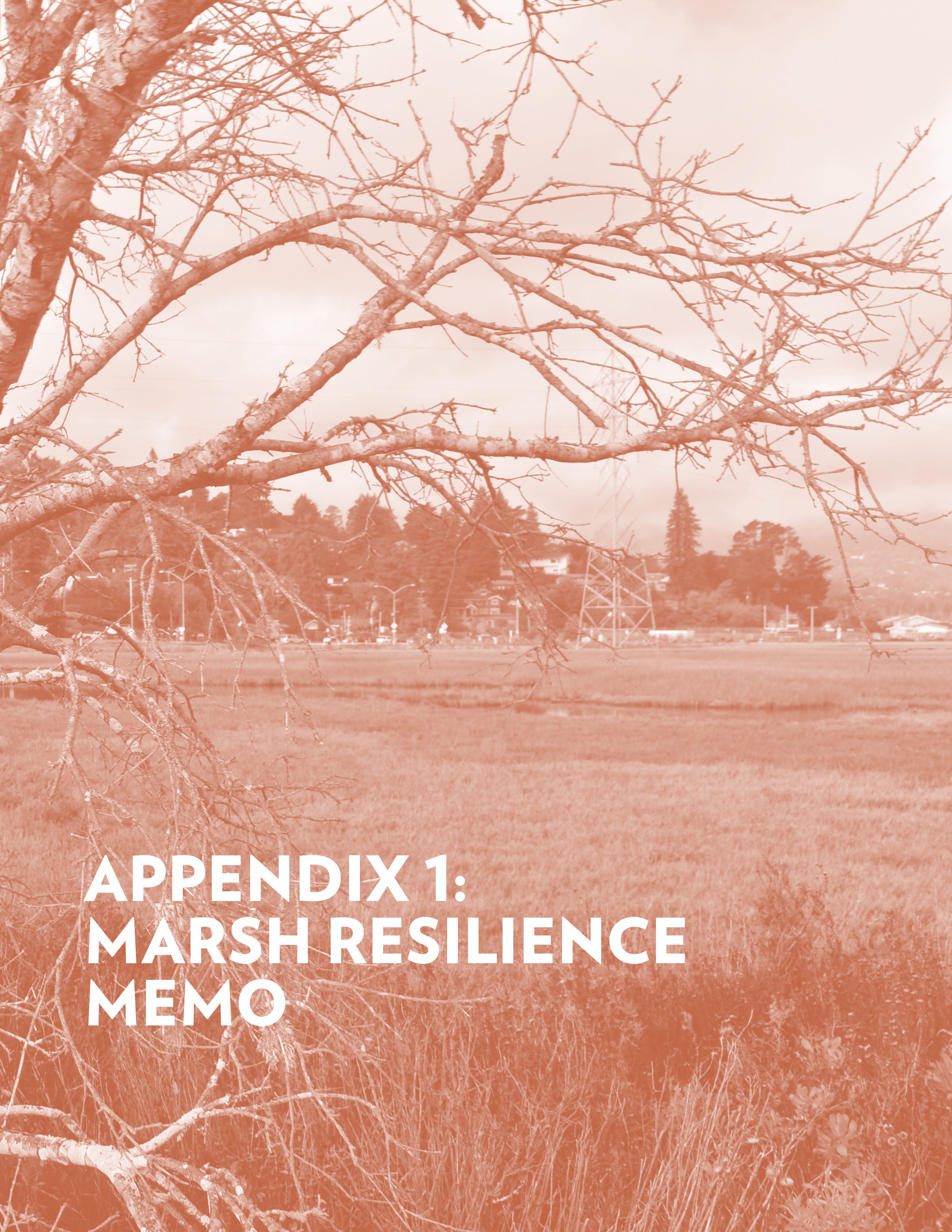


APPENDIX 1: MARSH RESILIENCE MEMO

Memorandum

date	April 13, 2021 (Revised May 16, 2021)
to	Veronica Pearson (Marin County Parks) and Rob LaPorte (GGNPC)
cc	Cristina Bejarano (WRT)
from	Eddie Divita, P.E.
subject	Sea-level Rise Resilience Assessment for Tidal Habitats for Bothin Marsh Design Alternatives

This memorandum presents analysis conducted by ESA to evaluate the resilience of tidal marshes and other habitats at the Bothin Marsh Preserve ("the Preserve") in Marin County, California under projected future rates of sea-level rise, sediment supply, and for project scenarios under consideration for the Bothin Marsh Preserve Adaptation Project ("Project").

The potential project measures aim to increase sediment accretion rates in the tidal marsh habitats and include combinations of re-aligning the Coyote Creek channel and different rates of "thin lift" sediment placement. The analysis and results presented in this memo assess the expected performance of the design measures in the context of projected sea-level rise (SLR) through 2100 and beyond in order to inform the evaluation and selection of measures to be included in a preferred project design alternative.

Contributors

This memorandum has been prepared with contributions from the following ESA staff: Eddie Divita, PE, Maureen Downing-Kunz, PhD, and Michelle Orr, PE.

The following members of the Project Team and Science and Technical Advisory Committee have provided review and input:

- Jeremy Lowe (SFEI)
- Christina Toms (CA State Water Quality Control Board)
- Roger Leventhal (Marin County Department of Public Works)

In addition, we thank ONE-TAM's joint project leads, Veronica Pearson (Marin County Parks) and Rob LaPorte (Golden Gate National Parks Conservancy), for their input and feedback.

Background

Tidally influenced habitats like mudflats, tidal marshes, and transition habitats, emerge and recede over time in response to changing physical and ecological processes, including sediment accretion and erosion, changing sea-levels, and human activities including direct impacts from construction, and indirect impacts such as changing land uses (influencing streamflow and watershed sediment supplies) and ship traffic (causing erosion due to ship wake waves). The following sections of this memorandum present ESA's evaluation of the key processes influencing formation and loss of tidal marsh habitats and other tidally influenced habitats at the Bothin Marsh Preserve and to estimate the resilience of these habitats under different combinations of potential project measures.

