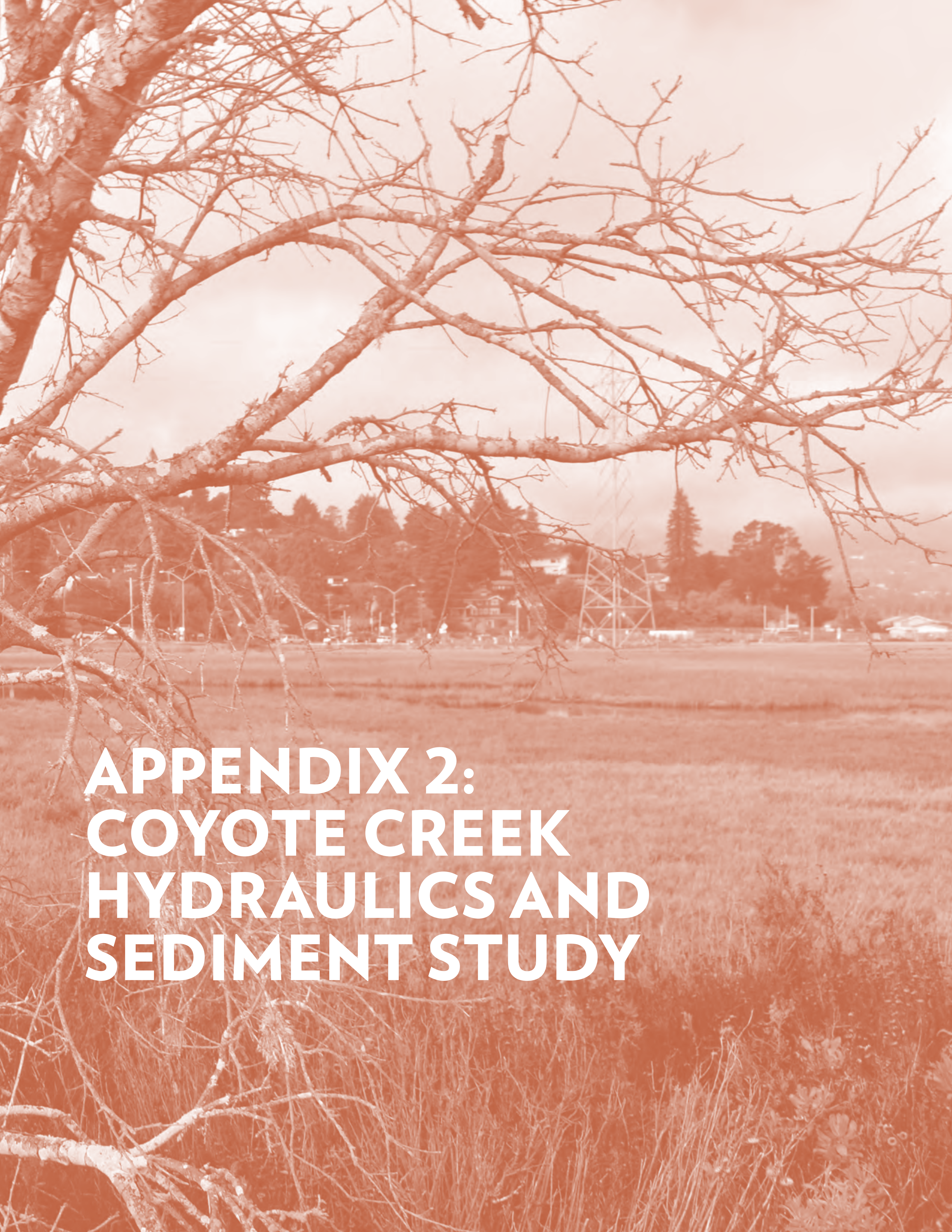

APPENDIX 2: COYOTE CREEK HYDRAULICS AND SEDIMENT STUDY

January 2021
Hydraulic Study of the Realignment of Lower Coyote Creek into Bothin Marsh

Lower Coyote Creek Realignment Hydraulic Modeling Report

Prepared for Marin County Flood Control District

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Lower Coyote Creek Realignment Hydraulic Modeling Report

Prepared for
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ABBREVIATIONS

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
Bay-Delta	Sacramento-San Joaquin Bay Delta
Bay Trail	Mill Valley-Sausalito Multi-Use Path
CCC	California Coastal Commission
cfs	cubic feet per second
cm	centimeter
COE	U.S. Army Corps of Engineers
DEM	digital elevation model
District	Marin County Flood Control District
FEMA	Federal Emergency Management Agency
FSS	fixed suspended solids
ft	feet
ft/s	feet per second
HAT	highest astronomical tide
HEC-RAS	Hydraulic Engineering Center River Analysis System
kg	kilogram
LiDAR	Light Detection and Ranging
m	meter
MHHW	mean higher high water
MLLW	mean lower low water
MLW	mean low water
MSL	mean sea level
NA	not applicable
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
OPC	Ocean Protection Council
QL1	Quality Level 1
RMSE	root mean square error
s	second
SLR	sea level rise
SR 1	State Route 1
SSC	suspended sediment concentration
Study	Hydraulic Study of the Realignment of Lower Coyote Creek into Bothin Marsh

SWAN	Simulated WAves Nearshore
TSS	total suspended solids
UnTRIM	Unstructured nonlinear Tidal Residual Intertidal Mudflat
USACE	U.S. Army Corps of Engineers

1 Introduction

Bothin Marsh and the adjacent infrastructure—including the Mill Valley-Sausalito Multi-Use Path (Bay Trail) and portions of California State Route 1 (SR 1)—are currently subject to regular flooding during the semiannual king tides (Figure 1-1). This area is highly vulnerable to even modest increases in tide levels due to sea level rise (SLR). There is concern that the existing marsh habit may be entirely lost due to SLR and that inundation of the Bay Trail will become more frequent. The Hydraulic Study of the Realignment of Lower Coyote Creek into Bothin Marsh (Study) is being conducted for the Marin County Flood Control District (District) to evaluate the realignment of Lower Coyote Creek into Bothin Marsh. The realignment options were originally proposed by Watershed Sciences during the first phase of Bothin Marsh studies (Baye and Collins 2018). This study, funded by a Caltrans SB1 grant to address SLR, is being implemented in coordination with parallel efforts, including the Bothin Marsh Evolving Shorelines Project, an SLR adaptation project being led by One Tam partners (Marin County Parks and the Golden Gate National Parks Conservancy) and their design team (WRT and ESA) to refine conceptual designs for channel realignment proposed by Watershed Sciences. The overall objectives of these studies are to restore the ecosystem's natural ability to adapt to SLR, reduce the risk of tidal flooding using nature-based strategies, and maintain a resilient and safe alignment for the Bay Trail.

Figure 1-1
Coyote Creek and Bothin Marsh Project Site Map

Specifically, the focus of this Study is to answer the following question: "*Does the realignment of Lower Coyote Creek increase marsh resilience to sea level rise without increasing flood risk?*" For the channel realignment project to move forward successfully, it needs to make sense from both a flood control and a marsh sustainability perspective. Hydraulic modeling of potential realignment alternatives of Lower Coyote Creek into Bothin Marsh was conducted to evaluate whether the realignment of Coyote Creek through Bothin Marsh can be achieved without adversely increasing flood risk. This report documents the hydraulic modeling and analysis conducted to answer this question and identifies the realignment alternative that resulted in the lowest predicted effect on flood risk due to both tidal and fluvial flooding. This alternative was further evaluated using a sediment transport model to evaluate whether the realignment of Coyote Creek into Bothin Marsh will increase the sediment supply to, and the sustainability of, Bothin Marsh. The scope of the sediment transport analysis was limited to analysis of one realignment alternative to provide an indication of benefits and impacts to sediment transport. A fuller analysis is recommended to refine this analysis under the next phases of design work.

1.1 Summary of Work

This report is divided into six primary sections that document each phase of the analysis conducted for this Study:

- **Section 1: Introduction.** This section provides a summary of the goals and objectives of the project and a summary of the scope and organization of this report.
- **Section 2: LiDAR Survey Data Evaluation.** This section includes a review of the 2019 Marin County Quality Level 1 (QL1) Light Detection and Ranging (LiDAR) dataset provided by Marin County (Quantum Spatial 2019) and comparison to the Bothin Marsh 2013 LiDAR dataset (Meridian 2013). Comparisons were also made between the 2019 Marin County QL1 LiDAR and the January 2020 terrestrial-based traditional survey of select locations in Bothin Marsh and Lower Coyote Creek area (Cinquini and Passarino 2020).
- **Section 3: Review and Update of Existing HEC-RAS Model.** An existing HEC-RAS 1D model of Coyote Creek provided by Marin County (GHD 2018) was updated with the 2019 Marin County QL1 LiDAR data, and high-flow simulations from the 2016 modeling effort were re-simulated with the updated model. The existing HEC-RAS 1D model was converted to a HEC-RAS 2D model in the Lower Coyote Creek channel and floodplain as well as Bothin Marsh using the 2019 Marin County QL1 LiDAR data. The 2016 high-flow simulations were re-simulated using the 2D model and compared to the results from the 1D model as a basic validation of model performance under existing conditions.
- **Section 4: Development of Realignment Geometry and Hydraulic Scenarios.** Three alignment alternatives and five hydraulic scenarios were developed in coordination with Marin County. Boundary conditions for the hydraulic scenarios were developed using results from the updated HEC-HMS model (Anchor QEA 2020a; Appendix B) and available tidal and SLR data.
- **Section 5: Evaluation of Lower Coyote Creek Realignment Alternatives.** Twenty hydraulic simulations were conducted for the evaluation of the three realignment alternatives. The five hydraulic scenarios were simulated under existing conditions and for each of the three realignment alternatives. Predicted water levels for each simulation were compared to evaluate the effect of each realignment alternative on maximum water surface elevation. The predicted water surface elevation and velocities were analyzed using time series, longitudinal profiles, and plan view maps.
- **Section 6: Evaluation of Effect of Realignment on Sediment Supply to Bothin Marsh.** This section presents the modeling conducted to evaluate whether the realignment of Lower

Coyote Creek into Bothin Marsh is likely to increase the sediment supply to Bothin Marsh. A coupled three-dimensional (3D) hydrodynamic, wind wave, and sediment transport model was applied to evaluate sediment transport to Bothin Marsh from Coyote Creek and from sediment exchange between the marsh and Richardson Bay.

- **Section 7: Summary and Conclusions.** Conceptual Alternative 1 developed by Watershed Sciences for Marin County Parks and the District in October 2019 (Watershed Sciences 2019) was used as the basis for the development of the first two alternatives, Alternative 1 and Alternative 2. These two alternatives follow the same alignment and have the same thalweg depth but include different assumptions for side slopes that result in different cross-sectional areas. The hydraulic modeling indicated that both Alternative 1 and Alternative 2 resulted in a significant increase in upstream water surface elevations during high flows. Based on these results, a third alternative (Alternative 3) was developed, in coordination with the Bothin Marsh Evolving Shorelines Project, that incorporated a larger cross-sectional area that roughly matches the cross-sectional area of the existing creek channel just upstream of the realignment and follows a much less sinuous alignment. Hydraulic modeling of Alternative 3 indicates that it meets the objective of allowing for the realignment of Coyote Creek through Bothin Marsh without significantly increasing upstream flood risk. The subsequent evaluation of Alternative 3 using a 3D hydrodynamic and sediment transport model suggests that the realignment is also likely to result in an ongoing increase in sediment contribution to Bothin Marsh, primarily due to greater deposition in the marsh of sediment originating in Coyote Creek and Nyhan Creek during periods of high creek flow. The third alternative was proposed as the minimal channel realignment alternative (minimum sinuosity and maximum channel cross-sectional area) to provide a bookend geometry to confirm that there is a possible realignment alternative that can work for channel realignment without significant upstream flooding. From this alternative, future design scopes can refine and iterate this concept layout to increase meander and narrow the cross-sectional area to potentially increase the ability of the creek to transport sediment to the backshore areas of the marsh under a wider range of storm events.

2 LiDAR Survey Data Evaluation

This section outlines the review of the 2019 Marin County QL1 LiDAR dataset provided by Marin County (Quantum Spatial 2019) and comparison of the 2019 Marin County QL1 LiDAR to the Bothin Marsh 2013 LiDAR dataset (Meridian 2013) and a January 2020 terrestrial-based traditional survey of select locations in Bothin Marsh and the Lower Coyote Creek area (Cinquini and Passarino 2020).

Marin County provided three topo-bathymetric elevation datasets for evaluation and use in the 2D hydrodynamic model development. Two of the datasets are LiDAR digital elevation model (DEM) terrain surfaces that include seamless topographic and bathymetric data. The third dataset is terrestrial-based (traditional) topographic survey spot elevation data collected in January 2020 to provide a "ground truth" on the LiDAR datasets. The datasets are summarized in Table 2-1.

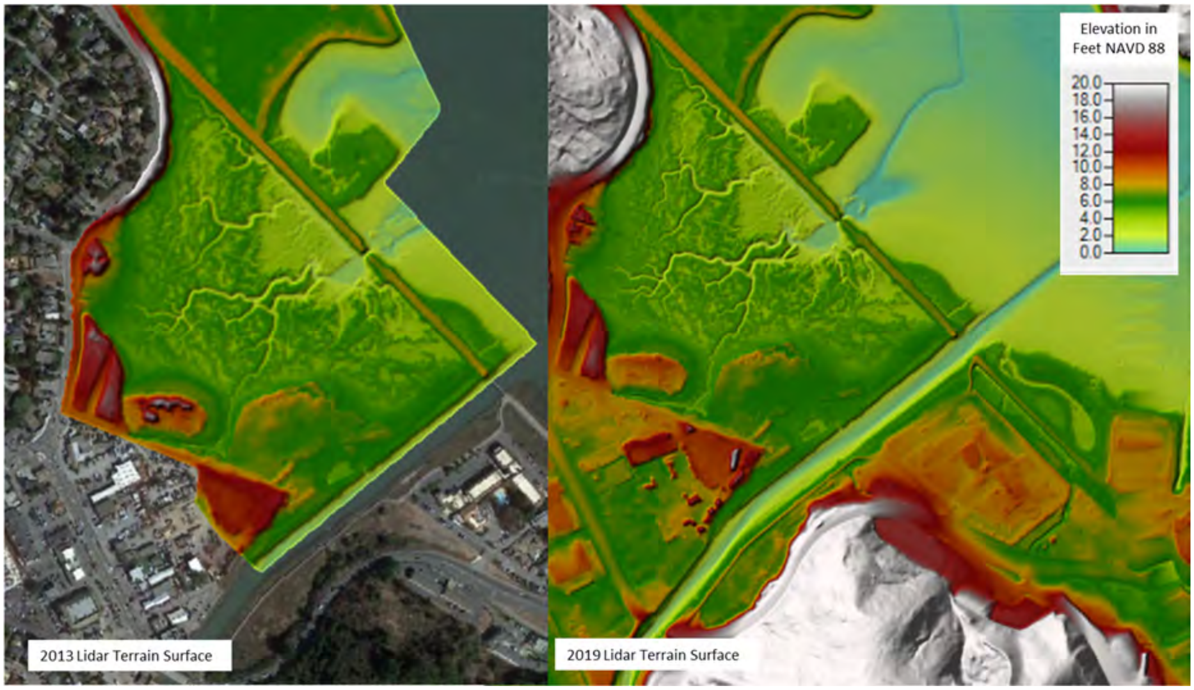
Table 2-1
Topo-Bathymetric Data Sources and Supporting Information

Dataset Name/Source	Description	Collection Dates	Horizontal Resolution	Vertical Accuracy
Bothin Marsh 2013 LiDAR	Composite DEM comprised of multiple topographic and bathymetric datasets of varying temporal and spatial resolutions (Meridian 2013)	2007 to 2010	0.5 meter	18 cm
2019 Marin County QL1 LiDAR	DEM from LiDAR collected by Quantum Spatial, Inc., for Golden Gate National Parks Conservancy (Quantum Spatial 2019)	December 2018 to March 2019	1.5 feet	15 cm
Cinquini & Passarino Spot Survey	Topographic survey spot elevations (traditional survey) collected at discrete locations within the site for the purpose of making comparison to LiDAR (Cinquini and Passarino 2020)	January 2020	NA	NA

Note:
NA: Spot check elevation data are available for select locations only.

Figure 2-1 shows a side-by-side comparison of the Bothin Marsh 2013 LiDAR dataset to the 2019 Marin County QL1 LiDAR dataset finalized in January 2020. The 2013 LiDAR dataset only covers Bothin Marsh and the left (northwest) bank of Coyote Creek. The 2019 Marin County QL1 LiDAR dataset (Quantum Spatial 2019) is a countywide coverage DEM, which includes the entire domain of the existing HEC-RAS 1D model for Coyote Creek and Bothin Marsh. The 2019 Marin County QL1 LiDAR had a higher return rate and is considered to be a higher quality dataset.

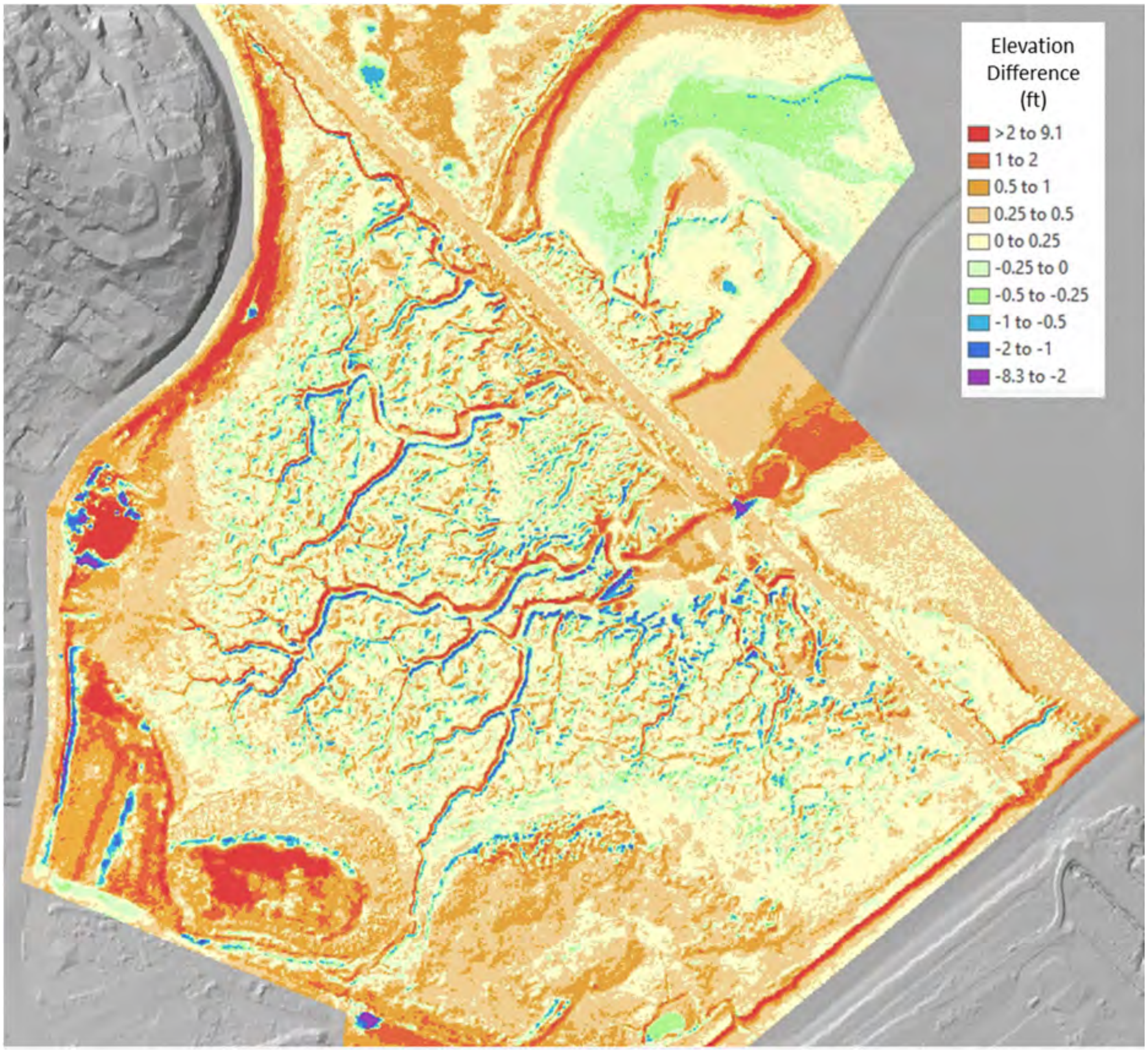
Figure 2-1
LiDAR Terrain Surface Data Coverage of Lower Coyote Creek and Bothin Marsh



2.1 LiDAR Assessment

The 2013 LiDAR surface elevation data were subtracted from the 2019 Marin County QL1 LiDAR, with the results showing the elevation differences at every horizontal location where the data overlap. The resulting difference map, shown in Figure 2-2, shows patterns indicative of a slight horizontal shift in the 2013 Marsh LiDAR data to the northwest relative to the 2019 Marin County QL1 LiDAR data. The orange and red colors areas are where the 2019 Marin County QL1 LiDAR elevation is higher than the 2013 LiDAR elevation. The cooler colors, green through purple, are areas where the 2019 Marin County QL1 LiDAR elevation is lower than the 2013 LiDAR elevation. The small tidal channels in Bothin Marsh as well as the left bank of Coyote Creek show that the northwest side of the channel is higher than the 2013 data, and the southeast side of the channel shows lower elevations than in 2013. The increase in elevation, likely due to this shift, is also seen on the edge of SR 1 on the west side of Bothin Marsh. In the non-channel areas of Bothin Marsh, the general difference in elevation between the 2013 and the 2019 Marin County QL1 LiDAR is relatively small, with differences on the order of plus or minus 3 inches (0.25 foot).

Figure 2-2
LiDAR Survey Comparison (2019 Minus 2013 Elevations)



Notes:
LiDAR survey elevations were compared only for the Bothin Marsh and nearshore area based on the coverage of the 2013 LiDAR data. Note that only the left bank of Coyote Creek was included in the 2013 LiDAR surface.

Due to the observed differences between the 2013 LiDAR and the 2019 Marin County QL1 LiDAR datasets, a third dataset was collected using traditional terrestrial-based survey equipment to "ground truth" the 2013 and 2019 datasets to determine the most accurate dataset for use in the updated HEC-RAS 2D model.

2.2 Terrestrial Survey (2020) Ground Truth Evaluation

Cinquini & Passarino, Inc., performed a spot survey using traditional terrestrial-based survey equipment at 74 point locations in Bothin Marsh, along the Bay Trail, and along the Coyote Creek north levee (Cinquini and Passarino 2020). The locations of these points are shown in Figure 2-3 and are color-coded by measurement type as noted by the surveyor.

Figure 2-3
Terrestrial Survey Point Locations for LiDAR Data Comparison

Appendix A shows three cross-section profiles comparing the 2013 LiDAR, 2019 Marin County QL1 LiDAR, and survey spot check point elevations for Bothin Marsh (Section A-A'), the marsh channel outlet and Bay Trail (Section B-B'), and the Coyote Creek north levee (Section C-C'). Table 2-2 provides a selection of survey points from the Bothin Marsh, the Bay Trail, and the Coyote Creek north levee. The table presents the spot survey elevation value as well as the elevations from the two LiDAR datasets and the computed difference between the spot elevation and the 2019 and

2013 LiDAR survey elevations at that location. The average differences in elevation were also computed for all 74 survey points and provided in the table for reference.

Table 2-2
Terrestrial Survey (2020) Spot Elevations Comparisons 2013 and 2019 Marin County QL1 LiDAR Data

Elevation Data	Area	Terrestrial Survey Elevation Minus LiDAR Elevation (feet)	
		Elevation Difference Range	Average Difference
Bothin Marsh 2013 LiDAR	**All Areas**	**-0.92 to +0.27**	**-0.25**
	Bothin Marsh	-0.35 to +0.27	-0.04
	North Levee	-0.46 to -0.17	-0.36
	Bay Trail	-0.58 to +0.27	-0.21
	Native Ground	-0.92 to +0.03	-0.34
2019 Marin County QL1 LiDAR	**All Areas**	**-1.01 to +0.46**	**-0.07**
	Bothin Marsh	-0.87 to +0.00	-0.39
	North Levee	-0.04 to 0.28	0.14
	Bay Trail	-0.87 to +0.46	-0.10
	Native Ground	-1.01 to +0.45	-0.01

Notes:

1. Estuary channel outlet locations were not included in the average difference calculations due to the post-processing in the LiDAR datasets in this area to account for the bridges resulting in inaccurate comparisons.
2. Table 2-2 includes select representative points from the terrestrial-based 2020 survey. The average difference between all of the terrestrial-based survey spot measurements excluding the estuary channel outlet locations (Figure 2-3) and the 2019 and 2013 LiDAR surveys were computed and provided in the last row of the table.

The root mean square error (RMSE) between the spot elevations and the two LiDAR surveys was calculated for areas combined, and individually for each of the four area types shown in Table 2-3 and indicated by different color points in Figure 2-3. The average difference between the spot elevation survey and the 2013 LiDAR is approximately -0.25 foot, and the average difference with the 2019 Marin County QL1 LiDAR is approximately -0.07 foot for all locations. The average difference between both surveys in each of these key areas was small (within a few inches).

Table 2-3
Root Mean Square Error in the Spot RMSE

Elevation Data	Area	Average RMSE (feet)
Bothin Marsh 2013 LiDAR	**All Areas**	**0.36**
	Bothin Marsh	0.23
	North Levee	0.38
	Bay Trail	0.33
	Native Ground	0.44
2019 Marin County QL1 LiDAR	**All Areas**	**0.37**
	Bothin Marsh	0.46
	North Levee	0.16
	Bay Trail	0.39
	Native Ground	0.42

Notes:
1. Estuary channel outlet locations were not included in RMSE calculations because the post-processing in the LiDAR datasets in this area to account for the bridges resulted in inaccurate comparisons.
2. Bothin_DEM_2013128.tif did not include coverage for 12 of the 2,020 survey points.

The variability of RMSE between the two datasets can be attributed to several factors, including the location of the Coyote Creek project site, vegetation, the LiDAR resolution, and the LiDAR vertical accuracy, which is higher for the 2019 LiDAR. The location of the Coyote Creek project site is in a tidally influenced estuary (excluding points on the Bay Trail). LiDAR point returns in environments with water surfaces may not be as dense as non-water returns and will often reflect from the water surface, rather than the underlying topography, resulting in additional error between any two surveys depending on the tide level, type of LiDAR, and post-processing method. A second complicating factor is that estuaries and other tidally influenced areas are highly dynamic; therefore, a comparison of data from one temporal scale to another can show a much different elevation at the same horizontal location due to estuarine channel migration as a result of shoaling and littoral transport. Lastly, vegetation can also be a significant factor influencing LiDAR accuracy. Year-over-year plant growth, as well as seasonal variations in canopy density, can influence LiDAR measurements and the effectiveness of the post-processing to remove vegetation from the LiDAR returns.

It is important to note the affect that LiDAR resolution has on the assessment. Each DEM consists of many cells, which are each assigned a single elevation value. The elevation is the average of the LiDAR point returns within the cell's area. The averaging can smooth the variability of data within the cell and result in a larger RMSE as compared to the spot elevation. This effect is most often seen in areas of more topographic relief, such as berms, dikes, roadway, and pathway prisms, which often have steeper slopes. The Coyote Creek project site has some areas where this effect is evident, particularly around the marsh channel outlet under the Bay Trail, where LiDAR elevations of greater variability are being averaged within a horizontal single cell and compared to a discrete topographic survey spot elevation meant to capture the top and toe of the bank at that location. In contrast, locations that are above the water surface and have less local variability in elevation, such as the top of the dike, show much lower RMSEs.

The inherent vertical accuracy and sources of error in LiDAR data should also be considered when making assessments of survey accuracy. LiDAR collection involves many dynamic elements, from the aircraft collecting the data, the GPS satellites resolving the aircraft and LiDAR sensor's location, to the processing of the collected data. Each of these elements can introduce some vertical error. Steps are taken in the processing to minimize this error, but it cannot be removed completely, and should therefore be considered in an overall assessment of the applicability of the data.

In addition to the above RMSE quantitative assessment, the LiDAR were also assessed qualitatively using hillshade products created from the DEMs to help visualize the relief of the topography. A visual assessment of the hillshades as compared to the 2018 orthophotography that was collected in parallel with the 2019 Marin County QL1 LiDAR appears to show a better alignment with the site topography and channel planforms than the 2013 Bothin Marsh LiDAR.

2.3 LiDAR Dataset Selection

Review of the RMSE indicates both LiDAR datasets compare similarly to the surveyed locations. The 2019 Marin County QL1 LiDAR dataset has a slightly better average elevation difference compared to the 2013 Bothin LiDAR dataset and has similar RMSE values for each area. In addition, the visual assessment of the data also shows the 2019 Marin County QL1 LiDAR having a better overall alignment with available aerial photography. Weighing the results of the statistical evaluation and the fact that the 2019 dataset would capture any changes in morphology, the 2019 Marin County QL1 LiDAR dataset was used for the terrain surface in the development of the updated HEC-RAS 1D and HEC-RAS 2D models described in the following sections.

3 Review and Update of Existing HEC-RAS Model

This section outlines the review and updates made to the existing HEC-RAS 1D model of Coyote Creek. An existing HEC-RAS 1D model of Coyote Creek provided by Marin County. The HEC-RAS 1D model was developed by HDR in 2016 (HDR 2016). The model was revised and updated in 2018 by GHD, Inc. (GHD 2018). The 2018 model was provided to Anchor QEA by Marin County for use in this Study. The existing HEC-RAS model (GHD 2018) utilized the 2013 LiDAR dataset covering the west bank of Coyote Creek and Bothin Marsh (Figure 2-1).

In 2019, countywide aerial-based LiDAR was flown at low tide, which covered the entire extent of the Coyote Creek project site spanning Lower Coyote Creek and Bothin Marsh (Quantum Spatial 2019). This dataset was finalized for public release in early 2020 and was used to update the HEC-RAS model for this Study after the data evaluation was completed (see Section 2).

Anchor QEA updated the existing HEC-RAS 1D model (GHD 2018) with the 2019 Marin County QL1 LiDAR data and re-simulated the high-flow simulations from the 2016 modeling effort using the updated HEC-RAS 1D model. The comparison of the original simulation and the simulation from the updated HEC-RAS 1D model was used to evaluate the effect of updating the HEC-RAS 1D model geometry using the 2019 Marin County QL1 LiDAR data. Next, the downstream portion of the HEC-RAS 1D model was converted to a HEC-RAS 2D model spanning the Lower Coyote Creek channel and floodplain as well as Bothin Marsh using the 2019 Marin County QL1 LiDAR data. The 2016 high-flow simulations were re-simulated using the combined HEC-RAS 1D/2D model and compared to the results from the updated HEC-RAS 1D model to evaluate the effect of incorporating a large 2D area in the downstream portion of the model grid. This simulation was also used as a basic validation of model performance to verify that the predicted water levels for the resulting HEC-RAS 2D model were similar to those from the original HEC-RAS 1D model (HDR 2016; GHD 2018).

3.1 1D Model Updates

The HEC-RAS 1D model developed by GHD (2018) was brought into the latest HEC-RAS release available for public use at the time of this evaluation (version 5.0.7). HEC-RAS version 5.0.7 is capable of both 1D and 2D hydrodynamic calculations. (Updated releases of HEC-RAS are generally backwards compatible with models developed in previous release versions.)

The 1D model that served as the baseline model for this Study includes approximately 1.2 miles of Coyote Creek upstream of its mouth at the Mill Valley-Sausalito Path overpass (stations 1211 to 7632). There is also approximately 1,000 feet of the Nyhan Creek tributary that converges with Coyote Creek at station 4045 (approximately 0.5 mile upstream of the mouth).

Coyote Creek 1D cross-section elevations for stations 1044 through 2800 were replaced with the 2019 Marin County QL1 LiDAR data terrain elevations. The transect at station 2800 is located approximately 85 feet downstream of the SR 1 pedestrian bridge (approximately 0.3 mile upstream of the mouth). Sections upstream of the cross section at station 2800 (i.e., stations 2832 through 7632) were not revised as part of this Study. Changes to the channel cross-sectional bathymetry in these upstream sections were not expected to have a significant effect on the hydraulics occurring in the focus area of this Study, which is the lower area of Coyote Creek. Specifically, this Study focused on the realignment of Coyote Creek through Bothin Marsh and the connection with Richardson Bay (stations 0 to 2050). The dimensions of the modeled bridges and conveyance structures provided as part of the 2018 model remained the same for the updated model. Figure 3-1 shows the layout of the lower 1D model and cross sections.

Figure 3-1
HEC-RAS 1D Model Cross-Sections in Lower Coyote Creek

Note:
Grey text indicates key transect stations in feet for the 1D model.

After updating the cross-sections downstream of station 2800 with the 2019 Marin County QL1 LiDAR data, the following three simulations from the GHD (2018) study were re-simulated:

- The 25-year return interval event flow rate (determined by the District) coupled with the sea level at mean higher high water (MHHW)
- The 100-year return interval event flow rate (determined by the District) coupled with MHHW
- The 100-year Federal Emergency Management Agency (FEMA) return interval event flow rate coupled with MHHW in 2050

These simulations were used to compare to the updated 1D and 2D models to the HEC-RAS 1D simulation results from GHD (2018). These comparisons provide an evaluation of how the changes to the channel and floodplain bathymetry and topography affect the predicted water surface elevation. These same simulations were repeated using the HEC-RAS 2D model described in Section 3.2.

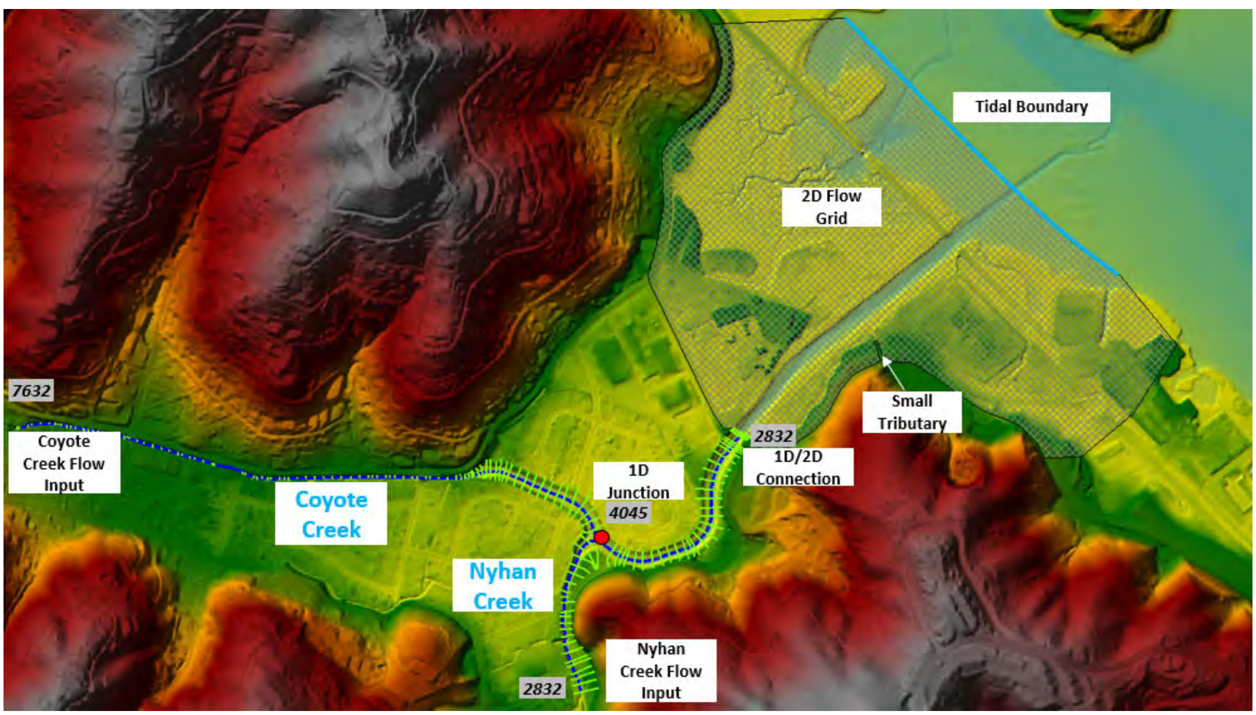
3.2 2D Model Development

The HEC-RAS 1D model developed by GHD (GHD 2018) predicted flows through the Lower Coyote Creek channel with some spillover flow into Bothin Marsh during high flows. However, 1D hydraulic models are typically not capable of predicting complex flows such as tidal circulation and changes in flow direction with varying flow rates that occur during bankfull overtopping onto the marsh. A 2D hydrodynamic model is capable of accurately predicting these hydrodynamic conditions. In addition, 2D models compute spatially varying depth-averaged velocities, which are important for understanding for sediment transport potential and informing erosion protection design. The HEC-RAS 2D model was selected to model the Lower Coyote Creek and channel realignment alternatives through Bothin Marsh.

The HEC-RAS 2D modeling software (version 5.0.07), is backwards compatible with the version used by GHD (2018). As discussed in Section 2, the HEC-RAS 1D model of existing conditions from the GHD (2018) study was updated to make use of the 2019 Marin County QL1 LiDAR data in the downstream cross-sections. This updated HEC-RAS 1D model was the starting point for developing the HEC-RAS 1D/2D model for this Study. The 1D model cross sections from stations 1250 through 2827 were removed, and this stretch of Lower Coyote Creek was converted into a 2D model domain. The 2D portion of the model domain covers the lower section of Coyote Creek and Bothin Marsh and extends beyond the Bay Trail into Richardson Bay. The 2D model domain connects to the existing HEC-RAS 1D model just downstream of the SR 1 bridge. The 2D model domain covers approximately 104 acres of the Lower Coyote Creek channel and floodplain including Bothin Marsh and extends out into Richardson Bay. The 2D model domain also includes the Manzanita Park and Ride Lot. The 2D model is composed of a “flexible mesh” network of approximately 65,181 model grid cell polygons with variable resolution, cell sizes ranging from 3 to 200 square feet, and an average cell size of 69 square feet.

At the upstream end of the 2D model domain, the 1D model was connected to the 2D flow area. This 1D/2D connection provides online coupling during the model simulations so that at each timestep in the simulation, hydraulic result information is conveyed between the 1D and 2D domain. Some transects near the SR 1 bridge and pedestrian bridge moved slightly, and an additional transect was added (transect 2827). Model simulations were set up such that the flow rate and water surface elevations predicted at the downstream end of the 1D reach (section 2827) were used as the upstream boundary condition for the 2D model. During unsteady flow simulations, these boundary conditions work together seamlessly to form a coupled model of the system. There was also a small tributary joining the 1D model at station 2150, which falls within the middle of the 2D flow area. The 2D model grid was modified slightly near station 2150 to retain this small tributary. Figure 3-2 shows a plan view of the model geometry, including the 1D sections of Coyote Creek and Nyhan Creek as well as the 2D model grid location covering Lower Coyote Creek and Bothin Marsh.

Figure 3-2
Existing Conditions HEC-RAS 2D Model Layout and Boundary Conditions



The upstream portions of Coyote Creek and Nyhan Creek in the 1D portion of the model domain include hydraulic jumps, which resulted in some model instabilities when using the hybrid HEC-RAS 1D/2D model domain shown in Figure 3-2. For the evaluation of the channel realignment alternatives (Section 4), the upstream reaches of these two channels were truncated at the hydraulic jump locations to improve model stability and allow for a more consistent evaluation of the realignment alternatives for the full range of hydraulic scenarios evaluated in this Study. To verify that the truncation of the upstream portion of the 1D channels did not have an effect on predicted water levels in the Study area, the predicted water levels from the truncated model (Figure 3-3) were compared to the predicted water levels from the full 1D/2D model (Figure 3-2) for the three high-flow simulations evaluated. Both the truncated and the untruncated existing conditions model will be provided to Marin County to allow for the use of either 1D channel domain with the downstream 2D grid in future releases of HEC-RAS, which are anticipated to improve numerical stability of combined 1D/2D domains through the numerical reformulation of the 1D computations in HEC-RAS.

