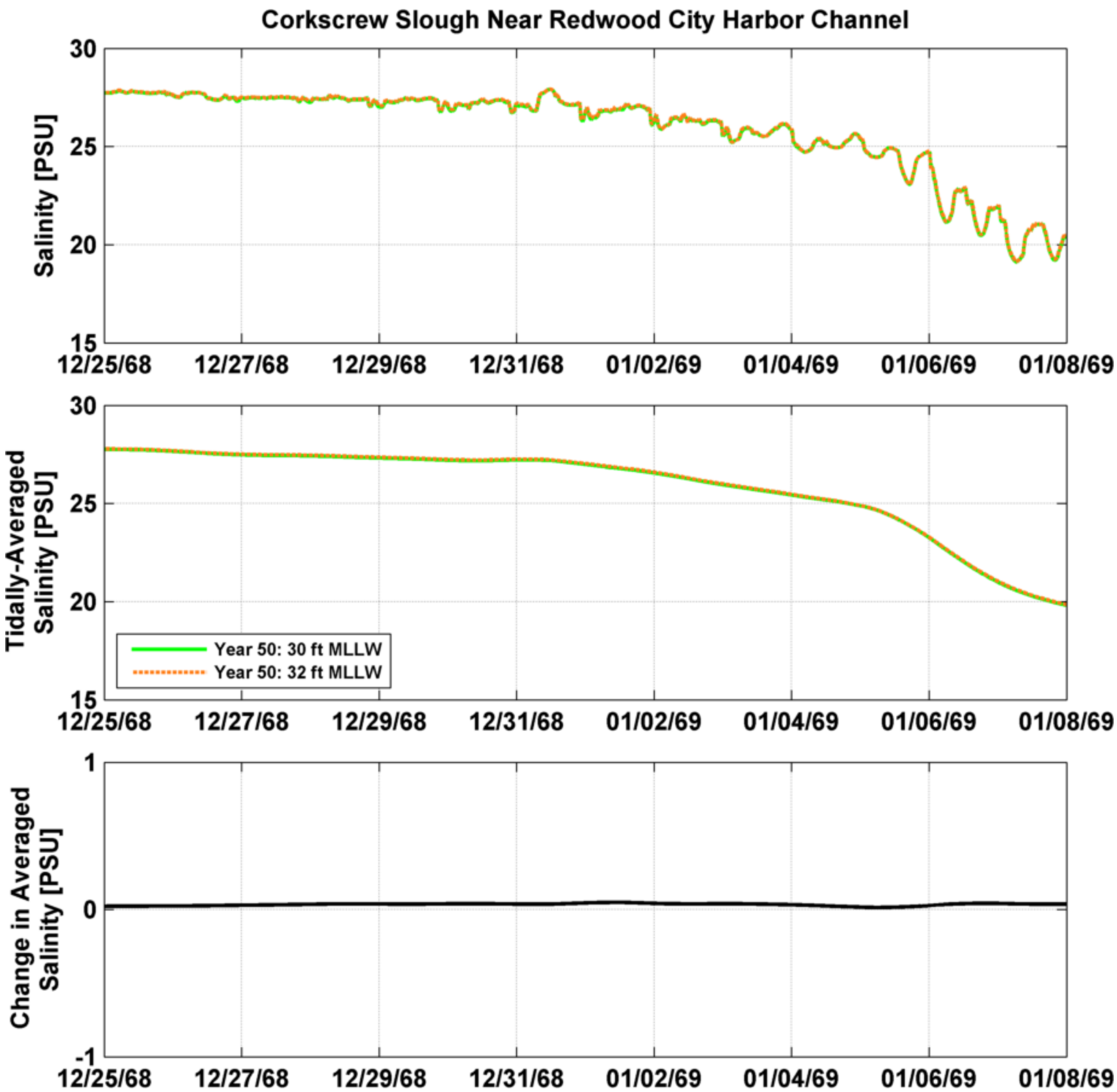


Figure 8.2-45

Predicted surface salinity in Corkscrew Slough near the Redwood City Harbor Channel (CSL, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

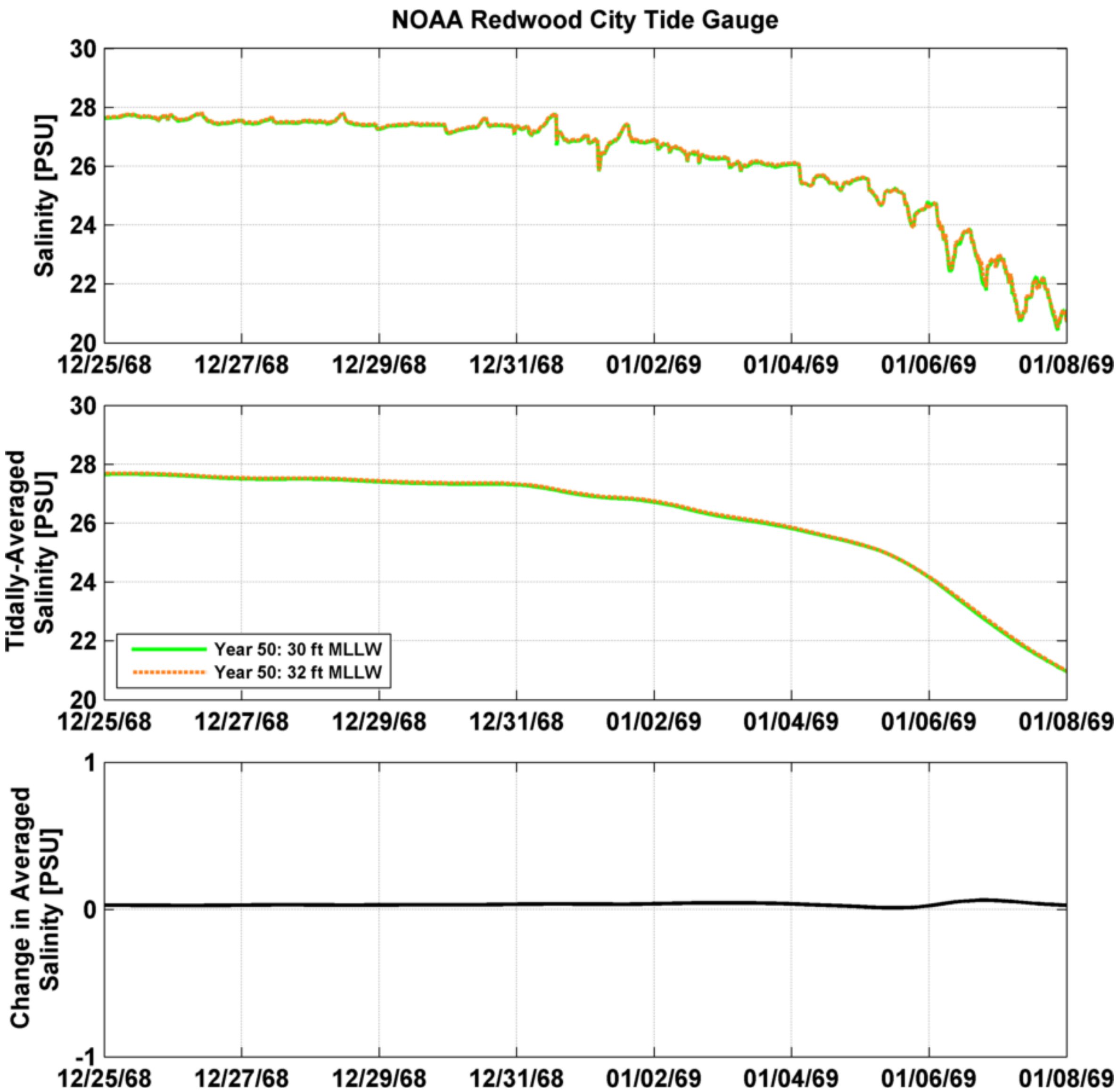


Figure 8.2-46
Predicted surface salinity at the NOAA Redwood City tide gauge (9414523, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

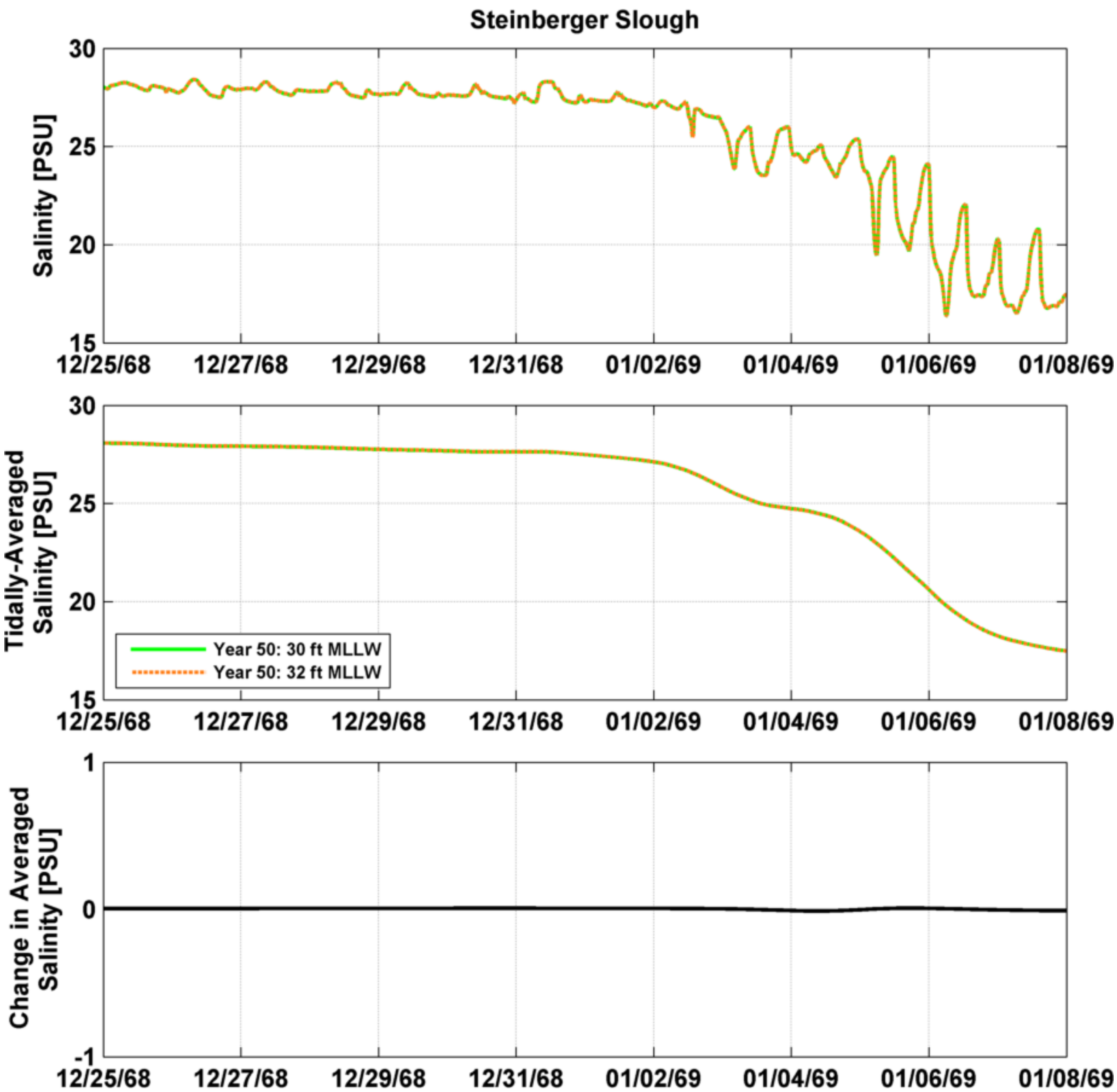


Figure 8.2-47
Predicted surface salinity in Steinberger Slough (STSL, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

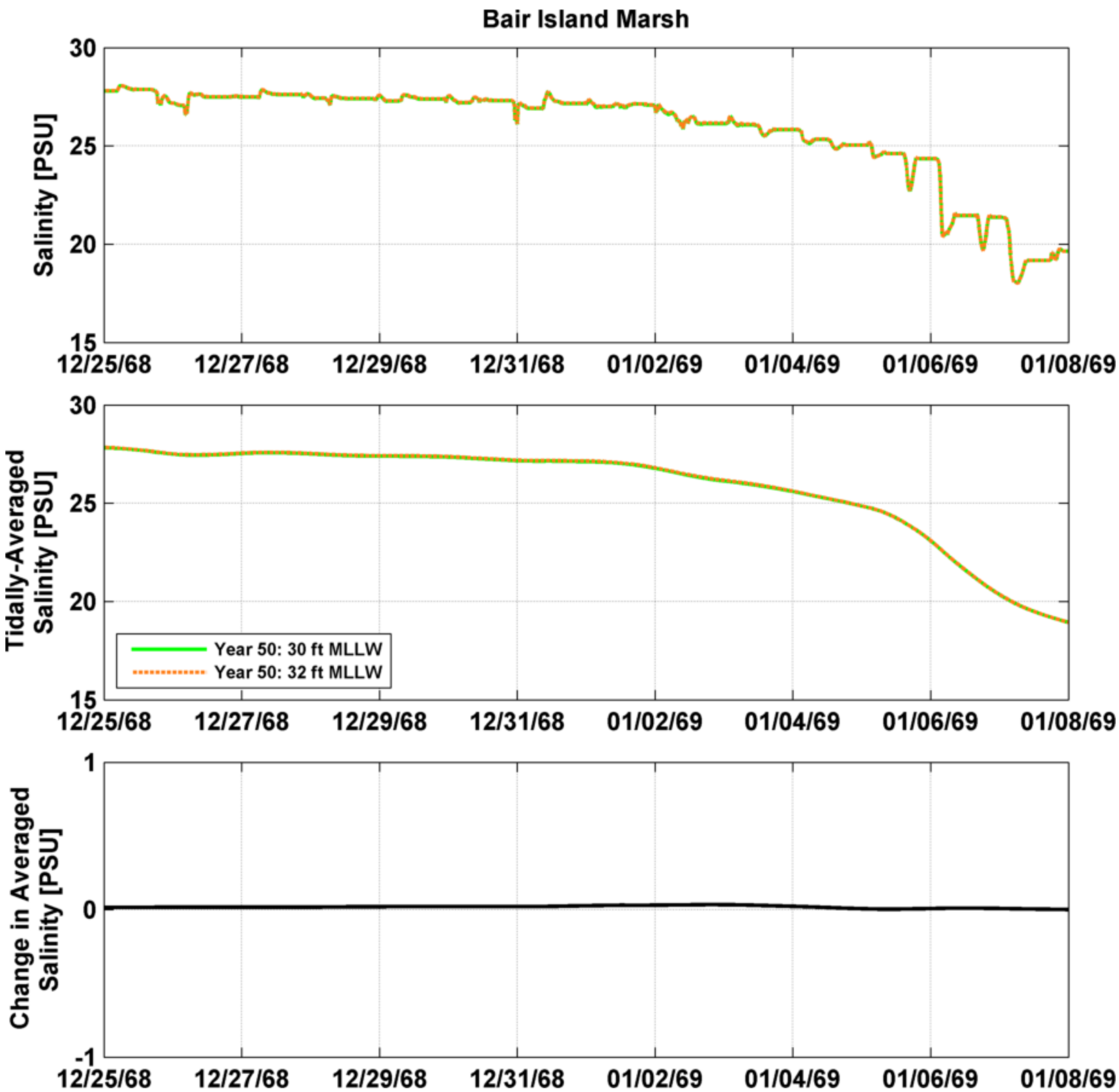


Figure 8.2-48
Predicted surface salinity in the Bair Island marsh (BIM, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

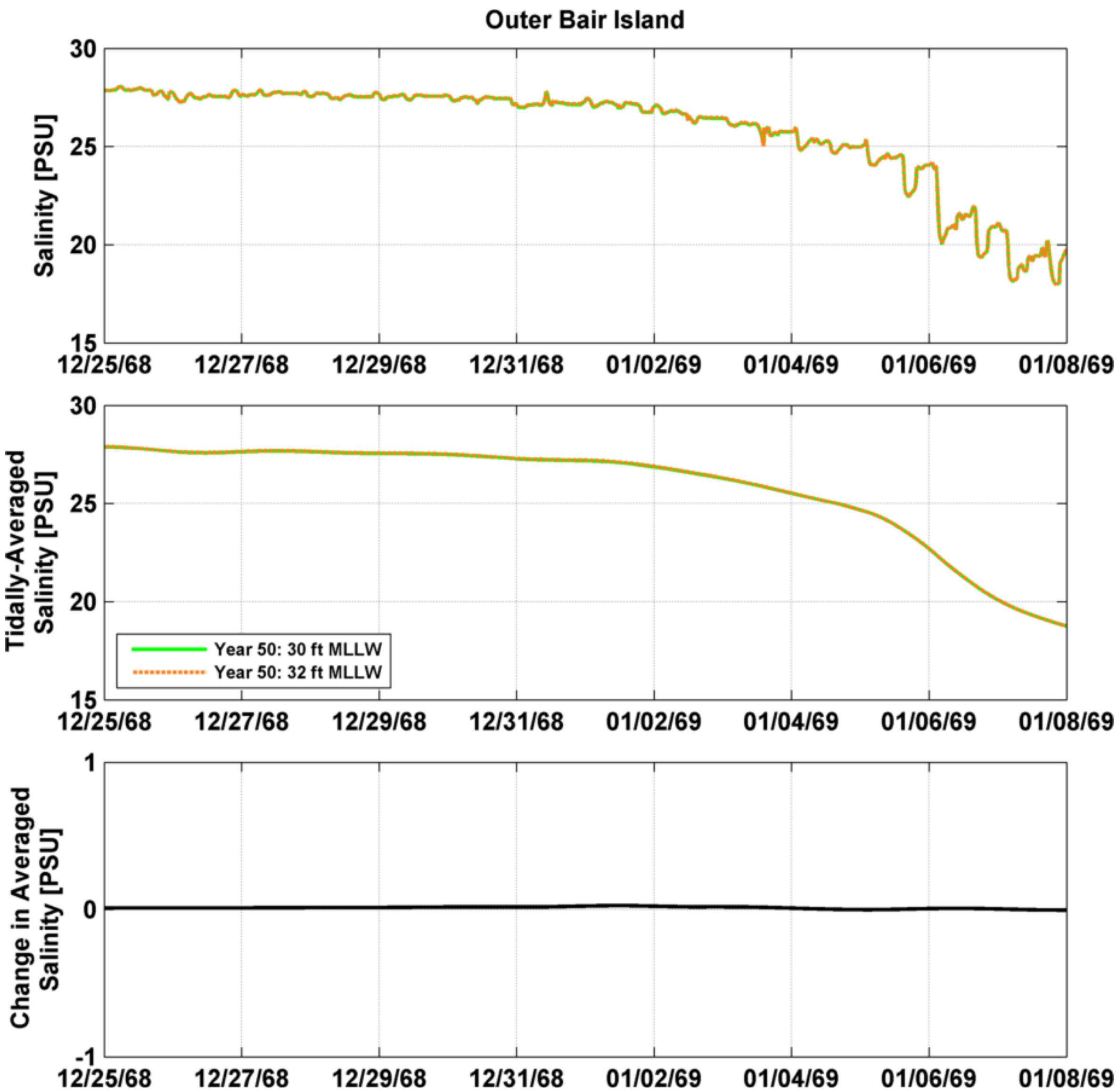


Figure 8.2-49
Predicted surface salinity in Outer Bair Island (OB, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