The Bothin Marsh Preserve is located along the northwest shore of Richardson Bay near the town of Mill Valley in Marin County, California. The area that is now the Preserve was once primarily open water and mudflat. The Preserve's present landscape is the result of a complex history of dredging, dike construction, and hydraulic placement of dredged sediments over the course of the late 1800s through the mid 1900s. Since the mid 1980s the Preserve has been managed as a public openspace habitat, and 60 acres of tidal marsh habitat have emerged in areas of former dredged fill. As described by Collins, et al. (2018), the marshes at the preserve are vulnerable to erosion and drowning due to rising sea-levels due to the limited supply of estuarine and watershed sediment reaching the marsh. The tidal marshes in the southern portion of the Preserve already display signs of vegetation drowning and erosion within the marsh interior due to the lower ground elevations (resulting from the historic fill placement) and constricted tides (due to the narrow inlet channel to the southern marsh).

For this study, ESA has applied a simple quantified conceptual model (QCM) in order to estimate the resilience of tidally influenced habitats to rising sea-levels under no-action and potential project scenarios. The aim of the QCM is to illustrate trends and differences between outcomes under different alternatives. No model is perfect, and the QCM applied for this analysis relies on several simplifying assumptions and estimated parameters which introduce uncertainty to the model's estimates. These assumptions and uncertainties are discussed in the "Limitations and Uncertainties" section of this memorandum. Acknowledging the limitations and uncertainties of the model, the results of the QCM analysis nonetheless illustrate differences in anticipated outcomes for different project scenarios, allowing for a comparison and prioritization of potential project measures and management actions.

Methods

The QCM applied for this study is based on the following key assumptions:

- The extents of different tidally influenced habitat types can be reasonably estimated by identifying typical elevation ranges for each habitat type relative to local tidal elevations.
- The elevation range for each habitat type will shift upwards over time at a rate nearly equal to the rate of future sea-level rise.
- Ground surface elevations within the study area will change over time due to the accretion of mineral and organic sediments, erosion, and subsidence.
- The rates of ground surface elevation change will vary under different project scenarios. Furthermore, it is assumed that simple calculations based on mass balance analyses can be used to reasonably estimate the variations in sediment transport and deposition rates associated with each project scenario.
- Future habitat extents can be estimated by comparing the future elevation range for each habitat type with estimated future ground surface elevations.

The individual components of the QCM are listed below and described in detail in the subsequent sections of this memorandum.

1) Identification of a suitable Digital Elevation Model (DEM) for the study area.

2) Elevation-based method for classifying expected future habitat extents based on ground elevation relative to future tides with sea-level rise;

3) Selection of sea-level rise projections;

4) Estimates of the sediment demand required to keep pace with projected sea-level rise;

5) Evaluation of the sources of sediment to the tidal marsh habitats and estimates of the associated rates of sediment accretion from each source;

6) Estimates of how the sources and rates of sediment supply differ under the proposed design alternatives compared to no action; and

7) A comparison of the projected resilience of the tidal marsh and other habitats under the different alternatives developed during the design process.

The following subsections present the methods and assumptions used for each of these components of the analysis.

1) Digital Elevation Model

This study uses the 2019 Marin County LiDAR DEM to describe existing ground surface elevations within the Preserve. Figure 1 shows the existing elevations within the study area. The elevations are color coded to reflect the habitats that are typically present in each elevation range. Note that the study area boundary (indicated by the extents of the elevation color-coding) has been selected to include the tidal marsh and adjacent upland areas, as well as areas of mudflat and subtidal habitat in the immediate vicinity of the marshes. The study area does not match the Preserve boundary (indicated in by the black line), but the study area does include all existing tidal marsh habitat within the preserve.

SOURCE: 2019 Marin County DEM, ft NAVD

Bothin Marsh Adaptation Project

Figure 1
Study Area and Existing Topography

2) Elevation-Based Habitat Classification

This study applies a simple elevation-based classification system to estimate the extents of different habitat types within the Preserve under existing conditions and future conditions with sea-level rise. Under this classification system, habitat areas are identified based on the local ground elevation relative to the assumed elevation ranges for the different habitat types.

Present-day habitats are classified based on the following elevation thresholds:

TABLE 1A
PROJECTED TIME HORIZONS FOR 1FT SLR INCREMENTS

Habitat Category	Lower Elevation	Upper Elevation
Upland (above 100-yr floodplain)	100-yr FEMA flood elevation (10 ft NAVD88)[1]	-
Upland (in 100-yr floodplain)	10-yr FEMA flood elevation (8.33ft NAVD)[1]	100-yr FEMA flood elevation (10 ft NAVD88)
Transition	Upper Limit for Pickleweed dominated vegetation (6.75 ft NAVD)[2]	10-yr FEMA flood elevation (8.33ft NAVD)
Tidal Marsh	Lower Limit for Cordgrass dominated vegetated areas[2] (3.24ft NAVD)	Upper Limit for Pickleweed dominated vegetated marsh (6.75 ft NAVD)
Mudflat	Mean Lower Low Water[3] (0.06ft NAVD)	Lower Limit for Cordgrass dominated vegetated areas (3.24ft NAVD)
Subtidal	-	Mean Lower Low Water (0.06ft NAVD)

Sources: [1]FEMA, 2017; [2]ESA ground surveys in North Bothin Marsh and South Bothin Marsh east of Bay Trail, unpublished; [3]ESA Tidal Datum Reckoning, 2020

For reference, estimated tidal datums at the Preserve are provided in Table 1B. Datums from two prior studies, ESA (2020) and CLE (2018) are provided. Both studies estimated datums at the Preserve based on short-term water level gage records, and differences between the calculated datums may be due to the short duration of the gage records. The datums calculated by NOAA for the San Francisco Golden Gate tide gage are also provided.

TABLE 1B
TIDAL DATUMS

South Bothin Marsh [1]	North Bothin Marsh [1]	Coyote Creek Bridge		NOAA SF Golden Gate[3]	
5.92	5.86	5.87[1]	6.07[2]	5.90	ft NAVD
5.35	5.28	5.29[1]	5.45[2]	5.29	ft NAVD
-	-	-	-	3.18	ft NAVD
-	-	-	-	3.24	ft NAVD
-	-	-	1.32[2]	1.19	ft NAVD
-	-	-	1.00[2]	0.06	ft NAVD

[1]ESA Tidal Reckoning (2020); [2]CLE Tidal Datums Memo (2018); [3]NOAA Tides and Currents (STA #9414290)

Future conditions habitat elevation ranges are adjusted to account for increased tide elevations due to sea-level rise and increased ground elevations due to sediment accretion at the project time-horizon for that amount of sea-level rise.