Figure 3-3
Existing Conditions HEC-RAS 2D Model Layout and Boundary Conditions with Upstream Channels Truncated

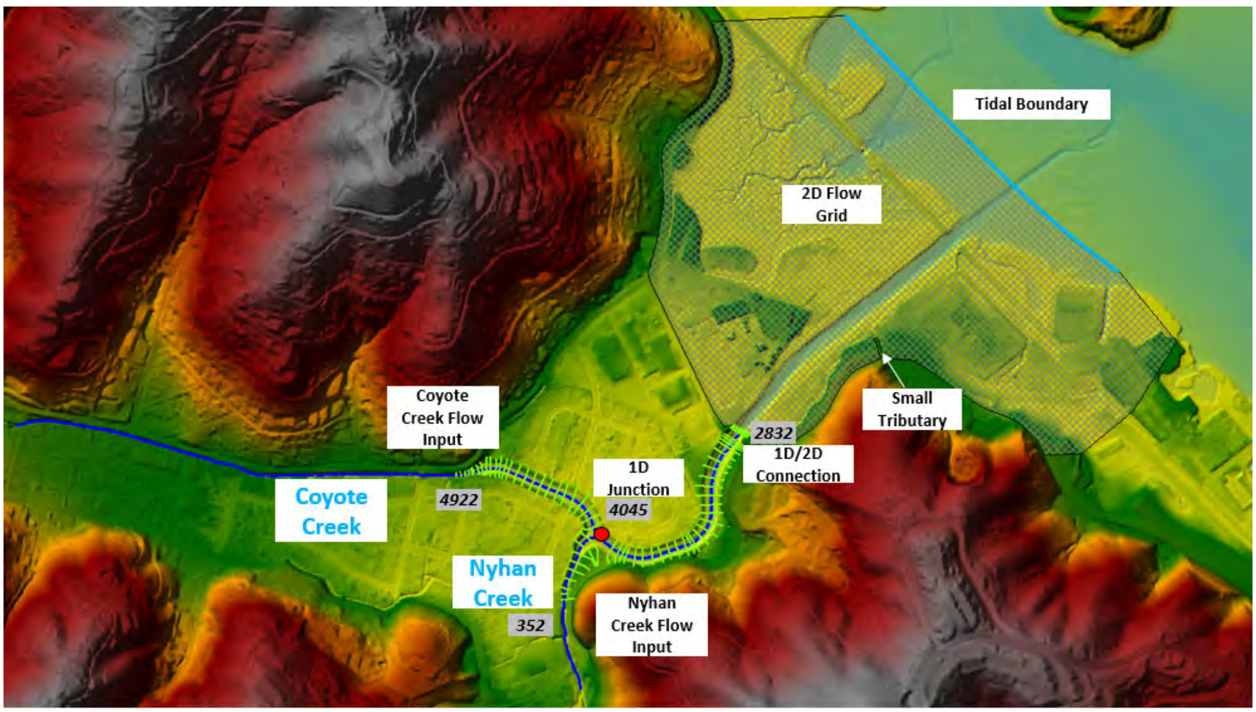
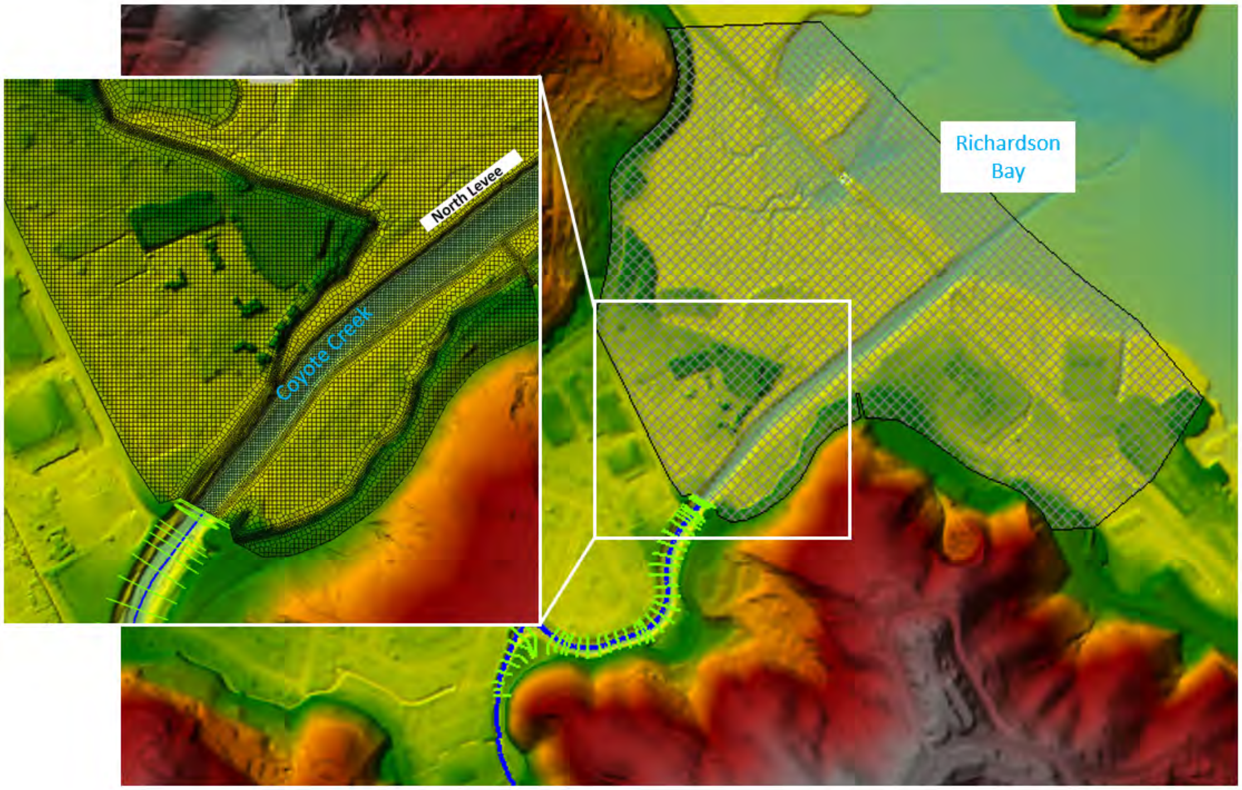


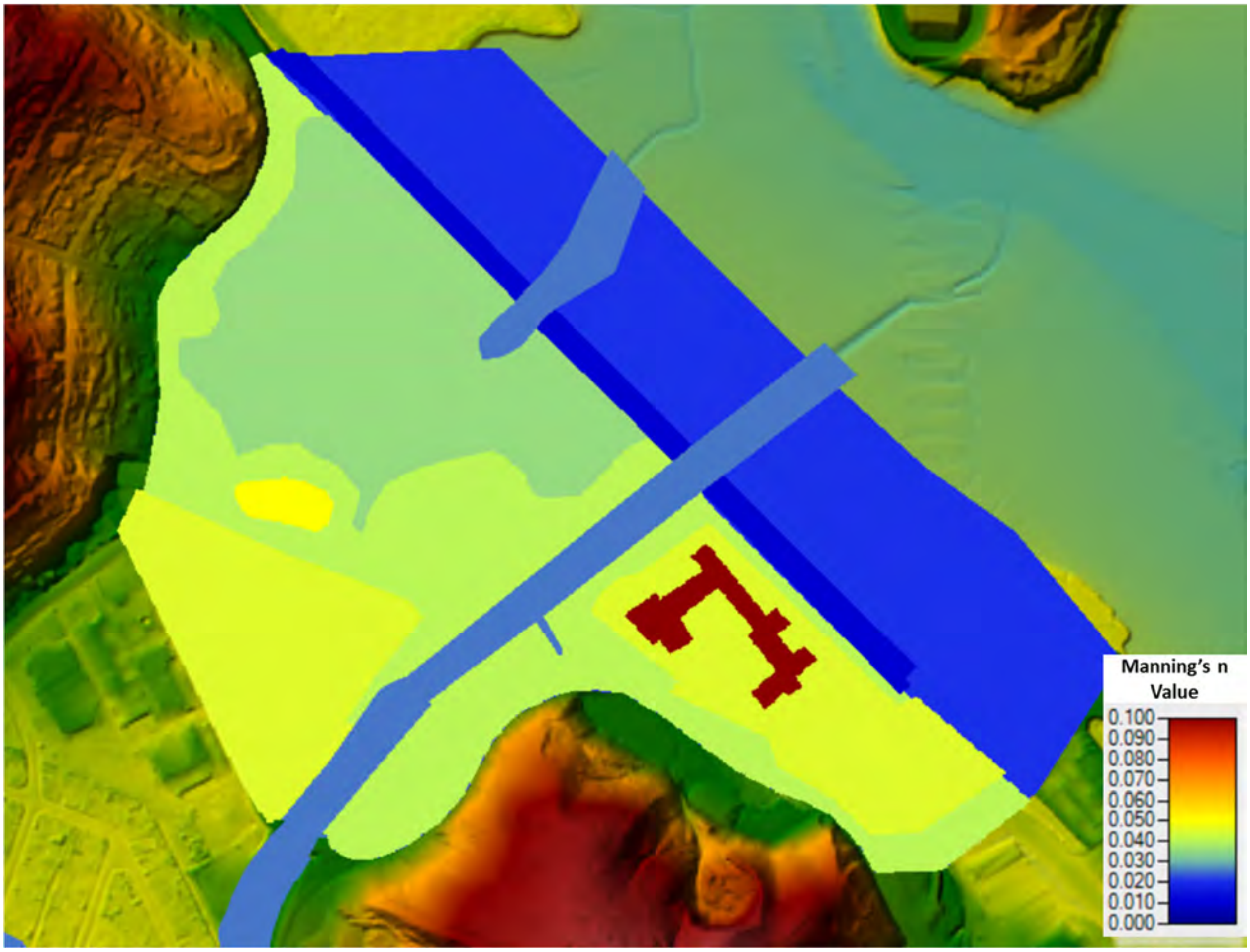
Figure 3-4 shows a zoomed-in view of the 2D model grid at the upstream connection with the 1D model (at left in Figure 3-4). The figure shows the variable resolution of the flexible mesh grid cells. Higher resolution (smaller) grid cells were used in areas where rapid changes in elevation occur, such as along levees or slope breaks. At the upstream section of the 2D flow area, the model is designed to predict flows in Coyote Creek and potential overtopping into adjacent commercial areas in the left floodplain (northwest of the channel). Additionally, the resulting HEC-RAS 2D model can predict flow in the Lower Coyote Creek channel and lateral flow into Bothin Marsh and out of the marsh inlet during high flows, high tide conditions, or any combination of the flows and tides.

Figure 3-4
HEC-RAS 2D Model Grid for Lower Coyote Creek



Model roughness was established with spatially varying Manning's n values, which were selected based on industry standard guidance documents (Chow 1959; USACE 2016), and based on observations of the Coyote Creek project site in-person and from aerial photography. Figure 3-5 shows the spatially varying Manning's n values of the 2D section of the model, which ranged from 0.035 to 0.1. A Manning's n roughness coefficient of 0.025 was selected for the Coyote Creek channel and the existing inlet channel for Bothin Marsh.

Figure 3-5
Spatially Varying Manning's n Roughness Values for Lower Coyote Creek

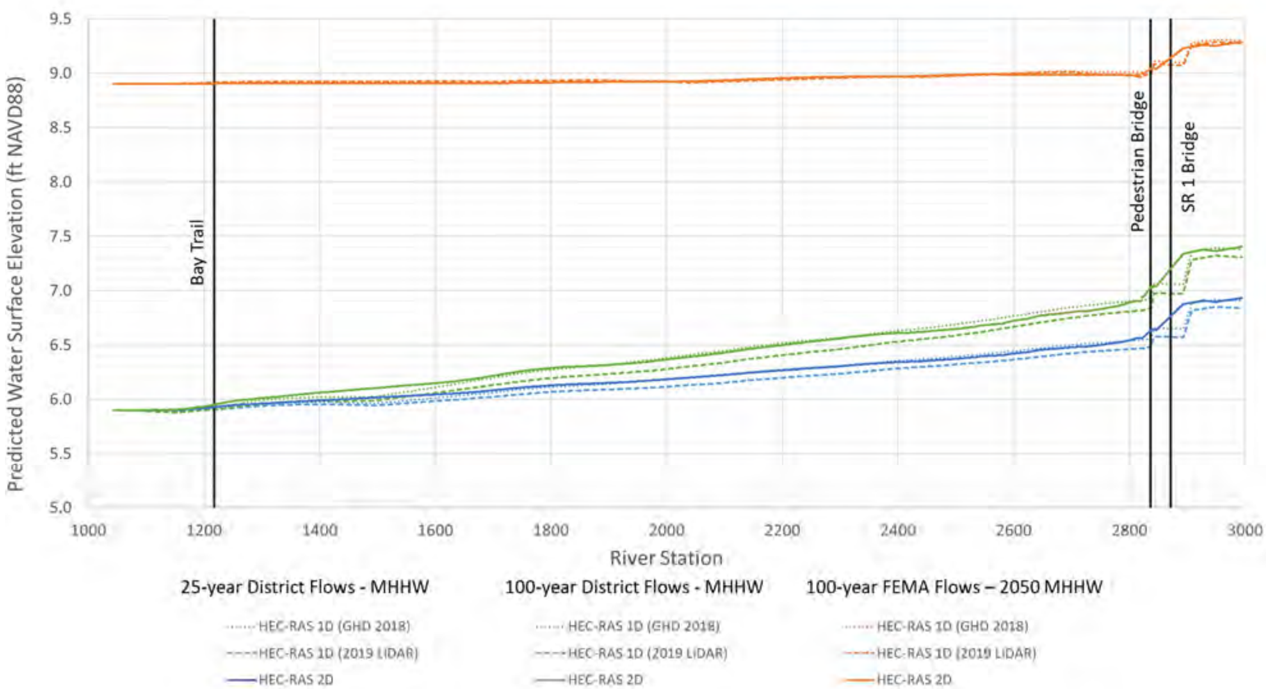


3.3 Existing Conditions Model Comparisons

No hydraulic data were collected as part of this Study. Therefore, calibration and validation efforts were limited. In order to evaluate the accuracy of the coupled 1D/2D model, three simulations that were previous performed as part of the GHD modeling study (GHD 2018) were re-simulated using the HEC-RAD 1D model with updated bathymetry, the newly developed HEC-RAS 1D/2D coupled model with the full 1D channel extent, and the 1D/2D coupled model with the upstream channels truncated. The 25-year and 100-year District flows (Marin County 2014), and the 100-year FEMA flow simulations were performed. The District flows used a downstream tidal elevation of MHHW (+5.9 feet North American Vertical Datum of 1988 [NAVD88]). The FEMA flow simulation used a downstream boundary condition water surface elevation based on the year 2050 predictions of SLR combined with MHHW (+8.9 feet NAVD88). Additional details from these simulations can be found in the GHD report (GHD 2018).

Each of the three simulations was re-simulated for the 1D model with updated 2019 elevations as well as the coupled 1D/2D models using updated 2019 elevations for the 2D model domain. The water surface elevation profile at the peak of each flood wave was extracted from the model results, including the simulation performed by GHD (2018). As shown in Figure 3-6, each water surface elevation was compared from upstream of the SR 1 bridge downstream to Richardson Bay.

Figure 3-6
Coyote Creek Water Surface Elevation Profile Comparison for HEC-RAS 1D and 2D Model Updates

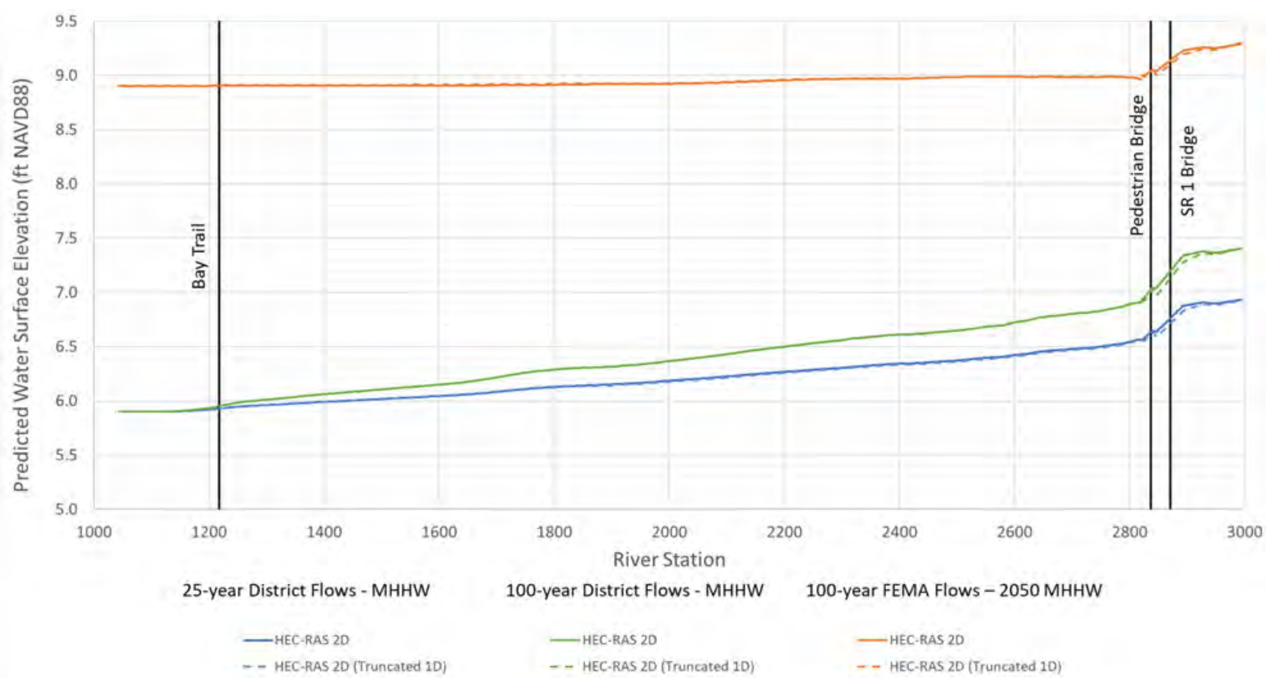


The results show that the predictions of water surface elevation for the revised HEC-RAD 2D model are generally within 0.1 foot (1.2 inches) of the previous modeling efforts using the HEC-RAS 1D (GHD 2018). The results of the updated HEC-RAS 1D model show that the predicted changes in water level resulting from incorporating the 2019 Marin County QL1 LiDAR data are also small. Overall, the 1D model with the 2019 updated LiDAR data show a slightly lower water surface elevation, which is within 0.1 foot of the previous 1D model results from GHD (2018). Near the SR 1 and pedestrian bridges, the cross-sections were adjusted slightly (with one added cross section) to better accommodate the connection to the 1D model, which resulted in some changes up to 0.2 foot (2.5 inches). These changes near the junction of the 1D and 2D portions of the HEC-RAS model domain improved the slope of the hydraulic grade line (more uniform slope) near the junction of the

1D and 2D portions of the model. Overall, the model predictions of water surface elevation were very similar to those reported by GHD (2018) which indicates that updating the model to use the 2019 Marin County QL1 LiDAR and incorporating a 2D grid in the downstream reach of Lower Coyote Creek did not have a significant effect on predicted water levels for these scenarios.

These same three scenarios from GHD (2018) were used to compare the predicted water surface elevation for the HEC-RAS 2D model that included the full 1D channels (Figure 3-2) and the HEC-RAS 2D model that truncated the upstream 1D channels (Figure 3-3). Figure 3-7 shows the comparison of water surface elevation results between these two HEC-RAS 2D models. The largest differences (less than 0.1 feet) were observed in the areas of the steep hydraulic gradient through the SR 1 and pedestrian bridges. These comparisons show that truncating the upstream reaches of the 1D channels did not significantly affect water levels in the Study area. The HEC-RAS 2D model with the upstream 1D channels truncated to improve the stability of the coupled 1D/2D model was used to evaluate three conceptual alternatives for the Coyote Creek channel realignment through Bothin Marsh for a variety of flow and tidal conditions.

Figure 3-7
Coyote Creek Water Surface Elevation Profile Comparison HEC-RAS 2D Model Updates



4 Development of Realignment Geometry and Hydraulic Scenarios

This section outlines the development of the model geometry for three realignment alternatives being considered in the restoration of Lower Coyote Creek and Bothin Marsh and the development of the boundary conditions for the five hydraulic scenarios used to evaluate the three realignment alternatives.

Conceptual Alternative 1 developed by Watershed Sciences for Marin County Parks and the District in October 2019 (Watershed Sciences 2019) was used as the basis for the development of the first two alternatives, Alternative 1 and Alternative 2. These two alternatives follow the same alignment and have the same thalweg depth but include different assumptions for side slopes that result in different cross-sectional areas. The hydraulic modeling indicated that both Alternative 1 and Alternative 2 resulted in a significant increase in upstream water surface elevations during high flows. Based on these results, a third alternative was developed, in coordination with the Bothin Marsh Evolving Shorelines Project, that incorporated a larger cross-sectional area and less sinuous alignment.

Five hydraulic scenarios were developed to bracket a wide range of tidal and flow conditions on Lower Coyote Creek (Table 4-1).

Table 4-1
Five Hydraulic Scenarios for Evaluation or Realignment Alternatives

Scenario	Conditions
1	Representative spring tides under low creek flow conditions
2	Q20 design storm at MHHW and spring tide boundary conditions
3	Q100 design storm at MHHW and spring tide boundary conditions
4	Q10 flow against a FEMA 100-year tide level (coastal flooding)
5	Q20 or Q100 design storm at MHHW plus 2.4 to 2.6 feet of SLR based on State of California SLR guidance

The specific flow and tidal boundaries for each of the five hydraulic scenarios were developed after reviewing the following information with the District:

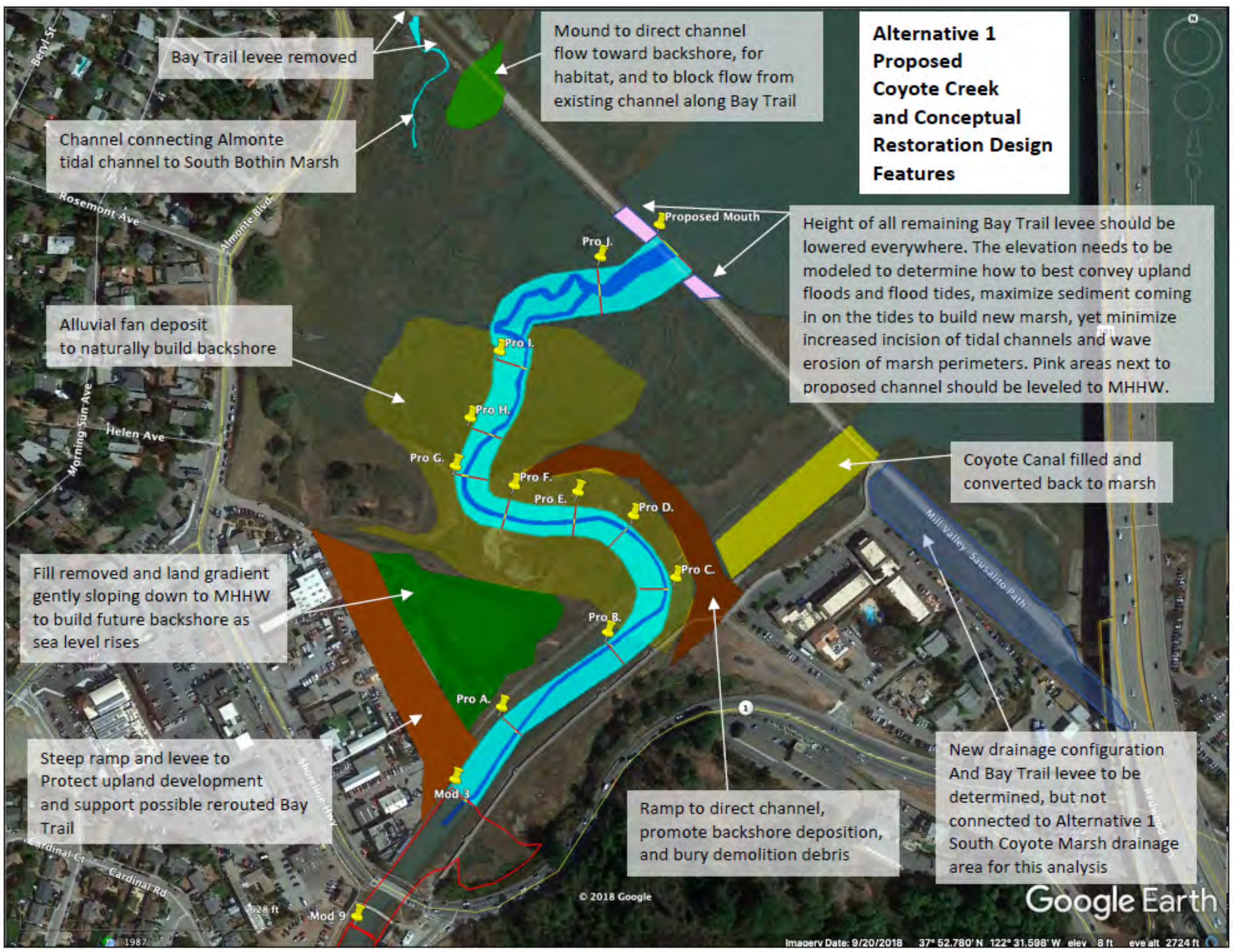
- HEC-HMS flows (Appendix A)
- National Oceanic and Atmospheric Administration (NOAA) tidal datums and spring tide predictions for the Sausalito, COE Dock (9414819) and measured tides from the NOAA San Francisco station (9414290)
- 2018 State of California SLR guidance (OPC 2018)
- SLR planning assumptions being used by the Bothin Marsh Evolving Shorelines Project

This information, discussed in additional detail in the Section 4.2, was used to develop the specific boundary condition assumptions for each of the five hydraulic scenarios evaluated.

4.1 Development of Realignment Alternatives

Three realignment alternatives for the restoration of Lower Coyote Creek and Bothin Marsh were developed. The first two realignment alternatives (Alternative 1 and Alternative 2) were based on the conceptual Alternative 1 (Figure 4-1) and the hydraulic geometry calculations proposed for conceptual Alternative 1 (Watershed Sciences 2019).

Figure 4-1
2019 Conceptual Alternative 1: Proposed Coyote Creek and Conceptual Restoration Design Features



Notes:
"Pro D" indicates the location of Profile D, which is used in Figure 4-2 for the comparison to the cross-sections for realignment Alternative 1 and Alternative 2.
Source: Watershed Sciences (2019)

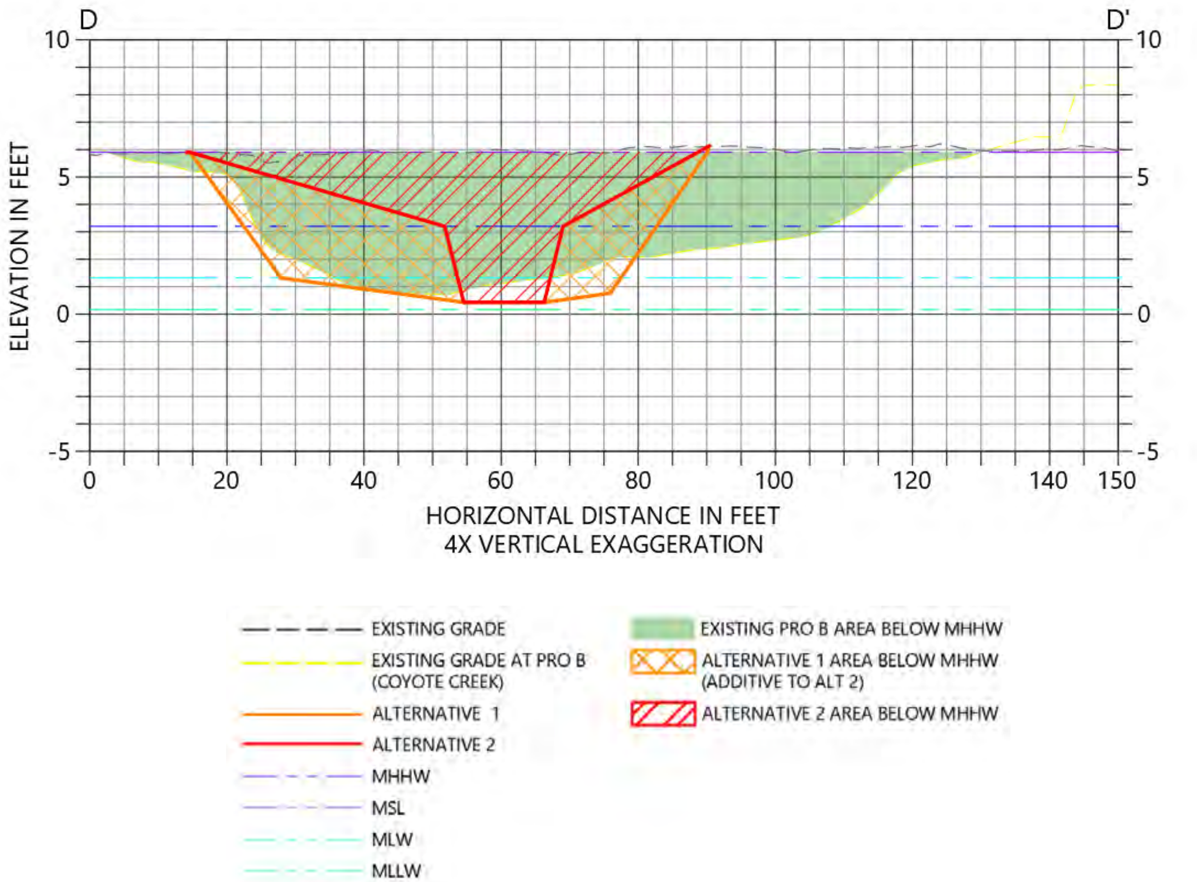
The hydraulic geometry developed for conceptual Alternative 1 by Watershed Sciences (2019) provides the channel width at mean lower low water (MLLW) and MHHW and the thalweg depth (Table 4-2). However, because this hydraulic geometry does not provide a target cross-sectional area, there are a wide range of side slopes that can be developed that maintain these widths at MLLW and MHHW but result in different cross-sectional areas. Two different assumptions were made for side slopes to develop cross-section geometries for realignment Alternative 1 and realignment Alternative 2 in this Study (Figure 4-2). Both of these cross-section geometries are consistent with the details of the hydraulic geometry proposed for conceptual Alternative 1 by Watershed Sciences (2019) since they have the same width at MHHW, the same width at MLLW, and the same thalweg depth. The cross sections for Alternatives 1 and 2 at Profile D (see Figure 4-1 for location) are shown in Figure 4-2. However, the cross section for Alternative 2 has a smaller area than the corresponding cross section for Alternative 1. These two cross sections are compared to the existing cross section of Coyote Creek at Profile B to illustrate that both Alternatives 1 and 2 have a smaller cross-sectional area than the existing channel. Both Alternative 1 and Alternative 2 included a berm on the east side of the realigned channel along the outside of the first channel meander, which directed the channel through the back of the marsh to promote backshore deposition (labeled as "ramp to direct channel" in Figure 4-1). For both Alternative 1 and Alternative 2, the crest elevation of this "ramp" was assumed to be 12 feet NAVD88.

Table 4-2
Proposed Width at MHHW, Proposed Thalweg Depth, and Proposed Low Water Depth for Alternative 1 from Watershed Sciences (2019), Which Were Used for the Development of Alternative 1 and Alternative 2 in This Study

	Alternative 1 and Alternative 2		
Cross-Section Name[1]	Width at MHHW (feet)	Thalweg Depth (feet)	Width at Low Water (feet)
Pro J.	119	6.8	30
Pro I.	86	5.9	16.6
Pro H.	81	5.76	14.8
Pro G.	84	5.66	14.9
Pro F.	79	5.54	13.4
Pro E.	78	5.4	12.6
Pro D.	75	5.3	11.7
Pro C.	78	5.18	11.7
Pro B.	70	4.8	10.1
Pro A.	70	4.6	9.3

Note:
1. Cross-section locations are shown in Figure 4-1.

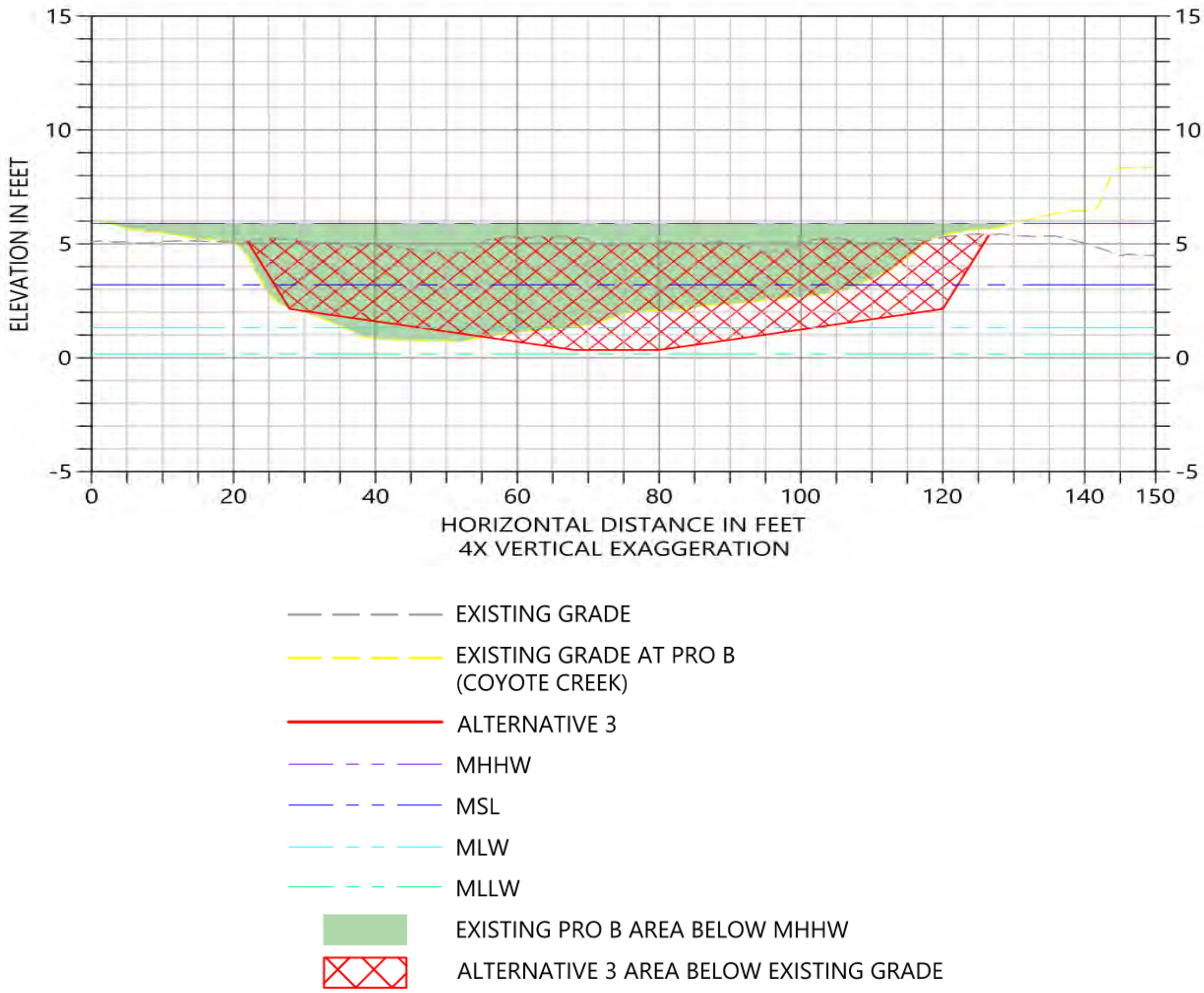
Figure 4-2
Example Cross-Section for Alternatives 1 and 2 at Profile D



Notes:
See Figure 4-1 for profile locations.
Elevation in feet NAVD88

A third realignment alternative (Alternative 3) was developed to more closely match the existing profile area and flow capacity. Figure 4-3 compares the existing cross-section geometry to a representative cross-section for Alternative 3. The goal of this new alternative was to provide a bookend for a wider, non-geomorphic channel with very limited sinuosity in order to assess if a minimal realignment alternative with the same channel cross-sectional area could be implemented without upstream flooding impacts. As such, this allows future design consultants to iterate different channel geometries and realignment locations that may better transport sediment onto the marsh and improve future marsh sustainability.

Figure 4-3
Example Cross-Section for New Alternative 3



Notes:
See Figure 4-1 for profile locations.
Elevation in feet NAVD88

While the Alternative 1 and 2 channels follow the channel alignment proposed in the conceptual Alternative 1 path developed by Watershed Sciences (Figure 4-1) and include a ramp adjacent to the channel. The channel alignment for Alternative 3 follows a less sinuous path from the existing channel to the Bay Trail pedestrian bridge over the existing entrance to South Bothin Marsh compared to Alternatives 1 and 2, and it excludes the ramp. Figures 4-4 through 4-7 show the 2D model grid and associated topography for the existing conditions and the three alternatives used in the realignment modeling analysis.

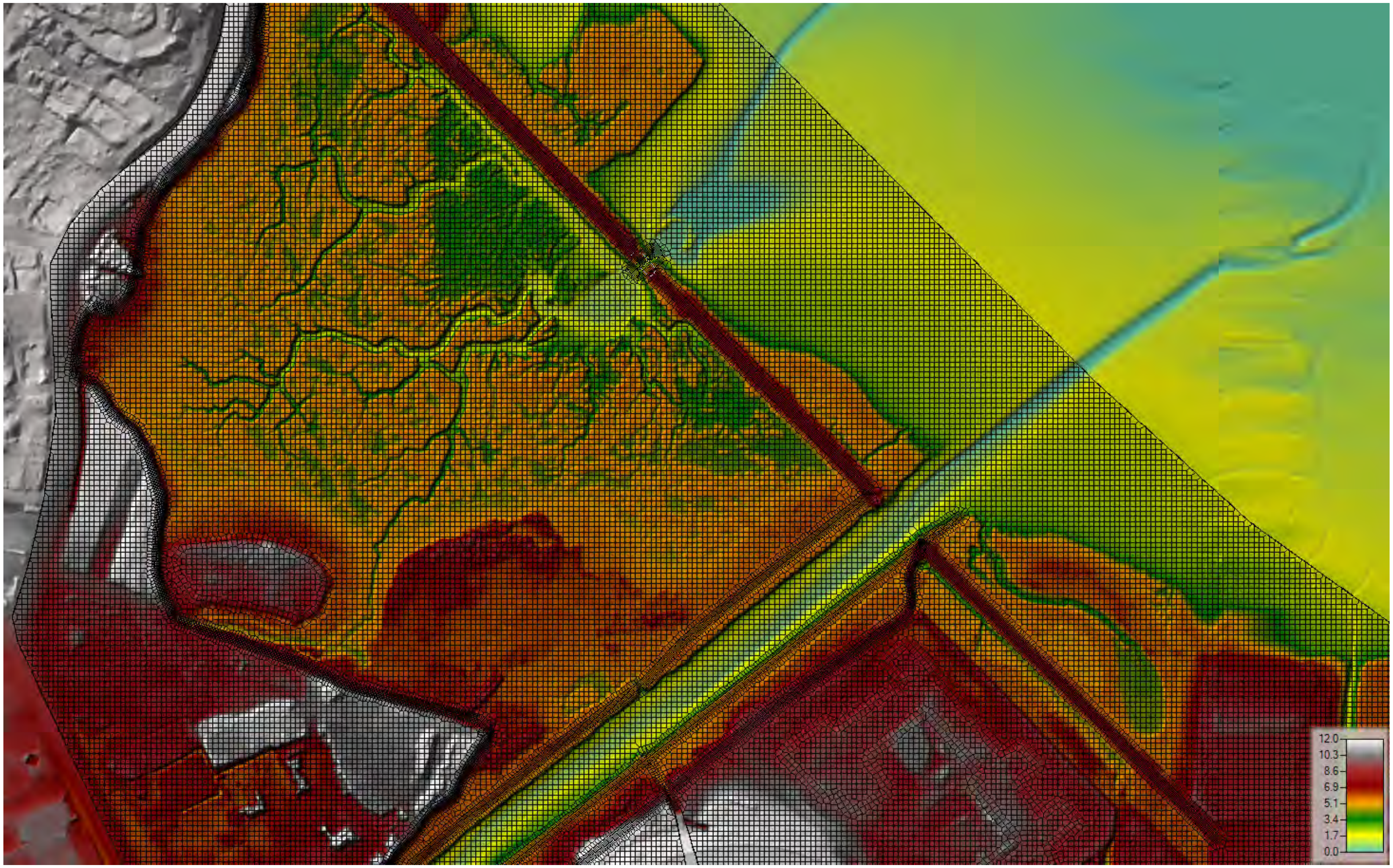
Anchor QEA developed grading plans for three channel realignment alternatives. All three grading plans incorporate the closure of the existing mouth of Coyote Creek and the realignment of Coyote Creek through Bothin Marsh. The geometry for each alternative was developed using AutoCAD 3D to allow for efficient creation of sections, cut and fill calculations, and conversion of the grading surfaces into 2D model surfaces for use in the HEC-RAS 2D model. Cut and fill calculations for the three realignment alternatives are provided in Table 4-3.