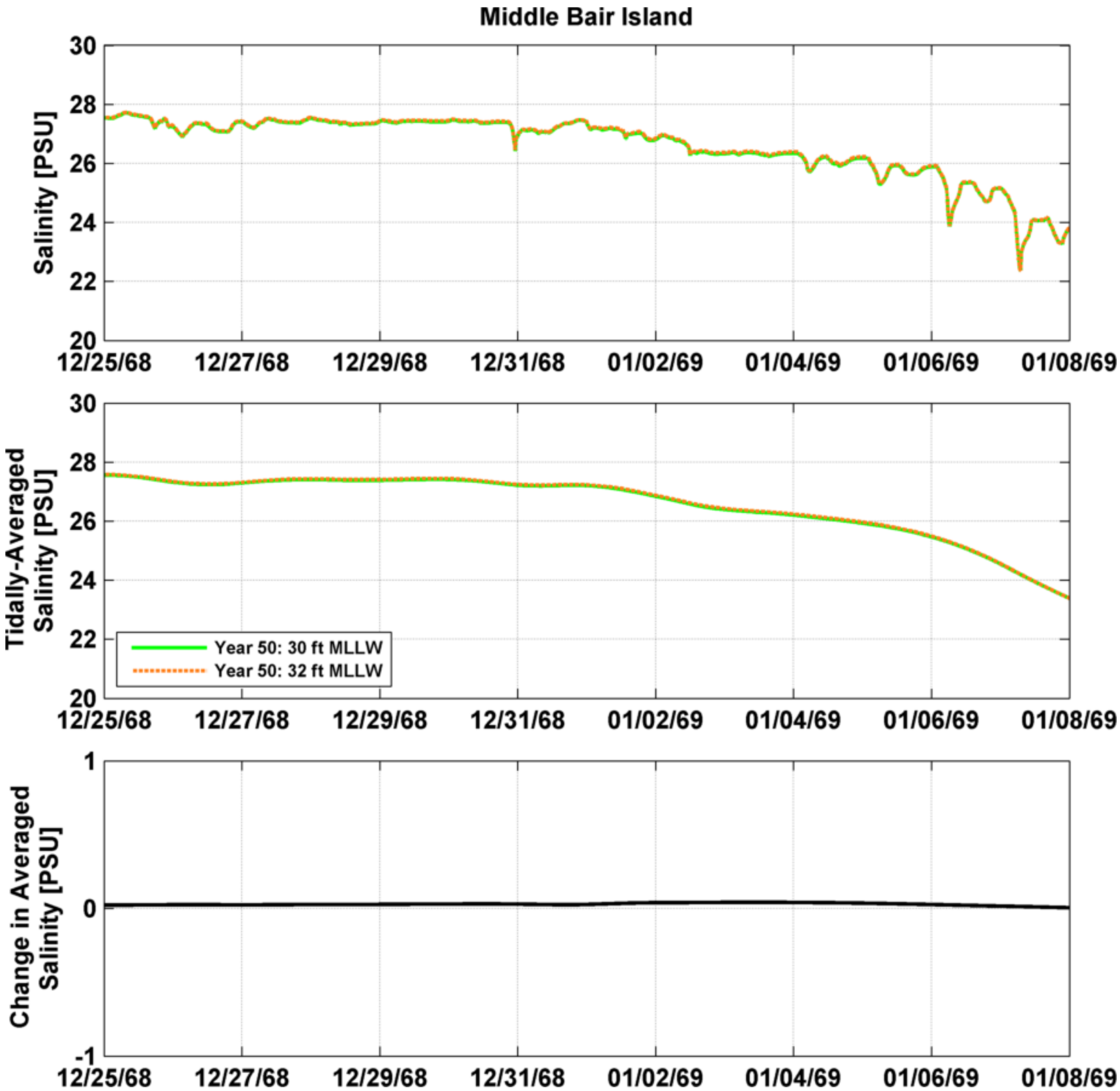


Figure 8.2-50
Predicted surface salinity in Middle Bair Island (MB, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

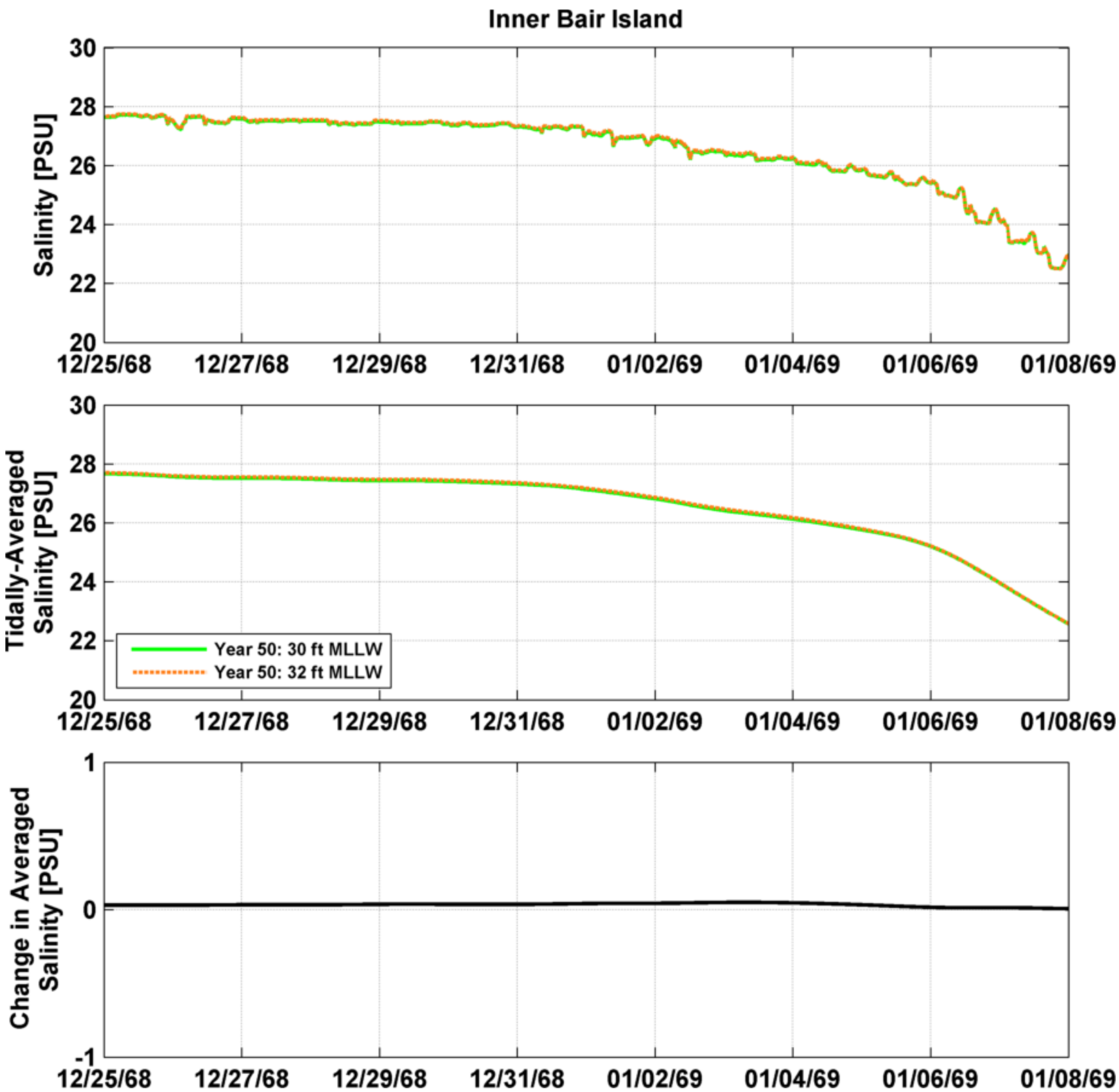


Figure 8.2-51
Predicted surface salinity in Inner Bair Island (IB, Figure 8.2-3) for without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions during the Year 50 scenarios.

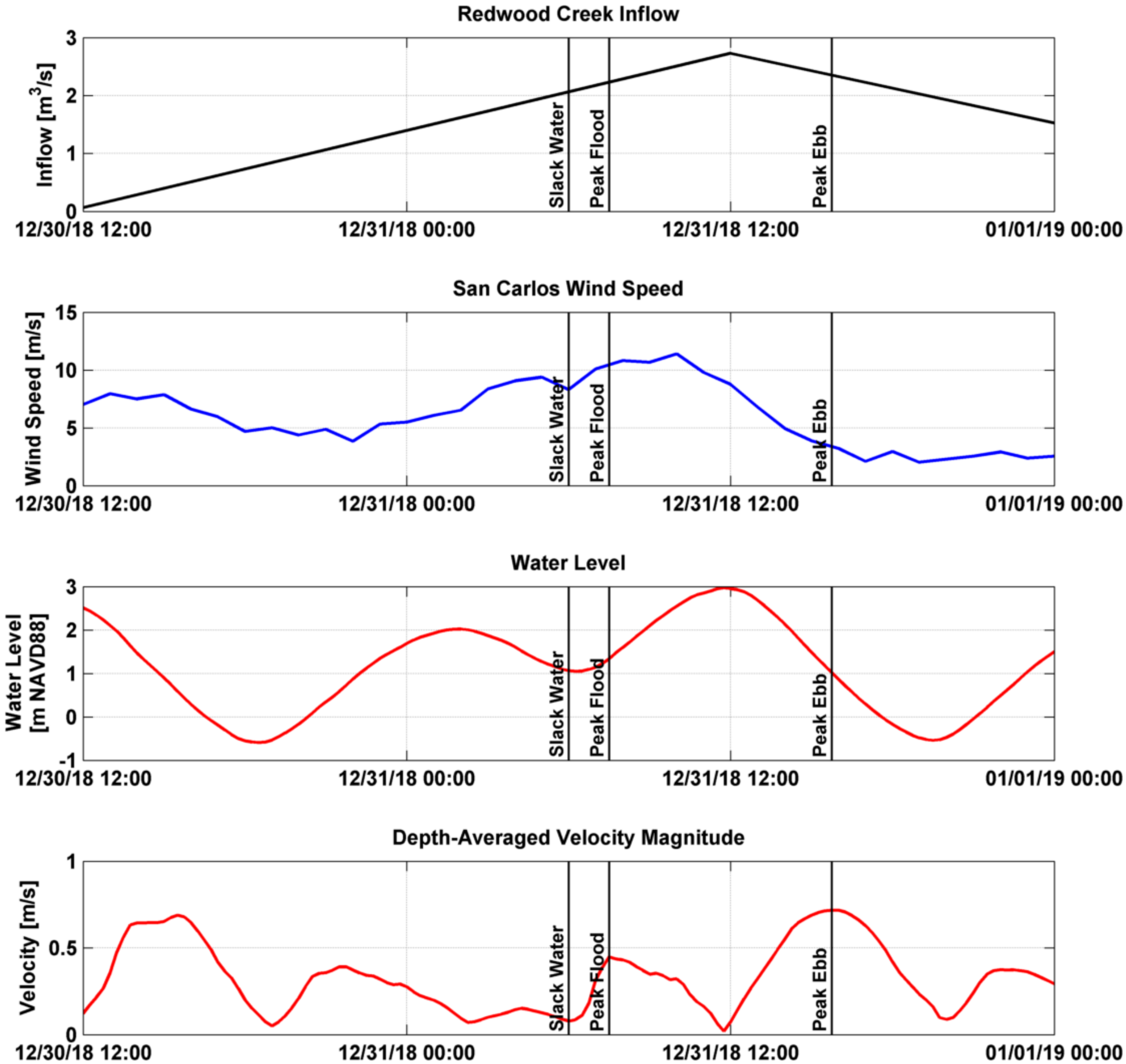


Figure 8.2-52
The Redwood Creek inflow, wind speed at San Carlos, predicted water level at the Redwood City tide gauge, and predicted depth-averaged velocity magnitude in the Redwood City Harbor Channel during the 30 feet MLLW project depth Year 0 simulation. Vertical lines mark the times of shear stress evaluation for slack water, peak flood velocity, and peak ebb velocity, from left to right.

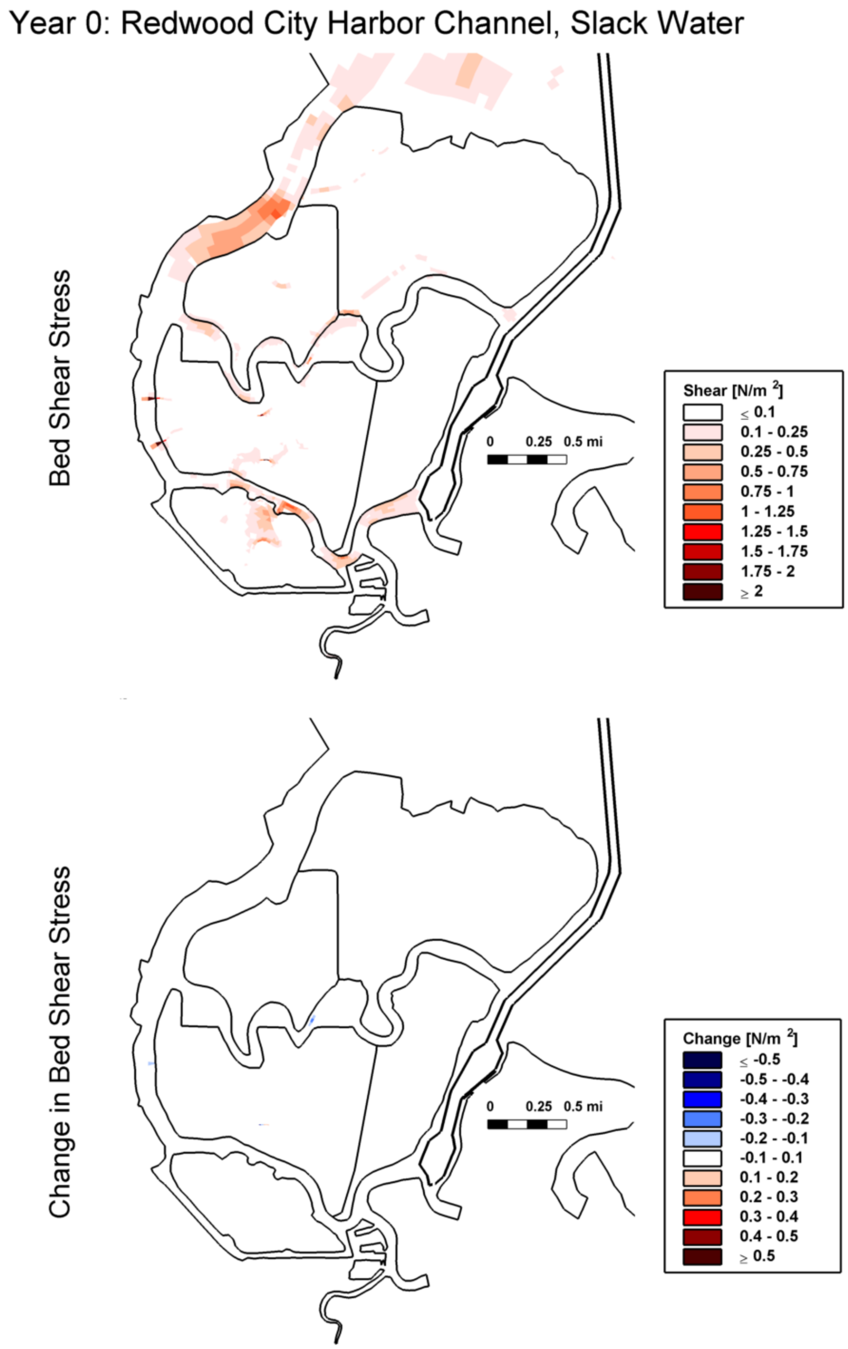


Figure 8.2-53
Predicted bed shear stress (Pa) in the vicinity of the Redwood City Harbor Channel and Bair Island during slack water for the 32 feet MLLW project depth Year 0 scenario (top); predicted change in bed shear stress in the 32 feet MLLW project depth Year 0 scenario relative to the 30 feet MLLW scenario (bottom).

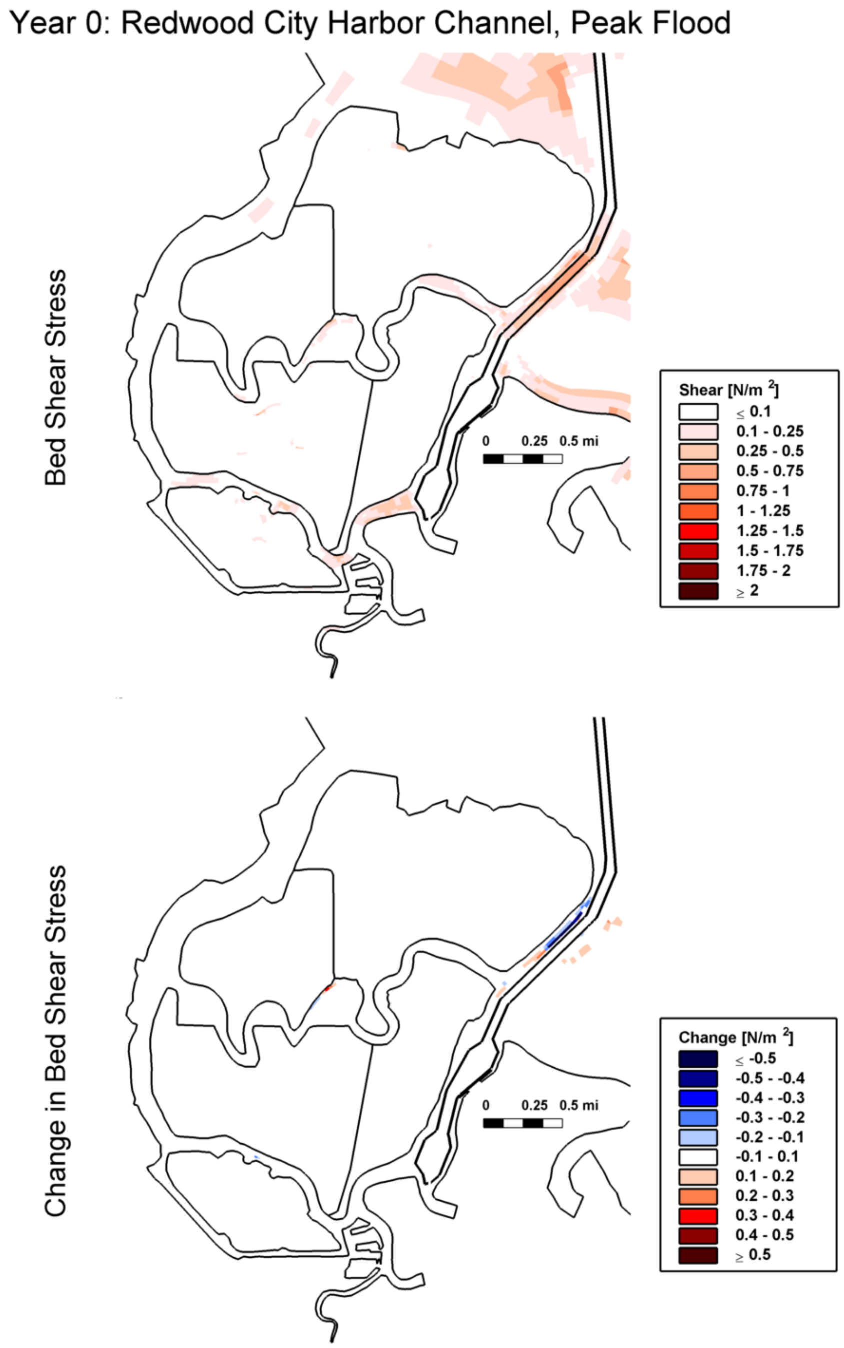


Figure 8.2-54
Predicted bed shear stress (Pa) in the vicinity of the Redwood City Harbor Channel and Bair Island during peak flood currents for the 32 feet MLLW project depth Year 0 scenario (top); predicted change in bed shear stress in the 32 feet MLLW project depth Year 0 scenario relative to the 30 feet MLLW scenario (bottom).