The primary advantage of the elevation-based classification approach is that it can be combined with a DEM and a geomorphic model of expected accretion to rapidly classify expected habitat extents across a wide area for both existing and projected future conditions with sea-level rise. While the method has considerable uncertainties and limitations, it does provide a valuable tool that can provide a coarse understanding of anticipated changes in future habitat distributions for different scenarios.

This simple approach has limited accuracy in areas where local hydrology differs substantively from the tidal hydrology in Richardson Bay (e.g., due to ponded water which limit drainage during low tide and/or berms and other barriers which limit inundation during high tides). In addition, this classification greatly simplifies the diversity of the exiting habitats, the system aggregates multiple plant communities into a few broad categories, and many secondary factors affecting habitat occurrence are ignored (eg. salinity, soil conditions, groundwater and surface runoff). Finally, the elevation-based approach assumes that the habitats are always in equilibrium with the hydrology, ignoring lag times for colonization and/or die-off as habitat areas transition from one type to another. This method ignores the time lag for plant communities to colonize new areas, and for existing vegetation to die-off due to changes in inundation frequency and other conditions.

3) Sea-Level Rise Projections

This study uses projected future rates and amounts of SLR based on the most recent State of California Sea-level Rise Guidance document (OPC 2018). The State Guidance document recommends a risk-based approach for determining appropriate SLR projections for use in project planning. The State Guidance presents several projected rates of sea-level rise, each associated with a different estimated probability of exceedance. These projected sea-level rise rates are categorized based on an associated level of risk aversion, and the State Guidance recommends that each project select an appropriate SLR project given the project's specific level of risk aversion. The state guidance document provides the following descriptions for the recommended SLR projections associated with different levels of risk aversion:

> ***Projection for decisions with low risk aversion:*** *Use the upper value of the "likely range" for the appropriate timeframe. This recommendation is fairly risk tolerant, as it represents an approximately 17% chance of being overtopped, and as such, provides an appropriate projection for adaptive, lower consequence decisions (e.g., unpaved coastal trail) but will not adequately address high impact, low probability events. Additionally, it is important to note that the probabilistic projections may underestimate the likelihood of extreme sea-level rise, particularly under high-emissions scenarios.*
>
> ***Projection for decisions with medium – high risk aversion:*** *Use the 1-in-200 chance for the appropriate timeframe. The likelihood that sea-level rise will meet or exceed this value is low, providing a precautionary projection that can be used for less adaptive, more vulnerable projects or populations that will experience medium to high consequences as a result of underestimating sea-level rise (e.g., coastal housing development). Again, this value may underestimate the potential for extreme sea-level rise.*
>
> ***Projection for decisions with extreme risk aversion:*** *Use the H++ scenario for the appropriate timeframe. For high consequence projects with a design life beyond 2050 that have little to no adaptive capacity, would be irreversibly destroyed or significantly costly to relocate/repair, or would have considerable public health, public safety, or environmental impacts should this level of sea-level rise occur, the H++ extreme scenario should be included in planning and adaptation strategies (e.g. coastal power plant). Although estimating the likelihood of the H++ scenario is not possible at this time (due to advancing science and the uncertainty of future emissions trajectory), the extreme sea-level rise*

projection is physically plausible and will provide an understanding of the implications of a worst-case scenario.

The State Guidance indicates that there is less than a 34% probability that sea-level rise will meet or exceed the Low risk Aversion projection[1]. The State Guidance attributes a 0.5% probability that sea-level rise will meet or exceed the Medium/High Risk Aversion projections. The Low level of risk aversion may be more appropriate for planning associated with ecological outcomes, while the Medium – High level of risk aversion may be more appropriate for planning associated with resilience of built infrastructure such as trails and bridges. The Bothin Marsh Preserve ("Preserve") includes features with both a low and medium/high level of consequences from future flooding due to SLR, and so this study has considered projected outcomes for habitat distribution for the projected rates of SLR associated with both the "Low" and "Medium – High" levels of risk aversion.

The State Guidance includes projections for both low and high emissions scenarios for time horizons beyond 2050. For this study we have only considered the high emissions scenarios. The OPC State Guidance states that sea-levels are anticipated to increase at an accelerating rate over the next century and beyond, and that the rate of future sea-level rise is uncertain due to both the limited scientific understanding of the relevant geophysical processes and feedbacks, as well as the potential influences of future economic and political policies which may result in increases or reductions in future greenhouse gas emissions.

This study considers total amounts of future sea-level rise in 1-foot increments between +0ft to +7ft relative to a year 2000 baseline. Present day conditions are somewhere between the +0ft and +1ft increments, and the recommended time-horizon for when planning efforts should assume that the +1ft and larger increments of sea-level rise will occur depends on the selected level of risk aversion and the associated sea-level rise projections. Table 2 summarizes the projected time-horizons associated with these 1-foot increments of sea-level rise for the Low and Medium – High levels of risk aversion based on the State Guidance (OPC 2018). In order to avoid implying greater precision in the timing for these sea-level rise increments, the time horizons are presented as a 10-year range by rounding up and down to the nearest whole decades in order to indicate that there is uncertainty in the timing for these increments of total sea-level rise. This rounding is an editorial convention and the 10-year range is not necessarily indicative of the actual level of uncertainty associated with the projections.

[1] The Low Risk Aversion projection represents the upper limit of "66% probability" range, and therefore the probability that sea-level rise meets or exceeds this projection will be equal to or less than 34%.

TABLE 2
PROJECTED TIME HORIZONS FOR 1FT SLR INCREMENTS

TOTAL SEA-LEVEL RISE (Relative to Year 2000 Baseline)	PROJECTED TIME HORIZON	
	Low Risk Aversion Projection	Medium – High Risk Aversion Projection
+0FT	2000 (baseline)	2000 (baseline)
+1FT	2040 to 2050	2030 to 2040
+2FT	2070 to 2080	2050 to 2060
+3FT	2090 to 2100	2060 to 2070
+4FT	2110 to 2120	2070 to 2080
+5FT	2130 to 2140	2080 to 2090
+6FT	2150 to 2160	2090 to 2100
+7FT	Approximately 2170 (no projection provided by OPC for this level of risk aversion, value has been estimated by linear extrapolation.	2100 to 2110

Source: Adapted from OPC 2018

4) Sediment Demand

Total Sediment Demand

Total sediment demand is calculated as the total volume of sediment required to raise the ground elevation in the Preserve at a rate that keeps pace with SLR. This sediment demand calculation is conducted relative to future amounts of sea-level rise, rather than relative to future dates, due to the uncertainties in the rates of SLR. Sediment demand is computed for a range of total height of SLR from one to seven feet. Demand is computed using the methods of Dusterhoff et al. (2020) which considers the habitat area, the total height of projected SLR, and the current sediment deficit. For this component, the Preserve is subdivided into North Marsh and South Marsh, with the two marsh areas divided by the Bay Trail.