Table 4-3
Cut and Fill Calculations for Realignment Alternatives in Cubic Yards

Feature	Alternative		
	1	2	3
Channel Cut	17,144	8,420	11,460
Ex. Channel Fill	9,288	9,203	11,356
FP Berm Fill	5,206	5,206	NA
Upland Regrade Cut	7,176	7,176	NA
Upland Regrade Fill	1,353	1,353	NA
Total Cut	**24,320**	**15,596**	**11,460**
Total Fill	**15,847**	**15,762**	**11,356**
Net	**C-8473**	**F+166**	**C-104**

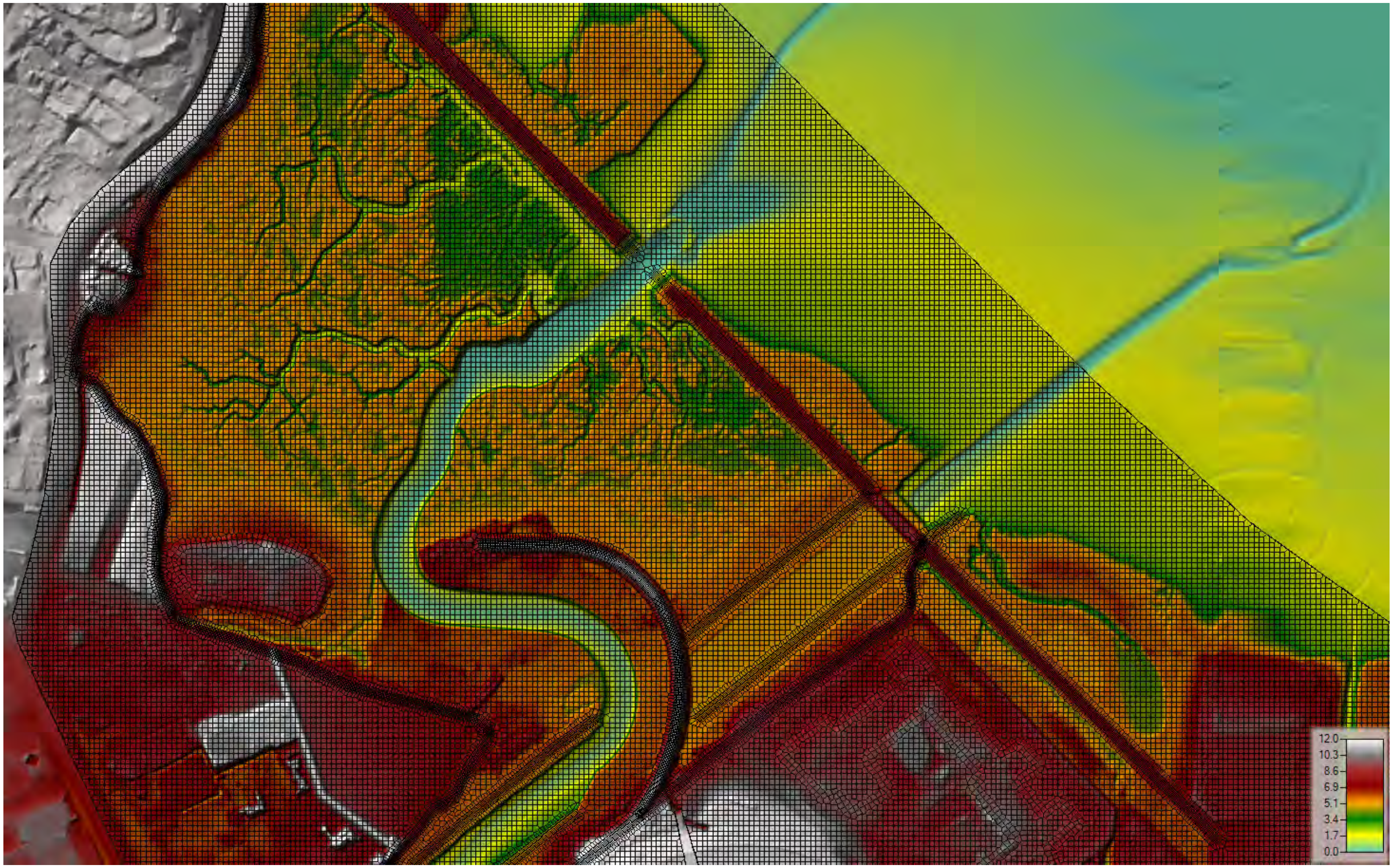
Notes:
All volumes are in cubic yards.
C: Cut
F: Fill

Figure 4-4
HEC-RAS 2D Model Geometry for Existing Conditions



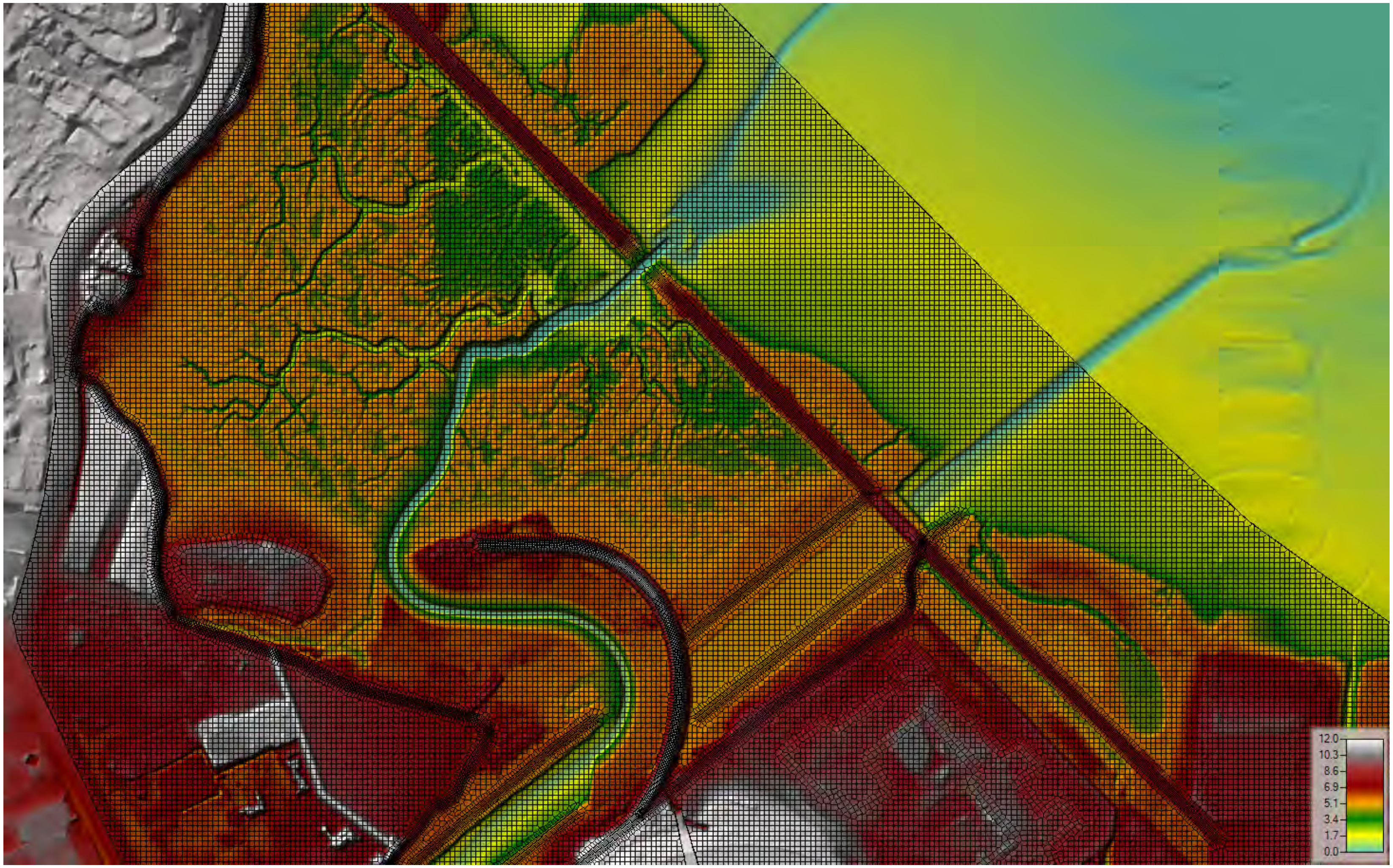
Note:
See Figure 3-2 for full model extent.

Figure 4-5
HEC-RAS 2D Model Geometry for Alternative 1



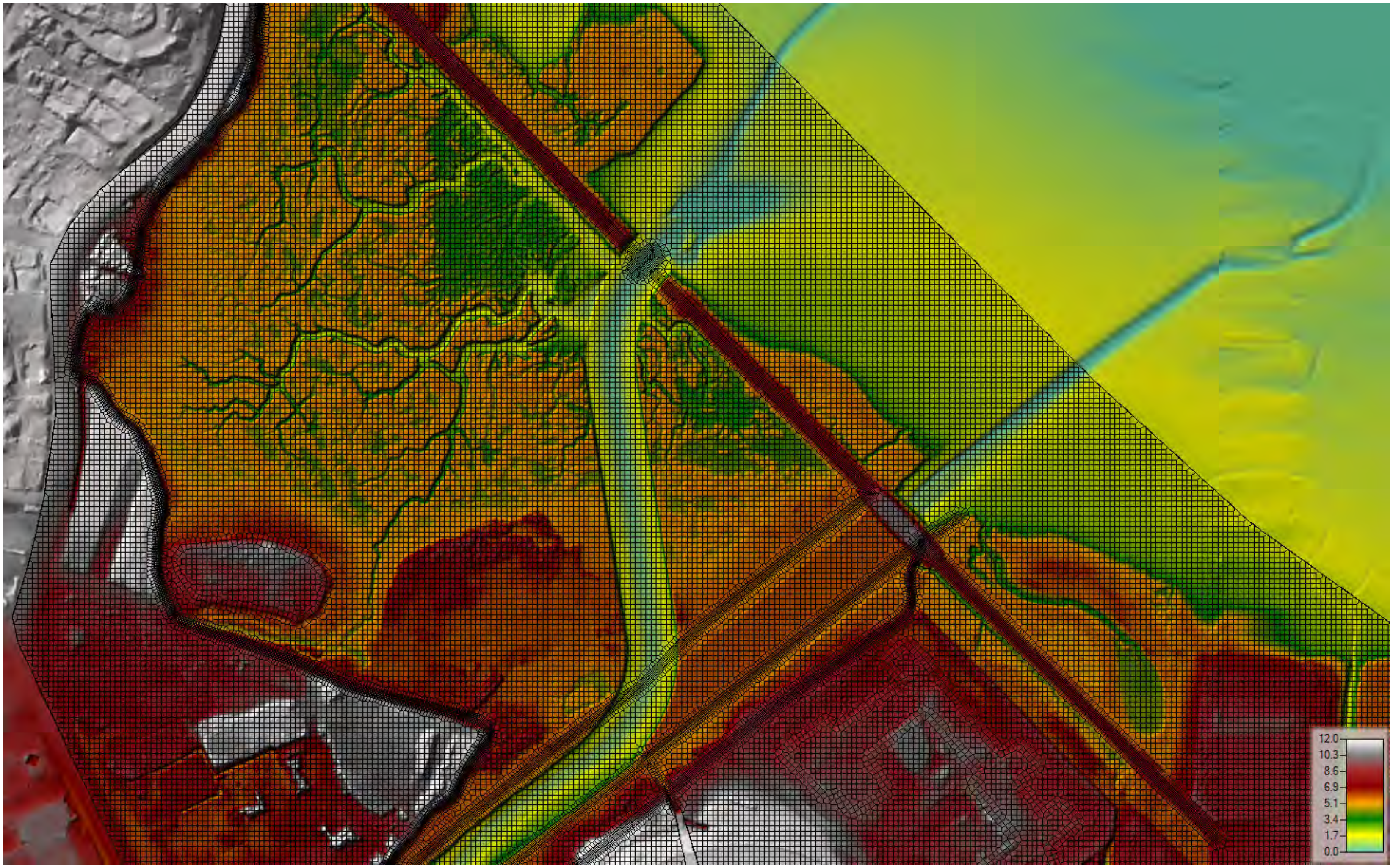
Note:
See Figure 3-2 for full model extent.

Figure 4-6
HEC-RAS 2D Model Geometry for Alternative 2



Note:
See Figure 3-2 for full model extent.

Figure 4-7
HEC-RAS 2D Model Geometry for Alternative 3



Note:
See Figure 3-2 for full model extent.

4.2 Model Boundary Conditions

This section describes the details of the boundary conditions for the hydraulic scenarios used to evaluate the three realignment alternatives. The boundary conditions for the five hydraulic scenarios (Table 4-1) were developed to bracket a wide range of tidal and flow conditions, and the specific details for each scenario were developed in coordination with the District.

4.2.1 HEC-HMS Flows

Following the review of previous flow studies for Coyote Creek and a review of the HEC-HMS modeling conducted by Marin County, recommended flow values were developed and presented in the memorandum *Coyote Creek Hydrology Flood Flow Estimates* (Anchor QEA 2020a), which is included as Appendix B. The recommended design flows from the HEC-HMS model are presented in Table 4-4.

Table 4-4
Recommended Design Flows: Coyote Creek Basin

Location	Recommended 10-year Peak Flow (cfs)	Recommended Design (25-year) Flow (cfs)[1]	Recommended 100-year Peak Flow (cfs)	Recommended Base Flow (cfs)
Coyote Creek at County Gage – Ash Street	528	672	910	2.7
Junction J12	386	497	678	2.7
Coyote Creek Subbasin 6	61	77	103	0.2
Coyote Creek Subbasin 5	34	43	57	0.1
Coyote Creek Subbasin 4	7.3	9.1	12	0.0
Coyote Creek Subbasin 3	38	48	63	0.1
Coyote Creek Subbasin 2	22	28	38	0.1
Crest Marin Creek Subbasin 1	30	37	49	0.1
Crest Marin Creek	86	110	149	0.5
Nyhan Creek Subbasin 1[2]	22	27	37	0.1

Notes:

1. Recommended design flow is based on the HEC-HMS results for the 25-year event.
2. Nyhan Creek is listed as Tennessee Creek in the FEMA Flood Insurance Study (FEMA 2017).

These design flow hydrographs from the HEC-HMS model were used as inflow boundary conditions in the HEC-RAS hydraulic scenarios. Hydraulic Scenario 1 is a steady state low creek flow condition, which was simulated using constant base flow values as presented in Table 4-4. Hydraulic Scenarios 2 through 5 used the storm flow hydrographs developed using HEC-HMS.

4.2.2 Tidal Datums and Water Level Predictions

The downstream boundary of the HEC-RAS model was driven by tidal elevations based on the NOAA tidal station at the Sausalito, COE Dock (9414819) and the San Francisco station (9414290) located near the southern side of the Golden Gate Bridge. The tidal datums for these stations are listed in Table 4-5.

Table 4-5
Tidal Datums for Sausalito, COE Dock and San Francisco (9414819 and 9414290)

Water Level	Sausalito, COE Dock (9414819) feet NAVD88	San Francisco (9414290) feet NAVD88
Highest Astronomical Tide	NA	7.32
MHHW	5.91	5.90
MSL	3.26	3.18
MLLW	0.17	0.06

Four of the HEC-RAS simulations use time-varying tidal elevations at the downstream boundary in Richardson Bay, and one scenario uses a constant downstream water level (Table 4-1). For Scenario 4, the downstream water level was held constant at the 100-year FEMA water level. The Flood Insurance Study for Marin County (FEMA 2017) lists the following still water elevations for San Francisco Bay coastal areas which are applicable at the Coyote Creek site (stations B161 and B162):

- 10-year: 8.3 feet NAVD88
- 50-year: 9.3 feet NAVD88
- 100-year: 9.8 feet NAVD88
- 200-year: 11.5 feet NAVD88

Based on these reported values, the downstream elevation for Scenario 4 was set to 9.8 feet NAVD88.

The remaining four hydraulic scenarios used time-varying tidal water surface elevations at the downstream boundary. Although tides and tidal range vary throughout the year, a representative spring tide condition was selected to specify the downstream water level for each hydraulic scenario. Because the primary comparisons in this Study are between the existing conditions and each realignment alternative, the selection of a representative spring tide condition is not likely to influence the conclusions of this Study because the same tidal conditions are used for to evaluate all alternatives. Several spring tide conditions were considered for developing the downstream boundary condition (Figure 4-8), including the following:

- May spring tides: Predicted tides from NOAA Sausalito, COE Dock station (9414819) for May 19 through May 25, 2020
- December spring tides: Predicted tides from NOAA Sausalito, COE Dock station (9414819) for December 10 through December 17, 2020
- Extreme spring tides: Measured Tides from NOAA San Francisco station (9414290) for the model simulation period (December 30, 2005, through January 1, 2006)

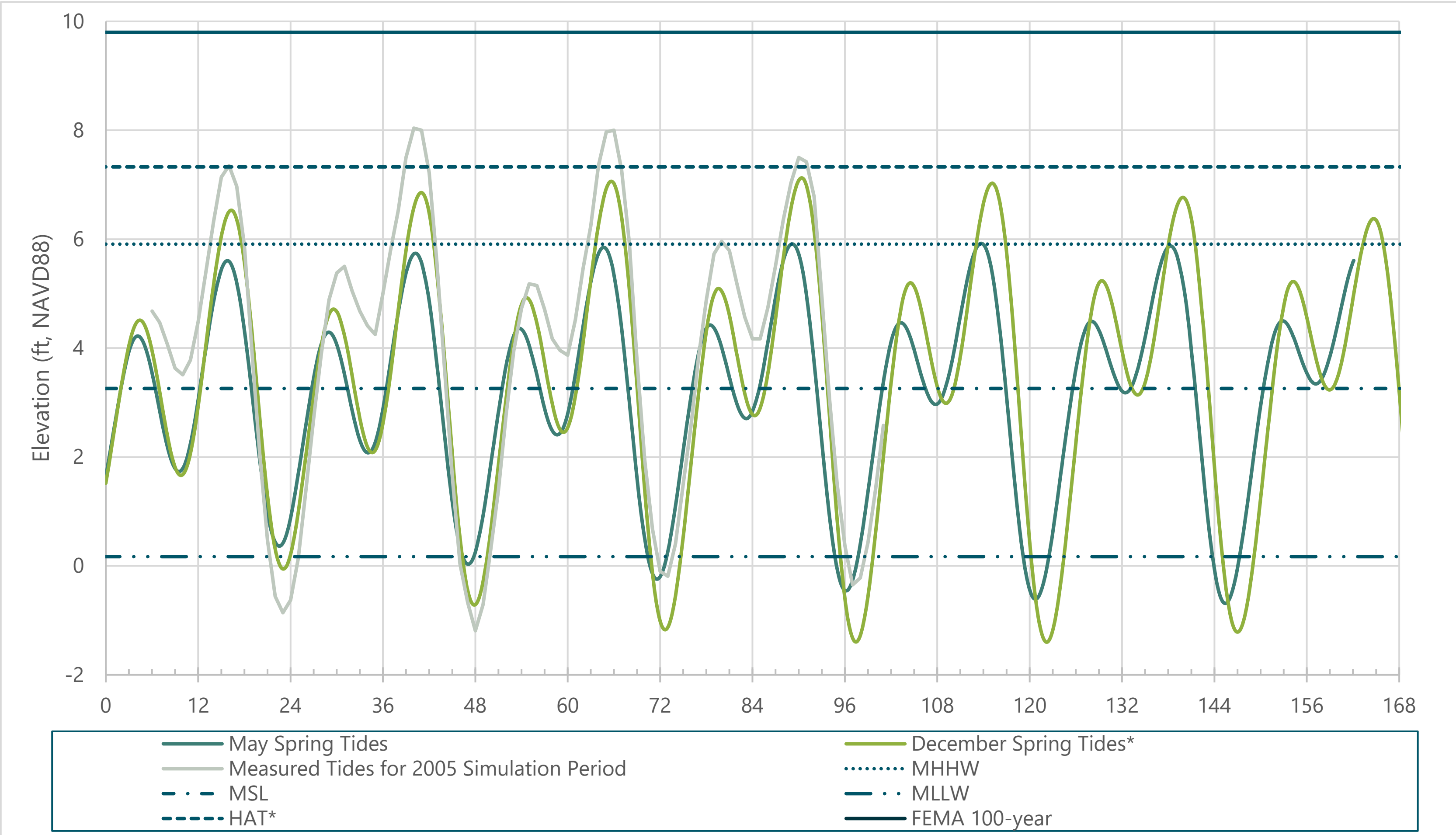
Following review of the tidal data with the District, the following downstream tidal boundary conditions were selected for the modeling scenarios (Table 4-6).

Table 4-6
Downstream Tidal Boundary Conditions for Hydraulic Scenarios

Hydraulic Scenario	Downstream Tidal Boundary Conditions
1	Measured tide data from NOAA San Francisco station (9414290) from December 30,2005, to January 2, 2006
2	Predicted December 2020 Spring Tides (Predicted tide data NOAA Sausalito, COE Dock [9414819])
3	Predicted December 2020 Spring Tides (Predicted tide data NOAA Sausalito, COE Dock [9414819])
4	A steady tidal boundary of 9.8 feet NAVD88
5	Measured tide data from NOAA San Francisco station 9414290 from December 30, 2005, to January 2, 2006, plus SLR

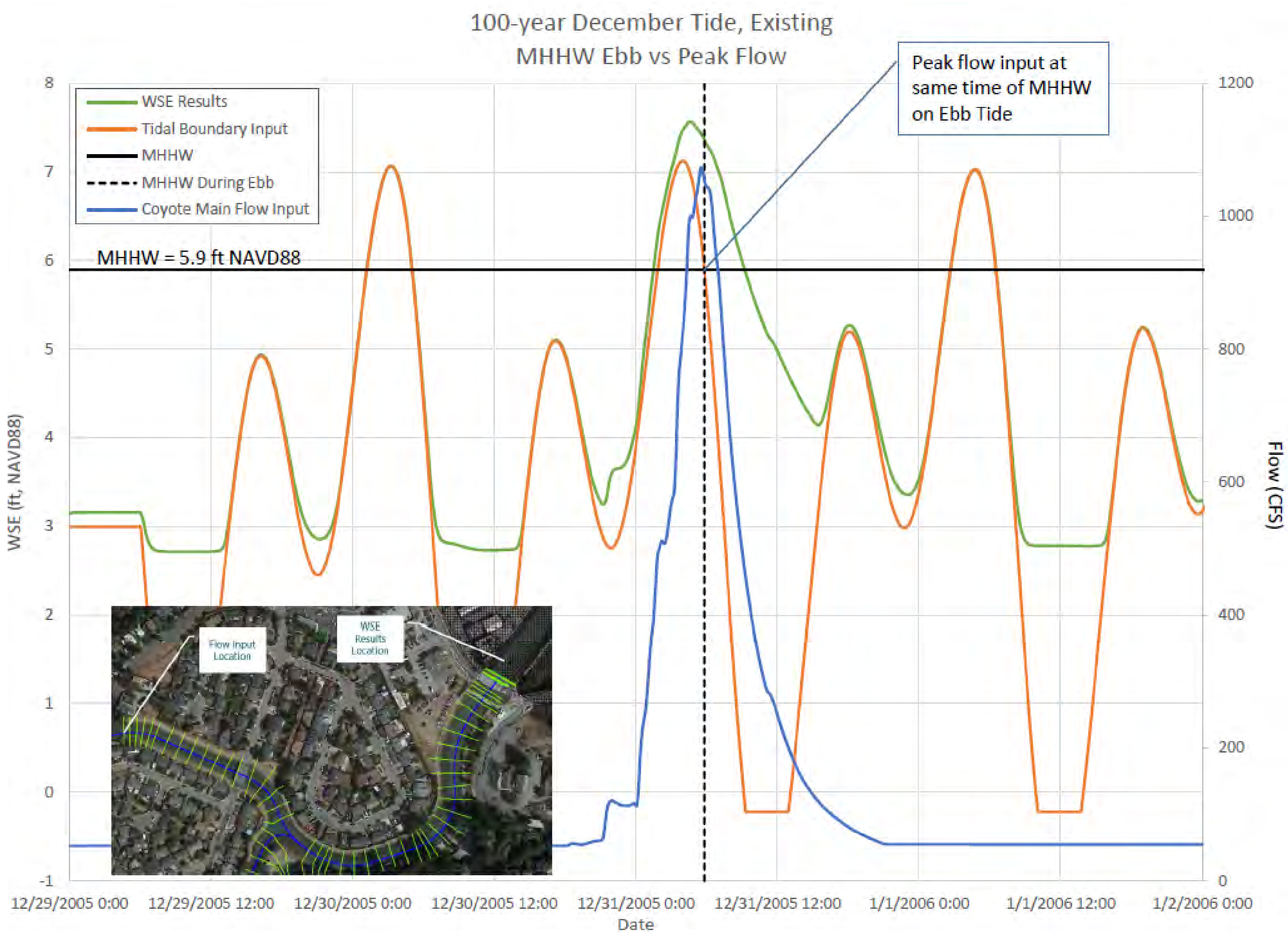
One other factor considered in establishing the boundary conditions was the timing of the peak flow relative to the peak tidal elevation. This can be important because the effect of a high flow at high tide results in a higher peak water level than the same flow with a peak near low water. However, assuming a 100-year flow exactly coincident with a 100-year tidal elevation can be overly conservative because the resulting event would have a longer expected return interval than 100 years. For hydraulic Scenarios 2, 3, and 5, the peak flow was specified to occur at MHHW during the ebb tide immediately following higher high water. To align the flow peak at MHHW, several HEC-RAS simulations were conducted and the flow hydrograph timing was adjusted until the peak flow occurred in the main channel of Lower Coyote Creek at MHHW under existing conditions. Figure 4-9 shows the water surface elevation results from Scenario 3-ex (100-year flow, existing conditions) and shows the relative timing of higher high water, the peak flow at the Coyote Creek project site, and the resulting water surface elevation. The same timing of the flow hydrograph relative to tidal water levels established based on existing conditions was used for each of the three realignment alternatives.

Figure 4-8
Comparison of Spring Tide Periods Evaluated for Downstream Boundary Conditions



Note:
*Highest astronomical tide (HAT) and December Spring Tides are based on the San Francisco station (9414290), while other water levels are based on the Sausalito, COE Dock station (9414819) and FEMA 100-year water level.

Figure 4-9
Peak Flow at MHHW on Ebb Tide



4.2.3 Sea Level Rise

SLR is expected to cause additional flooding to the Bothin Marsh area, which already experiences flooding at existing high tides. Hydraulic Scenario 5 was developed to evaluate the effect of the realignment alternatives on water levels during the 100-year flow with SLR.

SLR estimates for the Coyote Creek and Bothin Marsh project site were taken from the California Coastal Commission's (CCC) Sea Level Rise Policy Guidance (CCC 2018) for San Francisco. The CCC's SLR guidance is based on estimates from the Ocean Protection Council's (OPC's) *State of California Sea-Level Rise Guidance: 2018 Update* (OPC 2018). The various ranges of SLR estimates are outlined in Table 4-7

Table 4-7
Project Sea Level Rise (in feet): San Francisco

Year	Low Risk Aversion	Medium-High Risk Aversion	Extreme Risk Aversion
2050	1.1	**1.9**	2.7
2060	1.5	2.6	3.9
2070	1.9	3.5	5.2
2080	2.4	4.5	6.6
2090	2.9	5.6	8.3
2100	3.4	6.9	10.2
2110	3.5	7.3	11.9
2120	4.1	8.6	14.2

Note:
A 1.9-foot increase in sea level was selected for use in the modeling analysis of SLR.

OPC provides the following three scenarios for use in planning, permitting, investment, and other decisions:

- Low risk aversion scenario: The upper value for the "likely range" (which has approximately a 17% chance of being exceeded); may be used for projects that would have limited consequences or a higher ability to adapt
- Medium-high risk aversion scenario: The 1-in-200 chance (or 0.5% probability of exceedance); should be used for projects with greater consequences and/or a lower ability to adapt
- Extreme risk aversion: Accounts for the extreme ice loss scenario (which does not have an associated probability at this time); should be used for projects with little to no adaptive capacity that would be irreversibly destroyed, significantly costly to repair, and/or would have considerable public health, public safety, or environmental impacts should that level of SLR occur

Based on discussion with the District and coordination with Bothin Marsh Evolving Shorelines Project, the medium-high risk aversion scenario for 2050 value of 1.9 feet was selected for developing the SLR assumptions. Therefore, 1.9 feet of SLR was added for the evaluation of SLR under hydraulic Scenario 5.

4.3 List of HEC-RAS Model Simulations

The combination of four channel geometries—existing conditions plus three channel realignment scenarios—and five hydraulic conditions results in a total of 20 HEC-RAS model simulations. Table 4-8 lists the full scenario list with a summary of the boundary condition details for each scenario.

Table 4-8
Hydraulic Scenarios for Restoration Design Analysis

Scenario	Condition: Flow	Condition: Tidal Boundary	Design Alternative
1-ex	Steady Low Flow (see Table 4-4 Base Flows)	Extreme Spring Tides (Measured tide data from NOAA San Francisco station 9414290 from December 30, 2005, to January 2, 2006)	Existing
1-1			Alternative 1
1-2			Alternative 2
1-3			Alternative 3
2-ex	25-Year HEC-HMS Flow with peak flow occurring at MHHW during the ebb tide[1]	Predicted December 2020 Spring Tides (Predicted tide data NOAA Sausalito, COE Dock [9414819])	Existing
2-1			Alternative 1
2-2			Alternative 2
2-3			Alternative 3
3-ex	100-Year HEC-HMS Flow with peak flow occurring at MHHW during the ebb tide[1]		Existing
3-1			Alternative 1
3-2			Alternative 2
3-3			Alternative 3
4-ex	10-Year HEC-HMS Flow	FEMA 100-year coastal water level (Steady tidal boundary of 9.8 feet NAVD88)	Existing
4-1			Alternative 1
4-2			Alternative 2
4-3			Alternative 3
5-ex	100-Year HEC-HMS Flow with peak flow occurring at equivalent MHHW during the ebb tide[2]	Predicted December 2020 Spring Tides plus 1.9 feet of SLR (Predicted tide data NOAA Sausalito, COE Dock [9414819])	Existing
5-1			Alternative 1
5-2			Alternative 2
5-3			Alternative 3

Notes:
1. The flow input time was adjusted to correspond to the peak flow occurring in the main channel of Lower Coyote Creek at MHHW during ebb tide (see Figure 4-9).
2. The flow for Scenario 5 is identical to Scenario 3; however, the tides are increased due to SLR, and therefore the peak flow occurs in the main channel of Lower Coyote Creek at a higher tide level than existing MHHW.

5 Evaluation of Lower Coyote Creek Realignment Alternatives

The primary objective of the hydraulic modeling and analysis conducted as part of this Study was to evaluate the effect of the realignment on peak water levels under a wide range of tidal and fluvial conditions. As a result, the assessment of the realignment alternatives focuses on the predicted water surface elevation for each scenario. For each hydraulic scenario, the predicted water levels for each of the three realignment alternatives were compared to the predicted water levels under existing conditions. These comparisons included comparison of water surface elevation time series in the channel of Coyote Creek, comparisons of maximum water surface elevation profiles along Coyote Creek, and planform maps showing the maximum water surface elevation for each scenario. Additionally, planform maps of maximum predicted velocity were used to visually assess whether the channel geometries resulted in a noticeable change in peak velocities relative to existing conditions.

5.1 Water Surface Elevation Time Series

The predicted water surface elevation over time was compared at a single point across all realignment alternatives (including existing conditions) and hydraulic scenarios. The point selected for these comparisons is located in the main channel of Coyote Creek, just downstream of the SR 1 bridge and near the upstream extent of the 2D portion of the model domain (Figure 5-1). The location where the time series comparisons are made is upstream of the reach where the stream alignment varies between alternatives, which makes it an ideal location for comparing water level time series between different alignment alternatives.

Figures 5-2 through 5-6 show the water surface elevations over time at the reference point for the existing conditions and the three realignment alternatives for each of the five hydraulic scenarios. The predicted maximum water level for each scenario is shown in Table 5-1.

For hydraulic Scenario 1 (Low Flow, Extreme Tide), the predicted water surface time series for all four channel geometries is very similar, with the maximum predicted difference in peak water level between the four channel geometries of 0.03 foot. The predicted water levels for all four channel geometries show small timescale variability that results from using 6-minute observed water levels at the downstream boundary. This effect is not evident in Scenarios 2, 3, and 5, which use NOAA-predicted tides that are based on predictive harmonic analysis for the downstream boundary. Alternative 1 and Alternative 2 have slightly lower peak water levels than under existing conditions, reflecting a smaller channel capacity to propagate the flood tide in the downstream portion of Coyote Creek. This also results in slower draining towards low water for Alternative 2, which has the smallest channel capacity (grey line in Figure 5-2). The maximum predicted water level for Alternative 3, the alternative with the largest channel capacity in the realigned reach, is identical to the maximum predicted water level under Existing Conditions.

Table 5-1
Hydraulic Scenarios and Modeled Maximum Water Level Results for Restoration Design Analysis

Scenario	Hydraulic Scenario	Design Alternative	Modeled Maximum Water Level Immediately Downstream of SR 1 Bridge (feet NAVD88)	Change in Modeled Maximum Water Level Relative to Existing Conditions (feet)
1-ex	Scenario 1: Low Flow, Extreme Tide	Existing Conditions	8.22	NA
1-1		Alternative 1	8.20	-0.02
1-2		Alternative 2	8.19	-0.03
1-3		Alternative 3	8.22	0.00
2-ex	Scenario 2: 2: 25-Year Flow, December 2020 Predicted Tide	Existing Conditions	7.38	NA
2-1		Alternative 1	7.66	0.28
2-2		Alternative 2	8.11	0.73
2-3		Alternative 3	7.39	0.01
3-ex	Scenario 3: 100-Year Flow, December 2020 Predicted Tide	Existing Conditions	7.57	NA
3-1		Alternative 1	7.97	0.40
3-2		Alternative 2	8.53	0.96
3-3		Alternative 3	7.59	0.02
4-ex	Scenario 4: 10-Year Flow, FEMA 100-Year Coastal Water Level	Existing Conditions	9.81	NA
4-1		Alternative 1	9.85	0.04
4-2		Alternative 2	9.86	0.05
4-3		Alternative 3	9.82	0.01
5-ex	Scenario 5: 100-Year Flow, December 2020 Predicted Tide + SLR	Existing Conditions	9.07	NA
5-1		Alternative 1	9.16	0.09
5-2		Alternative 2	9.23	0.16
5-3		Alternative 3	9.07	0.00

Note:
NA: not applicable

For hydraulic Scenario 2 (Figure 5-3), the predicted water surface time series for all four channel geometries is very similar prior to and after the flow event, with slower draining towards low water for Alternative 2, which has the smallest channel capacity (grey line in Figure 5-3). During the peak flow, Alternative 1 and Alternative 2 result in an increase in maximum water level relative to existing conditions of 0.28 and 0.73 foot, respectively (Table 5-1). This indicates that the smaller channel capacity in Alternative 1 and Alternative 2 results in an increase in upstream water levels during high flows. For Alternative 3, the alternative with the largest channel capacity in the realigned reach, the maximum predicted maximum water level is 0.01 foot higher than under Existing Conditions.

For hydraulic Scenario 3 (Figure 5-4), the results are relatively similar to hydraulic Scenario 2. The predicted water surface time series for all four channel geometries is very similar prior to and after the flow event, with slower draining towards low water for Alternative 2, which has the smallest channel capacity (grey line in Figure 5-4). During the peak flow, Alternative 1 and Alternative 2 result in an increase in maximum water level relative to existing conditions of 0.40 and 0.96 foot, respectively (Table 5-1). This indicates that the smaller channel capacity in Alternative 1 and Alternative 2 results in an increase in upstream water levels during high flows. For Alternative 3, the alternative with the largest channel capacity in the realigned reach, the maximum predicted water level is 0.02 foot higher than under Existing Conditions.

For hydraulic Scenario 4 (Figure 5-5), the FEMA 100-year water surface elevation applied uniformly over time boundary results in a nearly constant water surface predicted for all four geometries, which is equal to the 9.8 feet NAVD88 elevation applied at the downstream boundary. The 10-year flow results in only a relatively small increase in water levels of between 0.01 foot (Existing Conditions) up to 0.06 foot (Alternative 2). This indicates that for this extreme tide scenario, the flows in Coyote Creek have only a small effect on maximum water surface elevation in the downstream portion of Coyote Creek.

For hydraulic Scenario 5 (Figure 5-6), the results are relatively similar to hydraulic Scenario 3, which differs from hydraulic Scenario 5 only in the additional 1.9 feet of SLR applied at the boundary. The predicted water surface time series for all four channel geometries is very similar prior to and after the flow event, with slower draining towards low water and a noticeably higher value of low water during each tidal cycle for Alternative 2, which has the smallest channel capacity (grey line in Figure 5-4). During the peak flow, Alternative 1 and Alternative 2 result in an increase in maximum water level relative to existing conditions of 0.09 and 0.16 foot, respectively (Table 5-1). This indicates that the smaller channel capacity in Alternative 1 and Alternative 2 results in an increase in upstream water levels during high flows. However, with SLR, the channel realignment results in a smaller effect on water levels than under Scenario 3. For Alternative 3, the alternative with the largest channel capacity in the realigned reach, the maximum predicted maximum water level is identical to the maximum predicted water level under Existing Conditions.

Figure 5-1
Time Series Data Location

Note:
Red circle indicates the location where water level time series are compared.