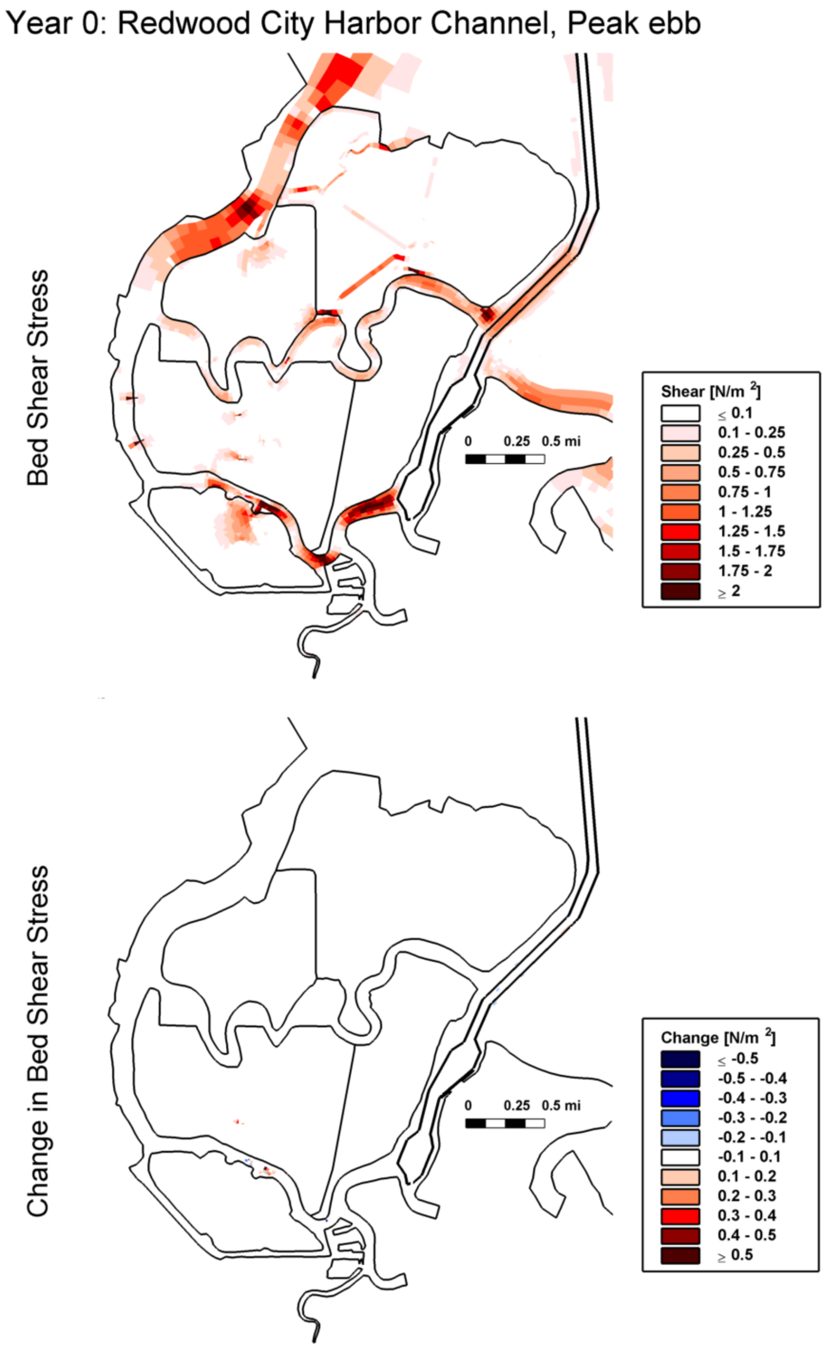


Figure 8.2-55
Predicted bed shear stress (Pa) in the vicinity of the Redwood City Harbor Channel and Bair Island during peak ebb currents for the 32 feet MLLW project depth Year 0 scenario (top); predicted change in bed shear stress in the 32 feet MLLW project depth Year 0 scenario relative to the 30 feet MLLW scenario (bottom).

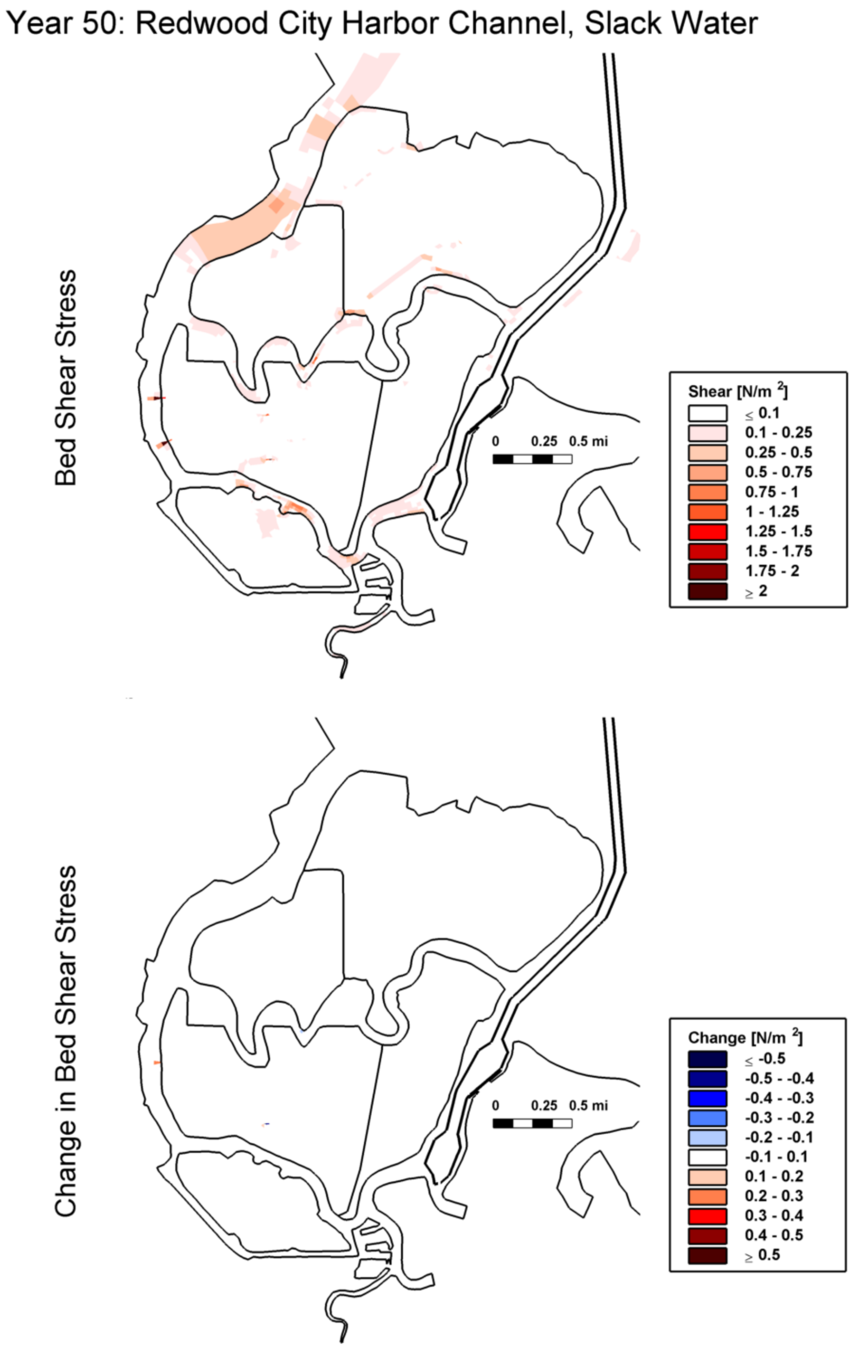


Figure 8.2-56
Predicted bed shear stress (Pa) in the vicinity of the Redwood City Harbor Channel and Bair Island during slack water for the 32 feet MLLW project depth Year 50 scenario (top); predicted change in bed shear stress in the 32 feet MLLW project depth Year 50 scenario relative to the 30 feet MLLW scenario (bottom).

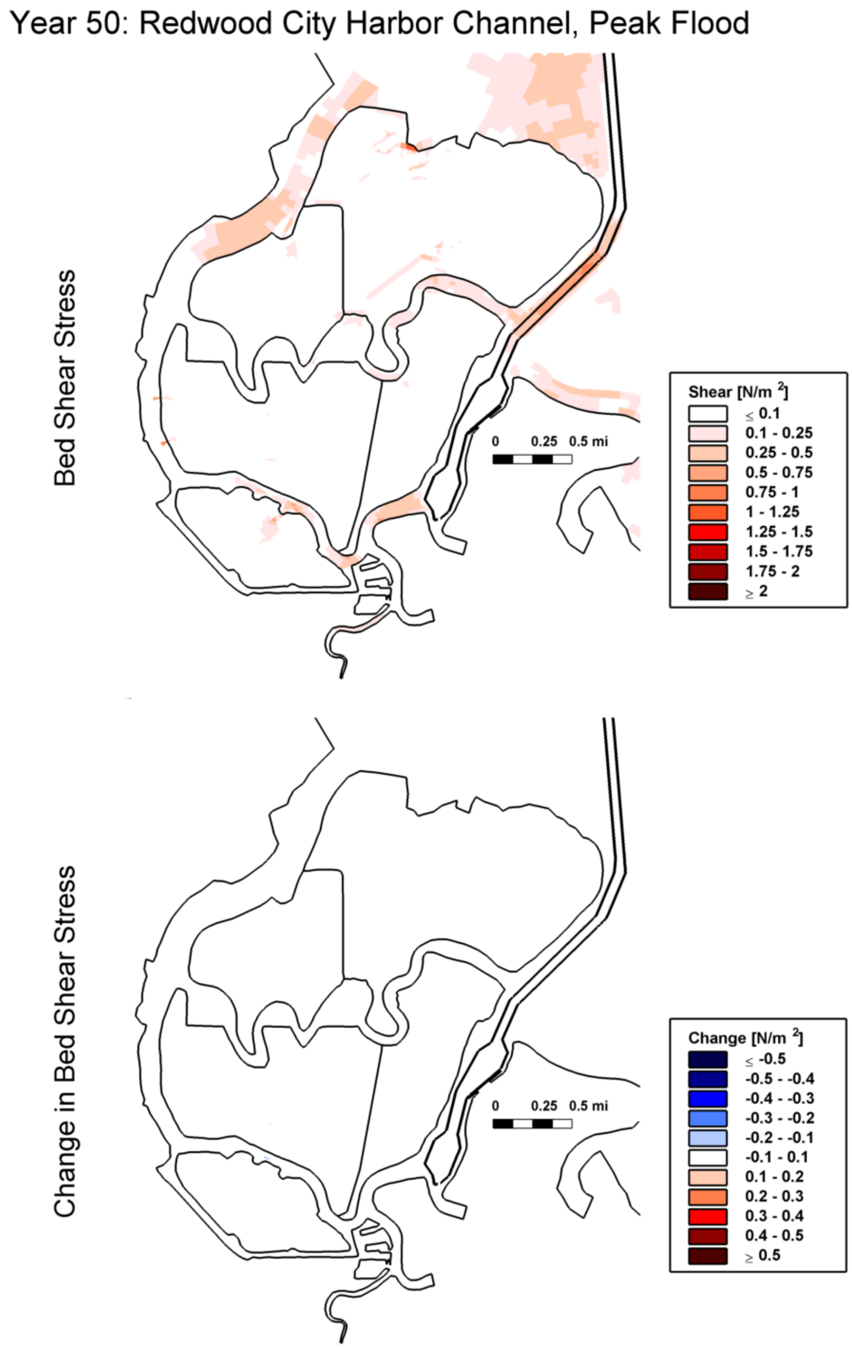


Figure 8.2-57
Predicted bed shear stress (Pa) in the vicinity of the Redwood City Harbor Channel and Bair Island during peak flood currents for the 32 feet MLLW project depth Year 50 scenario (top); predicted change in bed shear stress in the 32 feet MLLW project depth Year 50 scenario relative to the 30 feet MLLW scenario (bottom).

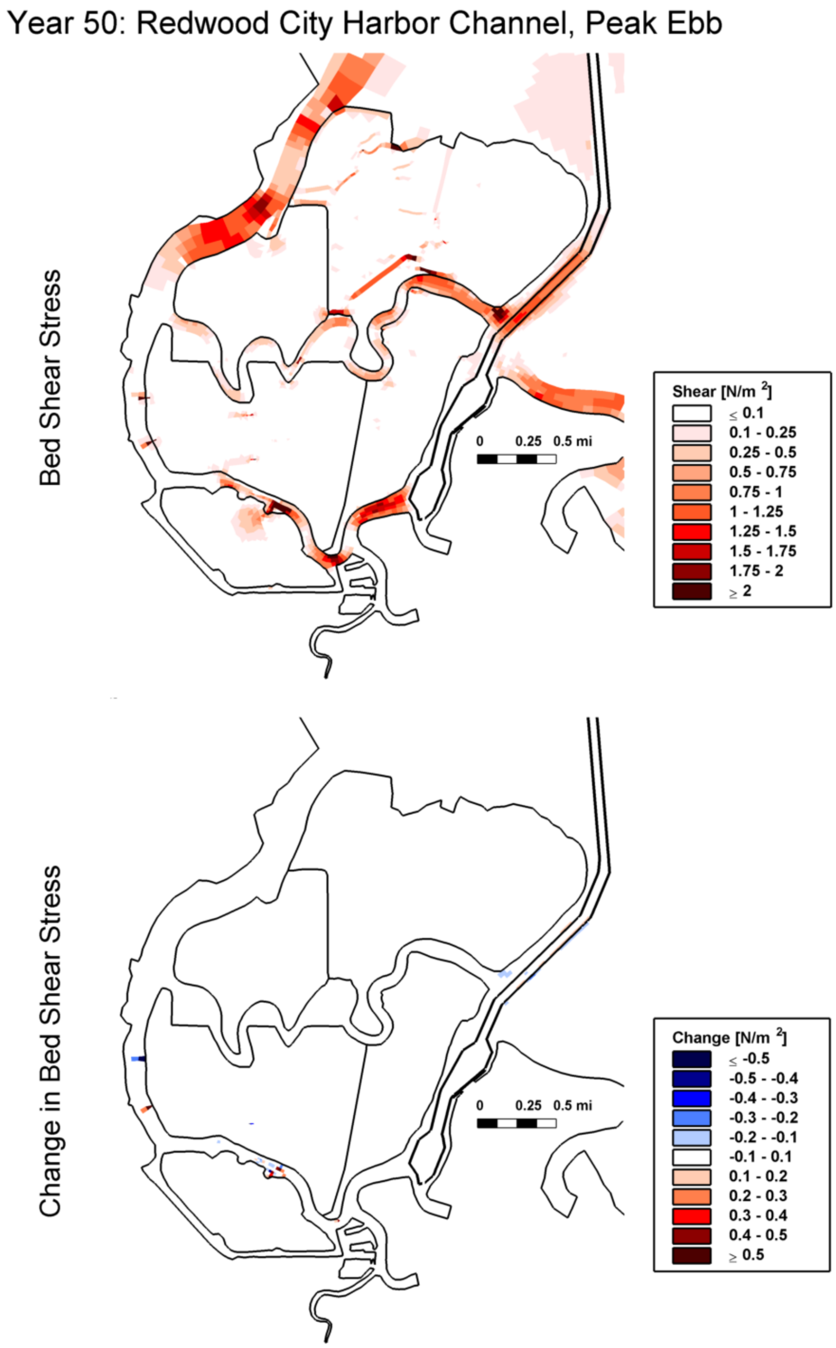


Figure 8.2-58
Predicted bed shear stress (Pa) in the vicinity of the Redwood City Harbor Channel and Bair Island during peak ebb currents for the 32 feet MLLW project depth Year 50 scenario (top); predicted change in bed shear stress in the 32 feet MLLW project depth Year 50 scenario relative to the 30 feet MLLW scenario (bottom).

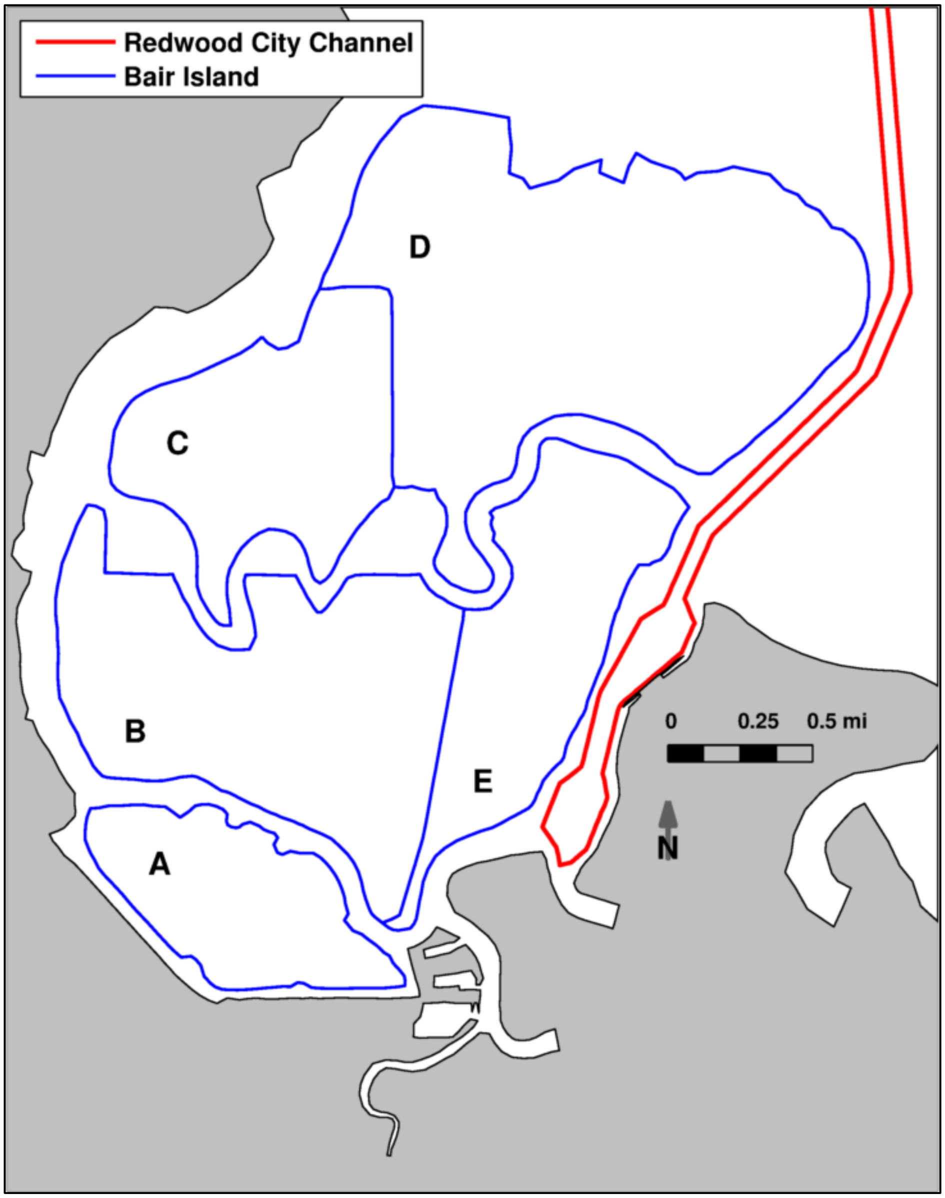


Figure 8.2-59
Outline of the five subregions of Bair Island considered in the calculation of sediment depositional volumes. The subregions are (A) Inner Bair Island, (B) Middle Bair Island, (C) Outer Bair Island, (D) the Outer Bair Island marsh, and the (E) Middle Bair Island marsh.