The total area of tidal marsh in the Preserve (50.4 ac) is split nearly equally between North Marsh (26.4 ac) and South Marsh (24 ac). Based on the 2018 Marin County DEM, the current sediment deficit (volume of material required to raise all areas of the marsh plain to present day MHHW elevation) at Bothin Marsh is 27,200 cubic yards (CY). Nearly all of the sediment deficit in the preserve is associated with the South Marsh (i.e., the current sediment deficit for North Marsh is nearly zero).

Additional sediment will be required to raise the marsh in order to keep pace with rising sea levels. The total sediment demand by region for total height of SLR ranging from one to seven feet is presented in Table 3.

TABLE 3
TOTAL SEDIMENT DEMAND IN CUBIC YARDS (CY) AS A FUNCTION OF TOTAL HEIGHT OF SEA-LEVEL RISE (SLR) IN FEET BY REGION OF BOTHIN MARSH. VALUES ROUNDED TO THREE SIGNIFICANT FIGURES AND REGION SUMS MAY NOT MATCH TOTAL DUE TO ROUNDING.

	Total height of SLR (ft)						
Region	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	Total sediment demand (CY)						
North Marsh	42,600	85,200	128,000	171,000	213,000	256,000	299,000
South Marsh	38,800	77,500	117,000	155,000	194,000	233,000	272,000
Total Bothin Marsh	**81,400**	**163,000**	**244,000**	**326,000**	**407,000**	**488,000**	**570,000**

NOTES:
[a] The total sediment demand values are cumulative (eg. the total given for +2ft SLR is the amount of sediment needed to accommodate a increase from +0 to +2ft of SLR). These values do not include the volume of sediment required to reach mature marsh elevation under present day sea-levels (+0 ft SLR).

SOURCE: ESA 2021

5) Sediment Sources

The following sources of sediment to Bothin Marsh were considered: transport from the open estuary—including inorganic deposition; organic productivity; delivery from the watersheds—Arroyo Corte Madera del Presidio to north Bothin Marsh and Coyote Creek to south Bothin Marsh; and mechanical placement of imported sediment from local maintenance dredging or other sources.

To relate mass to volume, the bulk density for both estuary and watershed-derived sediments deposited on the tidal marsh was assumed to be 28.9 lb/ft^3 (0.35 metric tons/cubic yard) based on McKnight et al. (2020). This bulk density factor is derived from measurements in tidal marshes, however this factor is used for all habitat types in the study.

Open Estuary

Sediment suspended in the water column in the open estuary flows onto the tidal marshes during each high tide and some of this sediment settles onto the marsh plain with each tide. The rate of sediment transport from the open estuary is influenced by the concentration of suspended inorganic sediment in the water column, the settling velocity of those suspended sediment particles, the frequency and duration of inundation, and rates of erosion due to waves, currents and other disturbances.

The rate of accretion associated with transport of inorganic sediments from the open estuary has been estimated using the Marsh98 model (Stralberg et al. 2011; PWA 2009a) assuming ambient suspended-sediment concentration of 35 mg/L. This assumed ambient suspended-sediment concentration is consistent with measured suspended sediment concentrations at the Coyote Creek Bay Trail bridge for calm-weather conditions (PWA 2009b; Leventhal unpublished data).

Organic Productivity

Accumulation of organic materials in the soil column due to plant growth and deposition of organic debris can contribute to the total accumulation of sediment in a tidal marsh. Estimating the marsh accretion due to organic productivity is a complex topic, and several methods have been developed to estimate how organic productivity contributes to marsh resilience. Simple "Constant-rate" models, such as the Marsh98 model, assume that vegetation growth contributes a constant rate of accretion in areas that are within the elevation range expected to support marsh vegetation. More complex formulations have been developed which account for a larger number of processes which affect vegetation growth, such as the WARMER (Takekawa et al. 2013) and MEM models (Morris, 2010). These models are sometimes referred to as "Cohort Models" because they track organic and mineral accretion in individual cohorts, thin slices of the soil column representing total accretion over a given time period (often one year).

For this study ESA has applied the simpler "Constant-rate" accounting for organic productivity. This simplified accounting of organic productivity was selected for expedience in order to develop reasonable estimates within the time and resources available for this study. The "Constant-rate" method has a significant advantage in that it requires only a single input parameter: the assumed average rate of vertical accretion due to organic productivity. The primary drawback of "Constant-rate" method is that it ignores several important processes which can have an important influence on the contribution of organic productivity to marsh accretion, including: changes in bulk density due to organic content of the soil; variations in organic productivity that are correlated with different elevations relative to the tides; and decay and decomposition of organic debris over time. A sensitivity analysis was conducted to evaluate the sensitivity of the model results to the assumed rate of organic accretion.

Cohort Models are more complex models which account for several of these additional physical processes. The main drawback of Cohort Models is that they require significantly more parameters in order to describe the vegetation growth dynamics and initial conditions. Specifically, these models require parameters characterizing 1) vegetation growth and 2) initial density and organic content vertical profiles of the marsh soil column. ESA has reviewed available datasets and was unable to find prior studies to support site-specific estimates for several of the input parameters required for the application of a Cohort Model of marsh accretion for Bothin Marsh without additional field data collection or unverified assumptions. Some potentially useful data is available; for example, Schile et al. (2014) have developed calibrated values of the relevant vegetation parameters for several marshes in the San Francisco Estuary. While none of these marsh sites are in Richardson Bay, the China Camp site in San Pablo Bay may be similar enough to Bothin Marsh to support use of the China Camp vegetation parameters, albeit with some added uncertainty.