Figure 5-2
Water Surface Elevation in the Main Channel of Coyote Creek for Scenario 1: Low Flow, Extreme Tide

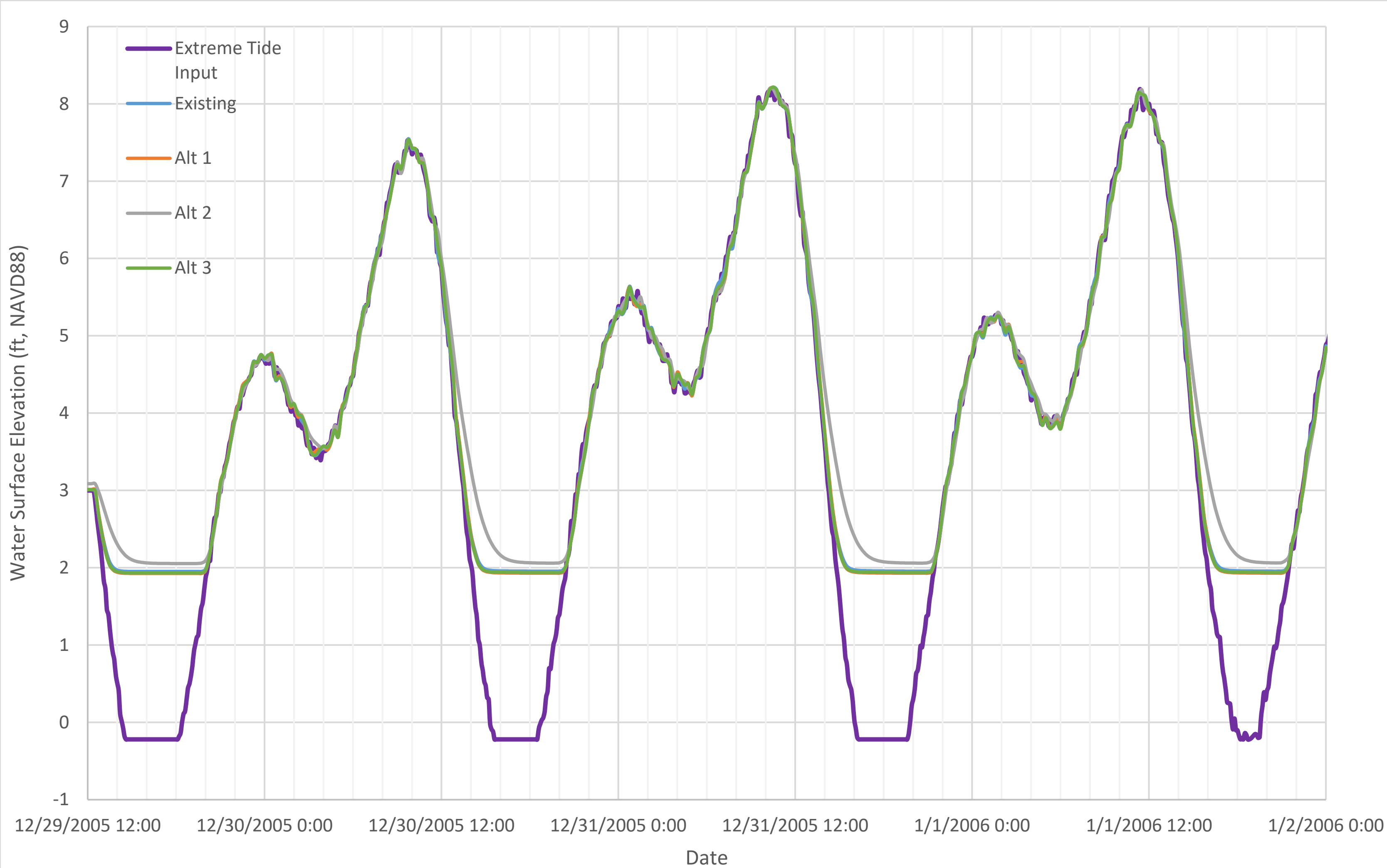


Figure 5-3
Water Surface Elevation in the Main Channel of Coyote Creek for Scenario 2: 25-Year Flow, December 2020 Tide

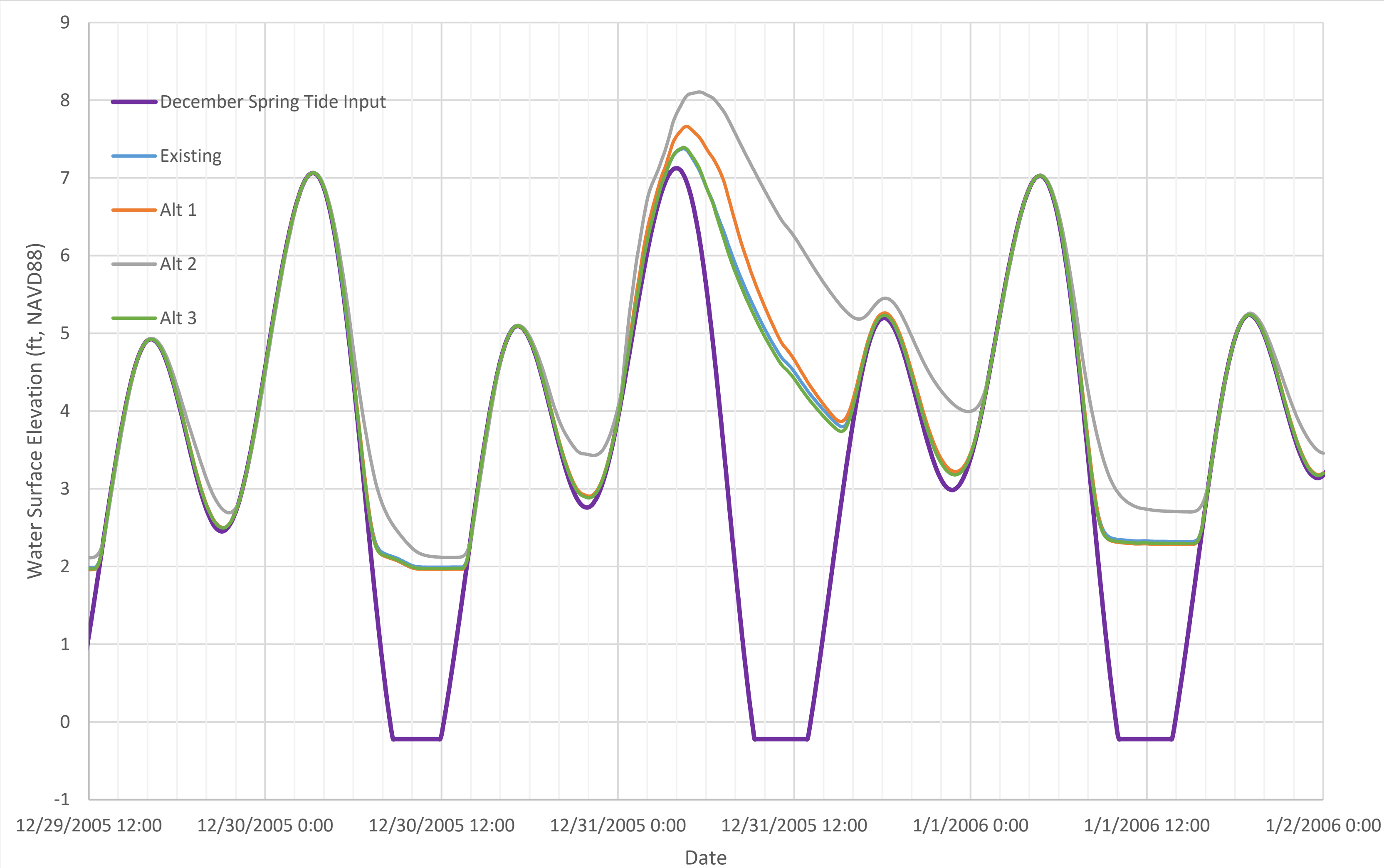


Figure 5-4
Water Surface Elevation in the Main Channel of Coyote Creek for Scenario 3: 100-Year Flow, December 2020 Tide

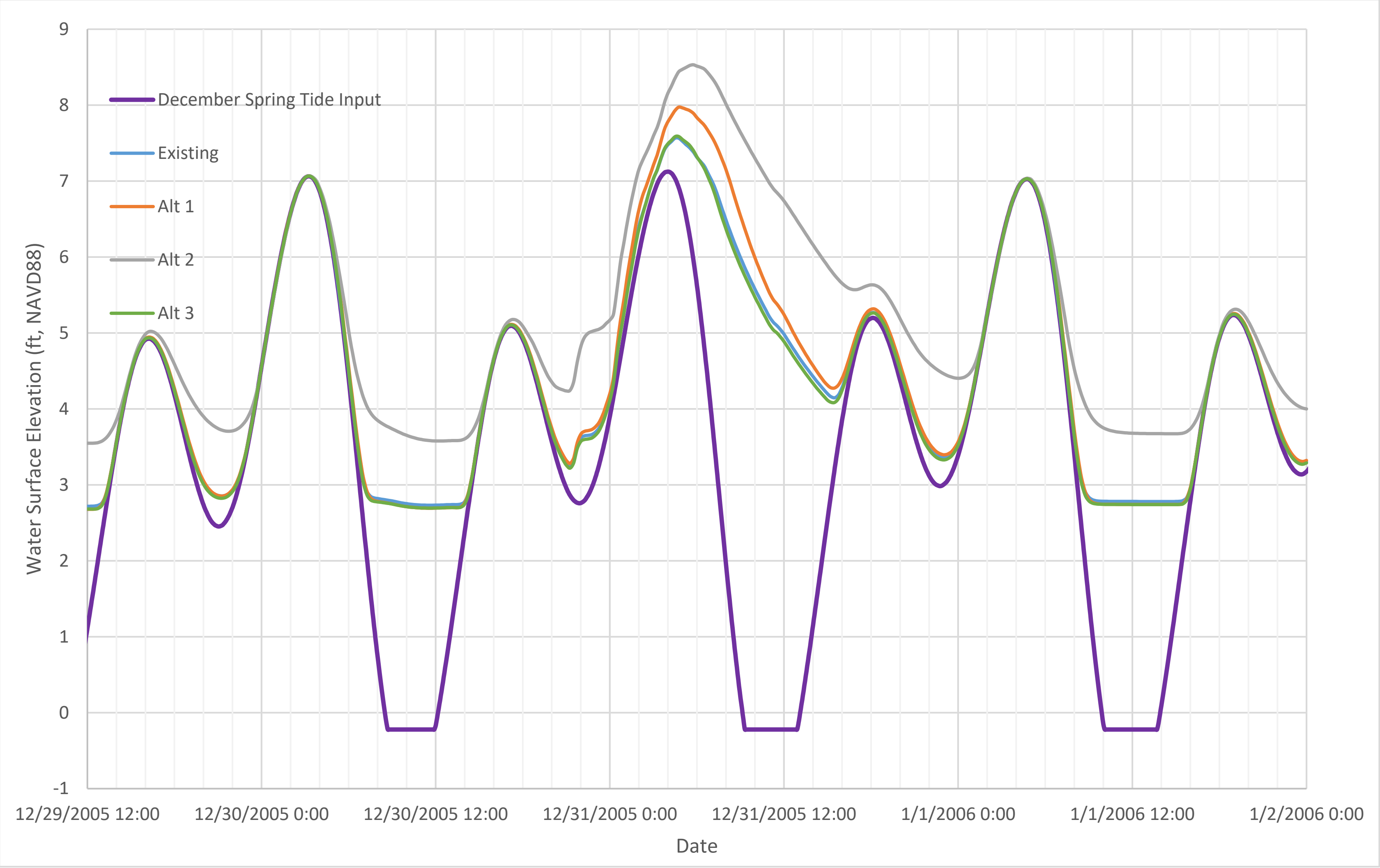


Figure 5-5
Water Surface Elevation in the Main Channel of Coyote Creek for Scenario 4: 10-Year Flow, FEMA 100-Year Coastal Water Level

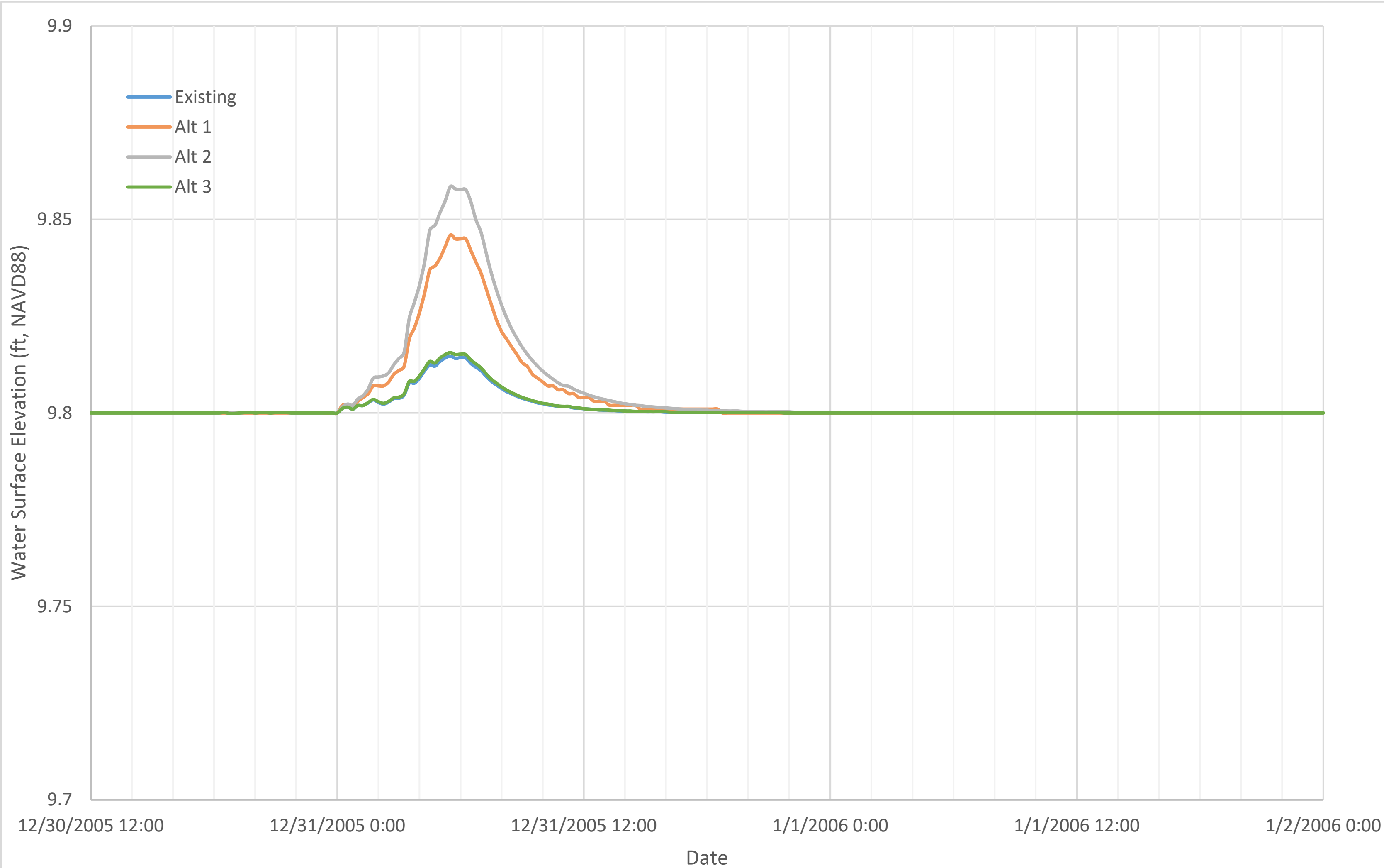
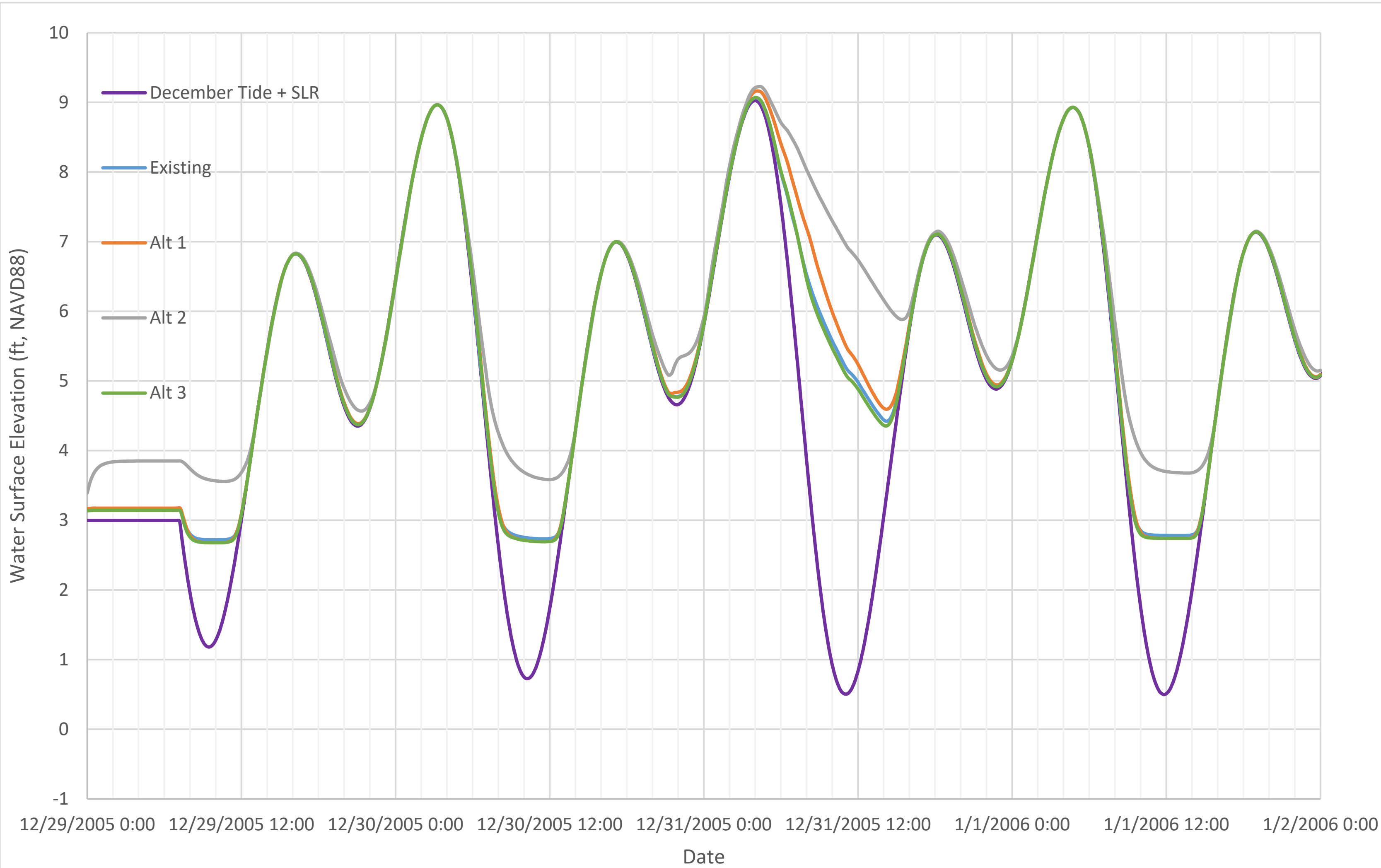


Figure 5-6
Water Surface Elevation in the Main Channel of Coyote Creek for Scenario 5: 100-Year Flow, December 2020 Tide + Sea Level Rise



5.2 Maximum Water Surface Elevation Profiles

Profiles of the maximum predicted water surface elevation along Coyote Creek for each hydraulic scenario were compared for each realignment alternative. The comparison of maximum predicted water surface elevation along Coyote Creek between alternatives provides a detailed evaluation of how the predicted water surface elevation along the axis of the creek would be expected to change for each realignment alternative.

Water surface profiles were developed along the centerline of each creek alignment. Because three different downstream alignments were considered, the profiles are measured from upstream. Downstream of the SR 1 bridge, the alignment of the profile varies between existing conditions, Alternatives 1 and 2, which follow the same path, and Alternative 3 (Figure 5-7).

Figures 5-8 through 5-12 show the maximum water surface elevations along Coyote Creek for existing conditions and each alternative. Each hydraulic scenario is shown on a separate figure. Note that different elevation ranges are shown for each hydraulic scenario to allow for better visualization of the differences between alternatives. The profile lines start at the upstream end of the model, and the total profile distance varies because of the different channel lengths in the downstream portion of Coyote Creek. The maximum water elevation along the profiles is irrespective of time; that is, the plotted water surface elevations are not a single instance in time, but the maximum elevation at any time over each simulation.

Figure 5-8 shows the maximum water surface elevation along Coyote Creek predicted for Scenario 1 for each alternative. Figure 5-8 also includes the channel elevation (terrain) for each alternative. Measured from upstream, the channel terrain is identical for the first 2,800 feet, and both the terrain and the length of the terrain profile vary downstream of the point where the channel realignment begins. The different lengths of the along-channel profiles are evident by comparing the distance from upstream to the Bay Trail bridge (three black vertical lines on the right of Figures 5-8 through 5-12) As shown in Figure 5-8, the maximum water surface elevation decreases moving downstream but is nearly identical between existing and all three realignment alternatives because the tide dominates the water surface elevation in the extreme tide with low flow scenario. This is consistent with the very small differences in maximum water level at the time series location for this scenario (Table 5-2).

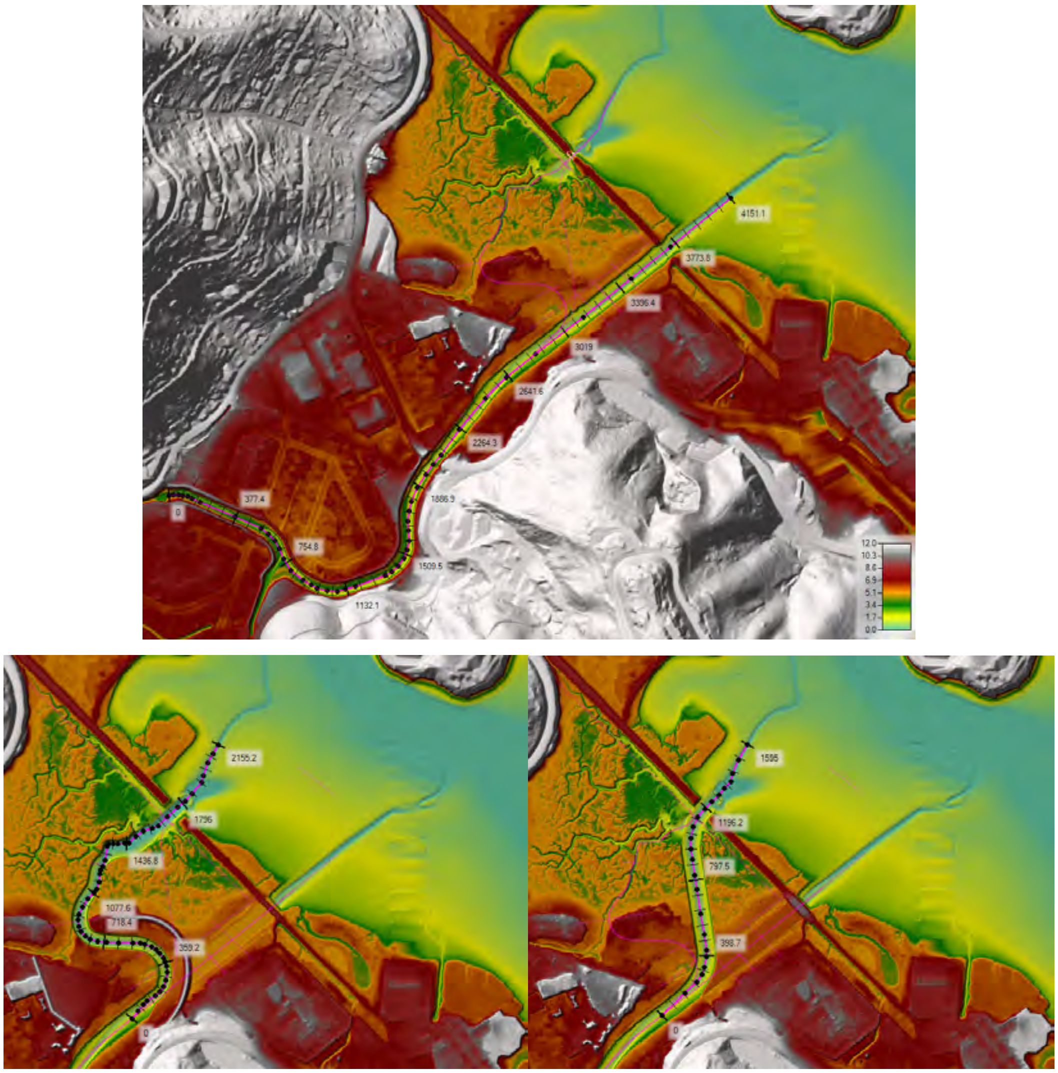
Figure 5-9 shows the maximum water surface elevation along Coyote Creek predicted for Scenario 2 for each alternative. Relative to existing conditions, Alternative 1 and Alternative 2 result in a noticeable increase in predicted maximum water surface elevations propagating upstream of Flamingo Road Bridge. This increase in upstream water levels during high flows results because the conveyance capacity of the realigned portion of the Lower Coyote Creek channel is significantly smaller under these two alternatives than under existing conditions (Figure 4-2). In contrast, the maximum predicted water surface elevation for Alternative 3, which has a channel capacity similar to existing conditions (Figure 4-3), is minimally different than under existing conditions except in the downstream portion of the profile where the channel alignments diverge. In this reach of the channel, comparisons at exact distances measured from upstream do not indicate an increase in water level at a specific location, so the profiles are not directly comparable.

Figure 5-10 shows the maximum water surface elevation along Coyote Creek predicted for Scenario 3 for each alternative. The results for Scenario 3 (100-year flow) are similar to those for Scenario 2 (25-year flow). Relative to existing conditions, Alternative 1 and Alternative 2 result in a noticeable increase in predicted maximum water surface elevations propagating upstream of Flamingo Road Bridge because the conveyance capacity of the realigned portion of the Lower Coyote Creek channel is significantly smaller under these two alternatives than under existing conditions. In contrast, the maximum predicted water surface elevation for Alternative 3 indicates relatively small differences in predicted maximum water surface elevation upstream of the channel realignment. In the portion of the channel downstream of the where the realignment occurs, differences in water levels between scenarios seen in Figure 5-10 are not directly comparable because the realignment alternatives follow different alignments and therefore water levels at the same channel distance are not from the same spatial location. In this reach of the channel (station distances greater than 2,800 feet measured from upstream), comparisons at exact distances measured from upstream do not indicate an increase in water level at a specific location, so the profiles are not directly comparable.

Figure 5-11 shows the maximum water surface elevation along Coyote Creek predicted for Scenario 4 for each alternative. Relative to existing conditions, Alternative 1 and Alternative 2 result in a noticeable increase in predicted maximum water surface elevations propagating upstream of Flamingo Road Bridge because the conveyance capacity of the realigned portion of the Lower Coyote Creek channel is significantly smaller under these two alternatives than under existing conditions. In contrast, the maximum predicted water surface elevation for Alternative 3 indicates only minimal differences in predicted maximum water surface elevation along the entire profile. For all channel alignment alternatives there is less than 0.4 foot difference between upstream and downstream maximum water levels for Scenario 4 due to the 100-year FEMA water level downstream dominating the water levels relative to the comparatively smaller flow.

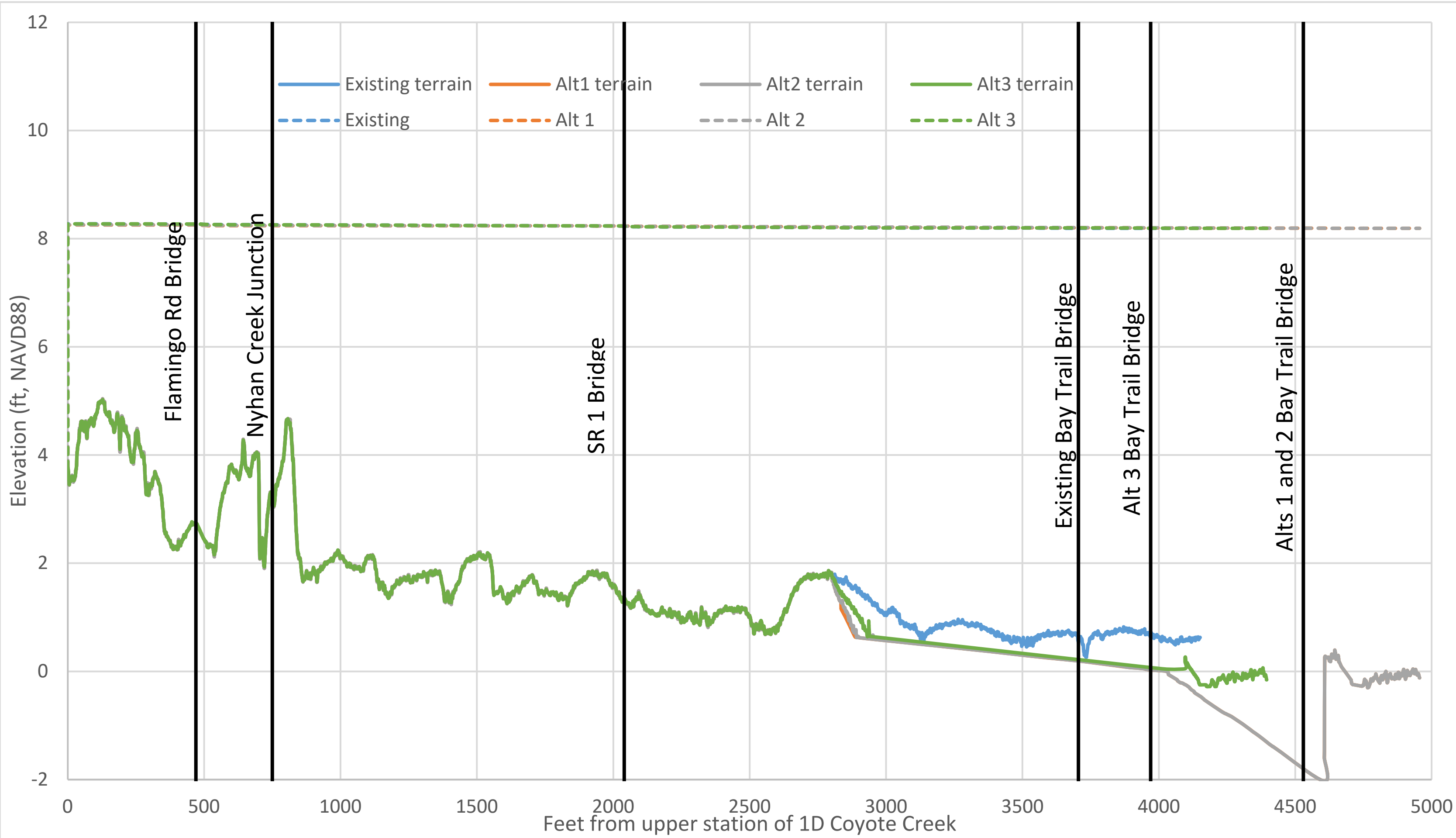
Figure 5-12 shows the maximum water surface elevation along Coyote Creek predicted for Scenario 5 for each alternative. Relative to existing conditions, Alternative 1 and Alternative 2 result in a noticeable increase in predicted maximum water surface elevations propagating upstream of Flamingo Road Bridge because the conveyance capacity of the realigned portion of the Lower Coyote Creek channel is significantly smaller under these two alternatives than under existing conditions. In contrast, the maximum predicted water surface elevation for Alternative 3 indicates only minimal differences in predicted maximum water surface elevation along the entire profile.

Figure 5-7
Profile Lines: Existing, Alternatives 1 and 2, and Alternative 3



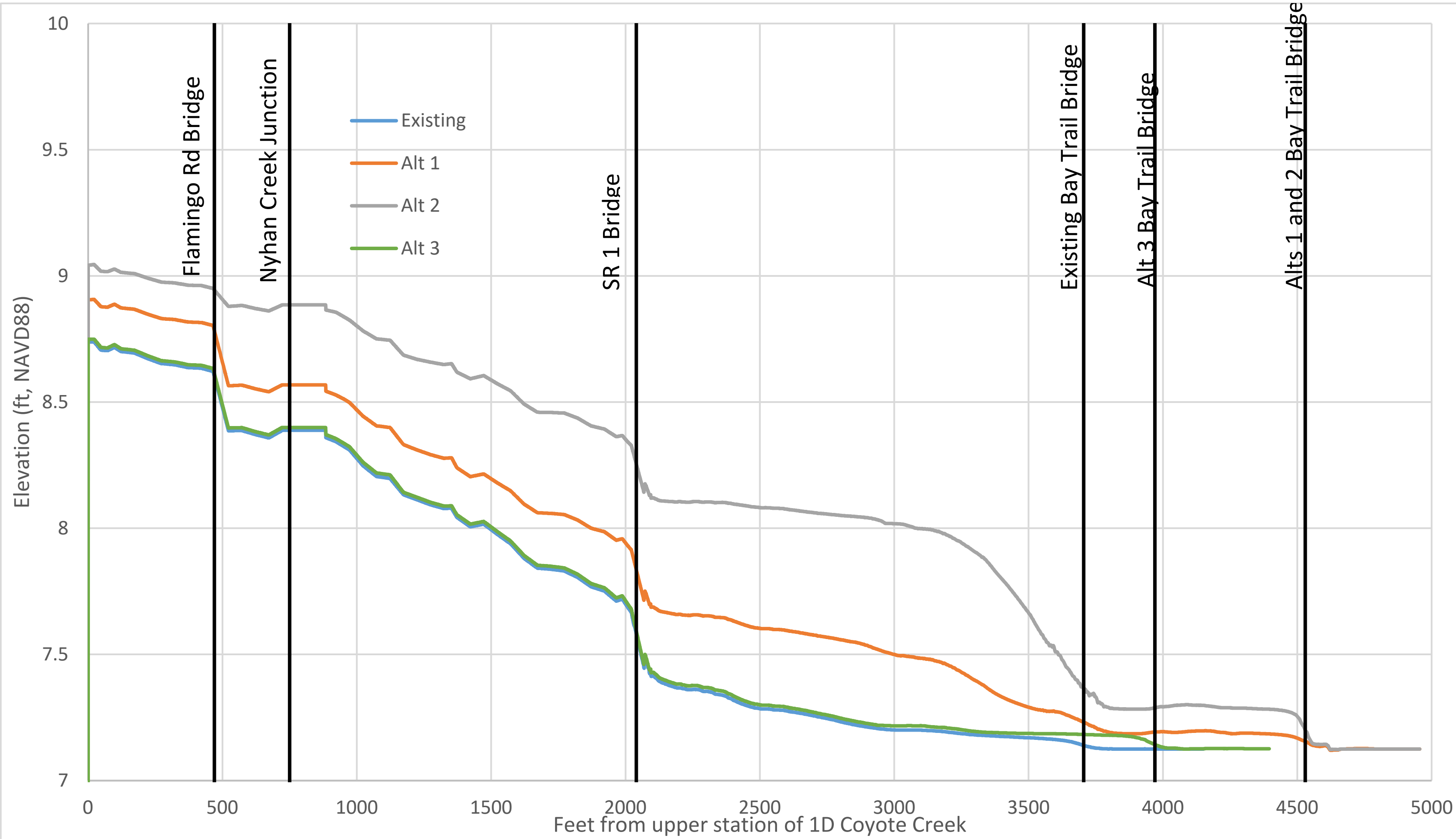
Note:
The profile lines follow the same upper creek path and diverge at station 2800 to follow the alternative downstream channel alignments.

Figure 5-8
Maximum Water Surface Elevation Profile along Coyote Creek for Scenario 1: Low Flow, Extreme Tide



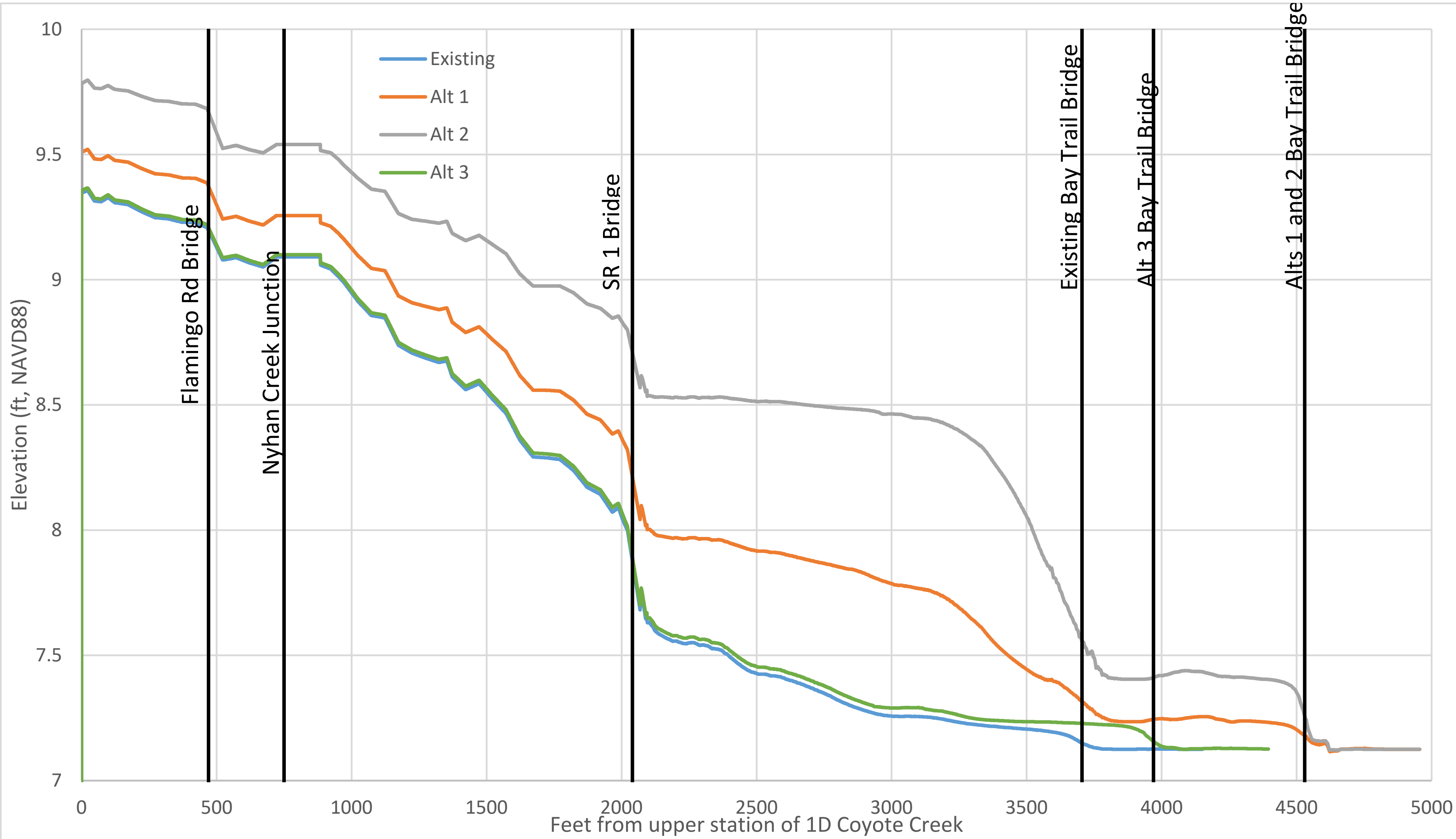
Note:
The profile lines follow the same upper creek path and diverge at station 2800 to follow the alternative downstream channel alignments.

Figure 5-9
Maximum Water Surface Elevation Profile along Coyote Creek for Scenario 2: 25-Year Flow, December 2020 Tide



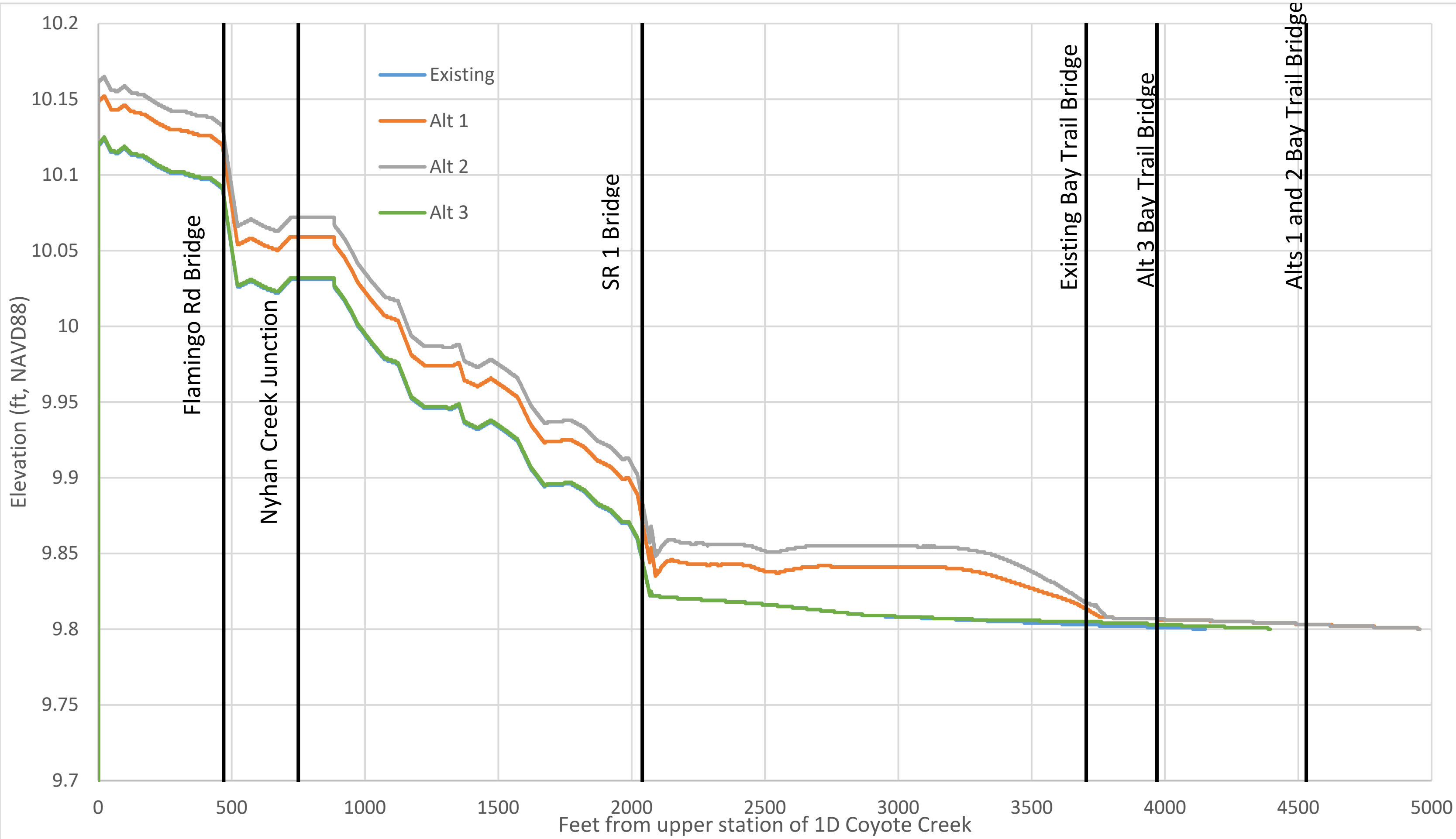
Note:
The profile lines follow the same upper creek path and diverge at station 2800 to follow the alternative downstream channel alignments.

Figure 5-10
Maximum Water Surface Elevation Profile along Coyote Creek for Scenario 3: 100-Year Flow, December 2020 Tide



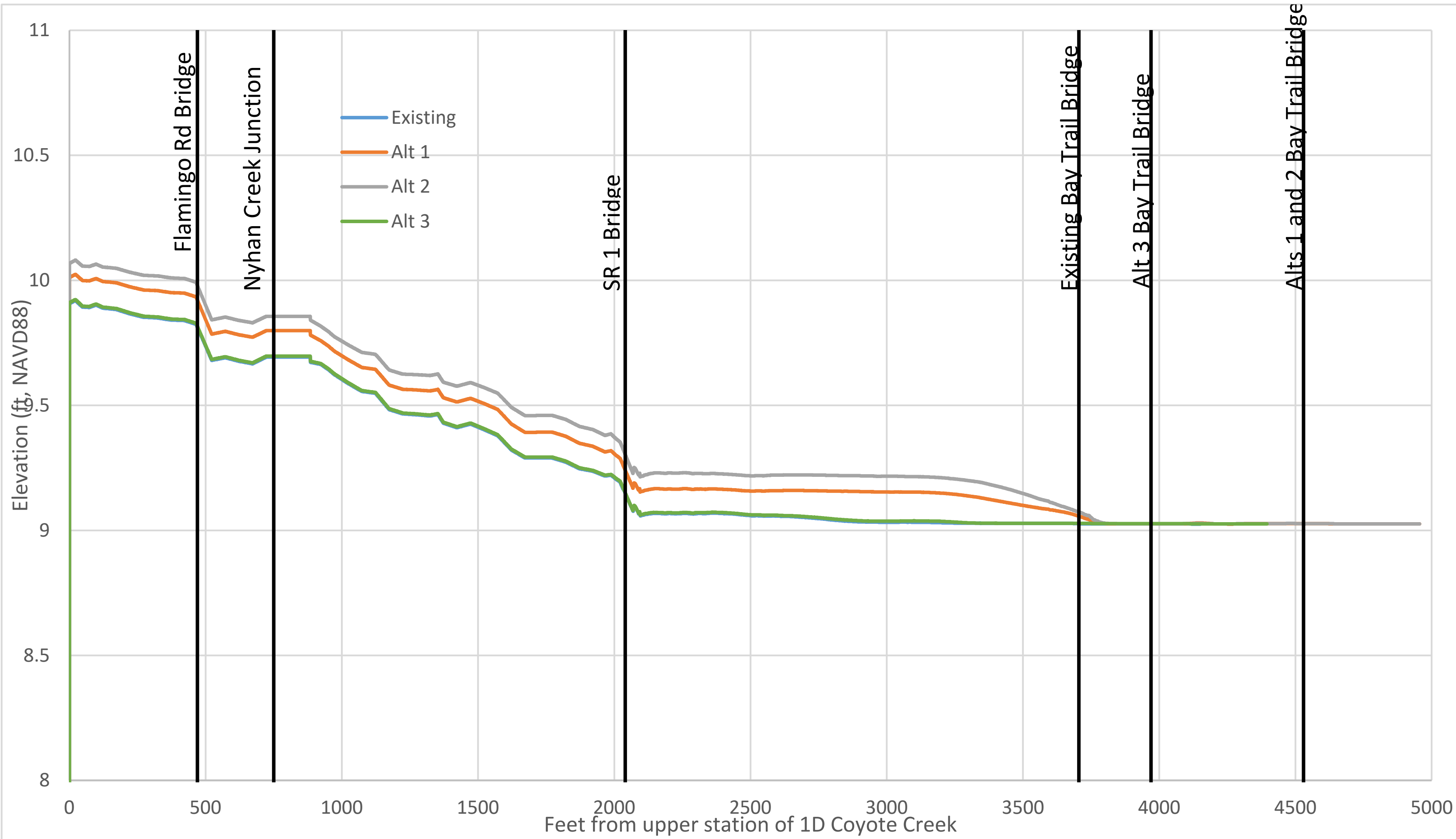
Note:
The profile lines follow the same upper creek path and diverge at station 2800 to follow the alternative downstream channel alignments.