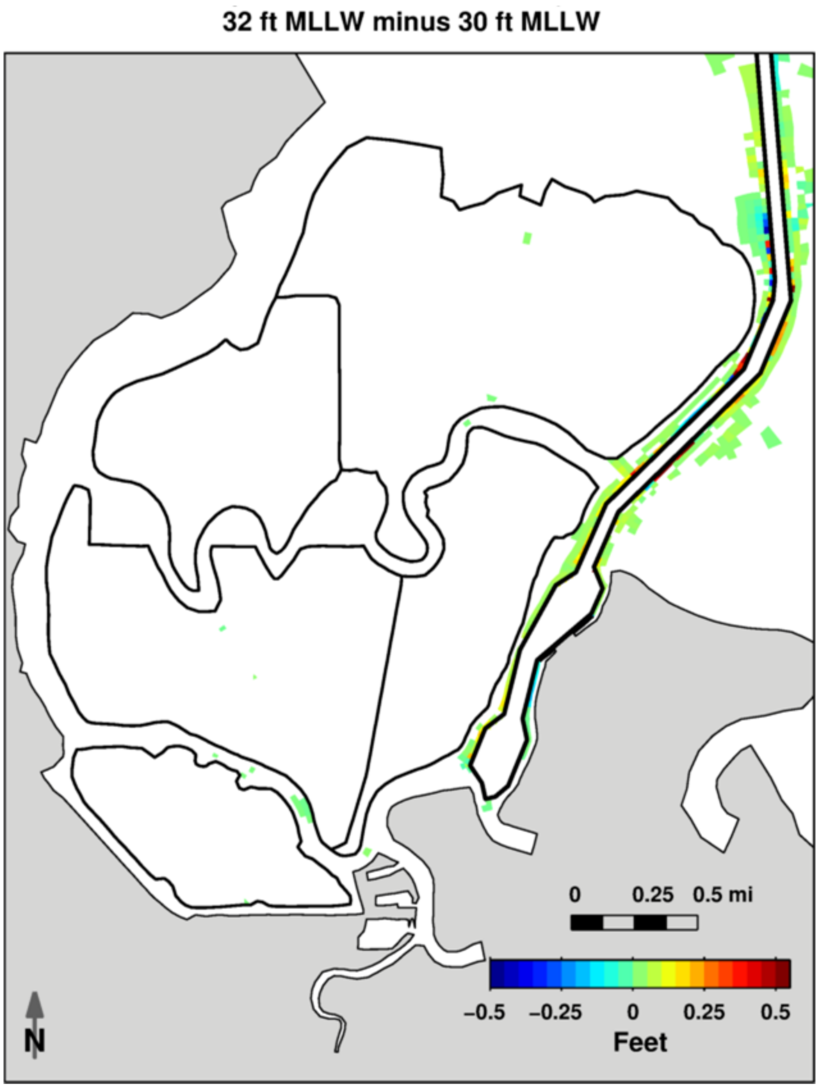


Figure 8.2-60
The predicted change in sedimentation resulting from increasing the project depth from 30 feet MLLW to 32 feet MLLW. Positive values indicate the deeper scenario had a thicker seabed while negative values indicate the deeper scenario had a thinner seabed. Areas inside the navigation channel are plotted as white to highlight the differences outside of the channel. Areas with less than 0.1 inch of difference were plotted as white. Regions of Bair Island are outlined for clarity.

8.3 Effect of Increased Project Depth on Harbor Resonance and Peak Water Levels

Detailed descriptions of the statistics used for model validation are available in Section 5.2 and MacWilliams et al. (2015). The water level validation during the 1983 storm demonstrated the model accurately predicted the water level at the San Francisco at Fort Point and the Redwood City NOAA tide gauges (Figures 8.3-1 and 8.3-2, Table 8.3-1). The peak water level during this storm was also well predicted by the model (Table 8.3-2). This simulation was shown to have a very similar degree of accuracy at San Francisco and Redwood City as the validation simulation included in the South San Francisco Bay Shoreline Study (MacWilliams et al. 2012b), indicating that the model is suitable for examining peak water levels in the vicinity of the validation stations.

Sea level rise of 0.23 foot at San Francisco in the Year 0 scenarios was predicted to result in an increase in the peak water level at Redwood City of about 0.21 foot. Sea level rise of 2.71 feet at San Francisco in the Year 50 scenarios was predicted to result in an increase in the peak water level at Redwood City of about 2.53 feet.

The influence of deepening the Redwood City Harbor Channel project depth on water level resonance was examined by determining the effect of increasing the project depth on the peak water levels at Redwood City. Deepening the project depth from 30 feet MLLW to 32 feet MLLW was predicted to have almost no effect on the peak water levels at Redwood City for both the Year 0 and the Year 50 scenarios (Table 8.3-3). The peak water level was predicted to change by less than 0.01 foot after deepening the project depth from 30 feet MLLW to 32 feet MLLW for both the Year 0 and Year 50 scenarios.

Table 8.3-1
Predicted and observed water level, cross-correlation statistics, model skills, and target diagram statistics for water level monitoring stations. The ubRMSD is the unbiased root-mean-square difference. The bias and the ubRMSD have both been normalized by the observed standard deviation.

Station Location	Data Source	Figure Number	Mean Water Level Observed (m NAVD88)	Mean Water Level Predicted (m NAVD88)	Cross Correlation Amp Ratio	Cross Correlation Lag (min)	r^2	Skill	Target Diagram Bias	Target Diagram ubRMSD
San Francisco (9414290)	NOAA	8.3-1	1.04	1.05	0.999	-1	0.997	0.999	0.016	0.052
Redwood City (9414523)	NOAA	8.3-2	1.09	1.12	0.989	4	0.996	0.999	0.036	-0.067

Table 8.3-2
The predicted and observed peak water levels during the 1983 storm.

Station Location	Observed Peak (feet NAVD88)	Predicted Peak (feet NAVD88)
San Francisco (9414290)	8.76	8.51
Redwood City (9414523)	9.74	10.06

Table 8.3-3
Predicted peak water levels at the Redwood City NOAA tide station (9414523) for the 1983 storm scenarios and the difference in peak water level between without-project and with-project conditions.

Analysis Year	Peak Water Level (feet)		
	Without-Project (30 feet MLLW)	With-Project (32 feet MLLW)	Difference
Year 0 (2018)	10.271	10.268	-0.003
Year 50 (2068)	12.590	12.586	-0.004

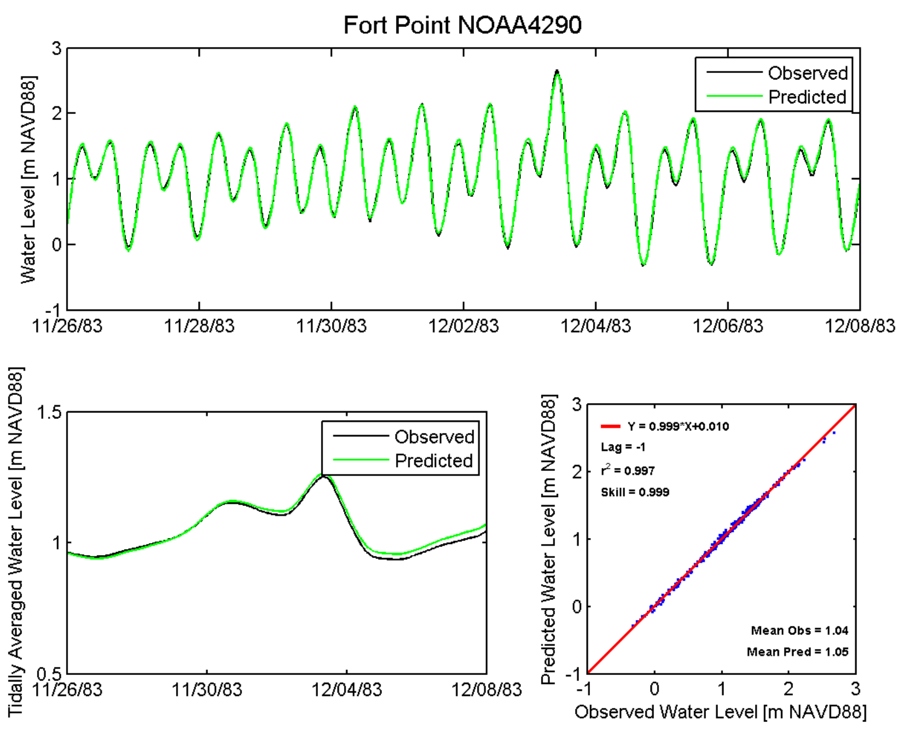


Figure 8.3-1
Observed and predicted water level at San Francisco at Fort Point during the 1983 simulation.

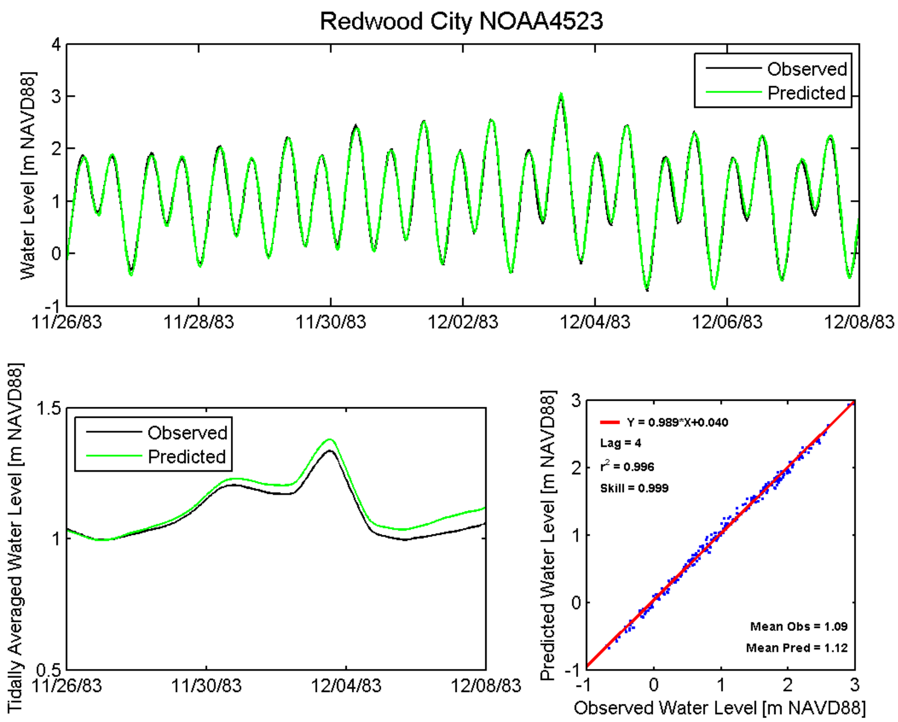


Figure 8.3-2
Observed and predicted water level at Redwood City during the 1983 simulation.

9 FLOW FIELD FOR SHIP NAVIGATION SIMULATIONS

This section documents the UnTRIM Bay-Delta hydrodynamic model simulations used to establish the flow field in both the Redwood City Harbor Channel and the San Bruno Shoal Channel for a future ship navigation simulation study to be performed by the USACE. The flow fields were predicted using both without-project and with-project conditions for Year 0 and Year 50. The period used to model the velocity fields for the ship navigation simulations is within the period used for model validation (Appendix C), so no additional model validation is presented in this section.

9.1 Regions of Provided Flow Field

This section describes the regions in the vicinity of the Redwood City Harbor Channel and the San Bruno Shoal Channel where the predicted flow field was output for the ship navigation simulations. The model grid used for the flow field simulations directly resolved the Redwood City Harbor Channel, the San Bruno Shoal Channel, and Bair Island (Figures 5.1-1 and 6.1-1). The outlines of the flow field regions were aligned with the edges of the model grid and were determined based on the configuration of the channels and the surrounding water depths. The entire Redwood City Harbor Channel was included in the provided flow field (Figure 9-1). The flow field region also included the mudflats, sloughs, and larger South San Francisco Bay main channel in the vicinity of the Redwood City Harbor Channel. The entire San Bruno Shoal Channel and the surrounding area were included in the flow field region of the San Bruno Shoal Channel (Figure 9-2).

9.2 Descriptions of Modeled Scenarios for Ship Simulation Flow Fields

Four hydrodynamic scenarios were used to predict the flow field for the ship simulations (Table 8.1-1). These simulations were identical to the four simulations used to determine the effects of deepening the Redwood City Harbor Channel on the hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island (Sections 8.1.1 and 8.2). The analysis period of the scenarios was developed using hydrology from December 25, 2005, through January 8, 2006, and included elevated discharge from Redwood Creek, strong winds, and spring tides (Figure 8.1-1). These scenarios included the future planned configuration of Bair Island and projected sea level rise between the model forcing year (2005) and Year 0 (2018) and the model forcing year and Year 50 (2068). The bathymetry in the vicinity of the Redwood City Harbor Channel and the San Bruno Shoal Channel was determined as explained in Section 8.1.1, using a without-project depth of 30 feet MLLW and a with-project depth of 32 feet MLLW and including 2 feet of overdepth. The open boundary water level at San Francisco was adjusted by 0.09 foot in the Year 0 scenarios and by 2.51 feet in the Year 50 scenarios to account for sea level rise, as explained in Section 8.1.1.

9.3 Flow Field Output Provided to USACE

The format of the output flow fields was the same as that provided as part of the Sacramento Deep Water Ship Channel study (MacWilliams 2011). The flow field was provided to USACE as the predicted depth-averaged velocity components at the center of each model grid cell in the flow field regions. During the analysis period, the depth-averaged velocity components were calculated at an interval of every 15 minutes. This resulted in a total of 96 output times during each day of the analysis period. The guidance criteria used to select the appropriate flow field output times were: a) spring tide, b) elevated discharge from Redwood Creek, c) strong winds in the study region, and d) periods of high flood velocity, high ebb velocity, and near slack water. The depth-averaged velocity magnitude at one location within each of the Redwood City Harbor Channel (Figure 9-1) and the San Bruno Shoal Channel (Figure 9-2) flow field regions was plotted to determine the output times associated with peak flood velocity, peak ebb velocity, and slack water. To meet the guidance criteria, the flow fields were extracted from the model results at the times of peak depth-averaged flood and ebb velocities and also at slack water in the two navigation channels, centered around the peak discharge from Redwood Creek (Figures 9-3 and 9-4). Deepening the Redwood City Harbor Channel and the San Bruno Shoal Channel from 30 feet MLLW to 32 feet MLLW did not change the phasing of the predicted depth-averaged velocity in either of the channels. As a result, the date and time of the ship simulation output is the same for each of the considered project depths (Tables 9-1 and 9-2). The timing of peak flood, slack water, and peak ebb were predicted to only change by up to 15 minutes (one output time step) in the Year 50 scenarios relative to the Year 0 scenarios (Tables 9-1 and 9-2).

The depth-averaged velocity predictions for each of the scenarios was provided to the USACE following the file format used as part of the Sacramento Deep Water Ship Channel study (MacWilliams 2011), and consists of tabular space delimited data:

GNW	Node #	Xcord	Ycord	Zcord	Ruff	Xvel	Yvel	Depth	WSELEV
GNW	1	6066615.7	2014888.0	-33.13	-99.0	0.086	0.150	36.44	3.31
GNW	2	6065731.5	2015061.9	-9.65	-99.0	0.366	0.593	12.97	3.31
GNW	3	6065414.8	2015087.1	2.76	-99.0	0.095	0.031	0.56	3.31
GNW	4	6066031.9	2015026.9	-33.13	-99.0	0.399	0.454	36.44	3.31
GNW	5	6066533.0	2014925.0	-33.13	-99.0	0.144	0.212	36.44	3.31
GNW	6	6066461.1	2014962.4	-33.13	-99.0	0.207	0.273	36.44	3.31

Where:
Xcord, Ycord, and Zcord are xyz coordinates.
Ruff is a placeholder variable, specified as -99.0
Xvel and Yvel are velocities.
Depth is the water depth.
WSELEV is the water surface elevation.

All data were provided in the North American Datum of 1983 (NAD83), California Sate Plane Zone 3, NAVD88, U.S. Survey Feet. Velocity was provided in feet per second. Some of the model grid cells in the vicinity of the Redwood City Harbor Channel are shallow and can become dry as the water surface elevation varies with the tides. Model grid cells that are dry at a specific output time were not included in the output for that specific time. As a result, the number of output points varies between each output time. Sample flow fields for the Redwood City Harbor Channel and for the San Bruno Shoal Channel during strong ebb velocities from the 30 feet MLLW Year 0 scenario are shown in Figures 9-5 and 9-6.

Table 9-1
The scenario matrix and flow field output times for all 12 files of the Redwood City Harbor Channel ship simulation output.

Scenario	Channel Project Depth (feet MLLW)	Project Year For Sea Level Rise	Hydrodynamic Conditions	Output Date/Time
1	30 (Without-Project)	Year 0 (2018)	Slack Water	12/31/05 06:00
			Peak Flood	12/31/05 07:30
			Peak Ebb	12/31/05 15:45
2	32 (With-Project)		Slack Water	12/31/05 06:00
			Peak Flood	12/31/05 07:30
			Peak Ebb	12/31/05 15:45
3	30 (Without-Project)	Year 50 (2068)	Slack Water	12/31/05 05:45
			Peak Flood	12/31/05 07:15
			Peak Ebb	12/31/05 15:45
4	32 (With-Project)		Slack Water	12/31/05 05:45
			Peak Flood	12/31/05 07:15
			Peak Ebb	12/31/05 15:45

Table 9-2
The scenario matrix and flow field output times for all 12 files of the San Bruno Shoal Channel ship simulation output.