A greater challenge in applying these advanced models to Bothin Marsh is determining appropriate initial conditions for the bed composition. Schile et al. (2014) developed initial soil profiles for mature tidal marshes by running the WARMER model through a 200-year spin-up period where the marsh plain is allowed to accrete under a constant rate of sea-level rise. This process results in a marsh soil column that is approximately in equilibrium with historic rates of sea-level rise and that has properties (porosity, bulk density, organic content) that were generally similar to soil cores collected at the study sites. However, the soil column of the marshes at the Bothin Marsh Preserve is expected to be highly influenced by historic fill placement that occurred during the early and mid-1900s. It is unclear whether this equilibrium spin-up method would produce reasonable initial conditions that are representative of the soil column for Bothin Marsh. Suitable initial conditions soil profile for Bothin Marsh could be developed through collection and analysis of medium depth (5-10ft deep) soil cores from the marsh, however such field data collection is beyond the scope of this study.

Watershed

Arroyo Corte Madera del Presidio and Coyote Creek flow into Richardson Bay along the north and south borders, respectively, of Bothin Marsh Preserve.

The Arroyo Corte Madera del Presidio ("ACMdP") watershed flows into Richardson Bay along a channel immediately north of the Preserve. Several small tidal channels connect the ACMdP creek channel to the North Marsh interior. The Coyote Creek watershed outflows adjacent to south Bothin Marsh. There are no channels directly connecting the creek to the South Marsh interior except during high tides when the northern bank of Coyote Creek overtops.

There are very limited data available describing the flow rates and sediment discharge from these two watersheds. The ACMdP watershed is larger (3900 ac compared to 2240 ac for Coyote Creek) but available data on sediment loading are sparse and no previous estimates are available. ESA has incorporated the findings from two prior studies estimating the sediment yield from the Coyote Creek watershed. SFEI (2017) estimated the sediment yield based on regional regression curves, and Anchor (2021) estimated the sediment loading a hydrologic model to estimate streamflows and a sediment concentration rating curve derived from a small number of suspended sediment measurements collected by Marin County DPW.

For this study, sediment loading for Arroyo Corte Madera del Presidio was computed by assuming equivalent sediment yield (i.e., sediment load per unit watershed area per unit time) to that of Coyote Creek using loading estimates from SFEI (2017) and Anchor (2021).

Maintenance Dredging and Beneficial Re-Use (Thin lifts)

Marin County is exploring the possibility of beneficially re-using material generated from regular maintenance dredging on Coyote Creek and elsewhere. As proposed in the "Coyote Creek to Bothin Marsh Dredge Sediment Beneficial Reuse Feasibility Study" by Leventhal and Baye (2017), the resilience of tidal marsh habitats could be enhanced by placing dredged material on the marshes at the Preserve in thin lifts. There are studies in progress by the NERR (NOAA 2021) and others to evaluate methods and ecological outcomes for thin lift sediment placements. For the purpose of this analysis, ESA assumes that future dredging rates for maintenance of lower Coyote Creek will be similar to historic dredging rates. Historic dredging rates have been documented by PWA (2009b) and SFEI (2017). There are currently no specific planed future dredging projects on Coyote Creek and future dredging may be constrained due to funding limitations (R. Leventhal, pers. coms. April 2021) This analysis also assumes that future dredging on ACMdP will be able to provide material to the North Marsh at a rate (per unit marsh area) comparable to the rate of material generated for South Marsh from dredging Coyote Creek. Opportunities for beneficial re-use of dredge material from ACMdP have not been studied in detail, consequently this assumption is speculative.

There may be other future dredging projects in the Richardson Bay region that could generate additional material for beneficial re-use at Bothin Marsh. This study has also evaluated a hypothetical scenario where additional dredged material becomes available to support a thin lift placement rate equal to twice that that could be provided by Coyote Creek and ACMdP dredging along.

6) Effects of Design Alternatives on Sediment Supplies

The proposed design alternatives include the following measures to increase sediment supply to the tidal habitats:

- Construction a new tidal channel that re-directs the flow of Coyote Creek through South Bothin Marsh in order to increase the delivery of watershed sediments from Coyote Creek to the tidal marsh habitats in South Bothin Marsh. The relative change in sediment delivery from the watershed under the new channel alignment is estimated based on Anchor's Analysis of Long-Term Sediment Supply to Bothin Marsh (2021), based on a conceptual design developed by Collins et al. (2018). Note that the Anchor study aimed to identify "bookend" scenarios to confirm the potential feasibility of the channel re-alignment concept. The scenarios modeled by Anchor, and their findings, do not necessarily reflect an optimal design. Additional study is needed to refine the channel-marsh connection to minimize cost/impacts and increase sediment delivery.

- Beneficial re-use of dredged sediments through thin lift sediment placements on the transition and tidal marsh habitat areas. The relative change in sediment delivery from beneficial re-use of dredged sediments is estimated based on the expected production rate of dredging on Coyote Creek, based on historic dredging records compiled by PWA (2009b). The potential applications of beneficiation re-use of dredged sediments at Bothin Marsh has been informed by the "Coyote Creek to Bothin Marsh Dredge Sediment Beneficial Reuse Feasibility Study" by Leventhal and Baye (2017)

The project alternatives also include measures to improve tidal drainage and circulation within the Preserve, which may increase tidal marsh plant productivity, which in turn may improve resilience. The potential increase in plant productivity has been assumed to be negligible for this analysis.

In addition, the project alternatives may include trail modifications such as significant re-alignments of portions of the trail, changes to the geometry of the existing trail embankment, and/or modification or replacement of the existing bridges. The trail modification options have not been directly evaluated in this study, however for all scenarios evaluated in this study (including the no-action scenario) it is assumed that the Bay Trail will be modified a manner that alleviates the tidal choking that currently affects South Bothin Marsh as recommended by Collins et al. (2018) while leaving a portion of the existing trail berm in place to block waves from eroding the south marsh as recommended by Anchor (2021)

7) Sea-Level Resilience for Design Alternatives

The final step is to evaluate the resilience of the design alternatives based on projected rates of SLR for the estimates of total sediment supply. The following eight scenarios have been evaluated:

- Zero Accretion: This scenario evaluates the anticipated change in habitat extents under hypothetical future conditions where no accretion occurs. This scenario is presented for informational purposes only and does not represent a likely actual future scenario.

- No Action: This scenario represents expected conditions if no project actions are taken.

- Creek Re-Align: This scenario represents expected conditions if Coyote Creek is re-aligned to flow through South Bothin Marsh.