Figure 5-11
Maximum Water Surface Elevation Profile along Coyote Creek for Scenario 4: 10-Year Flow, FEMA 100-Year Coastal Water Level



Note:
The profile lines follow the same upper creek path and diverge at station 2800 to follow the alternative downstream channel alignments.

Figure 5-12
Maximum Water Surface Elevation Profile along Coyote Creek for Scenario 5: 100-Year Flow, December 2020 Tide + Sea Level Rise



Note:
The profile lines follow the same upper creek path and diverge at station 2800 to follow the alternative downstream channel alignments.

5.3 Plan View Maps of Maximum Water Surface Elevation and Velocity

Plan view maps of maximum predicted water surface elevation and velocity in map form over the entire project area allow for visualization of potential flooding (water surface elevation) and areas of potential scour (velocities) for each of the realignment alternatives.

Plan view maps allow for a visual assessment of the extent of flooding and how water surface gradients vary between alternatives, as indicated by shifts in water surface elevation contours. For some hydraulic scenarios, the predicted water surface elevations are quite similar between alternatives (e.g., Scenario 1 as seen in Figure 5-8) or show very little gradient over the model domain (e.g., Scenario 4 as seen in Figure 5-11). For these scenarios, the profile figures provide a much more straightforward way to visualize water surface elevations along Coyote Creek.

In this section, plan view maps of maximum water surface elevation and maximum predicted velocity are shown for Scenario 3, which includes the 100-year flows in Coyote Creek (Table 5-2). Because this scenario results in the largest differences in predicted maximum water surface elevation between the alternatives as seen in Table 5-2 and Figure 5-10, this scenario was selected to illustrate how the realignment scenarios affect water surface elevation and velocity. Similar but smaller effects were predicted for Scenarios 2 and 5, which show a similar pattern in differences in water surface elevation along the Coyote Creek profile (Section 5.2).

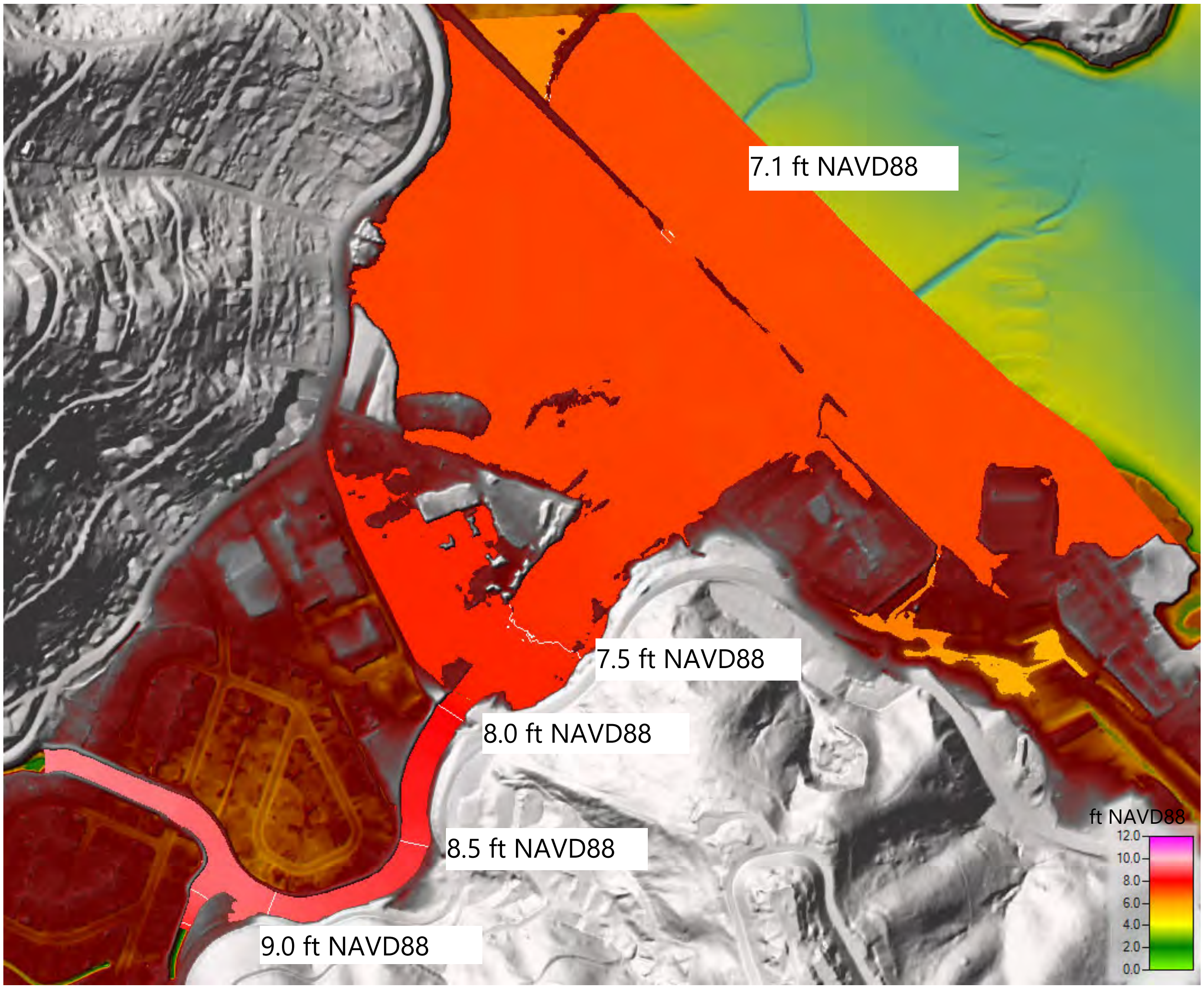
Table 5-2
Plan View Maps

Data Type	Scenario	Alternative(s) Presented	Figure Numbers
Maximum Water Surface Elevation	3: 100-Year Flow, December 2020 Tide	Existing Conditions	Figure 5-13
		Alternative 1	Figure 5-14
		Alternative 2	Figure 5-15
		Alternative 3	Figure 5-16
Maximum Velocity	3: 100-Year Flow, December 2020 Tide	Existing Conditions	Figure 5-17
		Alternative 1	Figure 5-18
		Alternative 2	Figure 5-19
		Alternative 3	Figure 5-20

The predicted maximum water surface elevation under existing conditions for Scenario 3 is shown in Figure 5-13. The 8.0 feet NAVD88 contour of maximum water surface elevation is near the SR 1 bridge. The predicted maximum water surface elevation under Alternative 1 for Scenario 3 is shown in Figure 5-13. The 8.0 feet NAVD88 contour of maximum water surface elevation is downstream of the SR 1 bridge, and the 7.5 feet NAVD88 contour has shifted downstream relative to existing conditions to the end of the constructed berm designed to redirect the channel into the marsh. A downstream shift in the elevation contours is indicative of higher water surface elevations further downstream. The predicted maximum water surface elevation under Alternative 2 for Scenario 3 is shown in Figure 5-15. Under this scenario, the 8.0 feet NAVD88 contour has shifted downstream to the end of the constructed berm designed to redirect the channel into the marsh. The predicted maximum water surface elevation under Alternative 3 for Scenario 3 is shown in Figure 5-16. Comparison of Figure 5-16 and Figure 5-13 shows very similar locations of the water surface elevation contours, which indicates that Alternative 3 results in minimal predicted differences in maximum water surface elevation relative to existing conditions.

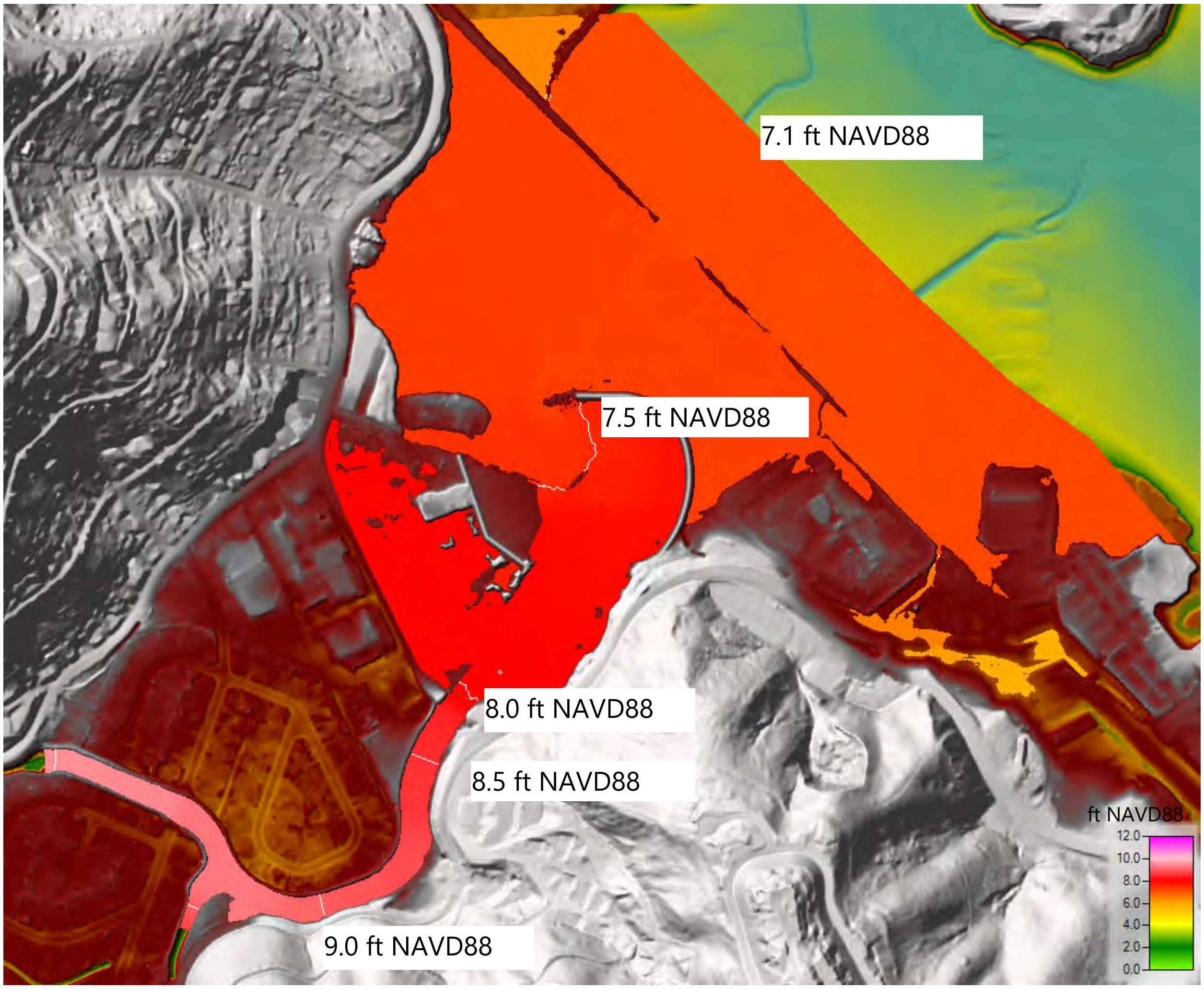
Figures 5-17 through 5-20 show the predicted maximum velocity for existing conditions, Alternative 1, Alternative 2, and Alternative 3 for Scenario 3. Under existing conditions (Figure 5-17), the predicted maximum velocity in Lower Coyote Creek is generally between 4 and 6 feet per second (ft/s), with slightly higher velocities under the Bay Trail bridge. Under Alternative 1 (Figure 5-18), the predicted maximum velocity shows more variability with some areas of higher velocity (orange color) through Bothin Marsh and some areas of lower velocity upstream of the constructed berm designed to redirect the channel into the marsh indicating a backwater effect. These same effects are more pronounced for Alternative 2 (Figure 5-19), which has the same alignment but a smaller channel capacity. Both Alternative 1 and Alternative 2 show some areas with higher velocities over the channel edges and extending into the marsh. The predicted maximum velocity for Alternative 3 (Figure 5-20) is more similar to existing conditions with a predicted maximum velocity in Lower Coyote Creek generally between 4 and 6 ft/s, with slightly higher velocities under the Bay Trail bridge at the opening to Bothin Marsh. This visualization of the maximum predicted velocity is consistent with the assessment of the changes in water surface elevation, which indicate that the channel capacity for Alternative 1 and Alternative 2 is too small to adequately convey the design flood flows. The channel capacity for Alternative 3 is designed to be similar to existing conditions and therefore results in a similar distribution of maximum velocities in the channel during high flows.

Figure 5-13
Maximum Predicted Water Surface Elevation under Existing Conditions for Scenario 3: 100-Year Flow, December Tide



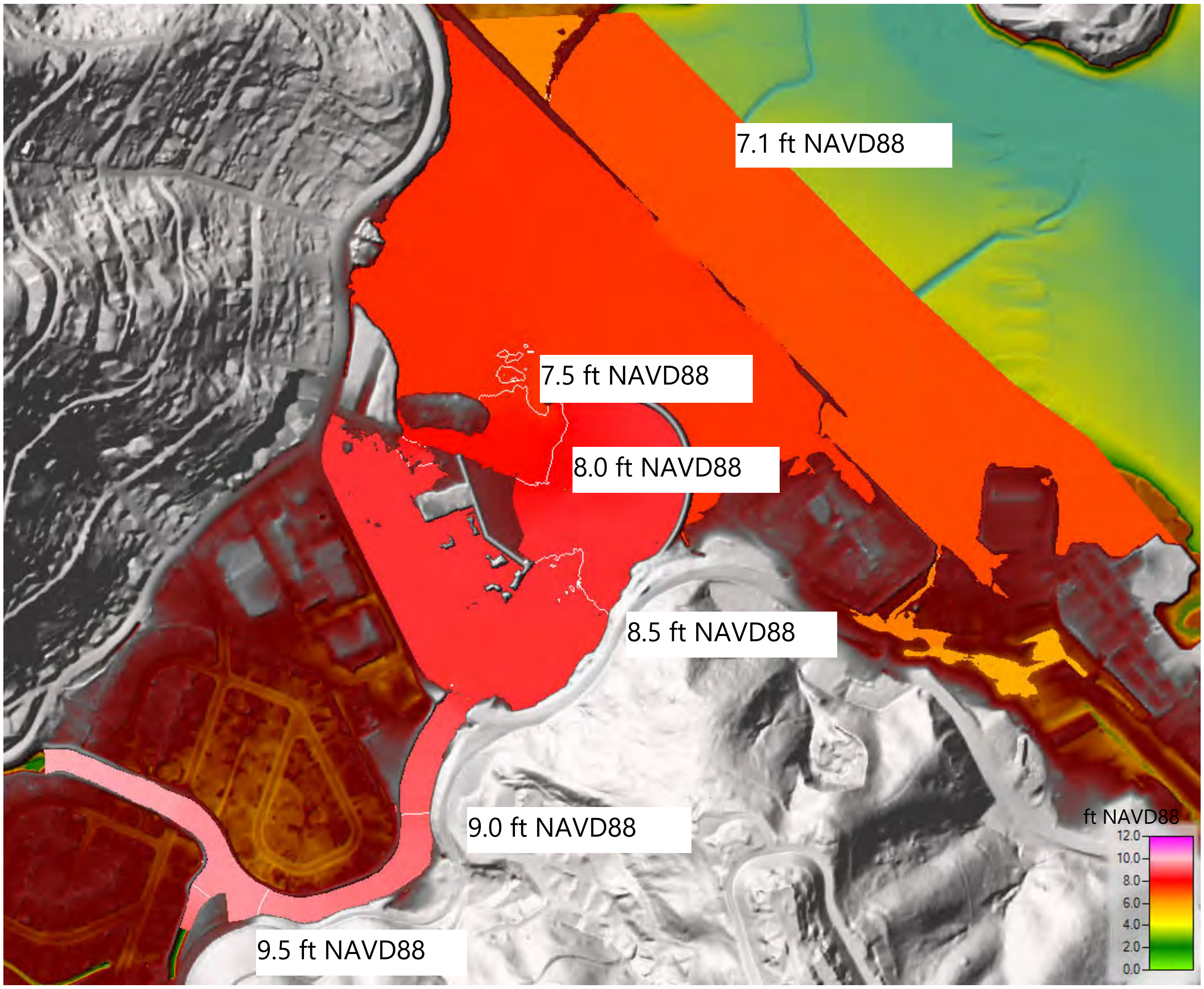
Note:
The 0.5-foot counter lines for water surface elevation are in white and labeled.

Figure 5-14
Maximum Predicted Water Surface Elevation under Alternative 1 for Scenario 3: 100-Year Flow, December 2020 Tide



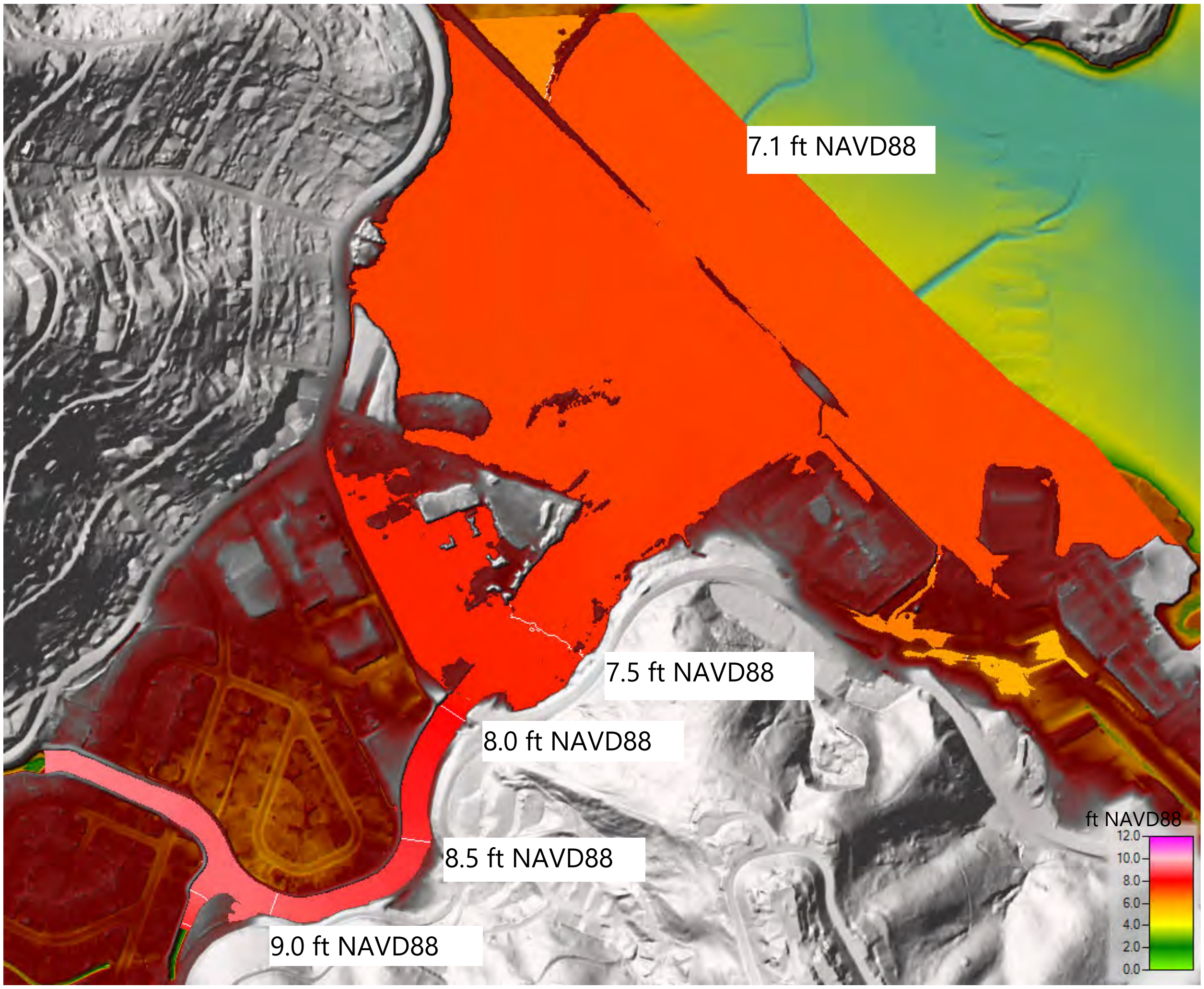
Note:
The 0.5-foot counter lines for water surface elevation are in white and labeled.

Figure 5-15
Maximum Predicted Water Surface Elevation under Alternative 2 for Scenario 3: 100-Year Flow, December 2020 Tide



Note:
The 0.5-foot counter lines for water surface elevation are in white and labeled.

Figure 5-16
Maximum Predicted Water Surface Elevation under Alternative 3 for Scenario 3: 100-Year Flow, December 2020 Tide



Note:
The 0.5-foot counter lines for water surface elevation are in white and labeled.

Figure 5-17
Maximum Predicted Velocity under Existing Conditions for Scenario 3: 100-Year Flow, December 2020 Tide

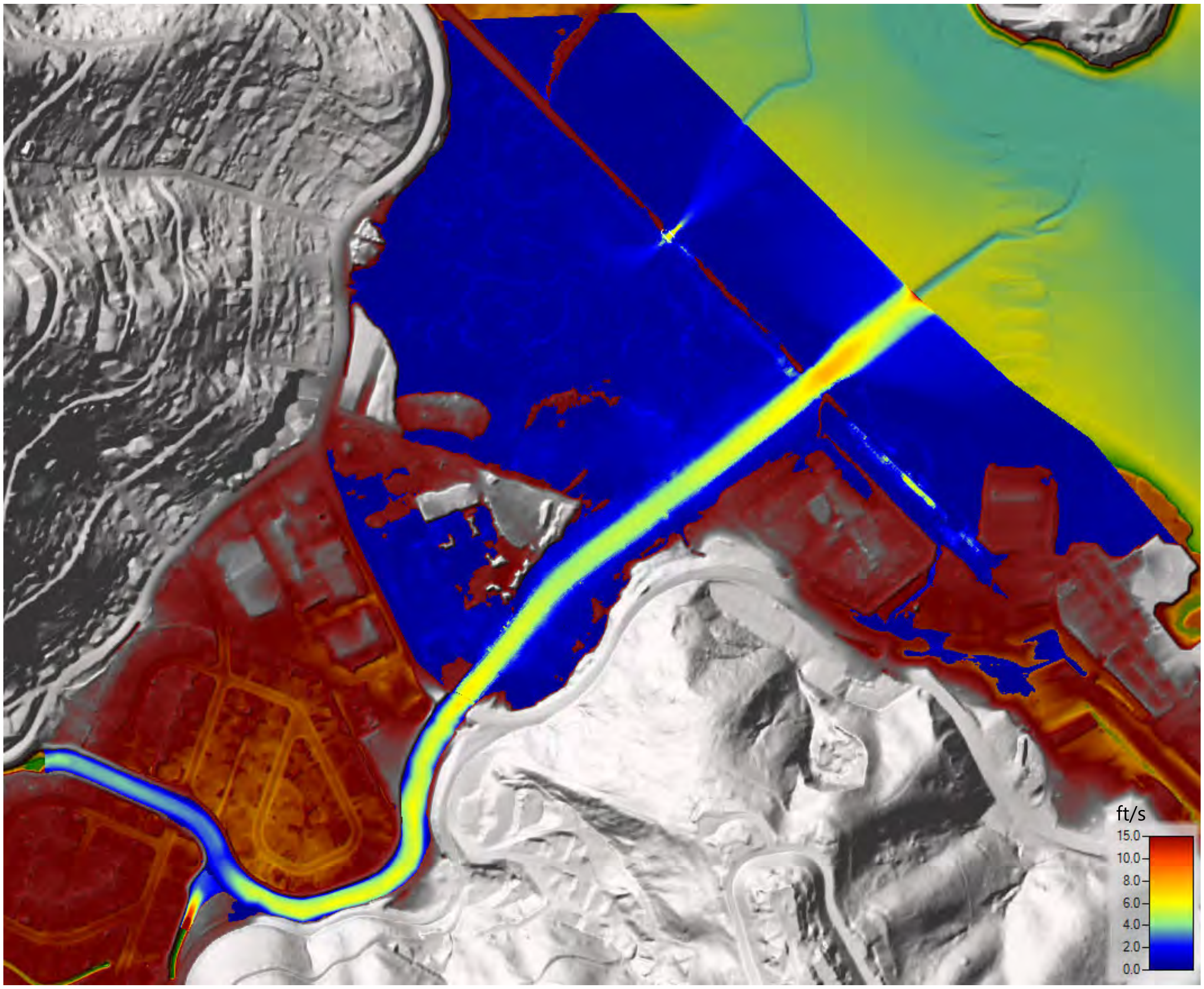


Figure 5-18
Maximum Predicted Velocity under Alternative 1 for Scenario 3: 100-Year Flow, December 2020 Tide

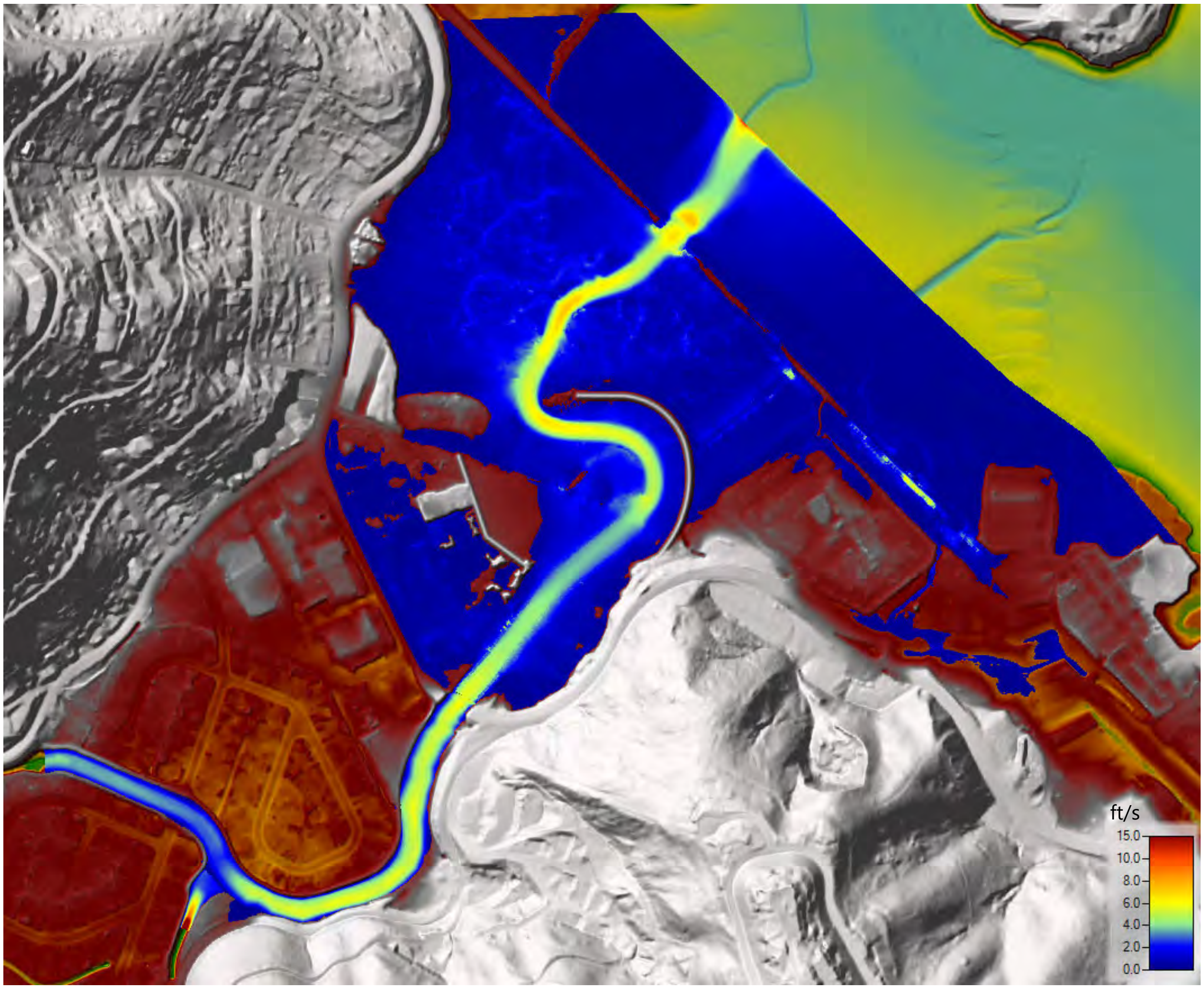


Figure 5-19
Maximum Predicted Velocity under Alternative 2 for Scenario 3: 100-Year Flow, December 2020 Tide

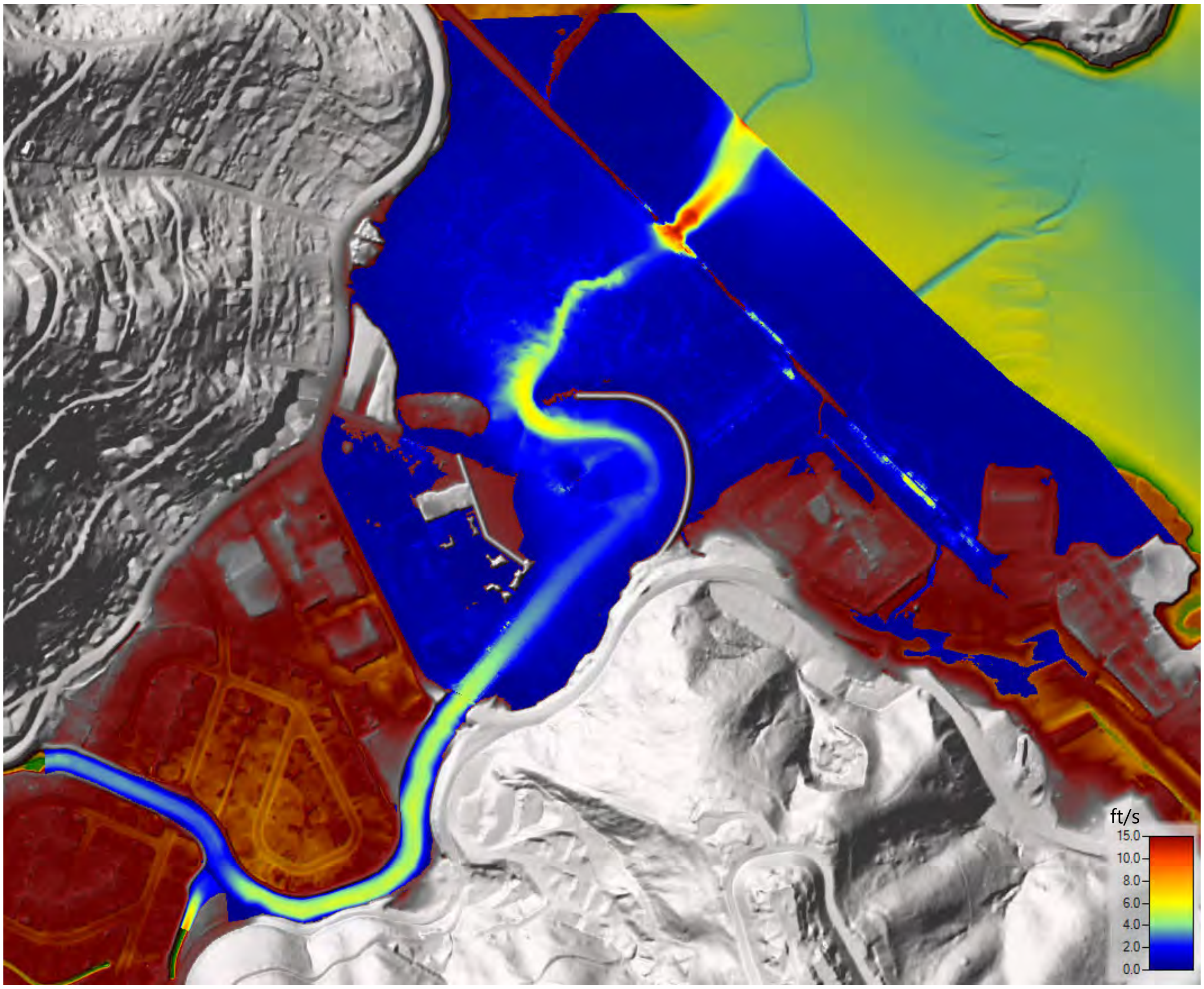
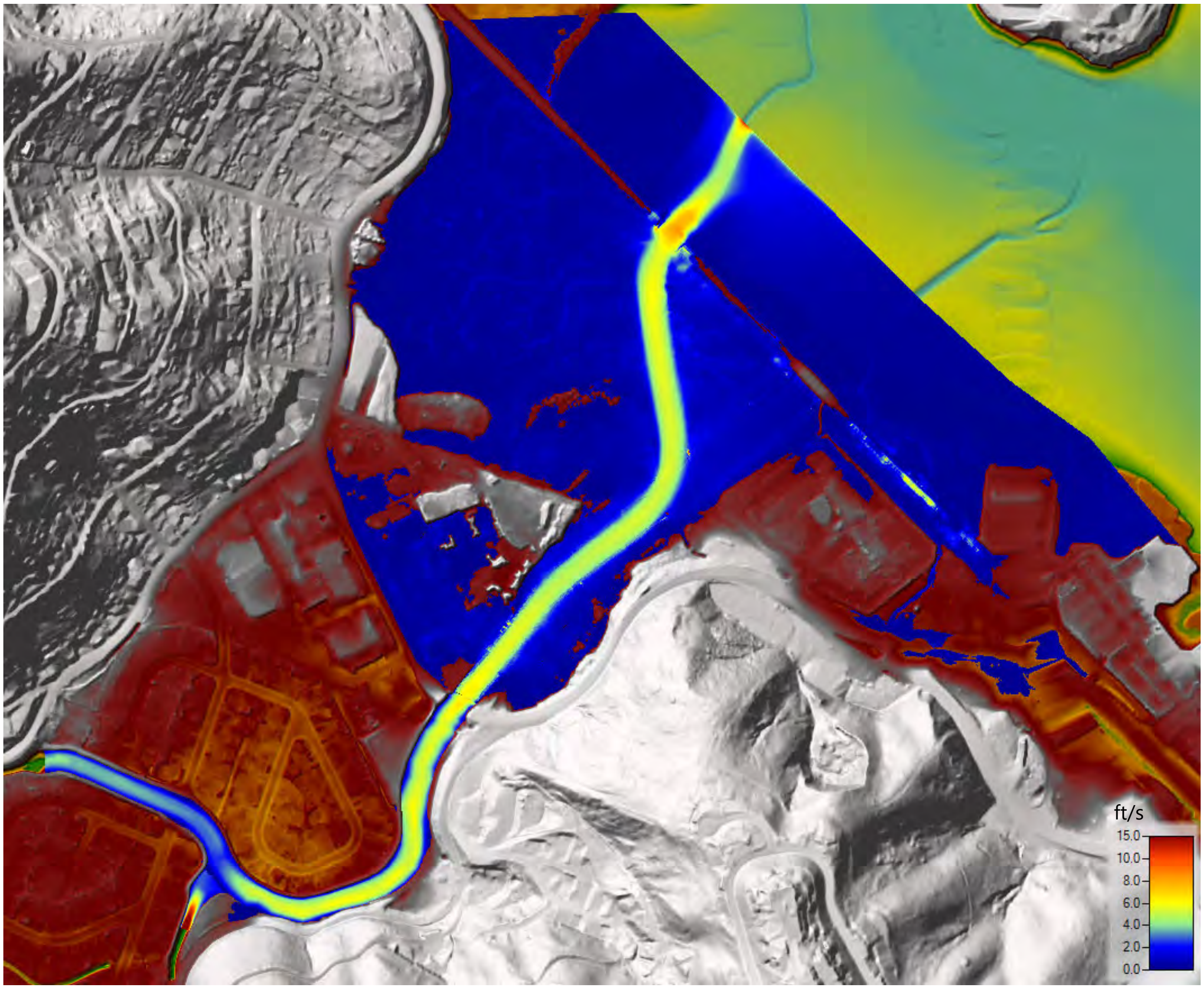


Figure 5-20
Maximum Predicted Velocity under Alternative 3 for Scenario 3: 100-Year Flow, December 2020 Tide



6 Evaluation of Effect of Realignment on Sediment Supply to Bothin Marsh

The realignment of Lower Coyote Creek through Bothin Marsh has the potential to result in changes to two aspects of the sediment supply to Bothin Marsh:

1. Changes in the inorganic sediment supply from Coyote Creek to Bothin Marsh during high-flow periods, which is important to support long-term marsh sustainability
2. Changes to the sediment and tidal exchange between Bothin Marsh and Richardson Bay if the realignment design results in changes to the geometry of the opening between Bothin Marsh and Richardson Bay

The relative change in these two factors that influence sediment supply are also influenced by elements of the channel realignment design. For example, realignment of the channel through the marsh results in a more direct flow of sediment onto the marsh, and a smaller cross-sectional area of the channel results in more flow spreading out onto the marsh during periods of high flow. Similarly, the size and number of connections between Bothin Marsh and Richardson Bay can influence the sediment exchange between Bothin Marsh and Richardson Bay and change the trapping efficiency of the marsh in retaining sediment that enters the marsh tidally.

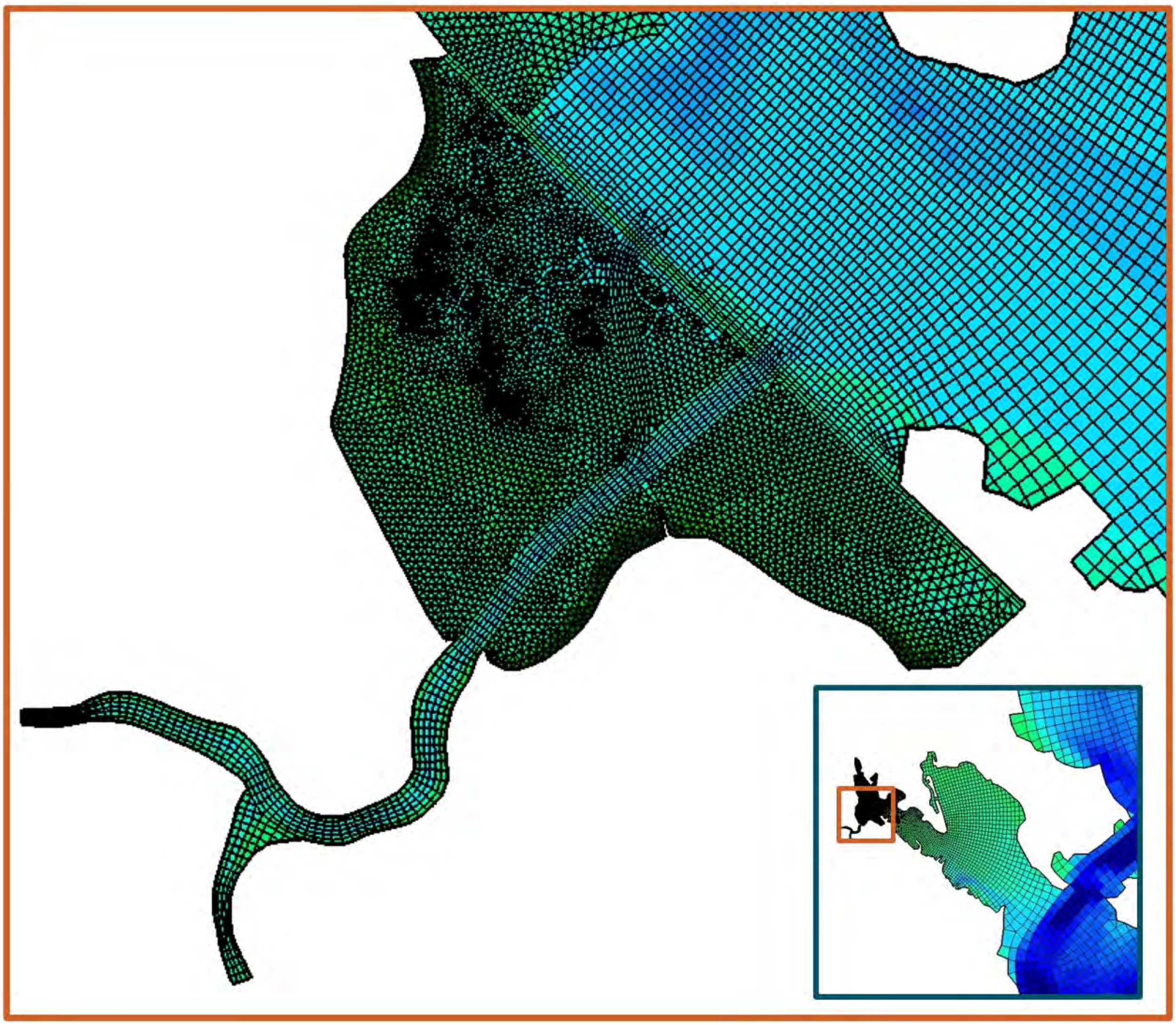
A coupled 3D hydrodynamic, wind wave, and sediment transport model was applied to assess whether the realignment of Lower Coyote Creek results in an increase in sedimentation in Bothin Marsh during high-flow events or during high coastal water levels, often referred to as king tides. Model simulations were conducted for both existing conditions and for Alternative 3, which was developed and verified through the hydraulic analysis (Section 5) as having the smallest effect on upstream water levels in Coyote Creek. This section provides an overview of the model used in this analysis, a discussion of the period simulated, the assumptions used to develop the model boundary conditions for Coyote Creek flows and sediment, and the results of the analysis.