Scenario	Channel Project Depth (feet MLLW)	Project Year For Sea Level Rise	Hydrodynamic Conditions	Output Date/Time
1	30 (Without-Project)	Year 0 (2018)	Peak Flood	12/31/05 08:45
			Slack Water	12/31/05 12:00
			Peak Ebb	12/31/05 15:30
2	32 (With-Project)		Peak Flood	12/31/05 08:45
			Slack Water	12/31/05 12:00
			Peak Ebb	12/31/05 15:30
3	30 (Without-Project)	Year 50 (2068)	Peak Flood	12/31/05 09:00
			Slack Water	12/31/05 11:45
			Peak Ebb	12/31/05 15:15
4	32 (With-Project)		Peak Flood	12/31/05 09:00
			Slack Water	12/31/05 11:45
			Peak Ebb	12/31/05 15:15

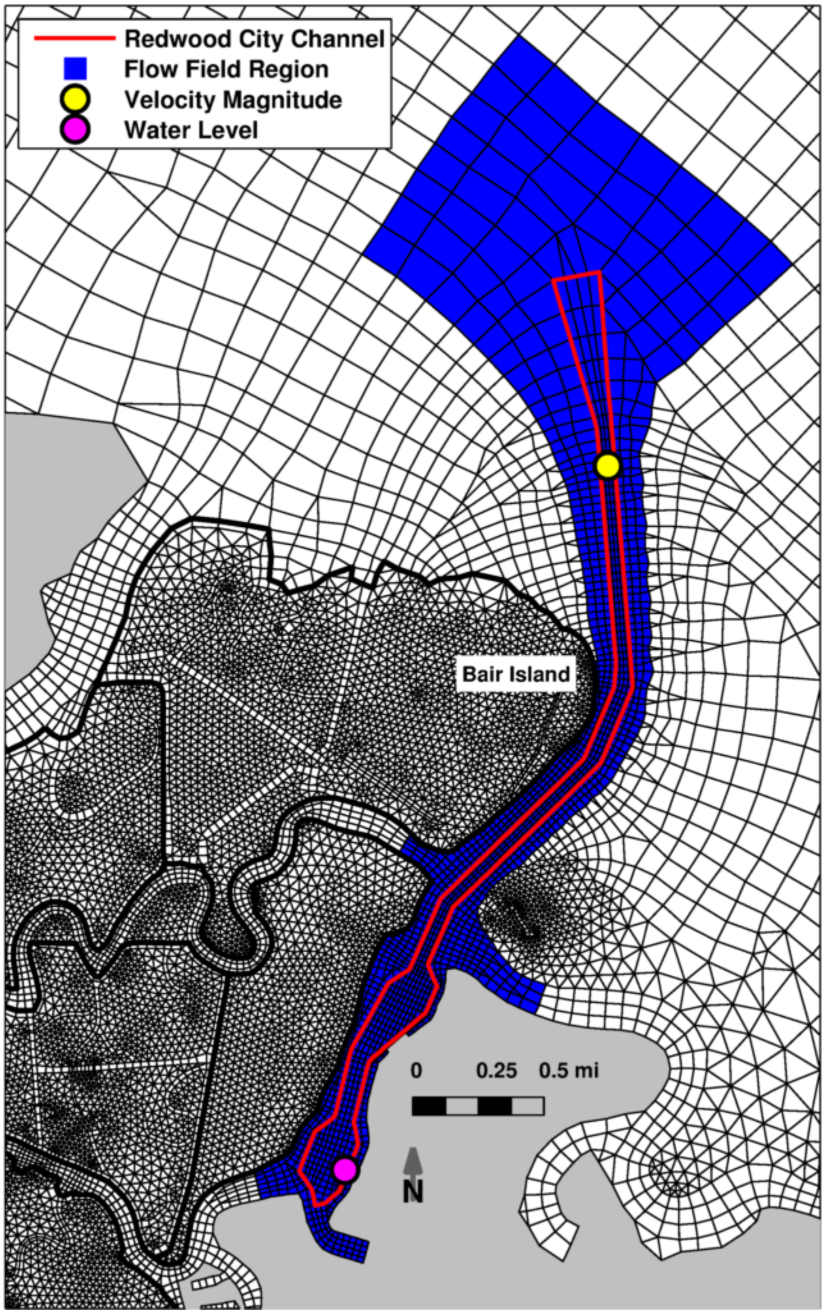


Figure 9-1
The region of the model grid in the vicinity of the Redwood City Harbor Channel that depth-averaged velocity was output for the future ship navigation simulations flow field. The Redwood City Harbor Channel is outlined in red and the flow field region is in blue. The depth-averaged velocity magnitude (yellow) and water level (magenta) stations for Figure 9-3 are shown with circles. Bair Island is outlined in dark black.

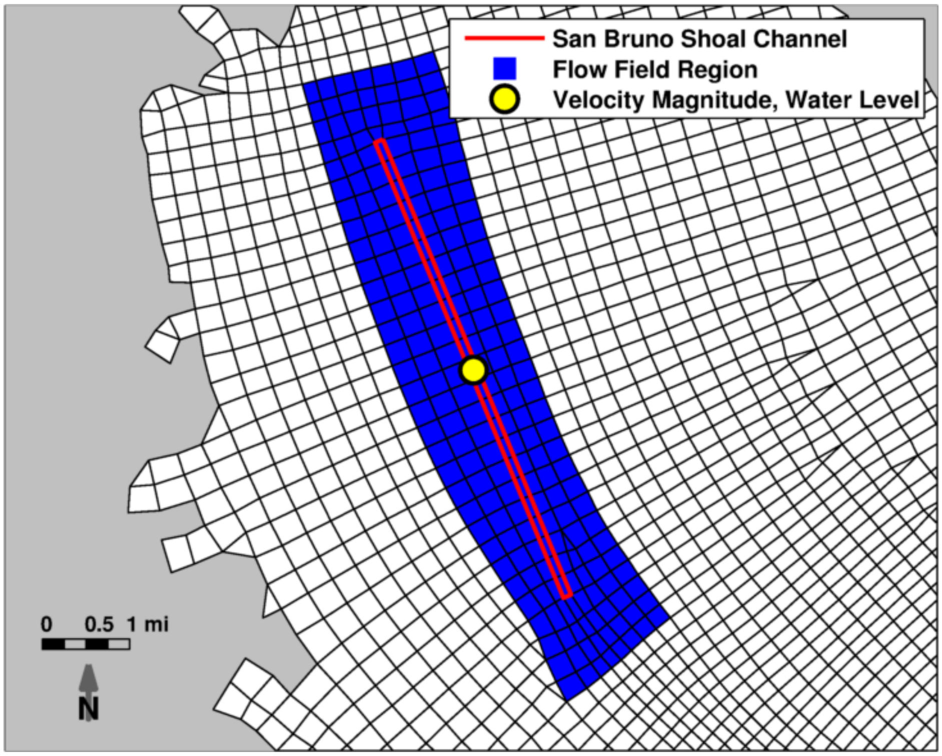


Figure 9-2
The region of the model grid in the vicinity of the San Bruno Shoal Channel that depth-averaged velocity was output for the future ship navigation simulations flow field. The San Bruno Shoal Channel is outlined in red and the flow field region is in blue. The depth-averaged velocity magnitude and water level station for Figure 9-4 is shown with a yellow circle.

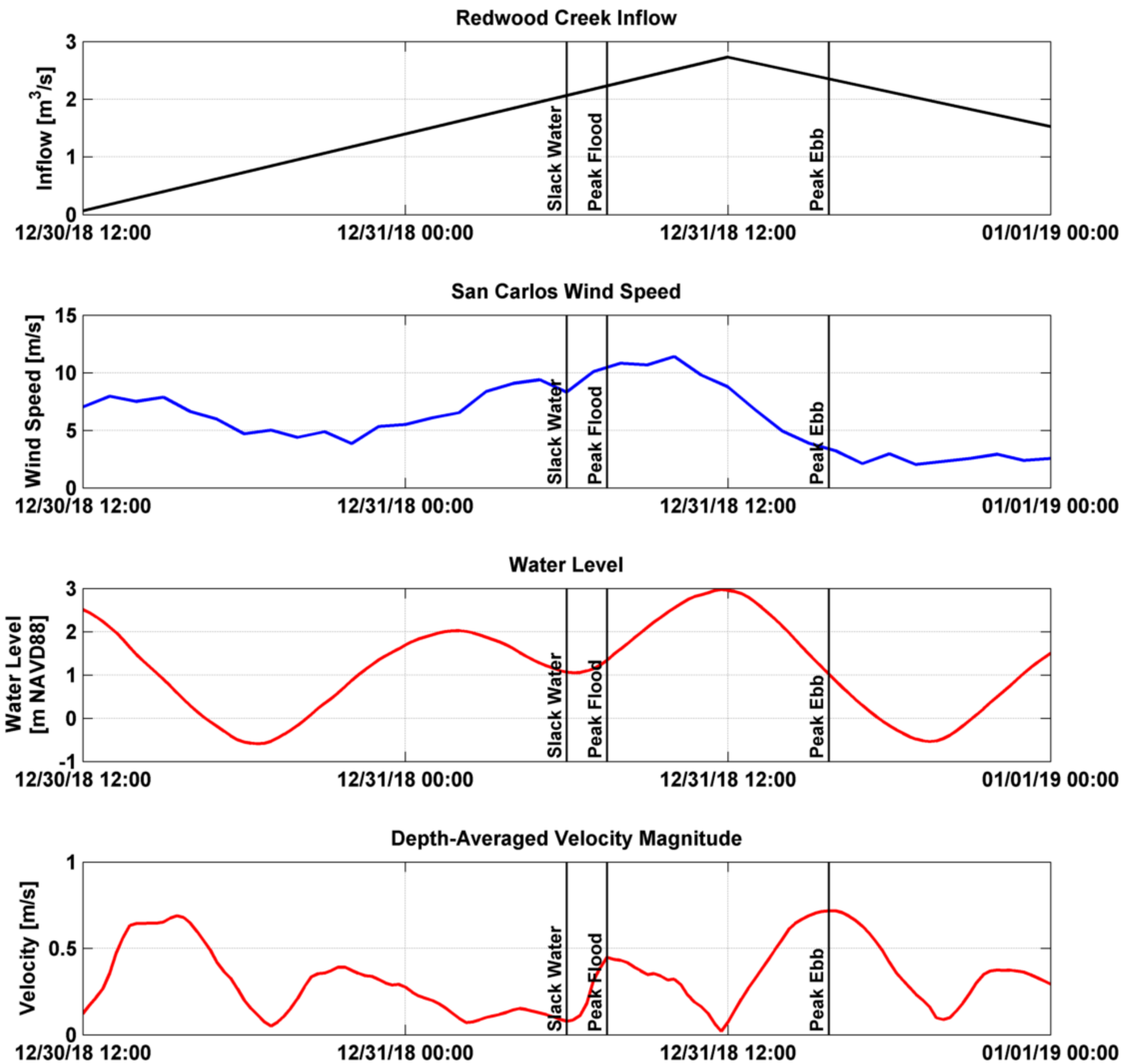


Figure 9-3

The Redwood Creek inflow, wind speed at San Carlos, predicted water level at the Redwood City tide gauge, and predicted depth-averaged velocity magnitude in the Redwood City Harbor Channel during the 30 feet MLLW project depth Year 0 simulation. The location of the velocity magnitude and water level are shown on Figure 9-1. Vertical lines mark the times of the ship simulation output for slack water, peak flood velocity, and peak ebb velocity, from left to right.

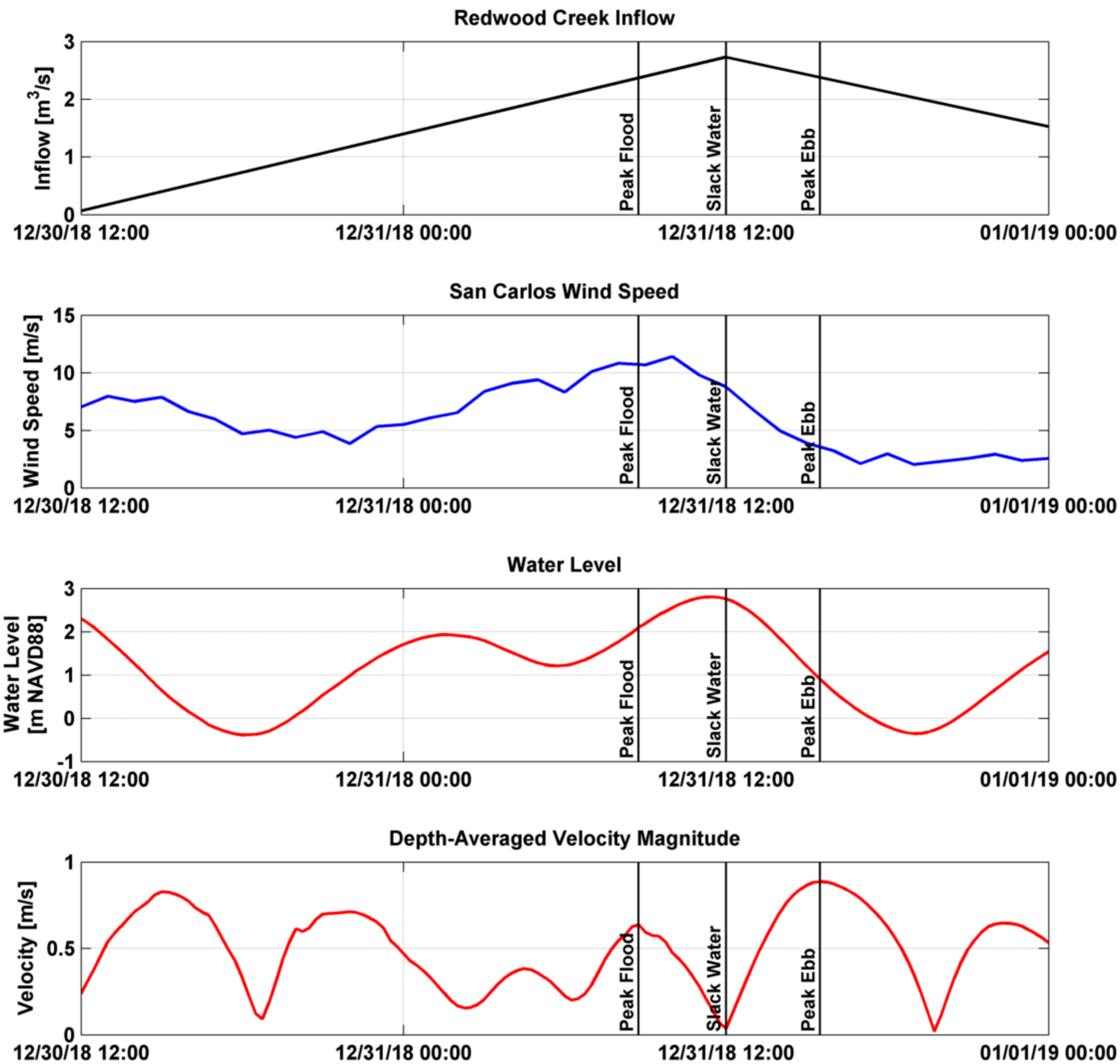


Figure 9-4
The Redwood Creek inflow, wind speed at San Carlos, predicted water level in the center of the San Bruno Shoal Channel, and predicted depth-averaged velocity magnitude in the San Bruno Shoal Channel during the 30 feet MLLW project depth Year 0 simulation. The location of the velocity and water level are shown on Figure 9-2. Vertical lines mark the times of the ship simulation output for peak flood velocity, slack water, and peak ebb velocity, from left to right.

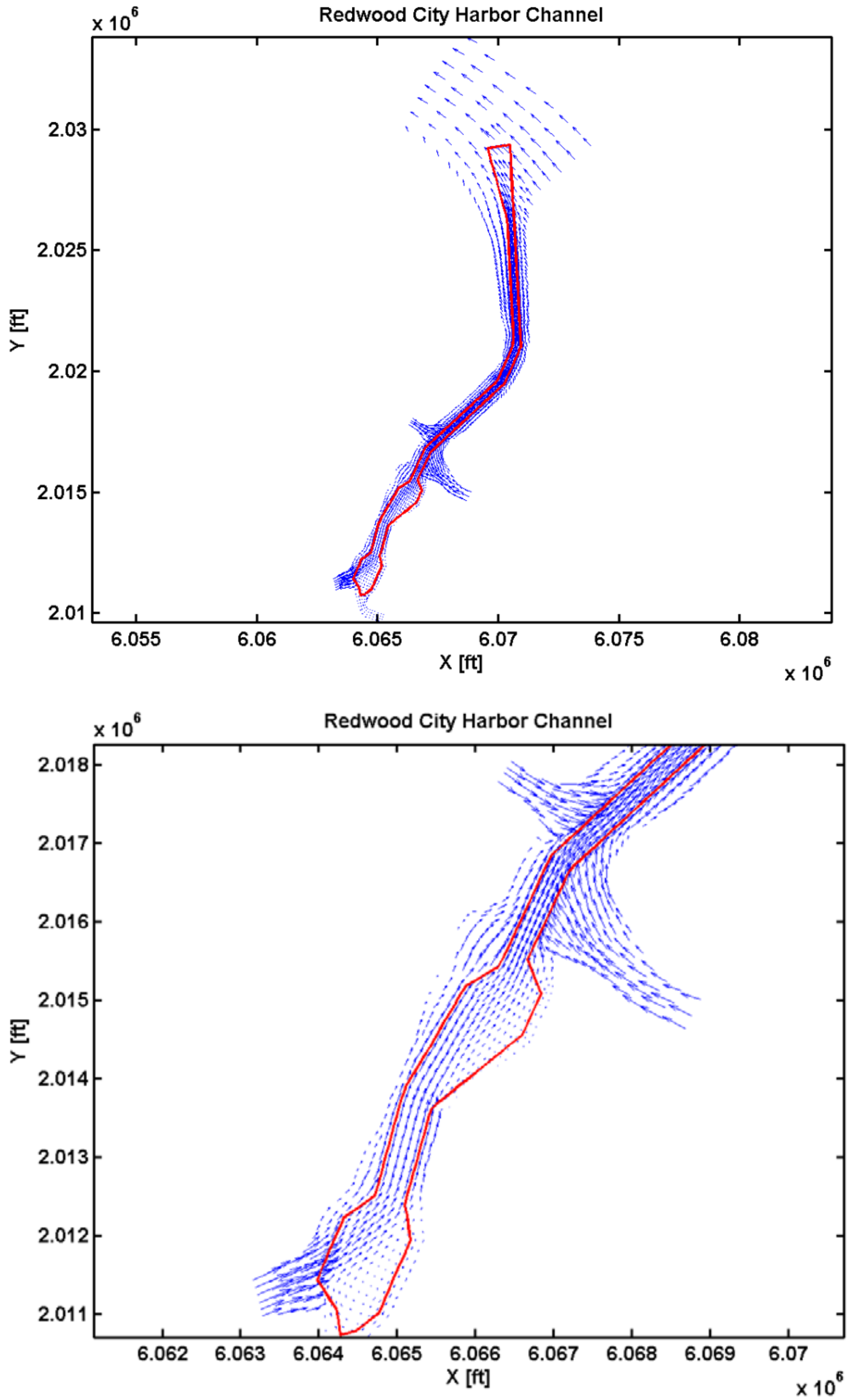


Figure 9-5
Depth-averaged velocity vectors from the ship simulation output in the vicinity of the Redwood City Harbor Channel during a period of strong ebb velocity (December 31, 2018 at 15:45) in the 30 feet MLLW Year 0 scenario. The top panel shows the entire flow field region and the bottom panel zooms in on the southern portion of the channel. The Redwood City Harbor Channel is outlined in red.