- Thin lifts (SBM): This scenario represents expected conditions if all material dredged from Coyote Creek is beneficially re-used to raise elevations in South Bothin Marsh through a series of periodic thin lift placements.

- Thin lifts (SBM & NBM): This scenario represents expected conditions if all material dredged from Coyote Creek is beneficially re-used to raise elevations in South Bothin Marsh, and if additional material is imported to north Bothin Marsh to raise the North Marsh at the same rate (potentially from maintenance dredging on Aroyo Corte Madera del Presidio).

- Creek Re-Align + Thin lifts (SBM): This scenario represents the combination of both the creek re-alignment and thin lifts (SMB) project actions.

- Creek Re-Align + Thin lifts (SBM & NBM): This scenario represents the combination of both the creek re-alignment and thin lifts (SBM & NBM) project actions.

- Creek Re-Align + 2x Thin lifts (SBM & NBM): This scenario represents the combination of both the creek re-alignment and thin lifts (SBM & NBM) project actions, and in addition the rate of thin lift sediment placements is doubled relative the baseline thin lifts scenario.

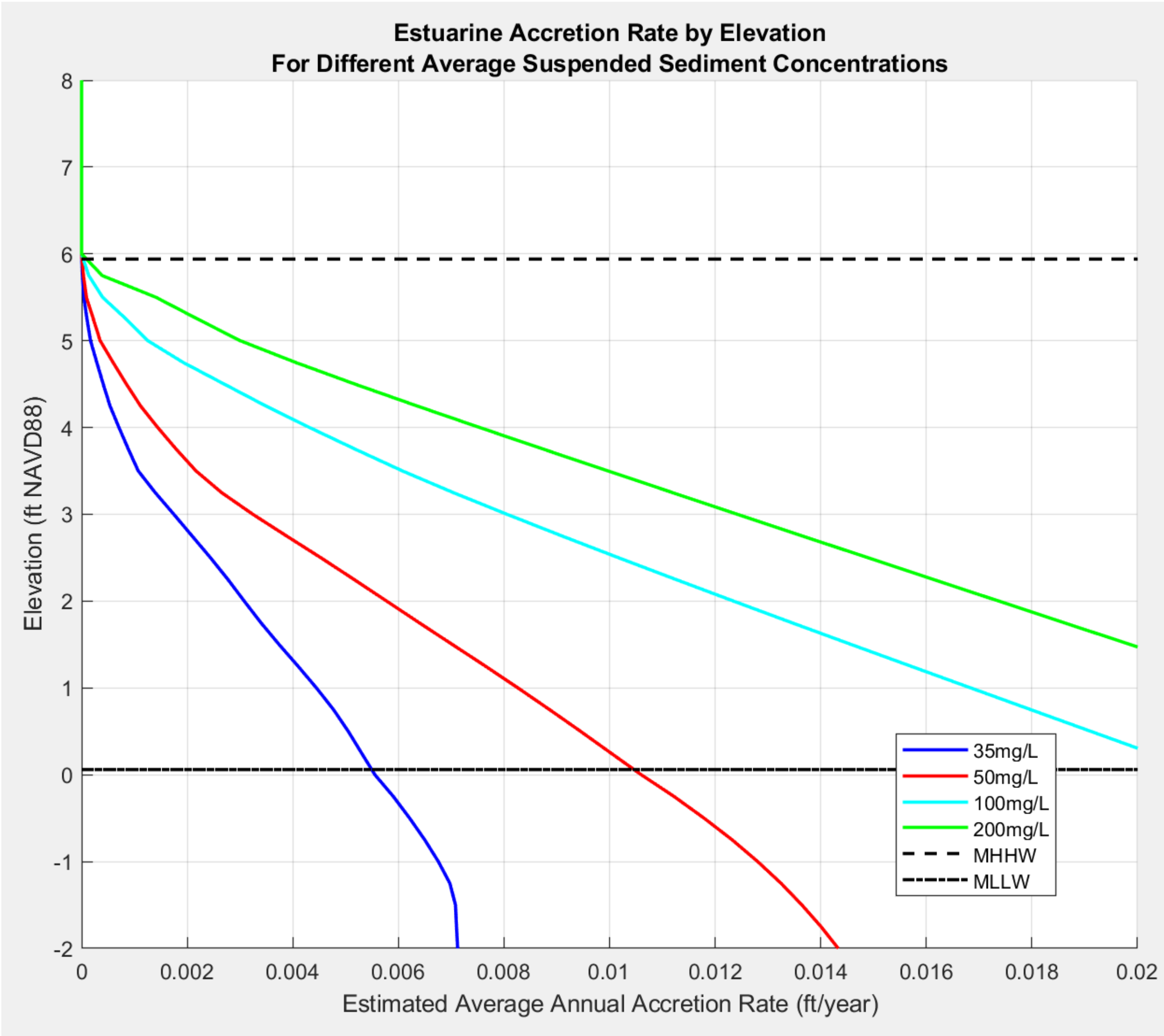
Sediment Sources and Rates for Each Scenario

This section describes accretion rates attributed to each sediment source for each scenario.

Estuarine Sediment

Estuarine sediment deposition is represented by applying a constant accretion rate to subtidal, mudflat, tidal marsh, and transition habitat areas. The rate of estuarine sediment deposition is proportional to the duration of inundation. Suspended sediment samples collected at the mouth of Coyote Creek reveal sediment concentrations varying between 6 and 108mg/L, with an average of 35mg/L. Higher suspended sediment concentrations are observed during periods of high streamflow, however for this study the sediment delivery from the watersheds during periods of high streamflow is handled separately as described in the Watershed Sediment section.

The Marsh98 sediment accretion model was used to estimate an average annual accretion rate associated with an average SSC of 35mg/L for different initial elevations. Figure 2 shows modeled accretion rates associated with different average SSC values and different elevations. The blue line indicates accretion rates for 35mg/L. Based on the Marsh98 values, ESA has identified the following typical average annual accretion rates for the different habitat zones: 0.007 ft/yr for subtidal areas (max estuarine accretion rate), 0.0035 ft/yr for mudflats (50% max), 0.0014ft/yr for tidal marsh (20% max) and 0.00035ft/yr for transition habitats (5% max).