6.1 Hydrodynamic and Sediment Transport Model Overview

6.1.1 Hydrodynamic Model Background

The UnTRIM Bay-Delta model is a 3D hydrodynamic model of the Sacramento-San Joaquin Bay Delta (Bay-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 Delta and 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 Delta. This approach offers significant advantages 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 model grid used in this study was refined in Richardson Bay and includes a high-resolution grid of the Study site spanning Coyote Creek and Nyhan Creek and Bothin Marsh (Figure 6-1). The resulting model contains more than 150,000 horizontal grid cells and more than 1 million 3D grid cells (Figure 6-2).

Figure 6-1
Model Grid Refinement in Study Area (Orange Box) Located in the Northwest Portion of Richardson Bay (Inset)

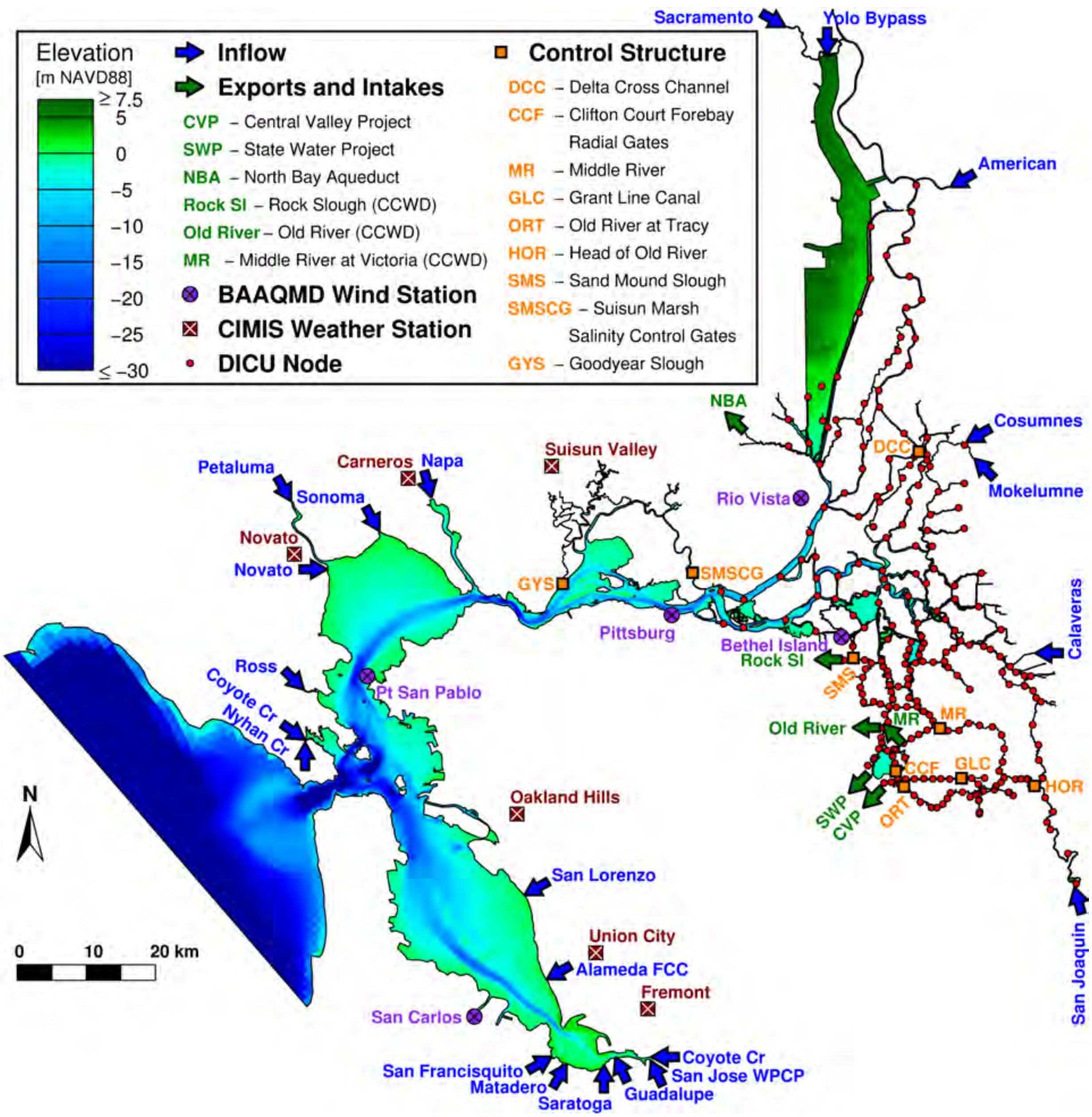


The UnTRIM Bay-Delta model has been applied to the Bay-Delta as part of the Delta Risk Management Strategy (MacWilliams and Gross 2007), several studies to evaluate the mechanisms behind the pelagic organism decline (e.g., MacWilliams et al. 2008), the Bay Delta Conservation Plan (MacWilliams and Gross 2010), and for examining X2 and the low salinity zone (MacWilliams et al. 2015). The UnTRIM

Bay-Delta model has also been applied for a range of studies by the U.S. Army Corps of Engineers (USACE), including the Hamilton Wetlands Restoration Project (MacWilliams and Cheng 2007), the Sacramento River Deep Water Ship Channel Deepening Study (MacWilliams et al. 2009), the San Francisco Bay to Stockton Navigation Project Deepening Study (MacWilliams et al. 2014), and the South San Francisco Bay Shoreline Study (MacWilliams et al. 2012a). The UnTRIM Bay-Delta model has also been applied to several studies of sediment transport in support of the San Francisco Bay Regional Dredged Material Management Program (MacWilliams et al. 2012b; Bever and MacWilliams 2013, 2014; Bever et al. 2014; Delta Modeling Associates 2015) and for turbidity modeling in the Bay-Delta (Anchor QEA 2017; Bever et al. 2018).

The UnTRIM Bay-Delta model has been calibrated using water level, flow, salinity, suspended sediment concentration (SSC), and turbidity data collected in the Bay-Delta in numerous previous studies (e.g., MacWilliams et al. 2008, 2009; MacWilliams and Gross 2010; Bever and MacWilliams 2013; MacWilliams et al. 2015; MacWilliams et al. 2016; Bever et al. 2018). The model has been shown to accurately predict salinity, tidal flows, water levels, and sediment transport throughout the Bay-Delta under a wide range of conditions.

Figure 6-2
High-Resolution UnTRIM San Francisco Bay-Delta Model Domain, Bathymetry, and Locations of Model Boundary Conditions, which Include Inflows, Export Facilities, Contra Costa Water District (CCWD) Intakes, 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



6.1.2 *Sediment Modeling Background*

The UnTRIM Bay-Delta model (MacWilliams et al. 2007, 2008, 2009, 2015) has been applied together with the Simulated WAves Nearshore (SWAN) wave model (SWAN Team 2009a) and the SediMorph sediment transport and seabed morphology model (BAW 2005), as a fully coupled hydrodynamic-wave-sediment transport model. This coupled modeling system has been used previously to predict sediment transport throughout the Bay-Delta system. Most recently, the model was used to estimate reductions in turbidity throughout Suisun Bay and the confluence region from observed decreases in the wind speed (Bever et al. 2018). The model has also been applied as part of two projects for USACE to investigate how SLR and reduced sediment supply to the Delta impacted sediment routing through the Bay-Delta system and sediment deposition within Suisun and San Pablo Bays (MacWilliams et al. 2012b; Bever and MacWilliams 2014). The coupled models were also used to investigate the effects of breaching Prospect Island on regional turbidity and sediment dynamics in the north Delta and Cache Slough region (Delta Modeling Associates 2014). Other applications of the sediment transport model include simulations of dredged material dispersal in Northern San Francisco Bay (MacWilliams et al. 2012b) and South San Francisco Bay (Bever and MacWilliams 2014; Bever et al. 2014) to determine the fate of dredged material and investigate whether open-water placements can be used to augment mudflat and marsh sedimentation. Bever and MacWilliams (2013) have also applied the coupled modeling system to investigate wave shoaling and sediment fluxes between the channel and shoals in San Pablo Bay.

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. In the coupled modeling system, the SWAN model runs on the same unstructured grid as UnTRIM, providing high resolution in areas where needed. Wind data interpolated from the BAAQMD stations used in the UnTRIM model (Figure 6-2) were used in the SWAN model, such that the primary source of wind data for the project site was the Point San Pablo station.

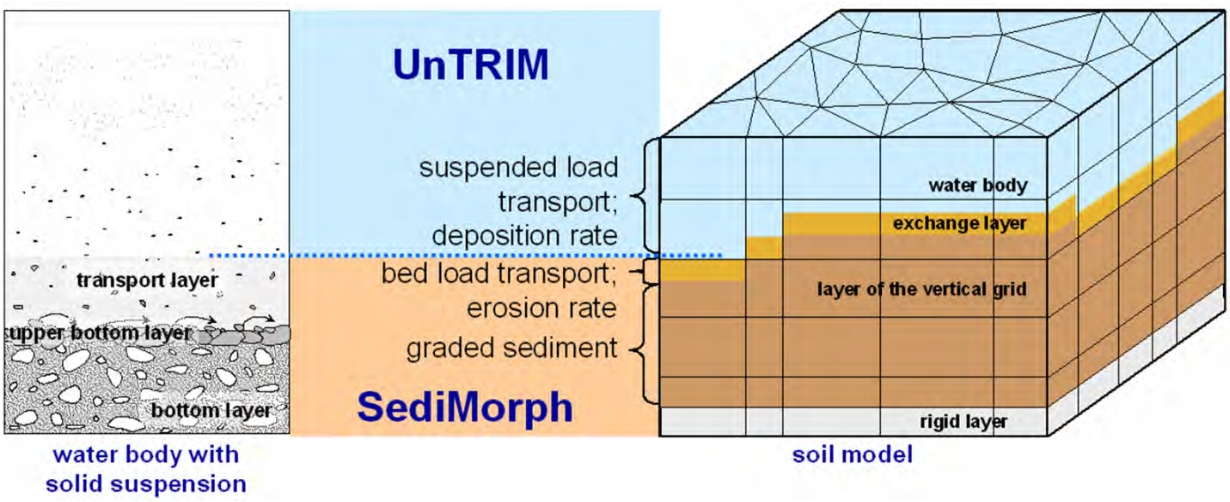
The primary purpose of the SediMorph module is to compute the sedimentological processes at the alluvial bed of a free-surface flow, including the following (Weilbeer 2005):

- 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 distribution within the bed exchange layer

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 predefined 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 6-3 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 structures.

Figure 6-3
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 2005

Sediment transport simulations using the UnTRIM San Francisco Bay-Delta Model include multiple sediment classes, an initial sediment bed based on more than 1,300 observed seabed grain size distributions within the Bay and Delta, sediment input from 11 Bay-Delta tributaries, and wave- and current-driven sediment resuspension and transport. In this coupled modeling system, UnTRIM calculates the flow, water level, salinity, sediment advection, sediment settling, and sediment mixing. SWAN calculates the temporally and spatially varying waves needed for accurate predictions of sediment resuspension in the presence of wind waves. SediMorph calculates the erosion and deposition of sediment and the seabed morphologic change, and it keeps track of the sedimentological properties within the seabed. The model bathymetry in each grid cell is adjusted each time step to account for erosion and deposition. The thickness of deposition or erosion for each sediment class is calculated based on the cell area, porosity, the deposited mass of each sediment class, and the density of each sediment class (Table 6-1). The configuration of the coupled modeling system and the sediment transport model used in this Study is nearly identical to that described in Bever et al. (2018). The one exception is that an additional sediment class was added to the tributary inflows before this Study to improve predicted SSC and turbidity in the Delta (Table 6-1). This sediment class represents very fine sediments that represent washload and settle very slowly. This sediment class represents only a small fraction of the sediment inflow from each tributary.

Table 6-1
Sediment Class Characteristics

Sediment Class	Settling Velocity (mm/s)	Critical Shear Stress (Pa)	Diameter	Density (kg/m^3)	Erosion Rate Parameter (kg/m^{2}s)
Fine Silt	0.001	0.0379	11 µm	2,650	2.5×10^{-5} to 10×10^{-5}
Silt	0.038	0.0379	11 µm	2,650	2.5×10^{-5} to 10×10^{-5}
Flocculated Silt and Clay	2.25	0.15	200 µm	1,300	3×10^{-5} to 12×10^{-5}
Sand	23	0.19	250 µm	2,650	5×10^{-5} to 20×10^{-5}
Gravel	NA	NA	8 mm	2,650	NA

The SWAN wave results have been calibrated and validated to observed wave properties in San Pablo Bay and Suisun Bay and at four locations south of Dumbarton Bridge. Wave data were not available for validation of the SWAM predictions in Richardson Bay, but the wave predictions from this Study were evaluated qualitatively and were found to be reasonable for the winds observed during the periods simulated. The sediment transport within the coupled modeling system has been calibrated using SSC time series at multiple locations within the Bay, continuous monitoring stations within Suisun Bay and the Delta, and vertical profiles of SSC along a transect along the axis of the Bay from the far South Bay to Rio Vista. The model has also been validated through comparison of observed and predicted deposition within a breached salt pond during the period following the initial breach (Bever and MacWilliams 2014). Turbidity has been validated using continuous-monitoring time series in the Bay and Delta and surface remotely sensed data (Anchor QEA 2017; Bever et al. 2018). A detailed validation of suspended sediment throughout San Francisco Bay was conducted for a recent study to evaluate sediment fluxes through the Golden Gate (Anchor QEA 2020b). These previous model validation comparisons demonstrate that the coupled hydrodynamic-wind wave-sediment model is accurately capturing the dominant processes that resuspend, deposit, and transport sediment throughout the Bay-Delta system, and would therefore be suitable for predicting SSC throughout the Bay-Delta. No further model calibration or validation was conducted as part of this Study, and the only changes to the model made for this Study were the incorporation of a higher resolution grid in Richardson Bay and in the Study area.

6.2 Model Simulation Period and Analysis Approach

This section describes the conditions during the model simulation and the analysis approach used to assess the effect of the realignment of Coyote Creek through Bothin Marsh on sediment supply to the marsh during periods of high flow in Coyote Creek and during periods of king tides in San Francisco Bay.

6.2.1 Model Simulation Period

This Study simulated hydrodynamics, wind waves, and sediment transport for a period spanning from October 16, 2018, through February 28, 2019. The model was initialized on October 16, 2018, allowing 1.5 months for spin-up prior to the beginning of the analysis period on December 1, 2018. A 3-month analysis period spanning from December 1, 2018, through February 28, 2019, was used in this analysis. This analysis period spans the 2 days when limited measurements of total suspended solids (TSS) were collected by Marin Flood District staff during a period of king tides on December 23, 2018 (Alpha Analytical Laboratories 2019a) and during a period of high flow in Coyote Creek on February 13, 2019 (Alpha Analytical Laboratories 2019b). The 13 TSS measurements collected on December 23, 2018, ranged from 12 to 27 mg/L, except for the TSS measurement at the north end of the Coyote Creek Bridge that was 140 mg/L (Table 6-2). The measurements of fixed suspended solids (FSS) were taken by Marin Flood District staff during the period of high flow in Coyote Creek on February 13, 2019, which ranged from 2,400 to 4,600 mg/L, with 3,800 mg/L FSS measured at the mouth of Coyote Creek (Table 6-2). One of the three samples was processed by oven drying and yielded a TSS measurement of 5,100 mg/L.

Table 6-2
TSS and FSS data from Water Samples Collected on December 23, 2018 (Alpha Analytical Laboratories 2019a) and February 13, 2019 (Alpha Analytical Laboratories 2019b)

Sampling Period	Sample Location	Date and Time of Sample Collection	Sample Concentration (mg/L)
December 2018 King Tide Period	Coyote Creek Bridge North	12/23/18 10:31	140
	Coyote Creek Bridge Middle	12/23/18 10:35	12
	Coyote Creek Bridge South	12/23/18 10:30	27
	Bridge 2	12/23/18 10:42	14
	Bridge 2	12/23/18 10:12	18
	ACMDP Middle	12/23/18 11:18	14
	ACMDP North (Middle)	12/23/18 11:21	16
	ACMDP North	12/23/18 11:24	16
	ACMDP South	12/23/18 11:27	23
	Bridge 2 (Ebb)	12/23/18 11:57	14
	Bridge 2	12/23/18 10:58	18
	Bridge 2 (Ebb)	12/23/18 11:54	13
	Coyote Middle (Ebb)	12/23/18 12:00	22
February 2019 High-Flow Period	Mouth of Coyote Creek	2/13/2019 12:05	3,800 (FSS)
	Flamingo Road Bridge	2/13/2019 12:17	2,400 (FSS)
	Enterprise Concourse Bridge	2/13/2019 12:27	5,100
	Enterprise Concourse Bridge	2/13/2019 12:27	4,600 (FSS)

Notes:
Sample location names are based on raw sampling notes and laboratory analysis report. The exact position of samples is not available from these sources.
Ebb: Denotes ebb tide
All sample concentrations are TSS, unless indicated as FSS.

The HEC-HMS model (Appendix A) was applied to develop hydrographs for both Nyhan Creek and Coyote Creek spanning the simulation period (Figure 6-4). The highest peak flow, which occurred in February 2019, was estimated to be approximately a 4-year return interval flow. The available TSS and FSS data were used to develop a rating curve for estimating sediment load in Coyote Creek as a function of creek flow (Figure 6-5). Due to the limited amount of data, the TSS data from the king tide period and the FSS data from the high-flow period were combined into one suspended sediment dataset. Given the very limited TSS data available for developing the rating curve, there is a large amount of uncertainty associated with the sediment loads estimated using this curve. Since there was no information available on grain size from the TSS data, the inflow sediment was based on the sediment distribution used in other San Francisco Bay tributaries in the model, which was developed based on more extensive data. Four additional sediment classes were added to the model so that the sediment entering the model from Coyote Creek and Nyhan Creek could be tracked separately from the other sediment in the Bay. For this analysis, it was assumed that the sediment entering the domain in Coyote Creek and Nyhan Creek was composed of 1% sand, 19% flocculated silt and clay, 70% silt, and 10% fine silt and thus was assigned the sediment characteristics shown in Table 6-1. Despite these necessary approximations, comparisons between the two alignments can still provide an assessment of the relative effect of the channel realignment. Since the same assumptions about the sediment load and sediment characteristics are made for both the existing and realignment simulations, relative differences in deposition between the two alignments can be evaluated.

Figure 6-4
Combined Coyote Creek and Nyhan Creek Inflow (Top) and Observed Water Level at the NOAA San Francisco (9414290) Tide Station (Bottom)

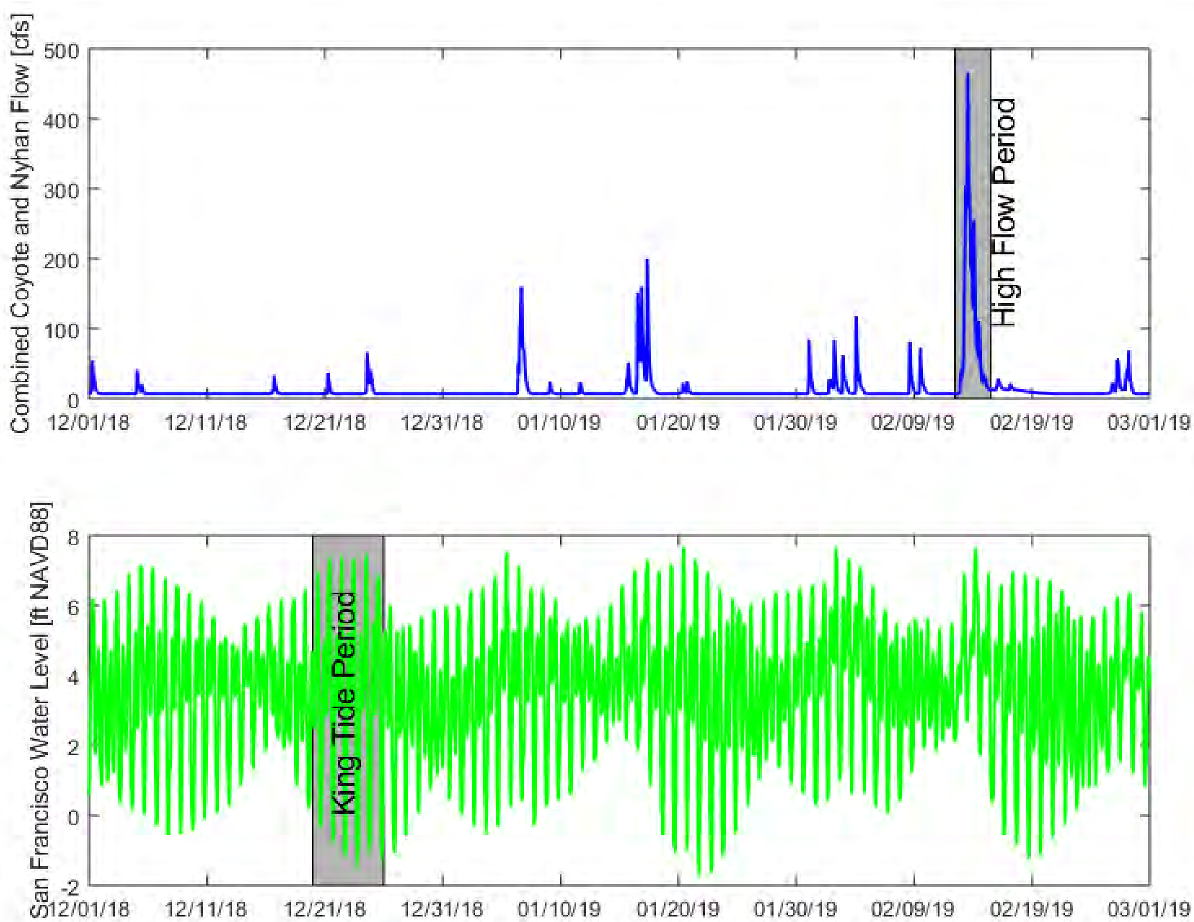
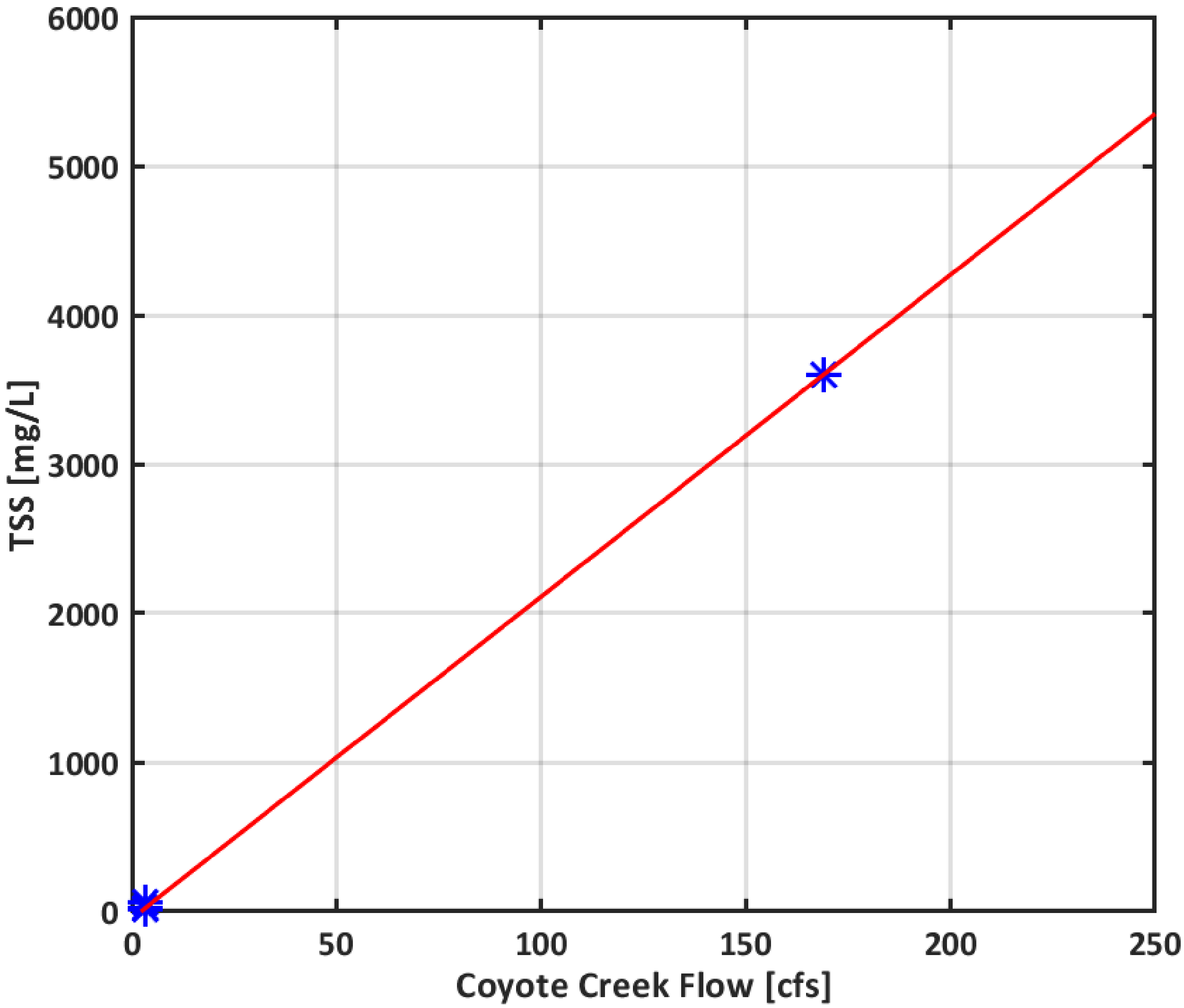


Figure 6-5
Sediment Rating Curve for Coyote Creek Developed Based on December 2018 and February 2019 TSS Samples



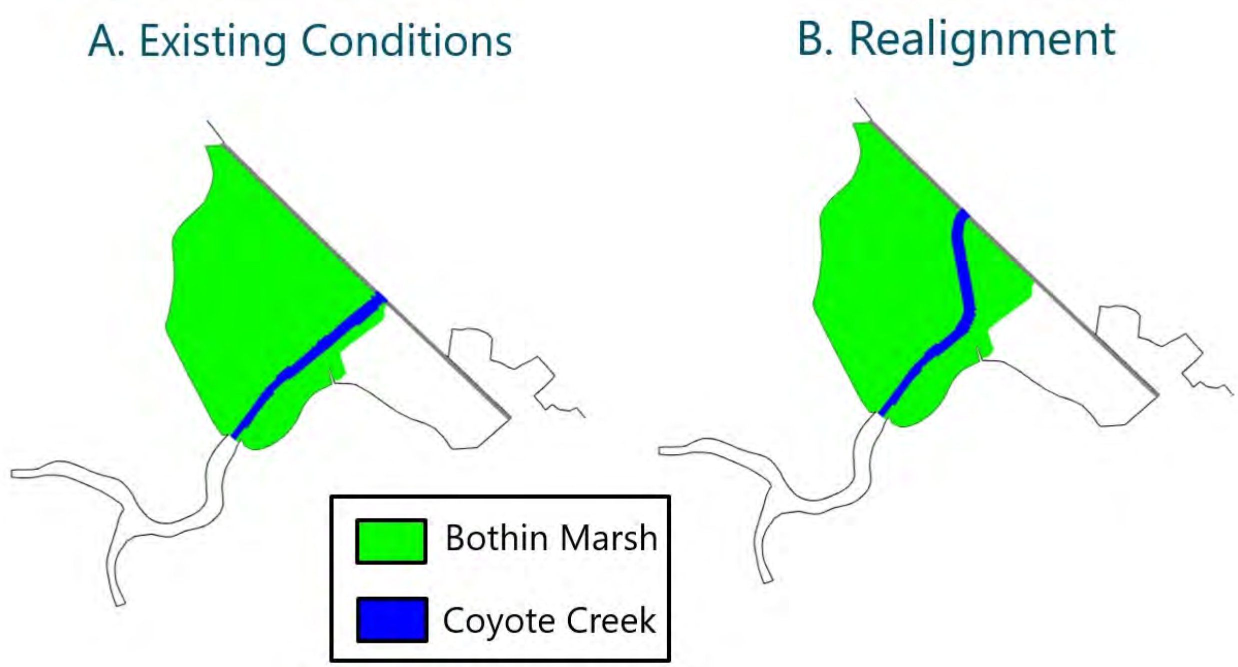
6.2.2 Sediment Model Analysis Approach

The effect of the realignment of Coyote Creek on sediment deposition in Bothin Marsh was evaluated by comparing the predicted change in sediment mass in Bothin Marsh over time under both existing conditions and for Alternative 3. For this analysis, a portion of the model domain spanning Bothin Marsh was delineated for both existing conditions and the realignment alternative modeled, Alternative 3 (Figure 6-6). Because Coyote Creek follows a slightly longer path through Bothin Marsh under Alternative 3, the total marsh area over which the sediment mass was calculated in Alternative 3 is approximately 0.6 acre smaller than under existing conditions (Figure 6-6).

After each hour during the simulation period, the sediment mass in Bothin Marsh that entered the model domain through Coyote Creek or Nyhan Creek during the simulation period and was deposited in Bothin Marsh was calculated over the regions shown in Figure 6-6. Because this sediment is also susceptible to re-erosion, this mass can go up or down over time.

Additionally, the change in total sediment mass in Bothin Marsh was calculated hourly for both existing conditions and Alternative 3 over the regions shown in Figure 6-6. The total sediment mass includes all sediment, which was on the initial sediment bed both in Bothin Marsh and in San Francisco Bay, and all sediment entering San Francisco Bay through all tributaries, including Coyote Creek and Nyhan Creek. Calculating the change in total sediment mass in Bothin Marsh gives an indication of both erosion and deposition over the full simulation period, and the comparison of the sediment mass between existing conditions and Alternative 3 provides an indication of how the realignment of Coyote Creek is likely to affect both erosion and deposition.

Figure 6-6
Analysis Polygons



The analysis of changes in sediment mass in Bothin Marsh focusses on three distinct periods. The first two periods correspond to a period of high flows in Coyote Creek and Nyhan Creek and a period of king tides. These two periods correspond to periods when TSS data were collected at the Study site. The third period evaluates changes over the full 3-month analysis period that spans both events.

First, the assessment of the increased inorganic sediment supply from Coyote Creek during high flows focuses on a 72-hour analysis period spanning from February 12, 2019, at 12:00 PST to February 15, 2019, at 12:00 PST (Figure 6-4 top). The comparison of predicted sediment deposition in Bothin Marsh during this period under existing conditions and Alternative 3 evaluated provides a quantitative measure for predicting whether the realignment will increase inorganic sediment supply to Bothin Marsh.

Second, the assessment of sediment exchange between Bothin Marsh and Richardson Bay during king tides focusses on the 6 days between December 20, 2018, at 0:00 PST to December 25, 2018, at 0:00 PST, when the maximum observed water level at the NOAA San Francisco (9414290) station exceeded MHHW (Figure 6-4 bottom). The comparison of predicted sediment deposition during the December 2018 king tide period under existing conditions and Alternative 3 allows for a direct assessment of how realigning Lower Coyote Creek and changing the geometry of the connection between Bothin Marsh and Richardson Bay affects deposition during extreme high tides. This comparison will provide a quantitative measure of the potential for the realignment to either increase or decrease the deposition in Bothin Marsh of suspended sediment transported onto the marsh from Richardson Bay.

Lastly, changes in sediment mass were evaluated over the full 3-month period between December 1, 2018, and March 1, 2019, which spans both of the other two periods. Evaluating trends over this longer time period provided an assessment of the combined effect of these two distinct periods and allowed for an assessment of sediment mass during periods with lower flows and smaller tidal ranges.

6.3 Sediment Transport Model Simulation Results

After each hour during the simulation period, the sediment mass in Bothin Marsh, which entered the model domain through Coyote Creek or Nyhan Creek during the simulation period and was deposited in Bothin Marsh, was calculated (Figure 6-7). Under both existing conditions and Alternative 3, the sediment mass in Bothin Marsh originating from Coyote Creek and Nyhan Creek generally increases over time. However, during some periods, most notably following the flow event in mid-January, the sediment mass in Bothin Marsh originating from Coyote Creek and Nyhan Creek is predicted to slowly decline (Figure 6-7 top).

In early December, the realignment results in more predicted sediment mass deposited in Bothin Marsh originating from Coyote Creek and Nyhan Creek, presumably from increased deposition at the end of a moderate flow event at the end of November just prior to the beginning of the analysis period. Between early December and mid-January, the predicted sediment mass in Bothin Marsh originating from Coyote Creek and Nyhan Creek is lower under Alternative 3 (Figure 6-7 bottom) than under existing conditions. This suggests some additional loss of sediment from

Bothin Marsh to Richardson Bay during this period with relatively low flows in Coyote Creek due to the larger tidal connectivity between Richardson Bay and Bothin Marsh in Alternative 3.

During the king tide period, the sediment mass in Bothin Marsh from sediment that originated in Coyote Creek and Nyhan Creek is predicted to increase under both existing conditions and Alternative 3, but the increase in sediment mass that originated in Coyote Creek and Nyhan Creek during this period is predicted to be 2% less under Alternative 3 than under existing conditions (Table 6-3). During periods of higher flow in Coyote Creek in mid-January and mid-February, the sediment mass in Bothin Marsh originating from Coyote Creek and Nyhan Creek increases rapidly under both existing conditions and Alternative 3. Under Alternative 3, sediment mass increases more rapidly during both events (Figure 6-7 bottom). The increase in sediment mass, which originated in Coyote Creek and Nyhan Creek during this period, is predicted to be 77% higher under Alternative 3 than under existing conditions (Table 6-2). During the full 3-month analysis period, the increase in sediment mass in Bothin Marsh that originated in Coyote Creek and Nyhan Creek during the simulation period is predicted to be 60% higher under the realignment scenario than under existing conditions (Table 6-3).

Figure 6-7
Predicted Cumulative Change in Sediment Mass in Bothin Marsh from Sediment Originating in Coyote Creek and Nyhan Creek during the Simulation Period (Top); Difference in Predicted Sediment Mass in Bothin Marsh from Sediment Originating in Coyote Creek and Nyhan Creek during the Simulation Period Resulting from the Realignment (Bottom)

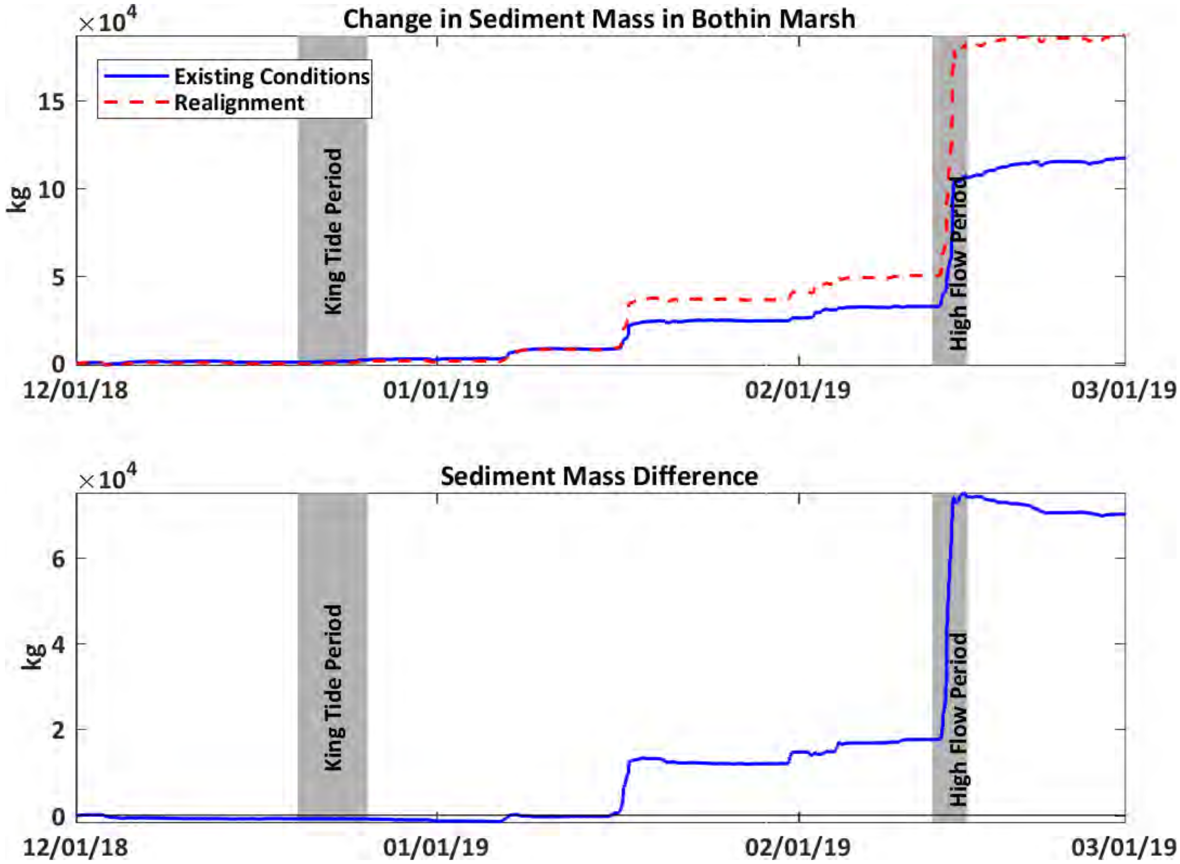


Table 6-3
Predicted Change in Sediment Mass in Bothin Marsh from Sediment That Originated in Coyote Creek and Nyhan Creek

		Predicted Change in Sediment Mass (kg)		Predicted Difference Due to Realignment	
Analysis Period	**Date Range**	**Existing Conditions**	**Realignment**	**kg**	**Percent**
King Tide	December 20, 2018, at 0:00 PST to December 25, 2018, at 0:00 PST	1,254	1,224	-30	-2%
High Flow	February 12, 2019, at 12:00 PST to February 15, 2019, at 12:00 PST	73,589	130,122	56,533	77%
Full Analysis Period	December 20, 2018, at 0:00 PST to December 25, 2018, at 0:00 PST	117,296	187,447	70,151	60%

The change in total sediment mass in Bothin Marsh was calculated hourly for both existing conditions and Alternative 3 (Figure 6-8). The total sediment mass includes all sediment, which was on the initial sediment bed in Bothin Marsh and in San Francisco Bay, and all sediment entering San Francisco Bay through all tributaries, including Coyote Creek and Nyhan Creek. Under both existing conditions and Alternative 3, the predicted total sediment mass in Bothin Marsh originating from all sources generally increases over time. However, during some periods, the sediment mass in Bothin Marsh originating from Coyote Creek and Nyhan Creek is predicted to slowly decline due to erosion and remobilization of sediment recently deposited in the marsh (Figure 6-8 top).

From the beginning of the analysis period through mid-January, the realignment results in less predicted sediment mass in Bothin Marsh under Alternative 3 than under existing conditions (Figure 6-8 bottom). This suggests some additional loss of sediment from Bothin Marsh to Richardson Bay during this period, with relatively low flows in Coyote Creek due to the larger tidal connectivity between Richardson Bay and Bothin Marsh in Alternative 3. During the king tide period, the sediment mass in Bothin Marsh from all sources is predicted to increase under both existing conditions and Alternative 3. The predicted increase in total sediment mass from all sources during the king tide period is 6% higher in Alternative 3 than under existing conditions (Table 6-4). This suggests that while sediment accumulation on Bothin Marsh may be slower under Alternative 3 during periods of lower high tides, greater sediment accumulation is predicted to occur during periods of king tides.

During periods of higher flow in Coyote Creek in mid-January and mid-February, the total sediment mass in Bothin Marsh originating from all sources increases rapidly under both existing conditions and Alternative 3. Under Alternative 3, sediment mass in Bothin Marsh is predicted to increase more rapidly during both events than under existing conditions (Figure 6-8 bottom). The increase in sediment mass in Bothin Marsh from all sources during this period is predicted to be 87% higher under Alternative 3 (Table 6-4). During the full 3-month analysis period, the total increase in sediment mass in Bothin Marsh that originated from all sources is predicted to be 37% higher under Alternative 3 than under existing conditions (Table 6-4).