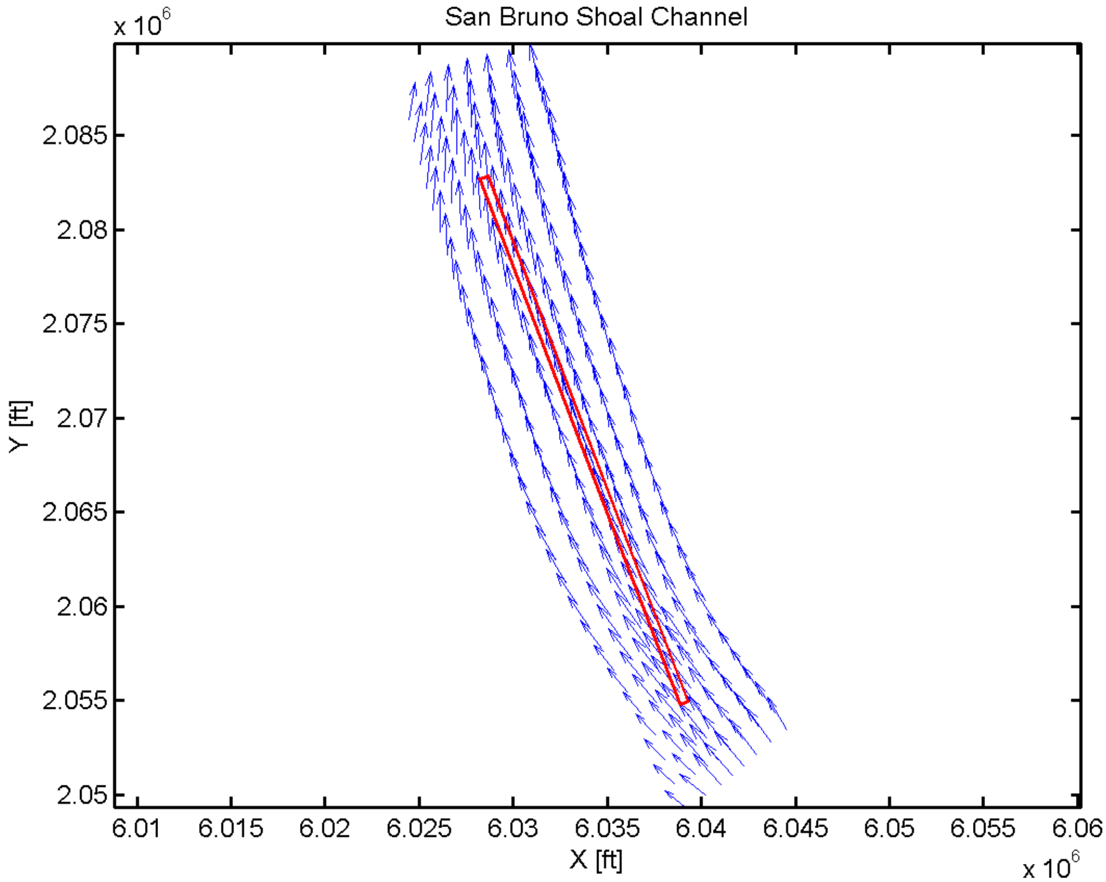


Figure 9-6
Depth-averaged velocity vectors from the ship simulation output in the vicinity of the San Bruno Shoal Channel during a period of strong ebb velocity (December 31, 2018 at 15:30) in the 30 feet MLLW Year 0 scenario. The San Bruno Shoal Channel is outlined in red.

10 SUMMARY AND CONCLUSIONS

This report documents the results of the Hydrodynamic and Sediment Transport Modeling for Navigation Channel Deepening of Redwood City Harbor project that was conducted in support of the Redwood City Harbor Navigation Improvement Feasibility Study. This project used both existing USACE hydrosurvey data and numerical model predictions to investigate the potential influence of increasing the project depth of the Redwood City Harbor Channel and the San Bruno Shoal Channel on shoaling rates. Sediment deposition was also evaluated for a potential realignment of the Redwood City Harbor Channel to assess whether the realignment of the channel could potentially decrease the above grade shoaling. The potential influence of channel deepening and sea level rise on water levels, flow, salinity, and shear stress in the vicinity of the Redwood City Harbor Channel was also evaluated.

Regular bathymetric surveys of the Redwood City Harbor Channel spanning an 8-year period were used to calculate an average sediment accretion rate of about 183,000 $yd^3\ yr^{-1}$. The short 176-day accretion rate calculated in 2012 during a winter to spring period potentially indicates that the sediment deposition in the Redwood City Harbor Channel is not constant throughout the year, but rather experiences periods of relatively higher sedimentation either seasonally or in response to storm events. Two hot spots within the Redwood City Harbor Channel were identified, where the hydrosurveys indicate deposition was consistently higher than in other portions of the channel. One hot spot is located southeast of Bair Island on the northwest side of the channel, and the other hot spot is located on the west side of the northern portion of the channel. These hot spots are potential candidates for advanced maintenance dredging or channel realignment to reduce the above grade shoaling problems in those areas. The hydrographic surveys of the San Bruno Shoal Channel suggested that the channel does not have a consistent rate of sediment accretion, but rather both periods of sediment accretion and erosion that lead to relatively little long-term net change of sediment volume in the channel.

The model predictions of sediment transport were validated using observations of suspended sediment concentration, estimates of observed sediment deposition volume and thickness in the Redwood City Harbor Channel and the San Bruno Shoal Channel, and estimates of the percentage of the Redwood City Harbor Channel that shoaled to above project depth derived from the hydrosurveys. The model accurately predicted the suspended sediment concentration at the Alcatraz station in the Central Bay for the 2006 simulation and acceptably for the 2008 simulation. The average suspended sediment concentration was higher than observed at the Dumbarton Bridge station in 2006 and slightly lower in the 2008 simulation, although the peak concentrations were lower than observed in both simulations. Analysis of along-Bay transects suggested the model more accurately predicted the suspended sediment concentration near the Redwood City Harbor Channel and the San Bruno Shoal Channel than at Dumbarton Bridge, but less accurately than at the Alcatraz station. The model predicted a lower total volume of sediment deposited in the Redwood City Harbor Channel than was estimated from the hydrosurvey data; however, the model prediction was within the error bars of the hydrosurvey derived deposition volumes for both years simulated. The model correctly predicted the locations of the two shoaling hot spots south of Bair Island and near the northern end of the channel that were identified in the hydrosurvey analysis. The model also predicted the correct across-channel location of the hot spots on the western side of the channel in the 2006 simulation. The predicted reduction in the sedimentation rate in the Redwood City Harbor Channel from the 2006 to the 2008 simulations agreed with the reduction derived from the hydrosurvey data (23% vs. 21%), indicating that the model very accurately predicted the relative change in the sedimentation rate due to different channel depths and environmental conditions. The model predicted a larger volume of sediment deposition in the San Bruno Shoal Channel than was estimated from the hydrosurvey data; however, the predicted deposition volume was the same order of magnitude as the deposition volume derived from the hydrosurvey data and was within the error bars of the hydrosurvey derived deposition volumes for both years simulated.

The model validation indicated that the model was sufficiently accurate for investigating relative changes in the sediment deposition volume due to channel deepening of the Redwood City Harbor Channel and San Bruno Shoal Channel. The validation also indicated that the predicted percentage difference in the sedimentation rate between scenarios will have less uncertainty and likely be more accurate than the corresponding absolute differences in deposition volumes between scenarios. Because there is less uncertainty in analyses that compare the relative difference in sediment depositional volumes between scenarios, the analyses in this report focused on the relative difference between scenarios and less on absolute differences between the scenarios. That is, the effect of channel deepening on sedimentation rates in the navigation channels is discussed predominantly as a percentage increase from the currently authorized 30 feet MLLW project depth and not as absolute deposition volume increases.

Increasing the project depth from 30 feet MLLW to either 32 feet MLLW or to 37 feet MLLW was predicted to increase sedimentation rates in both the Redwood City Harbor Channel and the San Bruno Shoal Channel. This suggests that the proposed channel deepening would result in an increase in annual maintenance dredging in both the Redwood City Harbor Channel and the San Bruno Shoal Channel. The sedimentation rate in the Redwood City Harbor Channel was predicted to increase relative to the 30 feet MLLW project depth by 13% with the 32 feet MLLW project depth and by 51% with the 37 feet MLLW project depth when evaluated over a full year. Based on the hydrosurvey derived average sedimentation rate of about 183,000 $yd^3\ yr^{-1}$, the predictions suggest an average future dredging requirement for the Redwood City Harbor Channel of about 207,000 $yd^3\ yr^{-1}$ with the 32 feet MLLW project depth. The average future dredging requirement for the Redwood City Harbor Channel with the 37 feet MLLW project depth was predicted to be about 276,000 $yd^3\ yr^{-1}$. However, these should be treated as approximations due to uncertainty in the model predictions, and potential variations due to interannual variability or future changes to sediment supply to the Bay.

The sedimentation rate in the San Bruno Shoal Channel was predicted to increase relative to the 30 feet MLLW project depth by 54% with the 32 feet MLLW project depth and by 86% with the 37 feet MLLW project depth when examining a complete year. The change in the sedimentation rate predicted for the San Bruno Shoal Channel may underestimate the increase in dredging requirements resulting from deepening the San Bruno Shoal Channel relative to the existing 30 feet MLLW project depth. This is because the results suggest that a larger portion of the channel may begin to experience above grade shoaling and require dredging for both the 32 feet MLLW and 37 feet MLLW project depths than currently occurs for the 30 feet MLLW project depth. The relative increase in the sedimentation rate caused by deepening project depths is likely to be relatively constant regardless of the water year type, even if the total deposition volume changes between different years, based on analysis of Oakland Harbor sedimentation rates (Delta Modeling Associates 2015). Analysis of the sedimentation rate over different seasonal time periods suggested the sedimentation rate in the Redwood City Harbor Channel is less sensitive to seasonal influences than the San Bruno Shoal Channel. This is potentially caused by the location of the Redwood City Harbor Channel farther from the Central Bay than the San Bruno Shoal Channel. The influence of large sediment supply events from the Delta and North Bay on sedimentation in the Redwood City Harbor Channel will be reduced compared to at the San Bruno Shoal Channel because the Redwood City Harbor Channel is located farther from the Central Bay.

Two additional scenarios were used to evaluate the influence of a proposed realignment of the Redwood City Harbor Channel on sedimentation in the channel for the 37 feet MLLW project depth and to evaluate whether or not the realignment of the channel would decrease the above grade shoaling south of Bair Island or decrease the annual maintenance dredging requirements. The proposed realignment of the Redwood City Harbor Channel was predicted to have a minimal effect on the sedimentation rate in the channel with a 37 feet MLLW project depth, and thus the realignment was predicted to not likely decrease shoaling south of Bair Island with project depths from 30 feet MLLW to 37 feet MLLW. The sedimentation rate was predicted to increase by 3% in the realignment scenario compared to the existing alignment. The thickness of the hot spot south of Bair Island was also predicted to increase in the realignment scenario relative to the existing alignment scenario.

The effects of deepening the project depth on the hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island were evaluated by examining the water level, flow, salinity, and shear stress under without-project and with-project conditions for both Year 0 and Year 50. Without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions were evaluated under Year 0 and Year 50 conditions over a 2-week period that included elevated outflow from Redwood Creek, high winds, and spring tides, resulting in a total of four scenarios. These comparisons demonstrated that the deepening of the project depth from 30 feet MLLW to 32 feet MLLW resulted in essentially no effect on the water level, flows, salinity, or shear stress in the vicinity of Redwood City Harbor and Bair Island for both the Year 0 and the Year 50 scenarios.

The four scenarios used to evaluate the effect of deepening the project depth on hydrodynamics in the vicinity of the Redwood City Harbor Channel and Bair Island under both Year 0 and Year 50 conditions were also used to provide flow fields for future ship navigation simulations. The predicted flow field was provided for two different regions, one in the vicinity of the Redwood City Harbor Channel and another in the vicinity of the San Bruno Shoal Channel. The depth-averaged velocity at each model grid cell in the two flow field regions was calculated at times of peak flood velocity, peak ebb velocity, and slack water. These four scenarios used for the ship navigation simulation output included both without-project and with-project channel bathymetry and Year 0 and Year 50 conditions. These flow field data were provided to USACE for future ship navigation simulations which are expected to be conducted during a later phase of this project.

Five additional scenarios were used to evaluate the effects of the channel deepening on peak water levels and storm surge in the Redwood City Harbor during a large storm event. One simulation was used to validate the peak water levels during the December 1983 storm, which had the highest peak water level ever measured at the NOAA Redwood City station. Without-project (30 feet MLLW) and with-project (32 feet MLLW) conditions were then simulated for both Year 0 and Year 50 conditions which included sea level rise. These four scenarios were used to determine the effect of increasing the project depth on water level resonance in Redwood City by examining the peak water levels in each scenario. Deepening the project depth from 30 feet MLLW to 32 feet MLLW was predicted to have almost no effect on the peak water levels and harbor resonance at Redwood City. The peak water level was predicted to change by less than 0.01 foot after deepening the project depth from 30 feet MLLW to 32 feet MLLW for both the Year 0 and Year 50 scenarios.

11 ACKNOWLEDGMENTS

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APPENDIX A
ASSUMPTIONS AND LIMITATIONS OF THE COUPLED MODELING SYSTEM

A.1 Data Sources Used Within the UnTRIM Bay-Delta Model

Detailed descriptions of the boundary conditions and the data used to develop the boundary conditions for the UnTRIM Bay-Delta model, the SWAN wave model and the SediMorph seabed and sediment transport model are presented in MacWilliams et al. (2015) and Bever and MacWilliams (2013). This appendix presents a summary of the model boundary conditions and data sources that can be used as a quick reference (Figure A-1, Table A-1), while the previously mentioned references should be consulted for detailed descriptions.

The UnTRIM Bay-Delta model grid was developed with varying grid resolution along the axis of the estuary as necessary to resolve the bathymetric variability, with smaller grid cells used in narrower channels and in regions of complex bathymetry. The bathymetry was incorporated into the model using the highest resolution data that were available at any location (MacWilliams et al. 2015). The observed water level at the NOAA San Francisco tide station (9414290) was used to force the tidal water level at the open boundary. The open boundary salinity was set using daily salinity observations from the Farallon Islands, approximately 20 km west of the open boundary (SCCOOS 2012). The initial salinity field in the Bay was specified based on vertical salinity profiles collected by the USGS at 38 stations along the axis of the estuary (USGS 2013) and in the Delta by interpolating from continuous monitoring stations (CDEC 2013). At the bottom boundary the roughness coefficient z_0 was specified according to the elevation of each grid cell edge following the approach used by Cheng et al. (1993), Gross et al. (2010) and MacWilliams and Gross (2013), with higher roughness coefficients in shallower and higher elevation areas.

River inflows to the model included tributaries to the Bay and Delta and discharges from water pollution control plants (Figure A-1). Daily water exports were also specified at six locations. Hourly wind data was specified for six subregions of the Bay-Delta based on observations from the Bay Area Air Quality Management District (BAAQMD). Evaporation and precipitation in the Bay was set based on hourly data from the California Irrigation Management Information System (CIMIS), while evaporation and precipitation in the Delta was included in the Delta Island Consumptive Use (DICU). Monthly estimates of DICU (CDWR 1995) were used to specify the seepage, agricultural diversions, return flows and return flow salinity within the Delta. Nine control gates and temporary barriers in the Delta were incorporated into the model to represent the effects of these gates and barriers on flow and transport in the Delta (Figure A-1). For each control structure, the seasonal timing of the installation, removal, and associated culvert and gate operations were specified (MacWilliams et al. 2009; MacWilliams and Gross 2013).

Sediment transport calculations included four sediment classes, each with different particle size, settling velocity, critical shear stress, density and erosion rate parameter. The four sediment classes were chosen to represent the dominant constituents in the real San Francisco Bay grain size distribution, and were single particle silt, flocculated silts and clays called "flocs," sand, and gravel, with characteristics based on data from San Francisco Bay (Kineke and Sternberg 1989; Sea Engineering 2008; Smith and Friedrichs 2011). Observed surface grain size distributions were used to generate a realistic initial sediment bed for the entire San Francisco Bay-Delta system. Grain size distribution data were compiled from a USACE Long Term Management Strategy report (Pratt et al. 1994), the dbSEABED west coast surface grain size distribution database (Jenkins 2010), the USGS sand provenance study (Barnard et al. 2013) and the Delta sediment grain size study (S. Wright, Pers. Comm. 2012). Suspended sediment was supplied through river input to the Sacramento-San Joaquin Delta, the North Bay and the South Bay. Sediment was supplied to the Delta by five tributaries representing nearly 100% of the sediment inflow to the delta (Wright and Schoellhamer 2005). Sediment was supplied to the North Bay by one tributary and to the South Bay by four tributaries. Suspended sediment concentrations were set based on time series concentrations from the USGS (T. Morgan-King, Pers. Comm. 2013), daily concentrations from USGS (2014), or rating curves (Wright and Schoellhamer 2005), depending on data availability.

The SWAN wave calculations used the same model grid and bathymetry as the UnTRIM hydrodynamic model, except that the quadrilaterals in the UnTRIM grid were converted to triangles, as explained in Bever and MacWilliams (2013). The wind was the same as that used in the hydrodynamic model and the bottom roughness was the Nikuradse roughness based on the roughness from the hydrodynamic model.

Table A-1
Summary of data sources used for model boundary conditions.

Boundary Condition Type	Boundary Condition / Forcing	Description / Sources
UnTRIM Initial Conditions	Bathymetry	High-resolution bathymetric data from several sources
	Navigation channel alignments in the grid	Provided by USACE
	Salinity	Based on USGS water quality sampling in the Bay (USGS 2013) and interpolated using continuous monitoring stations in the Delta (CDEC 2013)
Hydrodynamic Forcing	Tidal forcing	Six minute data from NOAA San Francisco tide station (9414290)
	Open boundary salinity	Daily salinity at Farallon Islands (SCCOOS 2012)
	Inflows	Daily using DAYFLOW (CDWR 1986, 2013) for Delta tributaries and USGS data (USGS 2014) for Bay tributaries
	Exports	Daily from DAYFLOW (CDWR 1986, 2013) and the California Data Exchange Center (CDEC 2013)
	DICU	Monthly based on the Delta Island Consumptive Use Model (CDWR 1995)
	Flow control structures	Seasonally nine Delta control structures (see MacWilliams et al. 2009)
	Evaporation / precipitation	Hourly data from California Irrigation Management Information System (CIMIS)
	Wind	Hourly data from Bay Area Air Quality Management District (BAAQMD)
	Seabed roughness	Elevation dependent Z_0 ranging from 0.001 mm to 1.0 cm
Sediment	Sediment settling velocity, critical shear stress, diameter and erosion rate	Based on data in San Francisco Bay from Kineke and Sternberg (1989), Sea Engineering (2008), Smith and Friedrichs (2011)
	Seabed grain size distribution	Based on surface grain size distributions from the USGS (Barnard et al. 2013; S. Wright, Pers. Comm. 2012), USACE (Pratt et al. 1994) and dbSEABED database (Jenkins 2010)
	Inflow suspended sediment concentration	Daily based on USGS time series observations, USGS daily measurements, or rating curves, based on data availability.
Waves	Bathymetry	Same as the hydrodynamic model
	Wind	Same as the hydrodynamic model
	Bottom roughness	Nikuradse roughness based on the roughness used in the hydrodynamic model

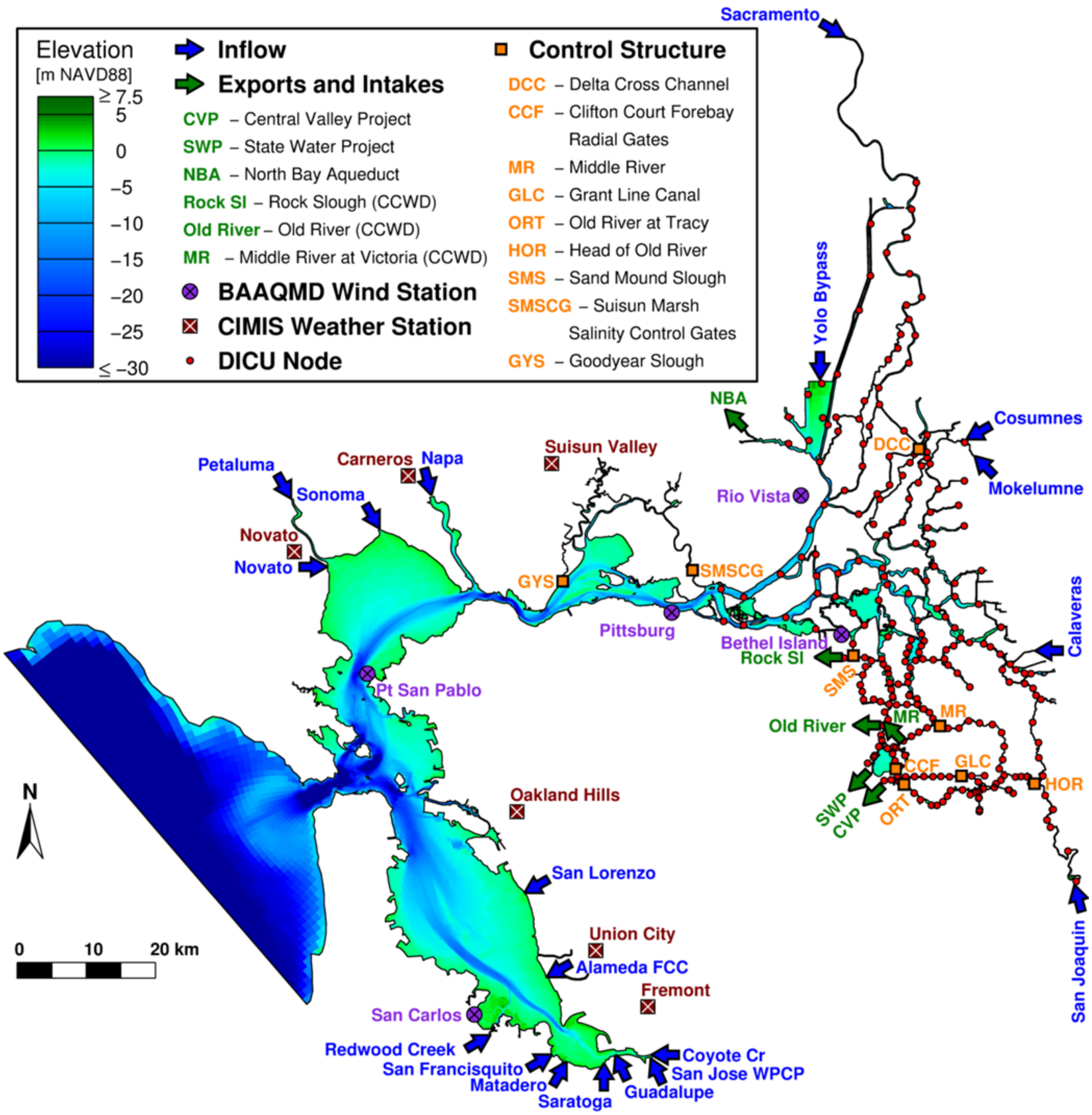

Figure A-1
UnTRIM San Francisco Bay-Delta model domain, bathymetry, and locations of model boundary conditions which include inflows, export facilities, intakes for the Contra Costa Water District (CCWD) wind stations from the Bay Area Air Quality Management District (BAAQMD), evaporation and precipitation from the California Irrigation Management System (CIMIS) weather stations, Delta Island Consumptive Use (DICU), and flow control structures. See Table A-1 for more information.