SOURCE: Marsh98 Model, ESA 2021

Bothin Marsh Adaptation Project

Figure 2
Estuarine Accretion Rates
For Different Values of SSC and Bed Elevation

Organic Sediment

This study assumes that organic productivity results in a constant average annual rate of accretion of 0.007 ft/yr (2mm/yr) for all scenarios. Because there is considerable uncertainty as to the actual rate of accretion from organic productivity, sensitivity tests were also conducted using the lower and higher rates of 0.01 ft/yr (3mm/yr) and 0.003 ft/yr (1mm/yr). These three rates are based on the rates presented as the middle, upper and lower (respectively) estimates in the Stralberg et al. (2011) study of marsh resilience in San Francisco Bay.

Watershed Sediment

Estimates of sediment loading from the local watersheds (Arroyo Corte Madera del Presidio and Coyote Creek) are presented in Table 5. There is high uncertainty on these estimates due to the limited direct measurements for these watersheds.

TABLE 5
ESTIMATES OF SEDIMENT LOADING FROM LOCAL WATERSHEDS (CY/YR) FOR YIELD ESTIMATES BASED ON SFEI (2017) AND ANCHOR (2021) FOR ASSUMED BULK DENSITY OF 28.9 LB/FT^3 (0.35 MT/CY).

	Watershed sediment yield (mt/km^2/yr)	
Watershed	**SFEI (2017): 361**	**Anchor (2021): 294**
	Average annual sediment load (CY/yr)	
Arroyo Corte Madera del Presidio	16,300	13,300
Coyote Creek	9300	7600

NOTES:
Abbreviations—CY: cubic yard; ft: feet km: kilometer; lb: pound; mt: metric ton; yr: year

SOURCE: Table Source

Compared to other local tributaries of San Francisco Bay, Coyote Creek is considered to have high watershed sediment yield for the period 2000-2013 (greater than 315 mt/km^2/yr, SFEI 2017). Relating these sediment load estimates to marsh accretion rates depends on the trapping efficiency of the marsh system.

According to Anchor (2021), trapping estimates for the existing and proposed alignments of Coyote Creek are 4.4% and 7%, respectively. These trapping efficiencies were used to estimate a total mass of trapped sediment from the Coyote Creek watershed during an average year and an average annual rate of accretion for South Bothin Marsh for existing and project conditions attributable to watershed sediments. The Anchor study did not evaluate whether and how these trapping efficiencies may change with rising sea-levels, and so for this study it is assumed that the watershed sediment trapping efficiencies will remain constant despite changing sea-levels. This may underestimate sediment trapping under future conditions with SLR. Higher average tide elevations will result in greater effective channel cross section areas, leading to lower flow velocities, which in turn would be expected to reduce erosion and scour during high flow events and cause increased net sediment deposition. SFEI has developed estimates of future sediment yields based on different climate change scenarios. These estimates have not been used for this study, but could be incorporated into future refined analysis.

TABLE 6
SUMMARY OF ESTIMATED AVERAGE ANNUAL ACCRETION RATES ASSOCIATED WITH WATERSHED SEDIMENTS

Creek and Marsh Connection	Avg. Annual Sediment Yield	Marsh Area	Estimated Avg. Annual Accretion Rate (ft/yr) Associated with Watershed Sediments for Given Trapping Efficiency		
				Re-Align Channel	No Action
	CY/yr	Acres	100% Trapping Efficiency	7.2% Trapping Efficiency	4.4% Trapping Efficiency
Coyote Creek to SBM (SFEI Estimate)	9291	26.4	0.218	0.016	0.010
Coyote Creek to SBM (Anchor Estimate)	7571	26.4	0.178	0.013	0.008
Coyote Creek to SBM (Average of SFEI and Anchor Estimates)	8431	26.4	0.198	0.014	0.009

SBM = South Bothin Marsh

Table 6 shows estimated accretion rates based on both the SFEI and Anchor estimates for Watershed sediment yield, and for the average of these two estimates. This study uses the average of the SFEI and Anchor estimates, 0.014ft/yr (4.3 mm/yr; re-align channel) and 0.009ft/yr (2.7 mm/yr; no action), for the habitat resilience estimates.

Maintenance Dredging and Thin Lifts

Maintenance dredging in lower Coyote Creek has historically occured approximately every 14 years with an average sediment volume of 9400 CY per occurrence (PWA 2009). Relating this to an annual average, maintenance dredging produces around 700 CY/yr. Since this sediment is dredged from Coyote Creek, which is adjacent to South Marsh, we compute the dredged sediment per unit area of South Marsh to estimate an accretion rate for dredged material placement. If this annual average volume of dredged sediment from Coyote Creek were mechanically placed in a thin layer evenly distributed across South Marsh, this would cause approximately 0.016 ft/yr of marsh accretion. For this study it is assumed that future dredging could occur at a rate matching the historic dredging, however no specific future dredging projects are currently in planning.

The "Thin Lifts (SBM)" scenarios apply this 0.016ft/yr additional accretion to the South Marsh area. The "Thin Lifts (SBM & NBM)" scenarios apply this additional accretion to both the south and North Marsh areas, assuming an additional supply of sediment can be identified to support thin lifts on North Marsh. While no specific sources for dredge material to be placed on North Marsh have been identified, it is plausible that material from future dredging projects on ACMdP or elsewhere in Richardson Bay could be used. A final scenario, "Creek Re-Align + 2x Thin lifts (SBM & NBM)" has been evaluated which applies higher rates of beneficial re-use of sediment. This applies 0.032ft/yr of accretion to both North and South Marsh, in order to illustrate the potential additional benefits associated with doubling the rate of thin lift sediment placement.

Distribution of Sediment in Different Habitat Zones

Sediment from different sources will be deposited on different portions of the landscape. Simple scaling factors are applied to represent the deposition of sediment from each source at different rates for each habitat type.

The deposition of estuarine sediments across different habitat zones is proportional to the frequency of inundation of each zone, resulting in accretion at the maximum potential rate in subtidal areas, and reduced accretion in higher elevation habitats.

Accretion due to organic productivity is assumed to occur at the maximum rate in both the tidal marsh and transition habitats and at 50% of the max rate in upland areas. It is assumed that no organic productivity occurs in mudflat and subtidal areas.

The deposition of watershed sediments is based on sediment transport modeling which considered deposition on the marsh plain, and so the full rate of watershed sediment accretion is applied for the tidal marsh habitat zone. The accretion rates for other habitat zones were assumed based on professional judgement: 50% of the watershed sediment accretion rate is applied to transition zones representing the reduced frequency of flooding affecting these areas, while 100% of the watershed sediment accretion rate is applied to mudflat and subtidal areas.