Figure 6-8
Predicted Cumulative Change in Total Sediment Mass in Bothin Marsh from All Sources during the Simulation Period (Top); Difference in Predicted Sediment Mass in Bothin Marsh from Sediment from All Sources during the Simulation Period Resulting from the Realignment (Bottom)

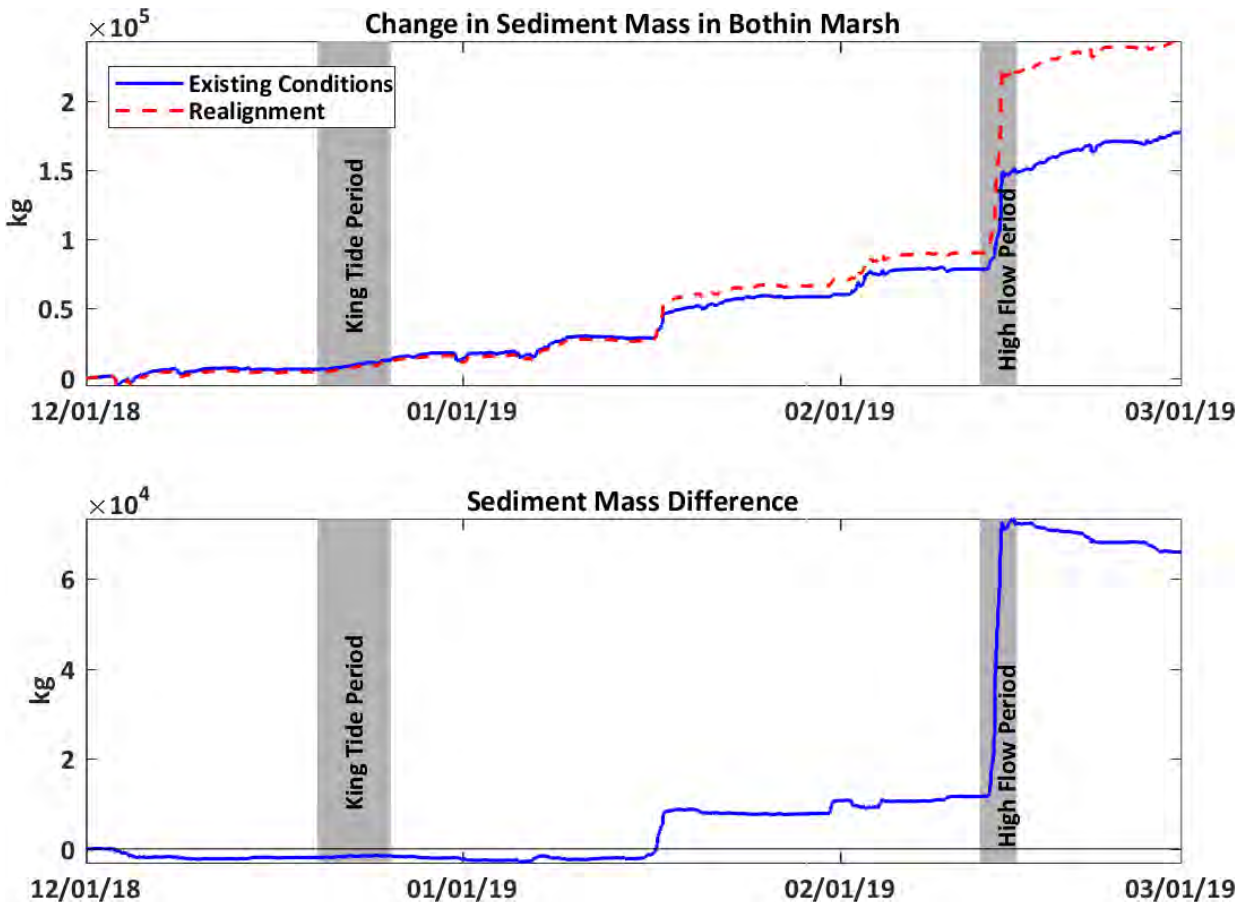


Table 6-4
Predicted Change in Sediment Mass in Bothin Marsh for Sediment from All Sources

Analysis Period	Date Range	Predicted Change in Sediment Mass (kg)		Predicted Difference Due to Realignment	
		Existing Conditions	Realignment	kg	Percent
King Tide	December 20, 2018, at 0:00 PST to December 25, 2018, at 0:00 PST	6,281	6,673	392	6%
High Flow	February 12, 2019, at 12:00 PST to February 15, 2019, at 12:00 PST	69,355	129,925	60,570	87%
Full Analysis Period	December 20, 2018, at 0:00 PST to December 25, 2018, at 0:00 PST	176,902	242,804	65,902	37%

Maps showing the predicted deposition and erosion allow for a comparison of the spatial differences in erosion and deposition between existing conditions and Alternative 3 during each time period. Deposition and erosion maps were created for both sediment originating in Coyote Creek and Nahyan Creek and the total sediment from all sources.

Under existing conditions, the predicted deposition of sediment originating in Coyote Creek and Nyhan Creek during the high-flow period deposits mainly in the channel in Coyote Creek and Richardson Bay, with some sediment depositing in Bothin Marsh (Figure 6-9A). For Alternative 3, the predicted deposition of sediment originating in Coyote Creek and Nyhan Creek during the high-flow period shows a similar pattern with visibly more deposition in Bothin Marsh, and the sediment fan at the mouth of Coyote Creek shifted further northwest (Figure 6-9B). The difference in predicted deposition between existing conditions and Alternative 3 (Figure 6-9C) highlights the regions that are predicted to experience more (green to red colors) and less (blue colors) net deposition due the realignment of Coyote Creek through Bothin Marsh.

Similar maps showing the deposition and erosion of sediment from all sources (Figure 6-10), highlight the erosion and deposition throughout the northwestern part of Richardson Bay under both existing conditions (Figure 6-10A) and under Alternative 3 (Figure 6-10B). The predicted differences in the total change in sediment deposition during the high-flow period from all sources (Figure 6-10C) shows a very similar pattern to the same comparison made using only sediment originating from Coyote Creek and Nyhan Creek (Figure 6-9C). This suggests that the predicted differences in sediment deposition in Bothin Marsh during the high-flow period are largely attributable to sediment originating from Coyote Creek and Nyhan Creek.

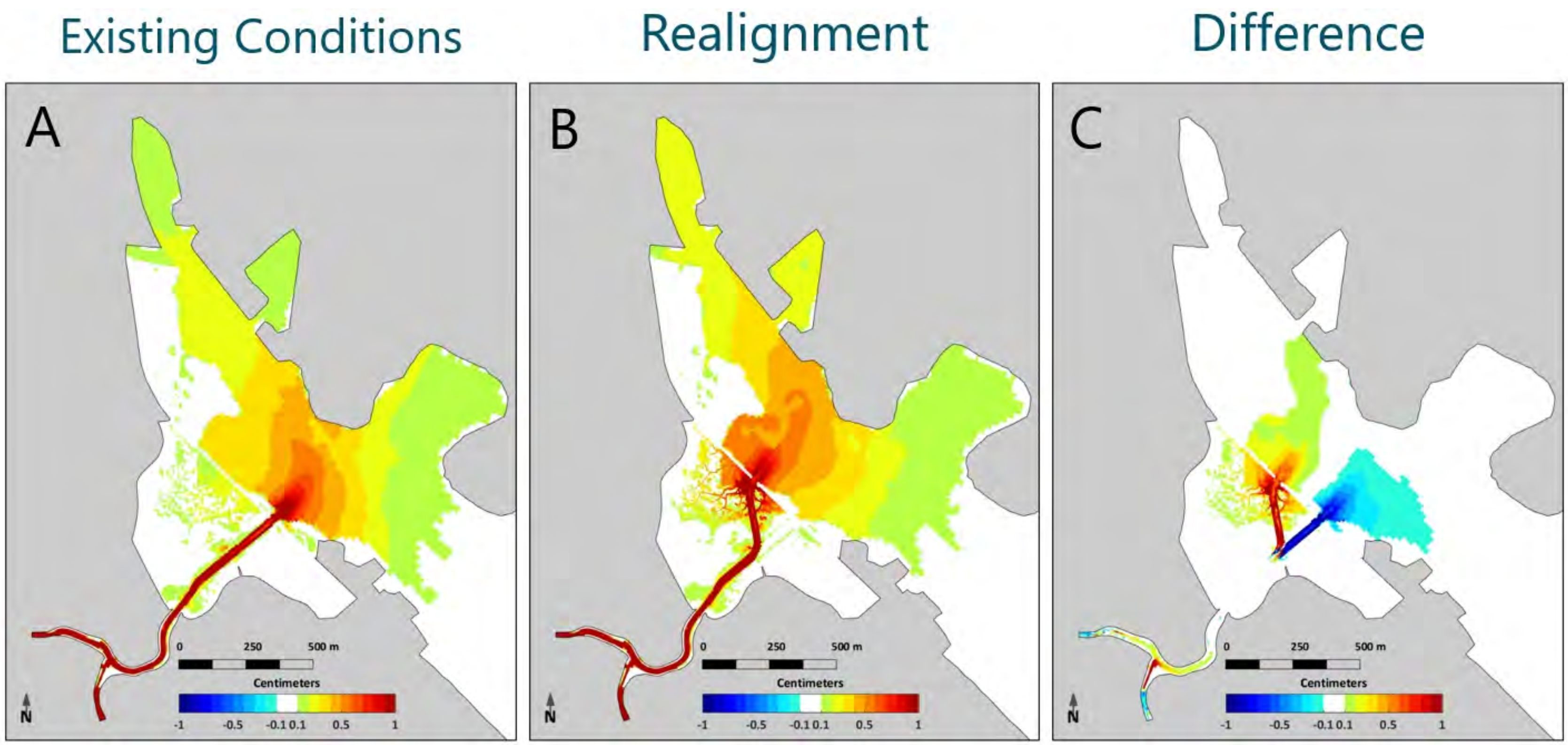
During the king tide period, flows and sediment load in Coyote and Nyhan Creek are low, and only a small amount of deposition of sediment originating from Coyote Creek and Nyhan Creek is predicted, mostly in the channel of Coyote Creek (Figure 6-11). The main differences between the existing conditions and realignment alternative in predicted deposition of sediment originating from Coyote Creek and Nyhan Creek during the king tide period is limited to the portions of Coyote Creek where the realignment occurs (Figure 6-11C).

Similar maps showing the deposition and erosion of sediment from all sources during the king tide period (Figure 6-12) highlight some predicted areas of erosion and deposition in Richardson Bay under both existing conditions and Alternative 3. The main differences between the existing conditions and realignment alternative in predicted erosion and deposition of sediment originating from all sources during the king tide period is most notable in the portions of Coyote Creek where the realignment occurs (Figure 6-12C).

Across the entire 3-month analysis period, the predicted net erosion and deposition of sediment originating in Coyote Creek and Nyhan Creek shows visibly more deposition in Bothin Marsh and the sediment fan at the mouth of Coyote Creek shifted further northwest in Alternative 3 (Figure 6-13B) relative to existing conditions (Figure 6-13A). The difference in predicted deposition of sediment originating in Coyote Creek and Nyhan Creek between existing conditions and Alternative 3 (Figure 6-13C) highlights the regions that are predicted to experience more (green to red colors) and less (blue colors) net deposition due the realignment of Coyote Creek through Bothin Marsh. The only regions with differences in deposition of sediment originating in Coyote Creek and Nyhan Creek, which exceed 0.2 cm are the upstream channels of Coyote Creek, the realigned portion of the channel, Bothin Marsh, and the portions of Richardson Bay nearest to the mouth of Coyote Creek (Figure 6-13C).

Across the entire 3-month analysis period, the predicted net erosion and deposition of sediment from all sources shows visibly more deposition in Bothin Marsh and the sediment fan at the mouth of Coyote Creek shifted further northwest in Alternative 3 (Figure 6-14B) relative to existing conditions (Figure 6-14A). Notably, some erosion of the fringes of Northern Bothin Marsh was predicted under both existing conditions and Alternative 3, with relatively little change in predicted deposition or erosion in Northern Bothin Marsh due to the realignment (Figure 6-14C). The difference in predicted deposition of sediment from all sources between existing conditions and Alternative 3 (Figure 6-14C) highlights the regions that are predicted to experience more (green to red colors) and less (blue colors) net deposition due the realignment of Coyote Creek through Bothin Marsh. The main regions with differences in erosion or deposition of sediment originating from all sources that exceed 0.1 cm are the upstream channels of Coyote Creek, the realigned portion of the channel, Bothin Marsh, and the portions of Richardson Bay nearest to the mouth of Coyote Creek (Figure 6-14C).

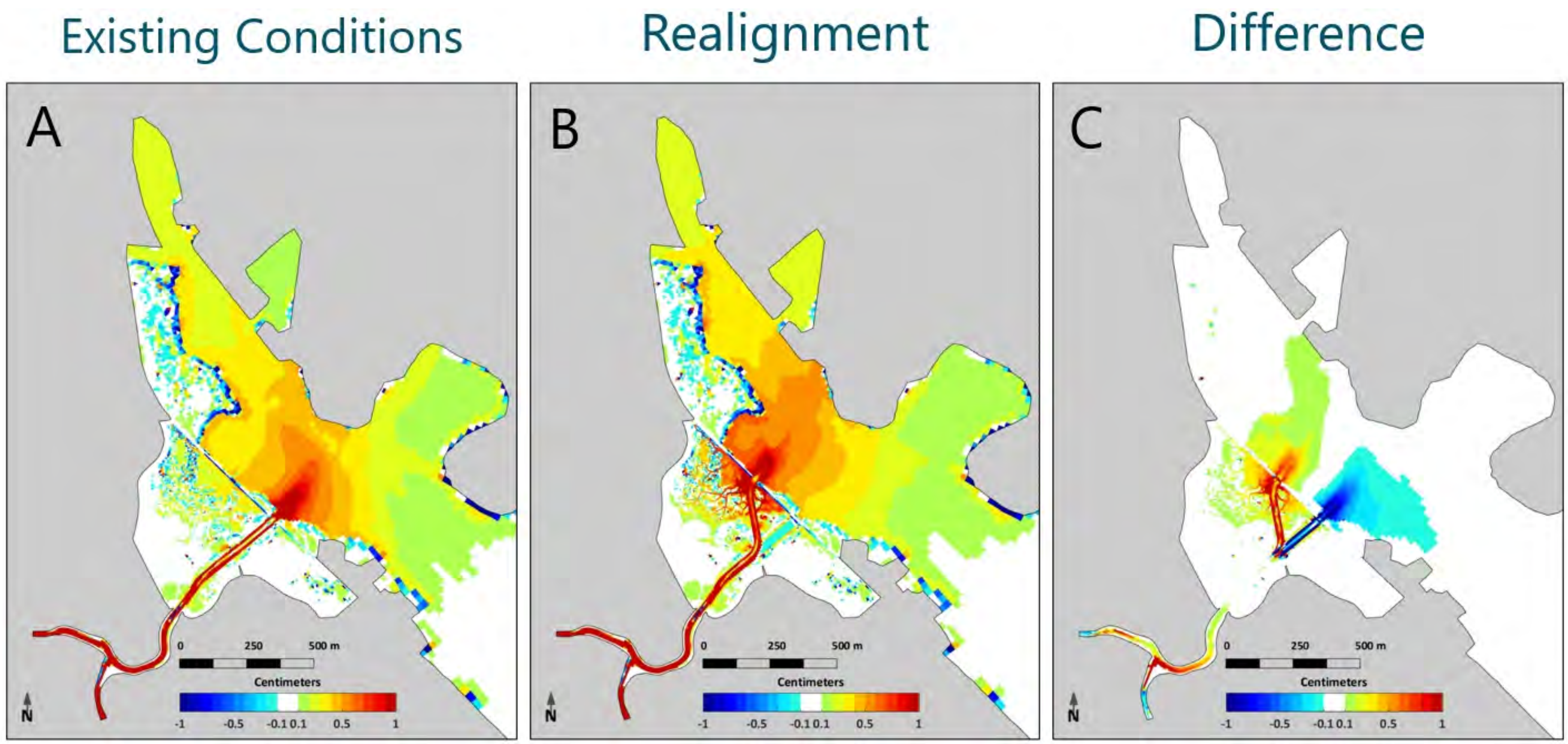
Figure 6-9
Predicted Deposition of Sediment Originating in Coyote Creek and Nyhan Creek during the High-Flow Period under (A) Existing Conditions, (B) with Coyote Creek Realignment, and (C) the Difference in Predicted Deposition Resulting from the Realignment during the High-Flow Period



Notes:

1. Sediment deposition in this figure shows only sediment entering the model domain from Coyote Creek or Nyhan Creek during the simulation period.
2. The difference is calculated as the predicted deposition in Alternative 3 minus the predicted deposition in the existing conditions simulation, such that positive values (green to red) indicate more predicted deposition in Alternative 3 and negative values (blue) indicate less predicted deposition in Alternative 3 than under existing conditions.

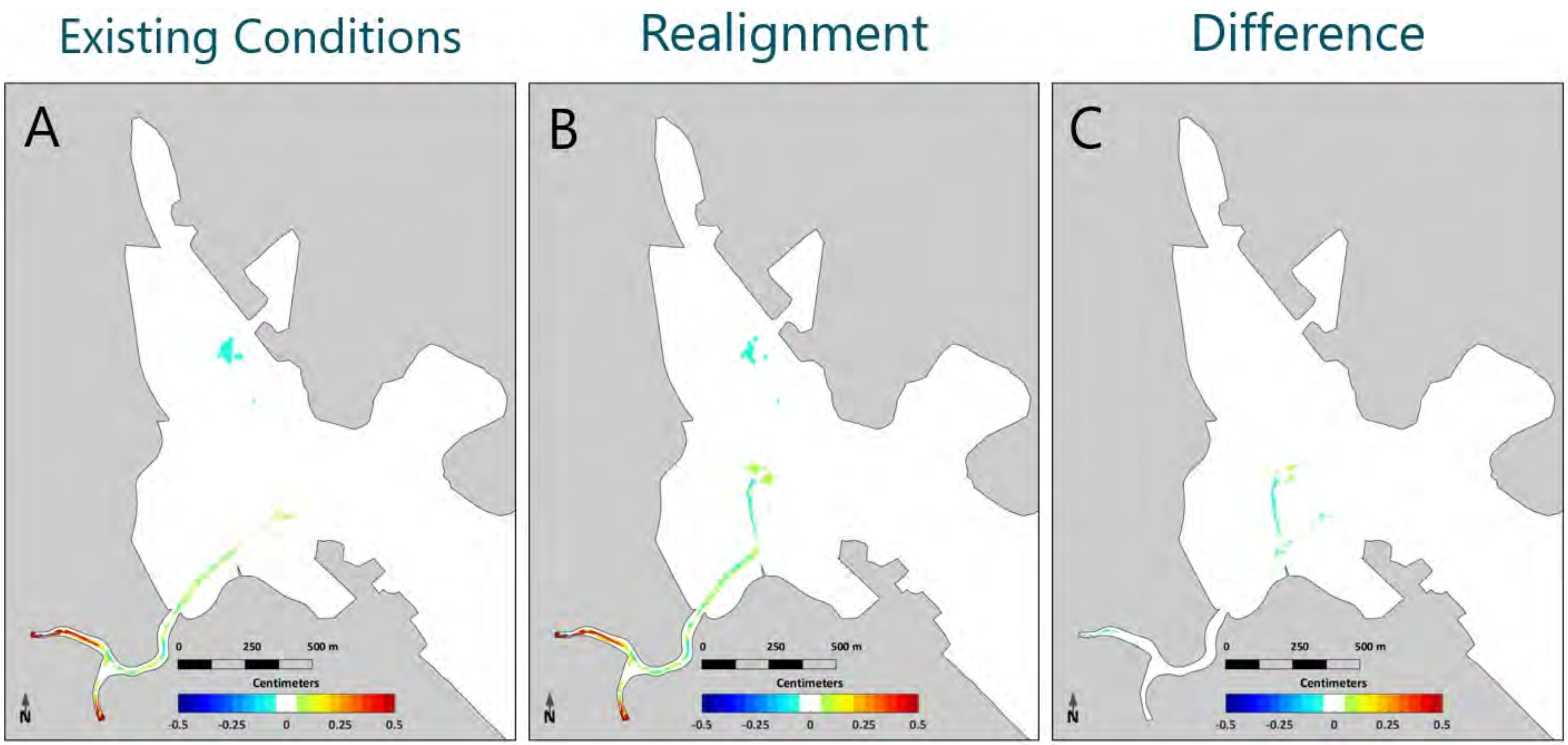
Figure 6-10
Predicted Change in Total Deposited Sediment during the High-Flow Period under (A) Existing Conditions, (B) with Coyote Creek Realignment, and (C) the Predicted Difference in Total Deposited Sediment Resulting from the Realignment during the High-Flow Period



Notes:

1. Total deposited sediment in this figure includes both sediment entering the model domain from Coyote Creek or Nyhan Creek and any changes in deposited sediment resulting from erosion or deposition of existing sediments during the simulation period.
2. The difference is calculated as the predicted bed thickness in Alternative 3 minus the predicted bed thickness in the existing conditions simulation, such that positive values (green to red) indicate either more predicted deposition or less predicted erosion in Alternative 3 and negative values (blue) indicate either less predicted deposition or more predicted erosion in Alternative 3 than under existing conditions.

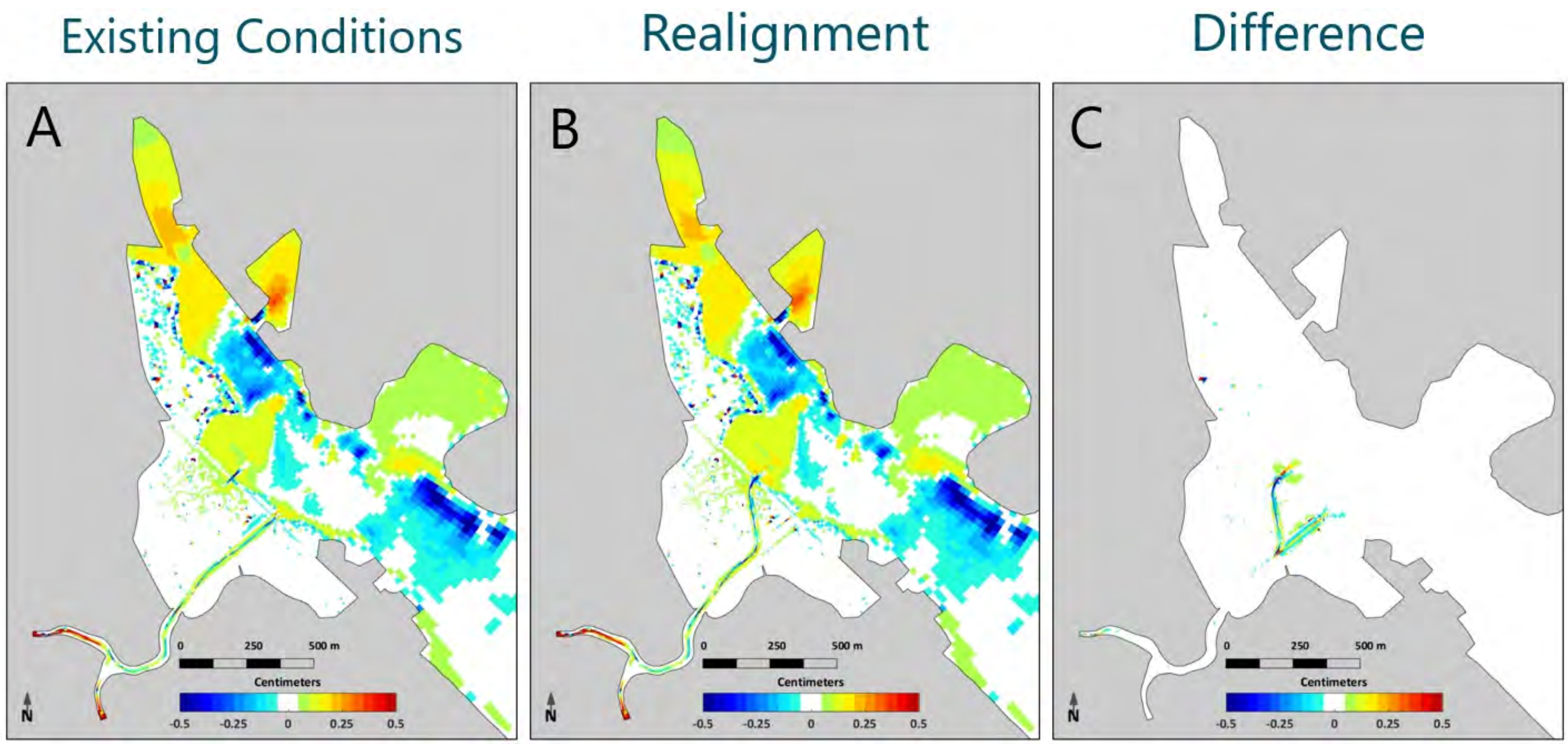
Figure 6-11
Predicted Deposition of Sediment Originating in Coyote Creek and Nyhan Creek during the King Tide Period under (A) Existing Conditions, (B) with Coyote Creek Realignment, and (C) the Difference in Predicted Deposition Resulting from the Realignment during the King Tide Period



Notes:

1. Sediment deposition in this figure shows only sediment entering the model domain from Coyote Creek or Nyhan Creek during the simulation period.
2. The difference is calculated as the predicted deposition in Alternative 3 minus the predicted deposition in the existing conditions simulation, such that positive values (green to red) indicate more predicted deposition in Alternative 3 and negative values (blue) indicate less predicted deposition in Alternative 3 than under existing conditions.

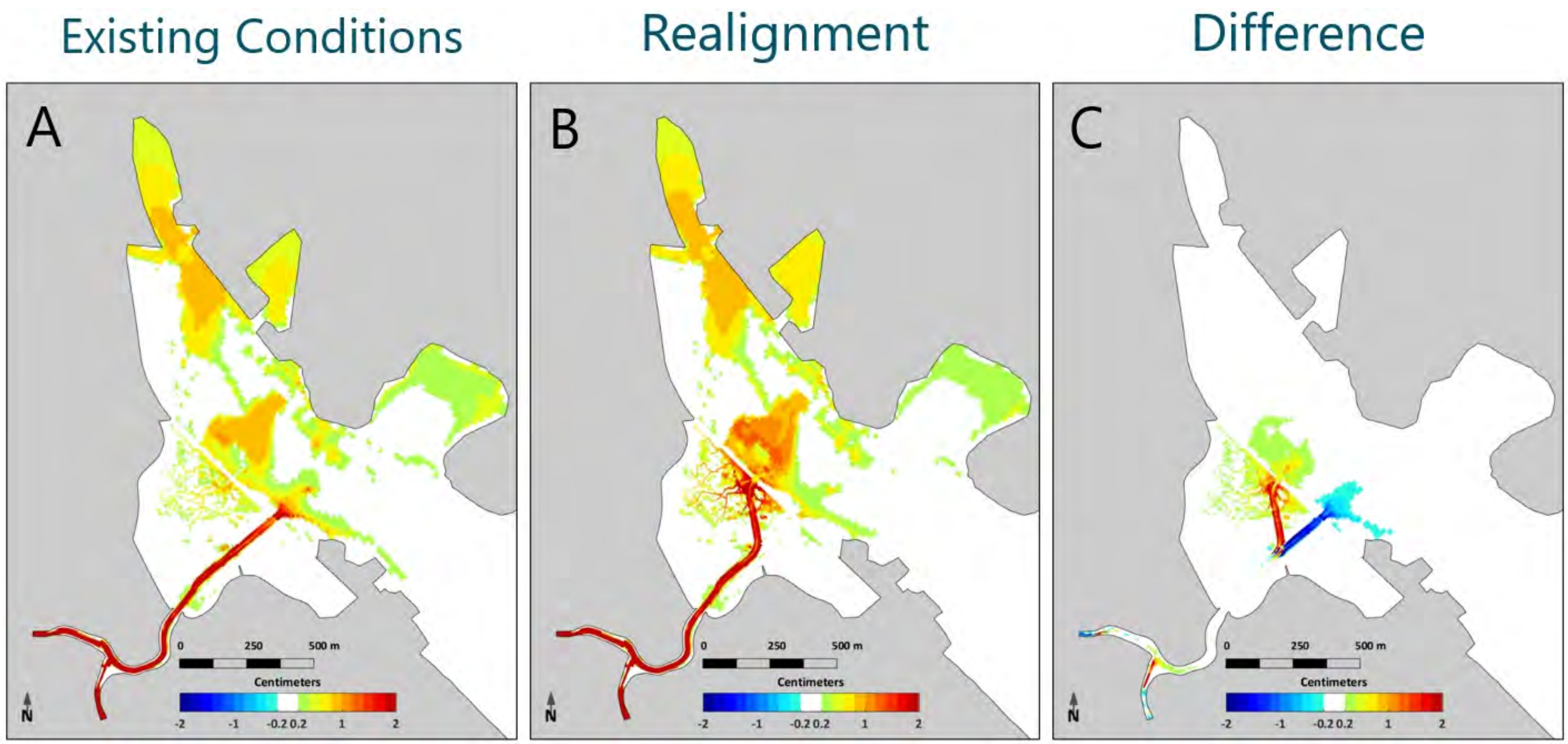
Figure 6-12
Predicted Change in Total Deposited Sediment during the King Tide Period under (A) Existing Conditions, (B) with Coyote Creek Realignment, and (C) the Predicted Difference in Total Deposited Sediment Resulting from the Realignment during the King Tide Period



Notes:

1. Total deposited sediment in this figure includes both sediment entering the model domain from Coyote Creek or Nyhan Creek and any changes in deposited sediment resulting from erosion or deposition of existing sediments during the simulation period.
2. The difference is calculated as the predicted bed thickness in Alternative 3 minus the predicted bed thickness in the existing conditions simulation, such that positive values (green to red) indicate either more predicted deposition or less predicted erosion in Alternative 3 and negative values (blue) indicate either less predicted deposition or more predicted erosion in Alternative 3 than under existing conditions.

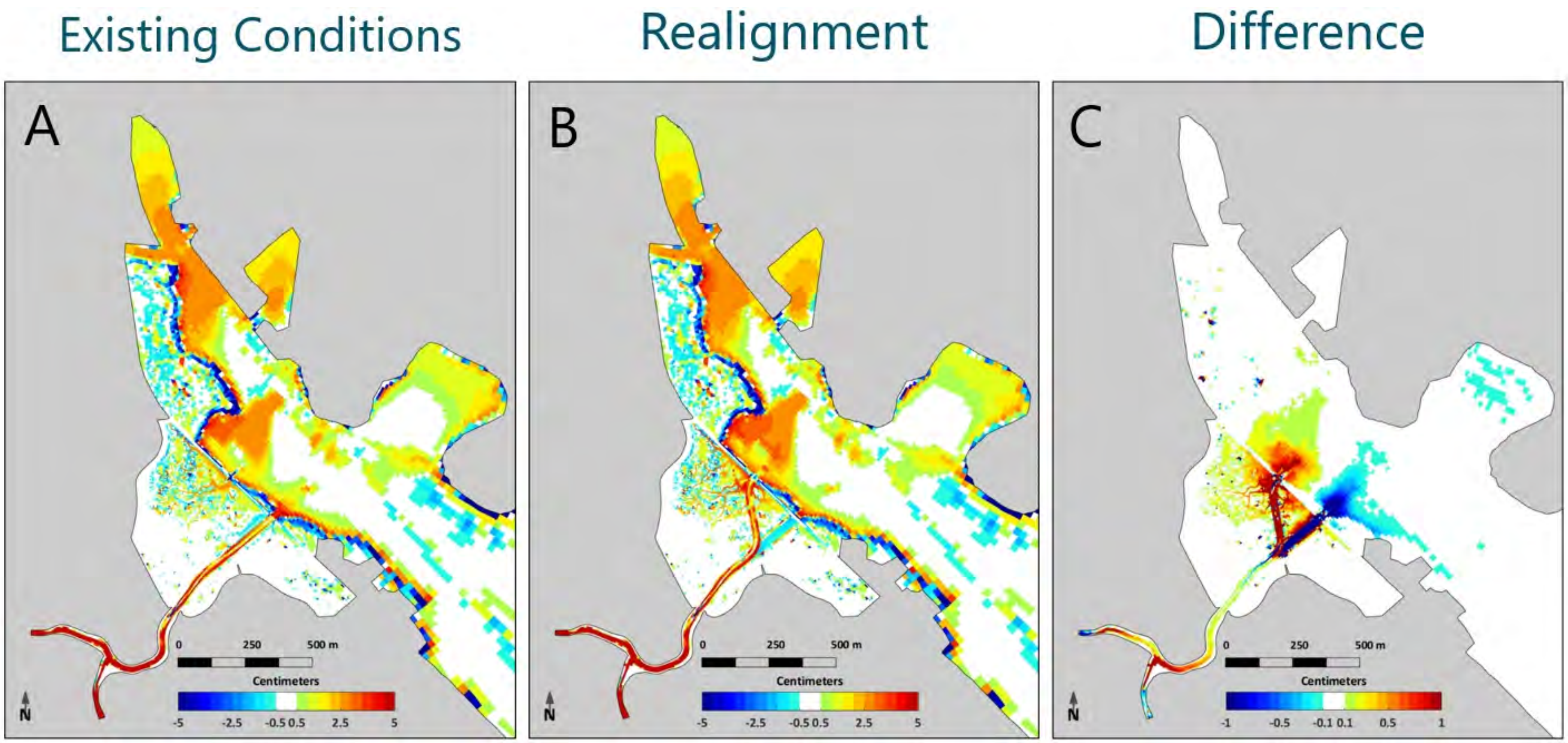
Figure 6-13
Predicted Deposition of Sediment Originating in Coyote Creek and Nyhan Creek during the Full 3-Month Analysis Period under (A) Existing Conditions, (B) with Coyote Creek Realignment, and (C) the Difference in Predicted Deposition Resulting from the Realignment during the 3-Month Analysis Period



Notes:

1. Sediment deposition in this figure shows only sediment entering the model domain from Coyote Creek or Nyhan Creek during the simulation period.
2. The difference is calculated as the predicted deposition in Alternative 3 minus the predicted deposition in the existing conditions simulation, such that positive values (green to red) indicate more predicted deposition in Alternative 3 and negative values (blue) indicate less predicted deposition in Alternative 3 than under existing conditions.

Figure 6-14
Predicted Change in Total Deposited Sediment during the Full 3-Month Analysis Period under (A) Existing Conditions, (B) with Coyote Creek Realignment, and (C) the Predicted Difference in Total Deposited Sediment Resulting from the Realignment during the 3-Month Analysis Period



Notes:

1. Total deposited sediment in this figure includes both sediment entering the model domain from Coyote Creek or Nyhan Creek and any changes in deposited sediment resulting from erosion or deposition of existing sediments during the simulation period.
2. The difference is calculated as the predicted bed thickness in Alternative 3 minus the predicted bed thickness in the existing conditions simulation, such that positive values (green to red) indicate either more predicted deposition or less predicted erosion in Alternative 3 and negative values (blue) indicate either less predicted deposition or more predicted erosion in Alternative 3 than under existing conditions.

6.4 Discussion of Sediment Transport Model Results and Implications for Marsh Sustainability

The overall goal of the sediment transport modeling conducted for this Study was to evaluate how the realignment of Lower Coyote Creek through Bothin Marsh has the potential to result in changes to the sediment supply to Bothin Marsh. Changes to sediment supply could result both from sediment supply from Coyote Creek and from potential changes to the sediment and tidal exchange between Bothin Marsh and Richardson Bay.

The 3-month period analyzed allows for an assessment of deposition on the marsh during king tides, during a period of high flow and sediment input from Coyote Creek, and over the full 3-month period spanning these two events. This period includes a period of high flow on Coyote Creek, which was estimated to be approximately a 4-year return interval flow, and therefore this 3-month period may not be representative of drier periods when flows on Coyote Creek and Nyhan Creek are lower for an extended period of time. Given that there is significant uncertainty in the magnitude of the sediment inputs due to the limited data available to develop the sediment rating curve for Coyote Creek, there is limited data in the study area beyond the few TSS samples collected for this Study, and this 3-month period with a high-flow event may not be representative of longer-term conditions, the primary conclusions drawn from this analysis are intended to be more qualitative in nature.

The following conclusions can be drawn from the sediment modeling:

1. Even under existing conditions, sediment originating in Coyote Creek and Nyhan Creek provides a significant portion of the sediment supply to Bothin Marsh based on the results of this 3-month analysis period. This is because during high flows, water from Coyote Creek can spread over Bothin Marsh even under existing conditions. Based on the sediment mass deposited over the 3-month analysis period, 66% of the net sediment deposited in Bothin Marsh originated in Coyote Creek and Nyhan Creek during the simulation period under existing conditions. Additional analysis would be required to evaluate whether this high relative contribution of sediment from Coyote Creek and Nyhan Creek is representative of annual or longer periods that also span drier summer conditions.

2. The realignment of Coyote Creek through Bothin Marsh is predicted to increase the sediment deposition in Bothin Marsh of sediment that originated in Coyote Creek and Nyhan Creek. Over the 3-month analysis period, the deposition of sediment that originated in Coyote Creek and Nyhan Creek is predicted to be 60% higher under the realignment scenario than under existing conditions (Table 6-2).

3. It is likely that realignment alternatives that have a smaller channel cross-sectional area through the marsh, such as Alternative 1 and Alternative 2, would result in an even greater increase in sediment deposition in Bothin Marsh from Coyote Creek and Nyhan Creek. However, these alternatives would need to be mitigated by raising the upstream levees to offset predicted increases in upstream water levels. The scope of this Study did not allow for simulating sediment transport for these scenarios.

4. Overall, the net change in sediment deposition from all sources in Bothin Marsh during the 3-month analysis period is predicted to be 37% higher under Alternative 3 than under existing conditions. However, the total predicted increase in sediment mass from all sources resulting from the realignment (Table 6-4) is less than the predicted increase in sediment mass originating in Coyote Creek and Nyhan Creek (Table 6-2). This indicates some reduction in net sediment accumulation from Richardson Bay in Bothin Marsh due to the channel realignment. The net loss of sediment from the marsh due to the realignment is evident during periods of lower high tides when the marsh is predicted to accumulate sediment more slowly under Alternative 3 than under existing conditions (Figure 6-8). This suggests that during some periods, the realignment may result in less sediment accumulation in Bothin Marsh than under existing conditions and indicates that that the greater connectivity between Richardson Bay and Bothin Marsh resulting from the realignment does not always result in an increase in sediment deposition in Bothin Marsh.

5. Because this analysis suggests that increased connectivity between Richardson Bay and Bothin Marsh can lead to lower deposition in Bothin Marsh during periods when flows and sediment supply from Coyote Creek are low and tidal range is smaller, additional sediment modeling may be warranted for any additional alternatives that include realignment or elevation of the Bay Trail. These alternatives could potentially result in even greater connectivity between Bothin Marsh and Richardson Bay than the realignment alternative evaluated in this Study, which could have implications for the net sediment accumulation in Bothin Marsh for these alternatives.

6. Overall, TSS measurements in Richardson Bay indicate comparatively low suspended sediment even during a period of king tides. Twelve of the 13 TSS measurements collected on December 23, 2018, ranged from 12 to 27 mg/L, although these samples were collected during a calm period with little to no wind waves. Based on previous analyses conducted using the WARMER model (Swanson et al. 2014), water entering Bothin Marsh from Richardson Bay with similarly low TSS concentrations is not likely to support marsh sustainability longer term without a large inorganic sediment supply from Coyote Creek. A more comprehensive, site-specific analysis using the WARMER model could be applied to estimate marsh sustainability at the Study site for different SLR scenarios to assess the range of SLR rates under which Bothin Marsh

would be sustainable. Information on inorganic sediment supply rates from Coyote Creek to Bothin Marsh developed in this Study can be used in that analysis.

7. Sediment supply augmentation is needed for marsh resilience. There are multiple ways of augmenting and delivering suspended sediment. Channel realignment directly into the marsh—considered in this Study—is one way, with benefits and drawbacks (e.g., cost, direct marsh impacts). Other alternatives (not modeled) that increase creek connectivity to the marsh without creek realignment or that use mechanical means to deliver dredged sediment to the marsh are also being considered as part of the Bothin Marsh Evolving Shorelines Project.

7 Summary and Conclusions

This report documents the hydraulic modeling and analysis conducted to evaluate whether the realignment of Coyote Creek through Bothin Marsh can be achieved without adversely increasing flood risk. Hydraulic modeling of potential realignment alternatives of Lower Coyote Creek into Bothin Marsh was conducted using HEC-RAS 2D. Five hydraulic scenarios were used to bracket a wide range of tidal and flow conditions. These five hydraulic scenarios were simulated under existing conditions and for three channel realignment scenarios.

Two initial alternatives, Alternative 1 and Alternative 2, were developed based on the conceptual Alternative 1 developed by Watershed Sciences for Marin County Parks and the District in October 2019 (Watershed Sciences 2019). These two alternatives follow the same alignment and have the same thalweg depth and channel widths at MHHW and low water (Table 4-2) but include different assumptions for side slopes that result in different cross-sectional areas. Both Alternative 1 and Alternative 2 included a ramp on the east side of the realigned channel along the outside of the first channel meander, which directed the channel through the back of the marsh to promote backshore deposition (Figure 4-1).The hydraulic modeling indicated that both Alternative 1 and Alternative 2 resulted in a significant increase in upstream water surface elevations during high flows. Based on these results, a third alternative (Alternative 3) was developed, in coordination with the Bothin Marsh Evolving Shorelines Project, that incorporated a larger cross-sectional area, a less sinuous alignment compared to Alternatives 1 and 2, and excludes the ramp on the east side of the realigned channel. Hydraulic modeling of Alternative 3 indicates that it meets the objective of allowing for the realignment of Coyote Creek through Bothin Marsh without significantly increasing flood risk.

Under the extreme tide scenarios (Scenario 1 and Scenario 4), water levels in Lower Coyote Creek were dominated by the downstream tides propagating into Coyote Creek from Richardson Bay, resulting in relatively small differences in predicted maximum water surface elevation resulting from the three realignment alternatives for these two tidally dominated scenarios (Table 5-1). However, for the hydraulic scenarios that included higher flows (Scenarios 2, 3, and 5), the reduced channel capacity in Lower Coyote Creek in Alternative 1 and Alternative 2 relative to existing conditions (Figure 4-2) resulted in an increase in predicted water levels over much of Coyote Creek under these realignment alternatives.

In contrast, the channel capacity for Alternative 3 was designed to be similar to existing conditions, and the maximum predicted water surface elevation downstream of the SR 1 bridge was predicted to increase by between 0 and 0.02 foot for the five hydraulic scenarios evaluated. Based on this evaluation, Alternative 3 was identified as the realignment alternative that results in the lowest predicted effect on flood risk due to both tidal and fluvial flooding. Further refinement of this alternative design may be able to reduce these effects further.