A.2 UnTRIM Numerical Model Uncertainty

As discussed in Section 3.1, the TRIM and UnTRIM models have been widely used in San Francisco Bay, and numerous detailed model calibrations have been performed (e.g., Cheng et al. 1993; Gross and Schaaf & Wheeler 2003; Gross et al. 2006; MacWilliams and Cheng 2007; MacWilliams and Gross 2007; MacWilliams et al. 2008, 2009, 2015). Due to this extensive history of application, these models are the best established three-dimensional models of San Francisco Bay.

The equations governing fluid motion and salt transport, representing conservation of water volume, momentum and salt mass, are well established, but cannot be solved analytically for complex geometry and boundary conditions. Therefore numerical models are used to give approximate solutions to these governing equations. Many decisions are made in constructing and applying numerical models. The governing equations are first chosen to represent the appropriate physical processes in one, two or three-dimensions and at the appropriate time scale. Then these governing equations that describe fluid motion and salt transport in a continuum are discretized giving rise to a set of algebraic equations. The resulting discretized algebraic equations must be solved, often requiring the use of an iterative matrix solver. The discretization and matrix solution must be developed carefully to yield a numerical scheme that is consistent with the governing equations, stable and efficient. To apply the models, the bathymetric grid, boundary conditions, initial conditions and several model parameters must be chosen. The accuracy of the model application depends on the appropriate choice of these inputs, including site-specific parameters, the numerical scheme for solving the governing equations, and the associated choice of time step and grid size.

The three-dimensional model applied in this project provides a more detailed description of fluid motion in San Francisco Bay than depth-averaged or one-dimensional models. The UnTRIM model, like almost all large scale hydrodynamic models, averages over the turbulent time scale to describe tidal time scale motions. The resulting three-dimensional hydrodynamic models represent the effect of turbulent motions as small scale mixing of momentum and salt, parameterized by eddy viscosity and eddy diffusivity coefficients, respectively. These turbulent mixing coefficients are estimated from the tidal flow properties (velocity and density) by turbulence closure models embedded within the three-dimensional models. Three-dimensional models estimate the variability in velocity and salinity in all dimensions and through the tidal cycle, and therefore provide a detailed description of hydrodynamics and salinity. However, several sources of uncertainty are inherent in the application of these three-dimensional models:

- Spatial resolution/computational speed – the spatial resolution of the bathymetry of the model domain, and velocity and salinity distributions, is limited by the large computational expense associated with high-resolution models. The description of the Bay-Delta bathymetry is improved by the use of a flexible unstructured grid, with coarser grid resolution used in the open bay portions of the grid and higher grid resolution within the project study area in Redwood City Harbor Channel and the San Bruno Shoal Channel to optimize computational efficiency. The computational speed of the Bay-Delta model roughly scales with the number of grid cells. For example, halving of the horizontal resolution of the model would lead to four times as many three-dimensional grid cells and an implementation that takes roughly four times the computation time, making general system wide reductions in grid resolution infeasible and showcasing the benefit of using grid refinement approaching study regions.
- Bathymetric data – limited spatial coverage and accuracy of bathymetric data can be a substantial source of uncertainty. Converting all data to a uniform vertical datum and horizontal datum can lead to some error. In particular, Light Detection and Ranging (LiDAR) data may have substantial errors in vertical datum and removing vegetation from the dataset can be difficult. In the present application, bathymetric data from multiple sources were merged to develop the model bathymetry.
- Bottom roughness – the UnTRIM model requires bottom friction coefficients to parameterize the resistance to flow at solid boundaries. These parameters are specified and adjusted in model calibration. The roughness values used in the present application have been applied in several recent applications (e.g., MacWilliams et al. 2007, 2008, 2009, 2015).
- Turbulence closure – the effect of turbulent motions on the tidal time scale motions is parameterized by a turbulence closure (Section 3.1.1), as is done in other 3-D hydrodynamic numerical models of similar spatial and temporal scale as the UnTRIM Bay-Delta model (e.g., Warner et al. 2005; Wang et al. 2011). While many turbulence closures are available (e.g., Warner et al. 2005), this is an ongoing area of research

and, particularly in stratified settings, the effect of turbulence on tidal flows and salinity is not easy to estimate accurately. Different turbulence closures may give significantly different results in stratified settings (e.g., Stacey 1996).

- Numerical errors – a numerical method approximates the governing equations to some level of accuracy. The mathematical properties of the numerical method of the TRIM and UnTRIM models are well understood due to detailed mathematical analysis presented in several peer reviewed publications. While the stability and conservation properties of the method are ideal, a remaining source of error in the numerical method is some limited numerical diffusion of momentum, which may cause some damping of tidal propagation.
- Boundary conditions and initial conditions – The salinity in San Francisco Bay varies laterally (e.g., Huzzey et al. 1990) but this lateral variability cannot be described by existing observations. In addition, only limited observations are available to describe the vertical distribution of salinity. Therefore, lateral and vertical salinity distributions must be achieved by interpolation and extrapolation from the limited observations to obtain initial salinity fields. Inflows to the estuary are also quite uncertain in several regions due to un-gauged portions of watersheds and uncertainty in estimates of outflows and diversions in the Sacramento-San Joaquin Delta.

Though additional potential sources of uncertainty can be identified, the largest sources of uncertainty for hydrodynamic predictions are the accuracy and resolution of available bathymetry and the grid resolution used to represent this bathymetry in the model. This study makes use of the best available high resolution bathymetric data, especially in Central Bay and South Bay and within the area around Bair Island and the Redwood City Harbor Channel, and the highest computationally practical grid resolution throughout the domain. However, many of the available bathymetric data sets in other portions of the San Francisco Bay are fairly outdated and they required vertical and or horizontal coordinate transformations for the grid used in this project. Additionally, the most recent bathymetry for the Delta does not include many in-channel islands and other subtidal areas that are subject to flooding at high water, particularly during spring tide.

The uncertainty in Delta outflows can also be a substantial source of uncertainty in predicting salinity intrusion during summer conditions, particularly when consumptive use within the Delta (which is only known approximately) is typically the same order of magnitude as Delta tributary flows. The current application makes use of monthly DICU estimates from DWR. However, because these estimates of diversions and return flows and salinities are approximate, they may not be representative of actual consumptive use in a particular year. This uncertainty would impact the accuracy of net Delta outflows predicted at the flow monitoring stations in the western Delta, when compared to observed flows, and would thereby influence salinity intrusion into the Western Delta during summer conditions. This uncertainty in Delta outflow may also influence the accuracy of sediment transport calculations.

A.3 SWAN Numerical Model Uncertainty

SWAN is a state-of-the-art and full featured spectral wave model. However, several simplifications and limitations are associated with this model. Wave-induced currents are not computed by SWAN. Because a phase-decoupled approach is used, SWAN "does not properly handle diffraction in harbors or in front of reflecting obstacles" (SWAN Team 2009b). Some additional uncertainty is introduced by interpolation of UnTRIM parameters and variables from side and cell center locations to node locations for use by SWAN. However, in practical SWAN applications, the uncertainty is likely to be driven primarily by the limited accuracy of input parameters such as wind velocity and bottom friction.

A.4 SediMorph Numerical Model Uncertainty

Significant uncertainty exists in the prediction of sediment transport. This uncertainty results from the complexity of representing sediment physics, the limited data available to characterize heterogeneous bed sediment and inflow sediment properties in a dynamic environment, and the difficulty in the specification of representative sediment parameters, such as settling velocity, critical shear stress, and erosion rate. Erosion and deposition processes are also highly sensitive both to the specified sediment parameters, and to the calculated bed shear stress, which in turn is sensitive to the selection or calculation of appropriate bed roughness parameters. Effective bed roughness is influenced by the grain size distribution of the bed material, and bed forms such as ripples and dunes, and can also vary significantly in both space and time.

A.5 Sediment Transport Modeling Assumptions and Limitations

The interaction of tides, winds, waves, and sediments results in complex physical processes which need to be simplified and parameterized in order to be represented in a numerical model. As a result, the numerical simulation of sediment transport processes requires some simplifying assumptions which can influence the accuracy of the model predictions. The interpretation of the model results must therefore take into account how these assumptions influence both the model predictions and any conclusions drawn from the model predictions. This section outlines the major assumptions and simplifications that were made in the development of the UnTRIM-SWAN-SediMorph coupled modeling system used in this study, and discusses how these simplifying assumptions may affect the interpretation of the model results.

The major simplifications made in this application were the partitioning of the full range of sediment sizes in the Bay to a discrete set of sediment classes with constant sediment parameters, assuming a single sediment class to represent flocculated particles rather than modeling the aggregation and disaggregation of sediment particles, and the treatment of sediment material in the seabed. Each of these simplifying assumptions is discussed below.

SediMorph allows for multiple sediment classes, each with different settling velocity, critical shear stress, erosion rate parameter, diameter, and density. In the simulations presented in this report the mud fraction was partitioned between the silt and floc sediment classes. The sediment properties for the four modeled sediment classes were selected to represent single particles of silt (silt), aggregated clay and silt particles which behave as flocculated particles (flocs), coarser material (sand), and gravel bedload (gravel). The characteristics of the "flocs" sediment class were set based on field observations of flocs within San Pablo Bay by Kineke and Sternberg (1989), from observations of the size and settling velocity of flocs in the plume from a suction hopper dredge in San Francisco Bay by Smith and Friedrichs (2011), from data on sediment mass eroded from the top of cores collected in San Pablo Bay by Sea Engineering (2008), and through comparison of modeled and observed time-series suspended sediment concentrations within San Francisco Bay. However, in reality, flocs continuously undergo aggregation and disaggregation due to physical and biological changes in the water (Mikkelsen et al. 2006), such as changes to turbulence and the Kolmogrov microscale, varying suspended sediment concentrations, compaction of the seabed and subsequent resuspension, sediment interaction with biofilms, and incorporation into fecal pellets (some examples in Eisma 1986; Fugate and Friedrichs 2003; Hill and McCave 2001). These processes are extremely complex and are not easily incorporated into a numerical model. Previous sediment modeling studies in San Francisco Bay (e.g., Bever and MacWilliams 2013, 2014; van der Wegen et al. 2011; Schoellhamer et al. 2008; Ganju and Schoellhamer 2009) have also made a similar simplifying assumption by specifying a sediment class with characteristics representing flocculated material but assuming that mass is not aggregated or disaggregated between sediment classes. This simplification potentially leads to decreased peak suspended sediment concentrations during energetic periods and faster settling of the sediment from the water column because large flocs are not broken into smaller flocs or constituent particles. The simplification may also lead to an underestimation of the amount of sediment transported out of a channel onto the mudflats, because flocs may be disaggregated during high tidal flows into smaller particles that are more easily transported out of the channel.

Because bed consolidation is not currently represented in the model, the model may overpredict the transport distance of the sediment. With bed consolidation, some sediment would consolidate during neap tide periods and be harder to erode the following spring tide. Neglecting bed consolidation may lead to increased suspended sediment concentrations at the start of spring tides in the model predictions, because the sediment deposited in the model during neap tides does not consolidate and is easily erodible as the currents start to increase approaching spring tides. Without seabed consolidation the model also does not dewater or compact the seabed, which would reduce the depositional thicknesses and volumes over time. On a spring-neap time scale, compaction likely only negligibly affects model predictions of depositional thicknesses because of the relatively small depositional and erosional thicknesses undergoing compaction. However, on longer time scales with thicker deposition compaction could affect model predictions of depositional thickness and the feedbacks on the hydrodynamics. This lack of compaction and dewatering is mostly counteracted by tuning the seabed porosity based on the estimates of sediment depositional volume and thickness from the hydrosurvey data so the modeled thicknesses and volumes agree with the hydrosurvey estimates. However, additional data are needed to more fully validate predictions of sediment fluxes and morphologic change outside of the ship channels.

The complexity inherent in sediment transport modeling detailed above results in the accuracy of sediment transport predictions based on numeric skill metrics such as those used by MacWilliams et al. (2015) being lower for comparisons of suspended sediment concentrations than is typical for modeling of salinity or water level. This is especially true when considering simulations such as those in this report that span one year or more in length and simulate the transport of sediment over large distances from upstream portions of freshwater rivers through the entire San Francisco Estuary and into the Pacific Ocean. However, when the comparisons between observed and predicted suspended sediment concentrations indicate that the model is predicting a similar magnitude of concentration as the observations, captures the seasonal and spatial trends, and captures the observed tidal time-scale variations and along-estuary spatial structure, this suggests that the model is capturing the primary physical processes responsible for sediment transport in the system.

APPENDIX B
COUPLING OF THE UNTRIM, SWAN, AND SEDIMORPH NUMERICAL MODELS

The UnTRIM Bay-Delta model (MacWilliams et al. 2007, 2008, 2009) has been coupled with the SWAN wave model (SWAN Team 2009a) and the SediMorph sediment transport and seabed morphologic model (BAW 2005) to create a fully coupled hydrodynamic-wave-sediment transport modeling system. The physics represented by each model are discussed in previous sections and provided citations, and validation of the coupled modeling system, including validation of the coupling of the models and initial wave and sediment transport results within San Francisco Bay is presented in MacWilliams et al. (2012a) and Bever and MacWilliams (2013, 2014). As such, this appendix is limited to a description of how the model coupling is performed and what role each model plays in the coupled modeling system.

B.1 UnTRIM-SWAN-SediMorph Coupling Overview

The UnTRIM, SWAN, and SediMorph models run concurrently and pass information between one another to create a fully three-dimensional hydrodynamic, wave, and sediment transport modeling framework. The model coupling is performed such that UnTRIM can run either as a standalone hydrodynamic model, coupled with SWAN, coupled with SediMorph, or coupled with SWAN and SediMorph, giving freedom to use only the portion of the coupled modeling system that is necessary for any specific modeling objective.

In this framework the SWAN executable is called by the main UnTRIM program at specified intervals, while UnTRIM and SediMorph are compiled as a single executable and communicate every time-step. SWAN runs in stationary 2-D mode and uses a hot restart from the previous SWAN output as initialization conditions. Through the writing and reading of ascii files, UnTRIM passes to SWAN the following:

- Grid geometry
- Bathymetry
- Wind velocity
- Depth-averaged currents
- Nikuradse bottom friction coefficient

Because the unstructured version of SWAN only does computations on triangular meshes, each UnTRIM quadrilateral is divided into two SWAN triangles prior to writing grid geometry and any other information for SWAN. However, the nodes remain identical between the quadrilateral cells and the resulting triangles, and SWAN calculations are made at the grid nodes. SWAN returns to UnTRIM the following:

- Significant wave height
- Peak wave period
- Peak wave direction

When the full UnTRIM-SWAN-SediMorph modeling system is run, these wave properties are held constant between iterations of the SWAN model.

UnTRIM and SediMorph run on identical grids, and because they are compiled as a single executable, UnTRIM and SediMorph do not require the reading and writing of files to pass information. SediMorph uses the currents, waves, and suspended sediment concentration from UnTRIM to calculate the seabed shear stress and the deposition and erosion fluxes, and then passes the net flux between the seabed and the water column back to UnTRIM for use in updating the suspended sediment concentration. SediMorph also calculates the bedload sediment transport and adjusts the bed elevation to account for erosion, deposition, and bedload within each grid cell. SediMorph then updates the fractions of each sediment class within the seabed. In this way the morphologic change of the seabed is calculated at every time-step and feeds back into the hydrodynamic calculations. Also, the bottom orbital velocity for shear stress calculations is calculated in the SediMorph sediment transport routines based on the provided wave properties, and thus the wave influence on seabed shear stress is impacted by the water depth at each time step. The suspended sediment advection, mixing, and settling are calculated in UnTRIM, which incorporates the suspended sediment concentration in the equation of state following Warner et al. (2008).

APPENDIX C
VALIDATION OF CENTRAL BAY AND SOUTH BAY WATER LEVEL AND SALINITY

Because the UnTRIM Bay-Delta model has already been extensively validated to water level, current speed, flow, and salinity in the San Francisco Bay-Delta system (MacWilliams et al. 2007, 2008, 2009, 2015), this appendix only presents an abbreviated model validation in the Central Bay and the South Bay at the stations closest to the study region.

C.1 Water Level Validation

Three NOAA water level stations in the Central Bay and South Bay were used to validate the predicted water levels for the 2006 simulation (Figure C-1). Using the target diagram statistics MacWilliams et al. (2015) defined very accurate model predictions as those whose length of the vector composed of the two target diagram statistics was less than 0.25, and using the model skill from Willmott (1981) they defined accurate water level predictions as greater than 0.975 (no threshold was set for very accurate using the Willmott (1981) skill metric). Using these thresholds for model accuracy Figures C-2 through C-4 and Table C-1 show the model very accurately predicted the water level at all three of the stations.

Table C-1
Predicted and observed water levels, cross-correlation statistics, model skills, and target diagram statistics for water level monitoring stations in Central Bay and South Bay. The ubRMSD is the unbiased root-mean-square difference. The bias and ubRMSD have both been normalized by the observed standard deviation. Station locations are shown on Figure C-1.

Station Location	Data Source	Figure Number	Mean Water Level Observed (m NAVD88)	Mean Water Level Predicted (m NAVD88)	Cross Correlation Amp Ratio	Cross Correlation Lag (min)	r^2	Skill	Target Diagram Bias	Target Diagram ubRMSD
2006 Water Level Stations										
San Francisco	NOAA	C-2	1.02	1.05	0.986	0	0.994	0.998	0.056	-0.081
Alameda	NOAA	C-3	1.01	1.09	0.981	10	0.992	0.994	0.130	-0.088
Redwood City	NOAA	C-4	1.06	1.12	0.977	5	0.992	0.996	0.075	-0.091

C.2 Salinity Validation

Salinity was validated at three USGS continuous monitoring stations (Figure C-5). MacWilliams et al. (2015) defined accurate salinity predictions based on the Willmott (1981) skill metric as greater than 0.85 (no threshold was set for very accurate using the Willmott (1981) skill metric). This validation showed the model accurately predicted the salinity in the Central Bay and South Bay using the thresholds for model accuracy detailed in MacWilliams et al. (2015) (Figures C-6 through C-9, Table C-2). However, the model predictions in the South Bay were generally more saline than the observations. This prediction of slightly higher salinity than observed is likely a result of the model not including the freshwater inflow from many small ungauged streams that only flow during rainfall events combined with 2006 being a very wet year.

Table C-2
Predicted and observed salinity, cross-correlation statistics, model skills, and target diagram statistics for salinity monitoring stations in Central Bay and South Bay. The ubRMSD is the unbiased root-mean-square difference. The bias and ubRMSD have both been normalized by the observed standard deviation. Station locations are shown on Figure C-5.

Station Location	Data Source	Figure Number	Mean Salinity		Cross Correlation		r^2	Skill	Target Diagram	
			Observed (PSU)	Predicted (PSU)	Amp Ratio	Lag (min)			Bias	ubRMSD
2006 Salinity Stations										
Alcatraz	USGS	C-6	25.63	24.90	0.974	18	0.947	0.983	-0.114	0.232
San Mateo Bridge Upper	USGS	C-7	21.99	22.48	0.877	19	0.981	0.989	0.086	-0.174
San Mateo Bridge Lower	USGS	C-8	22.59	23.09	0.886	35	0.966	0.986	0.094	-0.202
Dumbarton Bridge	USGS	C-9	18.92	19.85	0.832	-26	0.937	0.971	0.163	-0.273

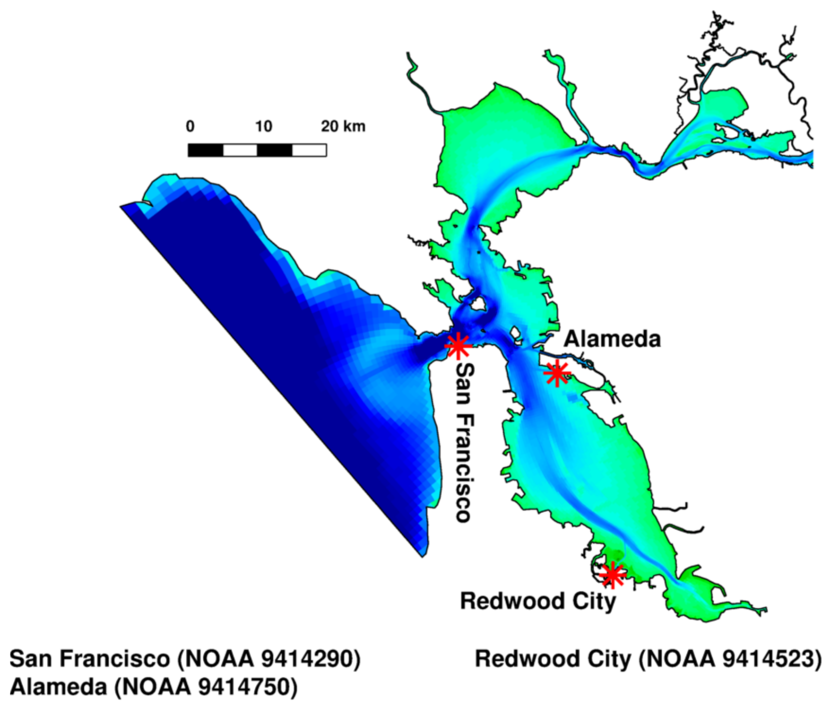

Figure C-1
Location of NOAA water level monitoring stations in the Central Bay and South Bay used for water level validation.

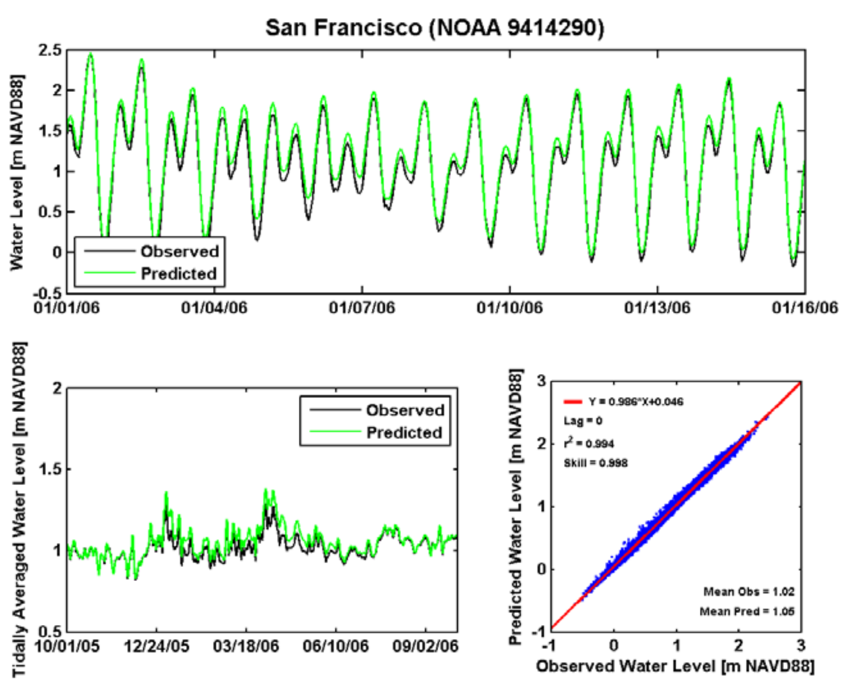

Figure C-2
Observed and predicted water level at San Francisco NOAA station (9414290) during the 2006 simulation period.

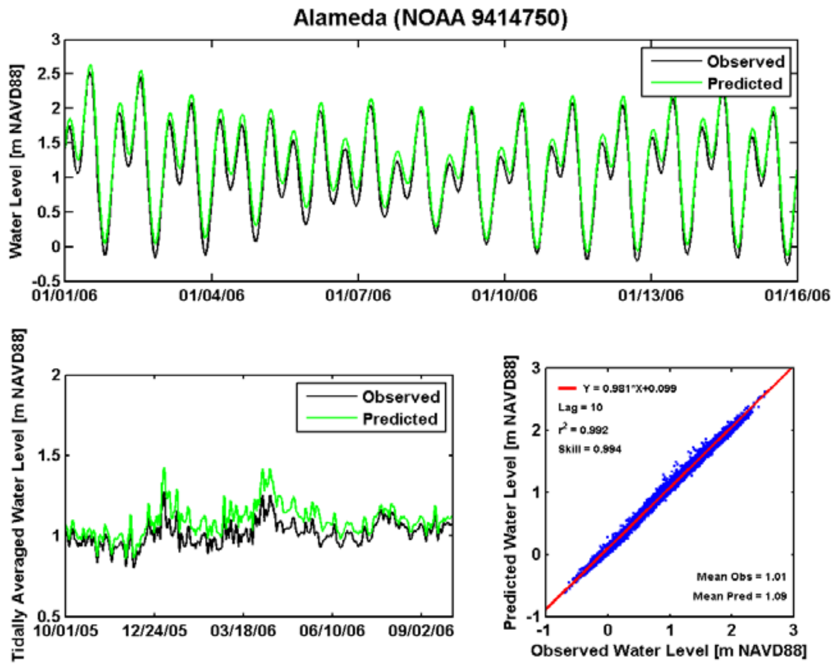

Figure C-3
Observed and predicted water level at Alameda NOAA station (9414750) during the 2006 simulation period.

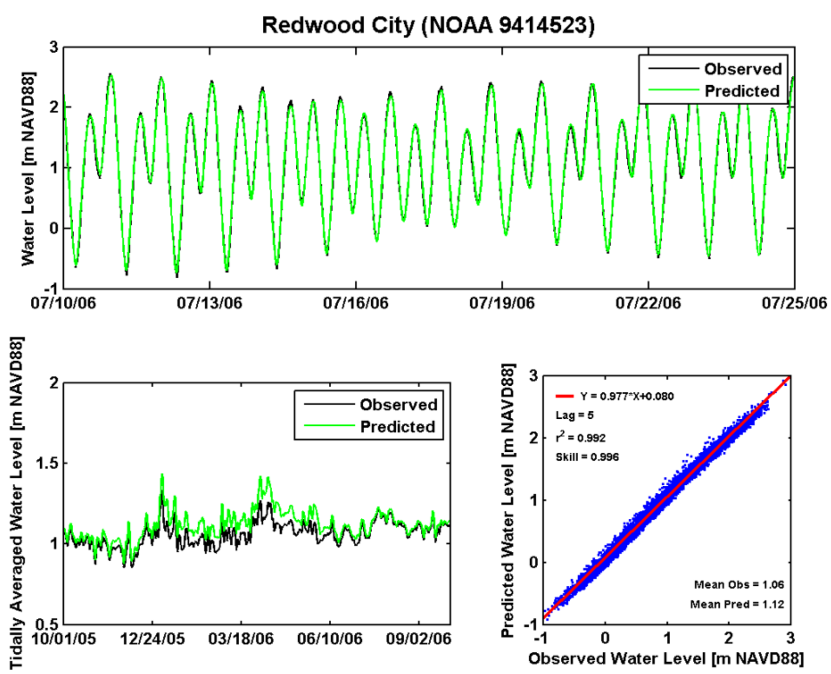

Figure C-4
Observed and predicted water level at Redwood City NOAA station (9414523) during the 2006 simulation period.

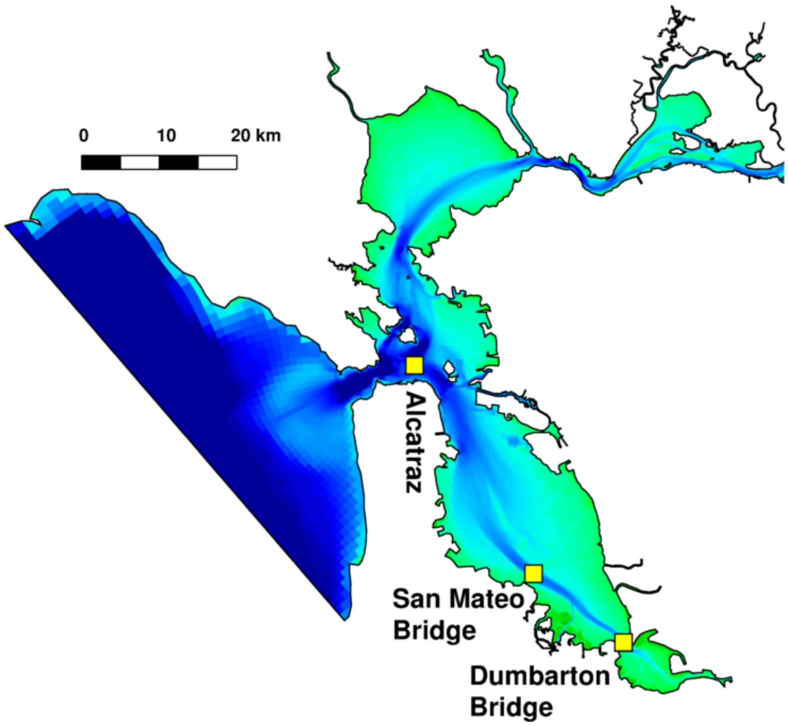

Figure C-5
Location of USGS salinity monitoring stations in the Central Bay and South Bay used for salinity validation.

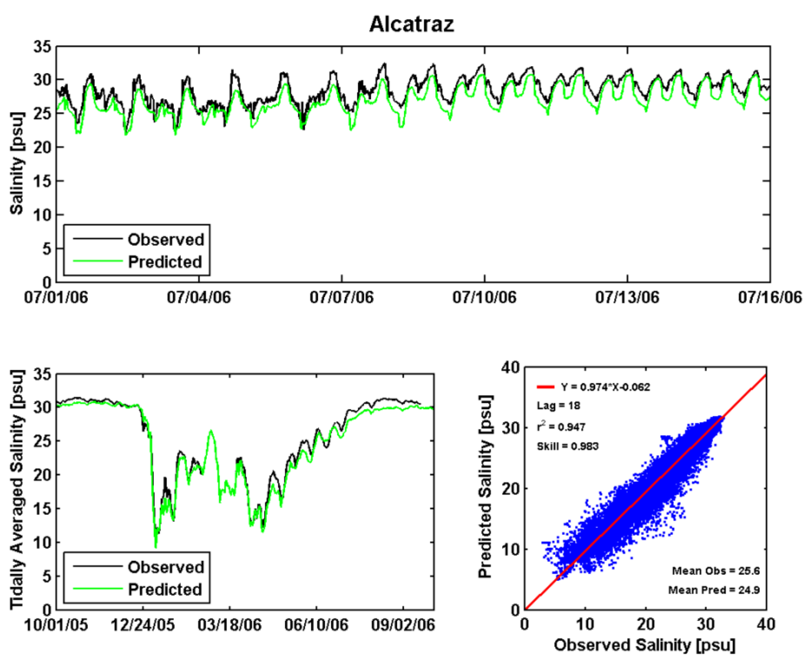

Figure C-6
Observed and predicted salinity at Alcatraz during the 2006 simulation period.

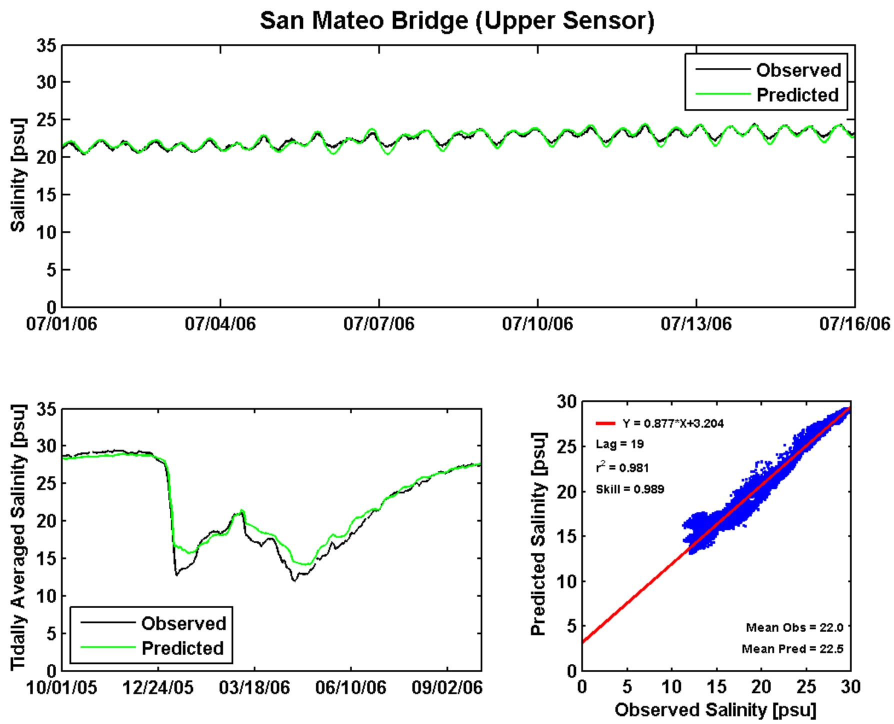

Figure C-7
Observed and predicted salinity at San Mateo Bridge (upper sensor) during the 2006 simulation period.

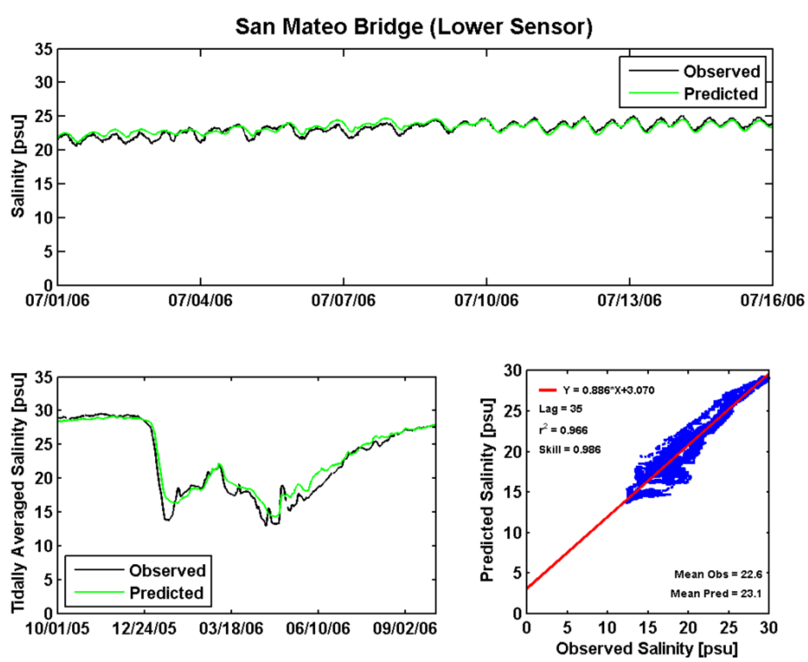

Figure C-8
Observed and predicted salinity at San Mateo Bridge (lower sensor) during the 2006 simulation period.

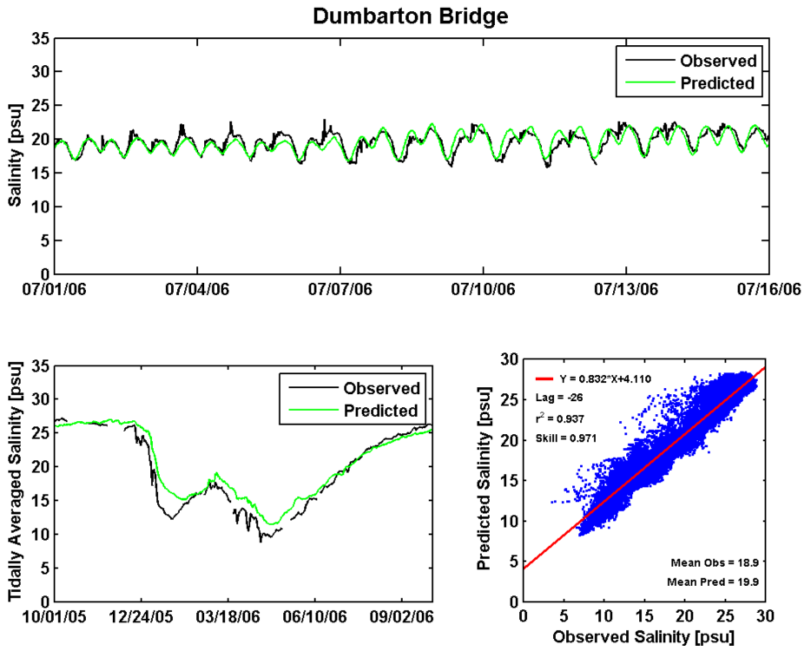

Figure C-9
Observed and predicted salinity at Dumbarton Bridge during the 2006 simulation period.