The evaluation of Alternative 3 using a 3D hydrodynamic and sediment transport model suggests that the realignment is also likely to result in an ongoing increase in sediment contribution to Bothin Marsh, primarily due to greater deposition in the marsh of sediment originating in Coyote Creek and Nyhan Creek during periods of high creek flow. Overall, the net change in sediment deposition from all sources in Bothin Marsh during the 3-month analysis period is predicted to be 37% higher under Alternative 3 than under existing conditions.

8 References

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Appendix A
Coyote Creek Topography Comparison Figures

SOURCE:

1. Marin County, California QL1 LiDAR collected by Quantum Spatial for Golden Gate National Parks Conservancy (2019).
2. Bothin DEM topographic/bathymetric composite provided by Marin County (2007-2010).
3. Topographic survey conducted by Cinquini & Passarino (January 2020).
4. Aerial photo acquired from Marin County (2018).

HORIZONTAL DATUM: California State Plane Zone III, North American Datum of 1983 (NAD83), U.S. Survey Feet
VERTICAL DATUM: North American Vertical Datum of 1988 (NAVD88)

LEGEND:

Surveyed Spot Elevation

A A' Transect Line

0 200
Feet

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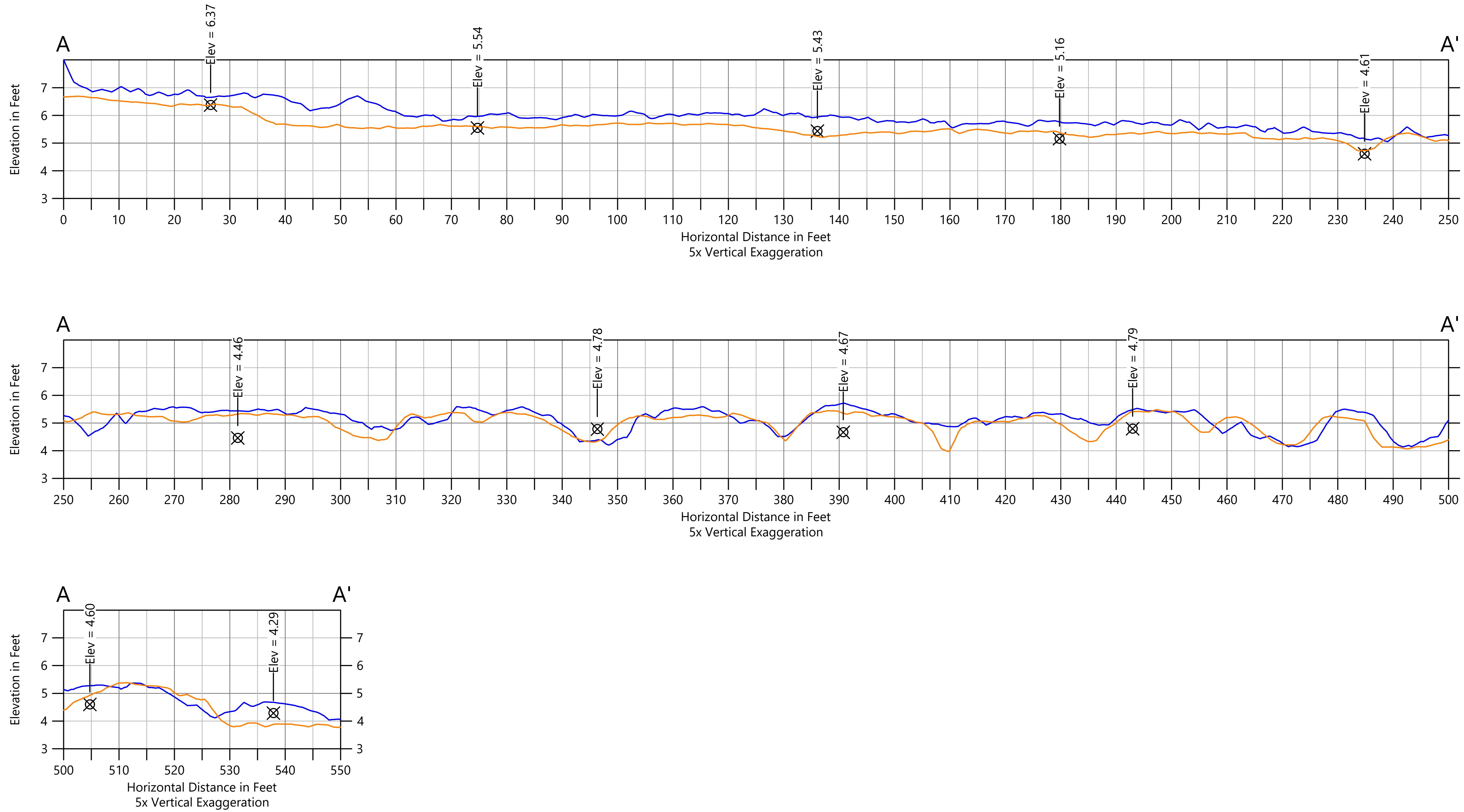
ANCHOR QEA

Figure A-1
Assessment Transects and Spot Survey Locations

Hydraulic Study of the Relocation of Lower Coyote Creek into Bothin Marsh
Lower Coyote Creek Realignment Hydraulic Modeling Report



SOURCE:

1. Marin County, California QL1 LiDAR collected by Quantum Spatial for Golden Gate National Parks Conservancy (2019).
2. Bothin DEM topographic/bathymetric composite provided by Marin County (2007-2010).
3. Topographic survey conducted by Cinquini & Passarino (January 2020).

HORIZONTAL DATUM: California State Plane Zone III, North American Datum of 1983 (NAD83), U.S. Survey Feet
VERTICAL DATUM: North American Vertical Datum of 1988 (NAVD88)

LEGEND:

Marin County QL1 2019 LiDAR

Bothin DEM

Surveyed Spot Elevation

Scale in Feet
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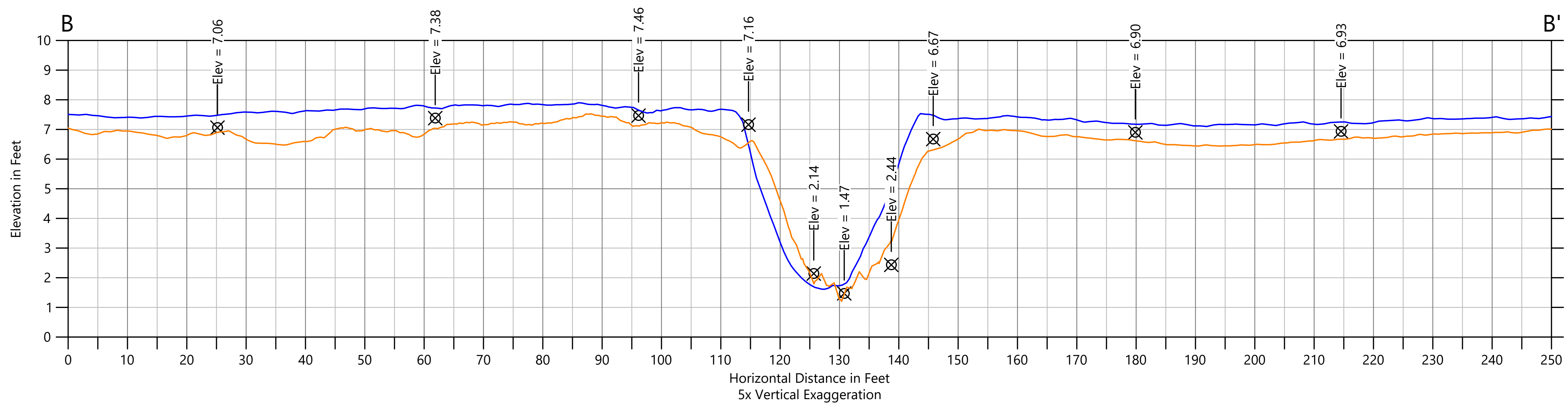
0 4 8
Vertical Scale in Feet
Vertical Exaggeration x 5

ANCHOR QEA

Figure A-2
Assessment Transect AA'



SOURCE:

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2. Bothin DEM topographic/bathymetric composite provided by Marin County (2007-2010).
3. Topographic survey conducted by Cinquini & Passarino (January 2020).

HORIZONTAL DATUM: California State Plane Zone III, North American Datum of 1983 (NAD83), U.S. Survey Feet
VERTICAL DATUM: North American Vertical Datum of 1988 (NAVD88)

LEGEND:

Marin County QL1 2019 LiDAR

Bothin DEM

Surveyed Spot Elevation

Scale in Feet
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0 4 8
Vertical Scale in Feet
Vertical Exaggeration x 5

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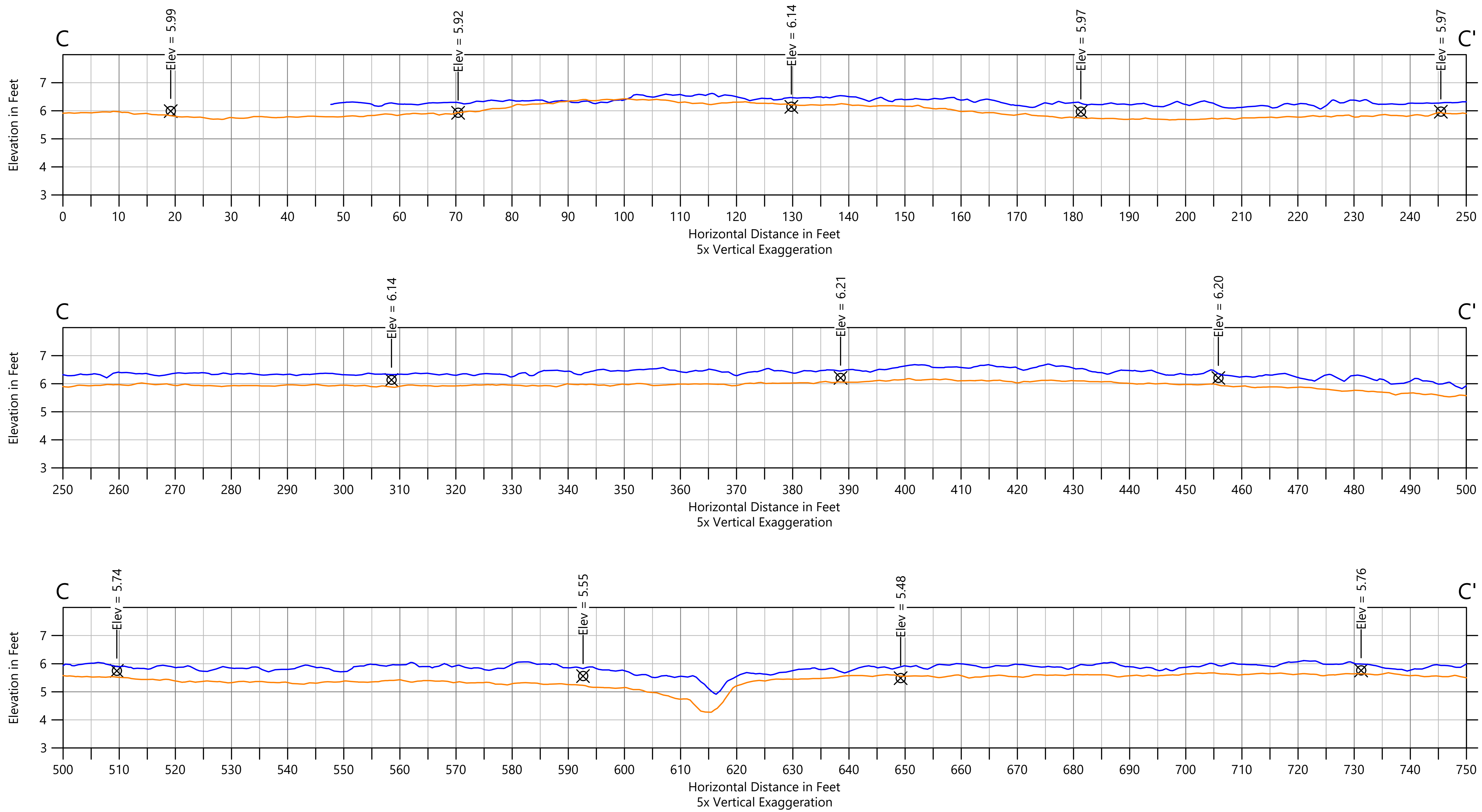
Figure A-3
Assessment Transects BB'

Hydraulic Study of the Relocation of Lower Coyote Creek into Bothin Marsh
Lower Coyote Creek Realignment Hydraulic Modeling Report



SOURCE:

1. Marin County, California QL1 LiDAR collected by Quantum Spatial for Golden Gate National Parks Conservancy (2019).
2. Bothin DEM topographic/bathymetric composite provided by Marin County (2007-2010).
3. Topographic survey conducted by Cinquini & Passarino (January 2020).

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VERTICAL DATUM: North American Vertical Datum of 1988 (NAVD88)

LEGEND:

Marin County QL1 2019 LiDAR

Bothin DEM

Surveyed Spot Elevation

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Vertical Scale in Feet
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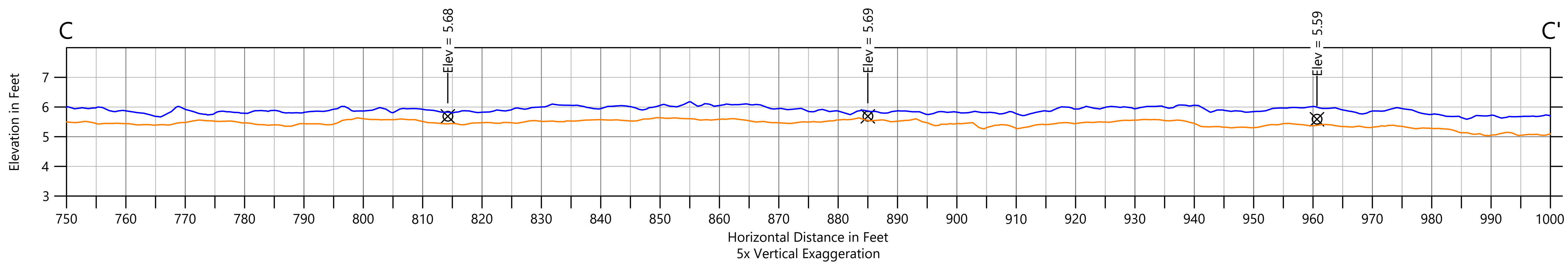
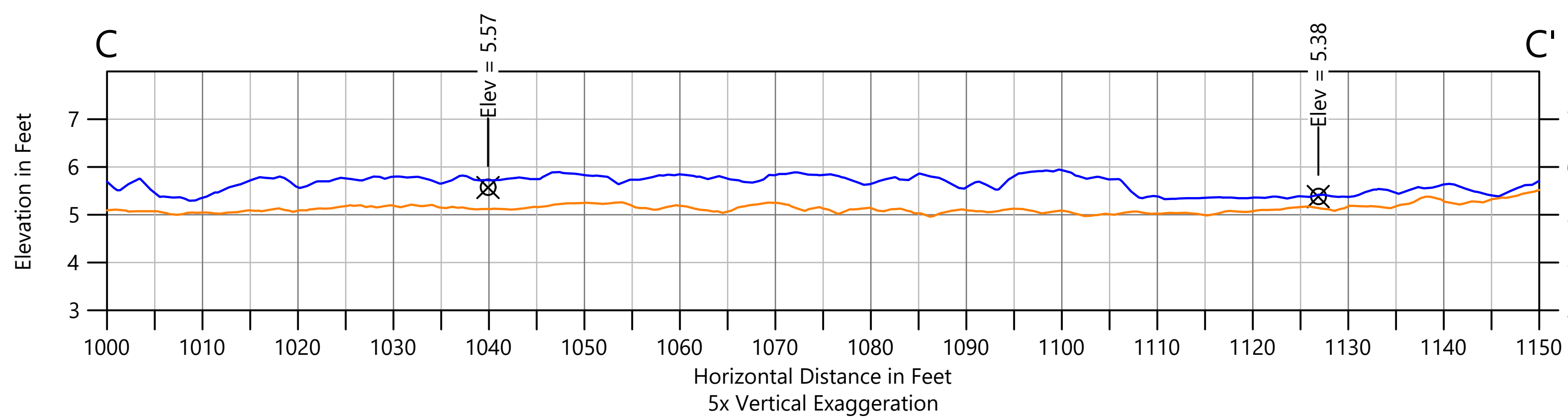
Figure A-4
Assessment Transect CC'

Hydraulic Study of the Relocation of Lower Coyote Creek into Bothin Marsh
Lower Coyote Creek Realignment Hydraulic Modeling Report





SOURCE:

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2. Bothin DEM topographic/bathymetric composite provided by Marin County (2007-2010).
3. Topographic survey conducted by Cinquini & Passarino (January 2020).

HORIZONTAL DATUM: California State Plane Zone III, North American Datum of 1983 (NAD83), U.S. Survey Feet
VERTICAL DATUM: North American Vertical Datum of 1988 (NAVD88)

LEGEND:

Marin County QL1 2019 LiDAR

Bothin DEM

Surveyed Spot Elevation

Scale in Feet
0 20 40
0 4 8
Vertical Scale in Feet
Vertical Exaggeration x 5

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Figure A-5
Assessment Transect CC'

Hydraulic Study of the Relocation of Lower Coyote Creek into Bothin Marsh
Lower Coyote Creek Realignment Hydraulic Modeling Report

Appendix B
Coyote Creek Hydrology Flood Flow Estimates

130 Battery Street, Suite 400
San Francisco, CA 94111
415.230.0862

Memorandum

February 26, 2020

To: Roger Leventhal, Marin County Department of Public Works

From: Adam Hill, PE (WA), and Michael MacWilliams, PE, Anchor QEA, LLC

Re: Coyote Creek Hydrology Flood Flow Estimates

Introduction and Purpose

Marin County received Senate Bill 1 grant funding to conduct an evaluation of a proposed relocation of the Coyote Creek Channel into Bothin Marsh. As part of this evaluation, a better understanding of design flow estimates is necessary to quantitatively assess alternatives for channel realignment. Several hydrologic analyses have been previously completed, and estimated design flows vary significantly between these studies.

The purpose of this memorandum is to present findings and recommendations from reviews of hydrology estimates for Coyote Creek prepared by the U.S. Army Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), Philip Williams & Associates, Ltd. (PWA), and Marin County, and a review of Marin County's HEC-HMS models.

Previous Studies

Several previous studies have been completed that discuss hydrology and peak flows at various locations in Coyote Creek. The studies note different cross-streets; all of these cross-streets are within a few blocks of each other and can be considered as a similar location. A brief summary of findings from studies reviewed is included in the following sections.

U.S. Army Corps of Engineers 1959 Detailed Project Report

The 1959 USACE report (USACE 1959) analyzed the hydrology of Coyote Creek using precipitation stations in nearby basins, rainfall-duration relationships, hydrographs derived from basin characteristics, and a slope-area computation using the January 1956 flood event. The design flood was set at the 20-year event because benefits would be only slightly reduced at this event compared to the standard 100-year design. Table 1 provides peak discharges for various channel reaches in Coyote Creek from the 1959 USACE report.

Table 1
Coyote Creek Peak Flood Discharges (USACE 1959 Report)

Channel Reach Station (feet)	Drainage Area (acres)	10-year Peak Discharge (cfs)	20-year Peak Discharge (cfs)	50-year Peak Discharge (cfs)	100-year Peak Discharge (cfs)
0+00 to 31+22[1]	2,200	1,500	1,750	2,100	2,350
31+22 to 54+50	1,035	1,000	1,100	1,350	1,500
54+50 to 67+82[2]	850	900	1,000	1,200	1,350
67+82 to 69+52	690	830	900	1,030	1,170

Notes:
Source: USACE 1959

1. State Highway No. 1 Bridge is at Station 18+76.
2. Maple Street is at Station 67+82.

Federal Emergency Management Agency 1997 Flood Insurance Study (Updated 2017)

The Flood Insurance Study (FIS; FEMA 1997) summarized discharges in Marin County, including Coyote Creek. The discharges listed in the 1997 FIS for Coyote Creek are based on multiple regression analyses from gaged streams in Marin County. The discharges are identical to those listed in the current FIS, effective 2017 (FEMA 2017). Table 2 provides the peak flood discharges for Coyote Creek from the FEMA reports.

Table 2
Coyote Creek Peak Flood Discharges (FEMA 1997 FIS)

Location	Drainage Area (square miles)	10-year Peak Discharge (cfs)	50-year Peak Discharge (cfs)	100-year Peak Discharge (cfs)	500-year Peak Discharge (cfs)
At State Highway 1 bridge	3.48	1,240	1,860	2,110	2,630
Downstream of confluence with Tennessee Creek	3.37	1,200	1,800	2,040	2,550
Upstream of confluence with Tennessee Creek	1.56	680	1,000	1,120	1,390
At Ash Street	1.32	540	800	910	1,130

Note:
Source: FEMA 1997

Philip Williams & Associates 2005 Reassessment

PWA's *Reassessment of Coyote Creek Channel Management Requirements* (2005) developed hydrologic models using HEC-HMS software and the Curve Number method. PWA developed HEC-HMS models for both Coyote Creek and Arroyo Corte Madera del Presidio (ACMdP). The ACMdP model was developed because the ACMdP basin had rainfall and stream stage data that were used to calibrate the Coyote Creek HEC-HMS model.

Watershed delineation was based on digital elevation models derived from 5-foot contours, and watershed characteristics were based on land use, soil type, and topography. These elements were used to supply the model parameters for the basins.

Flows for the 20-year event were updated for Coyote Creek based on the HEC-HMS modeling results. Table 3 provides these flows.

Table 3
Coyote Creek 20-year Peak Flood Discharge (PWA 2005 Reassessment)

Reach	20-year Peak Discharge (cfs)
North Branch confluence to Main Street	1,172
Main Street to end of concrete channel	1,172
End of concrete channel to Tennessee Creek confluence	1,172
Tennessee Creek confluence to Richardson Bay	1,952

Note:
Source: PWA 2005

Marin County 2014 Technical Memoranda

Two technical memoranda from the Marin County Department of Public Works (2014a, 2014b) analyzed various methods of determining hydrology and estimating peak flows in Coyote Creek. The methodology memorandum (Marin County 2014a) used rainfall patterns from a historical storm (New Year's 2006 flood) and applied the pattern to National Oceanic and Atmospheric Administration (NOAA) Atlas 14 rainfall recurrence intervals for input into the HEC-HMS model. Results using this method were compared to flow results in the ACMdP to check calibration and applied to the Coyote Creek HEC-HMS model. The additional information memorandum (Marin County 2014b) provided peak flow estimates using the updated hydrology for Coyote Creek at the gage site near Spruce Street and summarized other data sources. Flow data reported in the memorandum are provided in Table 4.

Table 4
Coyote Creek Peak Flood Discharges (Marin County 2014 Technical Memoranda)

Source	10-year Peak Discharge (cfs)	20/25-year Peak Discharge (cfs)[1]	50-year Peak Discharge (cfs)	100-year Peak Discharge (cfs)
2014 County Hydrology	322	411	482	557
2014 County Hydrology plus 15%	370	473	554	640
1997/2017 FEMA	540	653	800	910
1959 USACE	830	900	1,030	1,170
2005 PWA	--	1,172	--	--

Note:
1. The 2014 Marin County method uses NOAA Atlas 14 peak rainfall, which uses a 25-year event instead of a 20-year event.

HEC-HMS Modeling

As shown in Table 4, a wide range of flows are reported. Therefore, the HEC-HMS modeling was reviewed to better estimate appropriate flow rates to use for design. Both the ACMdP model and the Coyote Creek model were reviewed for inputs, parameters, and results. The HEC-HMS models and corresponding results updated in 2013 (for the ACMdP model) and 2014 (for the Coyote Creek model) were obtained from Marin County for review. The HEC-HMS version used was version 3.5, the same version as was run previously. While a newer version of HEC-HMS was available (Version 4.3), it was found that the newer version required additional variables that were not available with the existing model, so the previous version (Version 3.5) was used for model review. Models were checked for completeness and validity, and the models were rerun (using Version 3.5) to confirm results.

Review and Findings

As previously discussed, several elements were reviewed to determine the validity of the model and methodology results compared with other reports. Elements reviewed and findings from the review are described below.

Arroyo Corte Madera del Presidio Basin and Coyote Creek Basin Similarity

When the HEC-HMS models were initially developed, the Coyote Creek basin did not have any gaging stations. To calibrate the model, a model of the ACMdP basin was calibrated with the gage station that records precipitation and stream stage. For the calibration to be valid across both models, the basins must be similar enough such that hydrology is not impacted due to significantly different conditions between the basins. Upon review, the methodology developed in the initial development of the HEC-HMS models (PWA 2005) appears to be valid; the basins are adjacent and there do not appear to be major differences between the basins that would cause hydrologic variables to significantly vary.

HEC-HMS Model Parameters

Parameters in the HEC-HMS model were reviewed to confirm validity. Subbasins used the initial and constant loss method, the Clark unit hydrograph transform method, and recession baseflow. Reaches used the Muskingum-Cunge routing method. Parameters include losses, impervious and total subbasin area, time of concentration, baseflow discharge per area, reach slope, reach roughness, and reach length. Parameters reviewed appeared to have reasonable values for the reaches and subbasins.

Design Storm Rainfall Methodology

In the methodology memorandum from Marin County (2014a), combining rainfall patterns from a known storm event and scaling it to a design storm was described as the methodology used in developing precipitation hyetographs for use in the HEC-HMS modeling. In the methodology memorandum (Marin County 2014a), NOAA Atlas 14 1-hour, 1-day, 2-day, and 4-day rates for the 10-year, 25-year, 50-year, and 100-year events were obtained. These rates were compared against the New Year's 2006 storm precipitation rates obtained from the ACMdP gage to develop a hyetograph for various storm events that follow the New Year's 2006 storm event pattern but match the overall intensity of the NOAA Atlas 14 events.

Table 5 provides the rainfall data used in the analysis previously completed. Table 6 provides ratios developed from the analysis previously completed.

Table 5
Hyetograph Values for ACMdP Gage: New Year's 2006 Event and NOAA Atlas 14

Time	ACMdP Gage New Year's 2006 Event Rainfall (inches)	NOAA Atlas 14 10-year Event Rainfall (inches)	NOAA Atlas 14 25-year Event Rainfall (inches)	NOAA Atlas 14 50-year Event Rainfall (inches)	NOAA Atlas 14 100-year Event Rainfall (inches)
1-hour total	0.96	1.03	1.28	1.48	1.70
1-day total	4.24	5.32	6.57	7.55	8.57
1-day less 1-hour	*3.28*	*4.29*	*5.29*	*6.07*	*6.87*
2-day total	8.08	6.99	8.61	9.89	11.2
2-day less 1-day	*3.84*	*1.67*	*2.04*	*2.34*	*2.63*
4-day	9.72	8.74	10.7	12.3	14.0
4-day less 2-day	*1.64*	*1.75*	*2.09*	*2.41*	*2.8*

Note:
Source: Marin County 2014a

Table 6
Hyetograph Values for ACMdP Gage: Ratios Developed for Design Storm Scaling

Time	10-year Event Ratio	25-year Event Ratio	50-year Event Ratio	100-year Event Ratio
1-hour	1.07	1.33	1.54	1.77
1-day less 1-hour	1.31	1.61	1.85	2.09
2-day less 1-day	0.44	0.53	0.61	0.69
4-day less 2-day	1.07	1.27	1.47	1.71

Note:
Source: Marin County 2014a

From the data in Tables 5 and 6, it can be concluded that the New Year's 2006 storm had peak rainfall intensity of near or slightly below a 10-year event (based on the 1-hour and 1-day values), but the event had sustained rainfall, bringing the overall rainfall event to between a 10-year and 25-year event (based on the 2-day and 4-day values).

Every event is different and would have different values, but because of the availability of data for the New Year's 2006 event and the amount of rainfall that occurred during this event, it appears to be an appropriate storm for HEC-HMS model calibration. Additionally, the data and methodology developed when creating these hyetographs are appropriate and appear to be reasonable for design flow event modeling.

HEC-HMS Model Runs

The 2013 ACMdP HEC-HMS model and 2014 Coyote Creek model were rerun and results were compared against previous runs to confirm results were identical. To make the comparison, the DSS output files from the 2013 and 2014 HEC-HMS models were copied to a separate folder to ensure that they would not be overwritten by new data. This was confirmed by checking the file modified date. Both models were rerun for the New Year's 2006 event, and output hydrographs were compared at the gage sites and other locations to confirm the model outputs were identical. Figure 1 shows the comparison between the ACMdP model results. Figure 2 shows the comparison between the Coyote Creek model results.

Figure 1 and Figure 2 both show that rerunning the New Year's 2006 event gives results that replicate previous runs for both models. The ACMdP peak modeled flow was 1,710 cubic feet per second (cfs), which is comparable to the observed peak flow of 1,770 cfs. For Coyote Creek, the modeled peak flow was 470 cfs, which is 27% of the peak flow of the ACMdP peak flow.

Figure 1
ACMdP Calibration Run Comparison: Flow at ACMdP Gage, New Year's 2006 Event

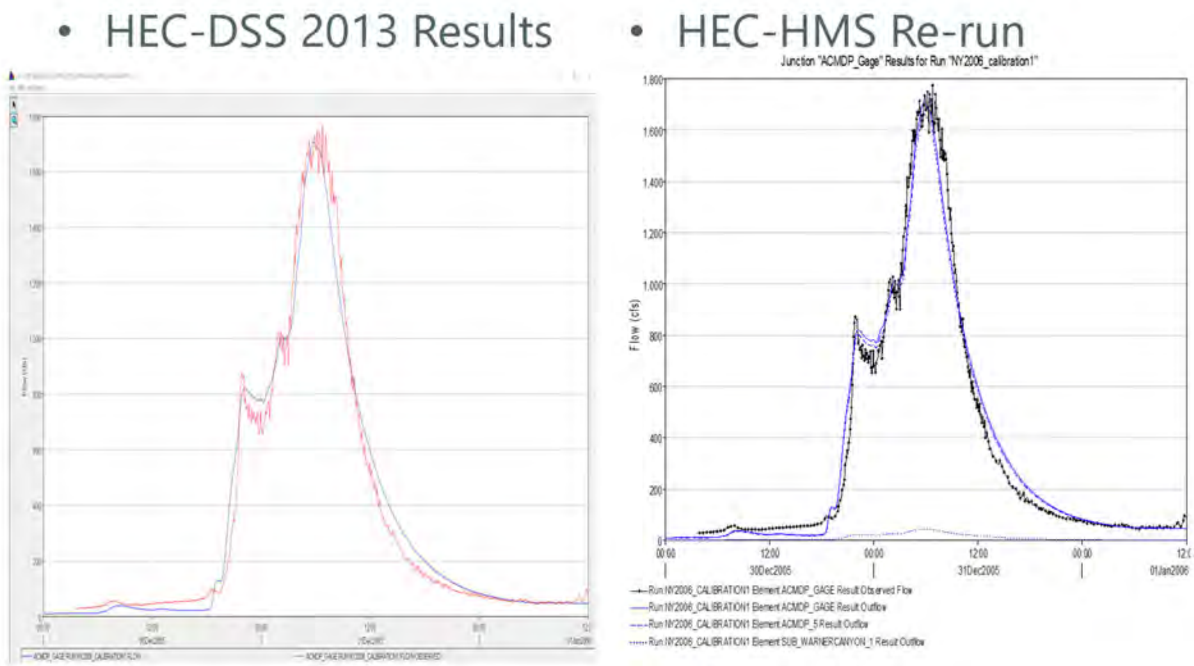
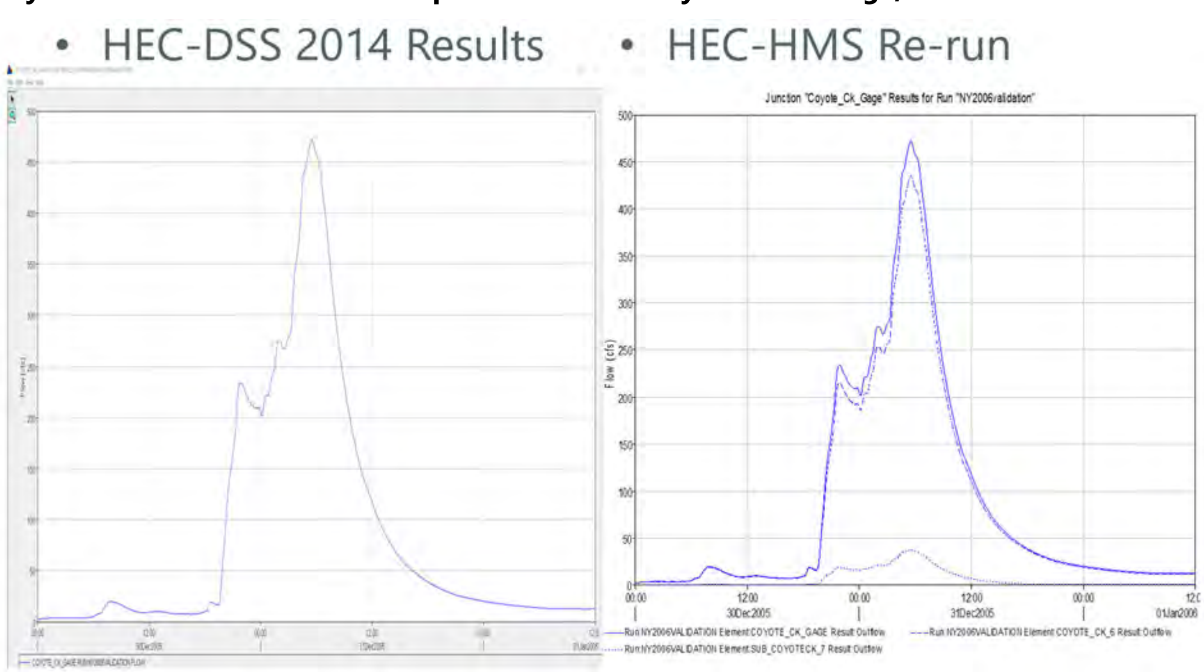


Figure 2
Coyote Creek Validation Run Comparison: Flow at Coyote Creek Gage, New Year's 2006 Event



For the 25-year event, the Coyote Creek model was run, and output hydrographs were compared at the gage sites and other locations to confirm the model output was identical to previous results. Figure 3 shows the comparison between the Coyote Creek model results.

Figure 3
Coyote Creek Design Flow Run Comparison: Flow at Coyote Creek Gage, 25-year Event

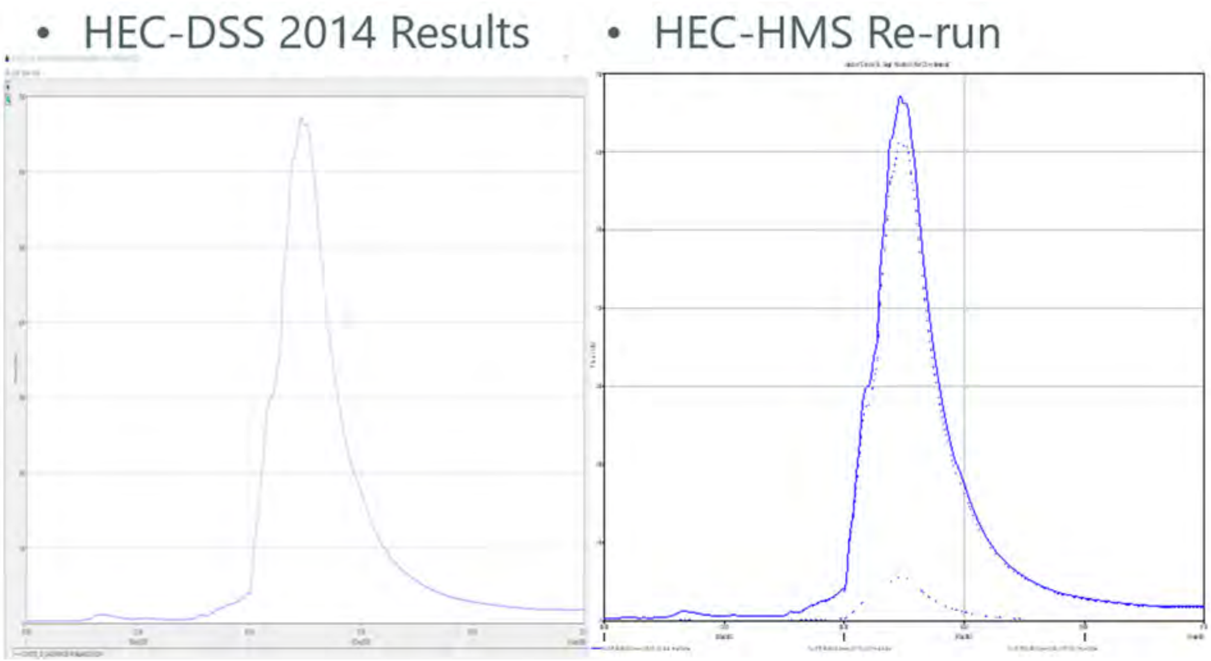


Figure 3 shows that rerunning the 25-year event for Coyote Creek model replicates results from the previous run. The Coyote Creek model had a peak flow of 672 cfs for the 25-year event. This flow rate is approximately 45% of the 25-year peak flow of 1,480 cfs for the ACMdP (Stetson Engineers 2016). When comparing 100-year events, the Coyote Creek model is 905 cfs, which is approximately 46% of the 100-year peak flow of 1,950 cfs for the ACMdP (Stetson Engineers 2016).

The peak flows against drainage area were compared for the Coyote Creek gage and the ACMdP gage for the 100-year event. At the gage, Coyote Creek has a drainage area of 1.34 square miles, and ACMdP has a drainage area of 4.52 square miles. For the 100-year event, the peak flow at the Coyote Creek gage is 675 cfs per square mile (1.06 cfs per acre). This is higher than the ACMdP 100-year peak flow per area at the gage, which is 431 cfs per square mile (0.67 cfs per acre). This is likely higher because of the channelized nature and lower roughness of Coyote Creek, which would cause higher channel velocities and less flow attenuation.

Because the model results were replicated, and the modeling methodology and parameters reviewed appear reasonable, the modeled flow estimates for Coyote Creek should be reasonable to use for design flows.

Peak Flow Comparisons

A comparison of peak flows from reports discussed previously and from the HEC-HMS model was made to analyze differences in the reports. Table 7 summarizes modeled or reported flows for Coyote Creek at or near the gage location for various events.

Table 7
Coyote Creek Peak Flood Discharges at or near Gage Location

Flow Source	10-year Peak Discharge (cfs)	20/25-year Peak Discharge (cfs)[1]	50-year Peak Discharge (cfs)	100-year Peak Discharge (cfs)
2014 County Hydrology[2]	322	411	482	557
2014 County Hydrology plus 15%[2]	370	473	554	640
1997/2017 FEMA[3]	540	*653*[4]	800	910
1959 USACE[5]	830	900	1,030	1,170
2005 PWA[6]	--	1,172	--	--
HEC-HMS Model	528	672	786	905

Notes:

1. The 2014 Marin County method and HEC-HMS modeling use a 25-year event. Other reports use a 20-year event.
2. Source: Marin County 2014a
3. Sources: FEMA 1997, 2017
4. This flow was not reported in either FEMA report. However, it was reported in the Marin County (2014a) report.
5. Source: USACE 1959
6. Source: PWA 2005

From the flows listed in Table 7, the HEC-HMS flows generally agree with the FEMA FIS flows. Because the flows are reasonably close and because FEMA flows are already a type of regulatory flow, design flows could use the FEMA flows where available and the Coyote Creek HEC-HMS model flows for locations or flow rates that were not established in the FEMA FISs.

HEC-HMS model peak flows at additional locations within the Coyote Creek watershed were also reviewed and are presented in Table 8.

Table 8
Coyote Creek Watershed Peak Flood Discharges: HEC-HMS Model

Location	10-year Peak Discharge (cfs)	25-year Peak Discharge (cfs)	50-year Peak Discharge (cfs)	100-year Peak Discharge (cfs)
North Fork Coyote Creek	325	412	481	553
South Fork Coyote Creek	142	182	213	246
Coyote Creek Gage	528	672	786	905
Coyote Creek at Mouth	1,218	1,537	1,797	2,074
Nyhan Creek	516	662	779	900

Recommendations

Based on the findings discussed above, it is recommended that FEMA flows should be used for design flows where available. Where not available, flows from the Coyote Creek HEC-HMS model completed in 2014 are valid for design flow estimates. Because the 25-year event was modeled instead of the 20-year event due to the NOAA Atlas 14 events available, the 25-year event is an appropriate design flow because the difference is not large and should not have a major impact on the design. Table 9 provides the recommended design flow at various locations in Coyote Creek basin for the 10-year, 25-year, and 100-year events, as well as the recommended base flow for hydraulic modeling. Flows for additional locations are available in the HEC-HMS model and can be made available upon request.

Table 9
Recommended Design Flows: Coyote Creek Basin

Location	Recommended 10-year Peak Flow (cfs)	Recommended Design (25-year) Flow (cfs)[1]	Recommended 100-year Peak Flow (cfs)	Recommended Base Flow (cfs)
Coyote Creek at County Gage – Ash Street	528	672	910	2.7
Junction J12	386	497	678	2.7
Coyote Creek Subbasin 6	61	77	103	0.2
Coyote Creek Subbasin 5	34	43	57	0.1
Coyote Creek Subbasin 4	7.3	9.1	12	0.0
Coyote Creek Subbasin 3	38	48	63	0.1
Coyote Creek Subbasin 2	22	28	38	0.1
Crest Marin Creek Subbasin 1	30	37	49	0.1
Crest Marin Creek	86	110	149	0.5
Nyhan Creek Subbasin 1[2]	22	27	37	0.1

Notes:

1. Recommended design flow is based on the HEC-HMS results for the 25-year event.
2. Nyhan Creek is listed as Tennessee Creek in the FEMA FIS.

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