Sediment placed in thin lifts is assumed to be distributed across the transition, tidal marsh and mudflat habitats. This analysis assumes that the transition zone receives 25% of the material, tidal marsh receives 62.5% of the material, and mudflats receive 12.5% of the material. This assumed fractional distribution of material is simply a rough guess based on a conceptual understanding that the thin lift placement methods will aim to create a mix of transition and high marsh habitat, and that while the placement methods will aim to minimize export of material to mudflats and subtidal areas, some export of material (assumed to be 12.5%) is likely unavoidable. This assumed distribution of material could be refined through modeling or by monitoring existing thin lift projects in similar marsh settings. The distribution of sediments will be influenced by the design and methods of thin lift sediment placements, for example by adjusting the water content of the sediment slurry and by adjusting the duration and intensity of slurry pumping.

Summary of Key Parameters for Accretion Estimates

Table 7 presents a summary of the key parameters used to estimate accretion rates:

TABLE 7A
SUMMARY OF KEY MODEL PARAMETERS FOR ACCRETION ESTIMATES

	Max Average Annual Accretion Rate		Fraction of Max Average Annual Accretion Rate Applied to Each Habitat Zone (from 0 to 1)				
	No Action	Creek Re-Align or Thin Lifts	Subtidal	Mudflat	Tidal Marsh	Transition	Upland
Open Estuary	0.007ft/yr (2 mm/yr)		1	0.5	0.2	0.05	0
Organic Productivity	0.007 (2 mm/yr)		0	0	1	1	0.5
Watershed	0.009 ft/yr (2.75mm/yr)	0.014 ft/yr (4 mm/yr)	1	1	1	0.5	0
Thin lifts	0 ft/yr (0 mm/yr)	0.016 (5 mm/yr)	0	0.125	0.625	0.25	0

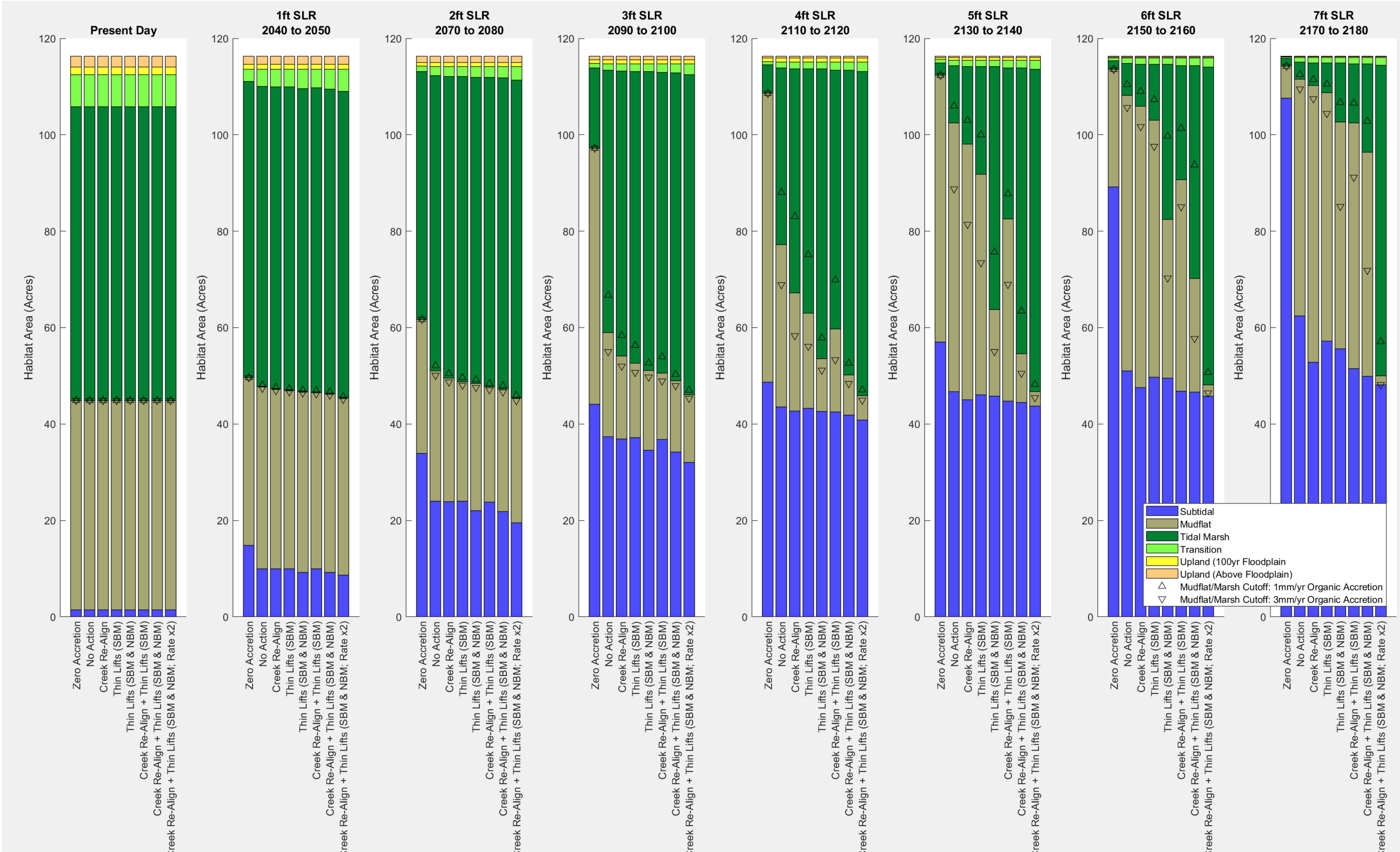
Results

The following subsections present the results for each of the analyses conducted for this study.

Distribution of Habitats at Different Sea-Levels

For each of the design scenarios, habitat extents by area and their evolution over time in response to SLR are presented for the “Low” (Figure 3) and “Medium – High” (Figure 4) risk aversion cases (OPC 2018). For the Low risk aversion case, SLR varies from +0 to +5.8 ft (rounded to +6 ft) over approximately 150 years between 2000 to approximately 2150. For the Medium – High risk aversion case, SLR varies from +0 to +7 ft over 100 years between 2000 to approximately 2100.

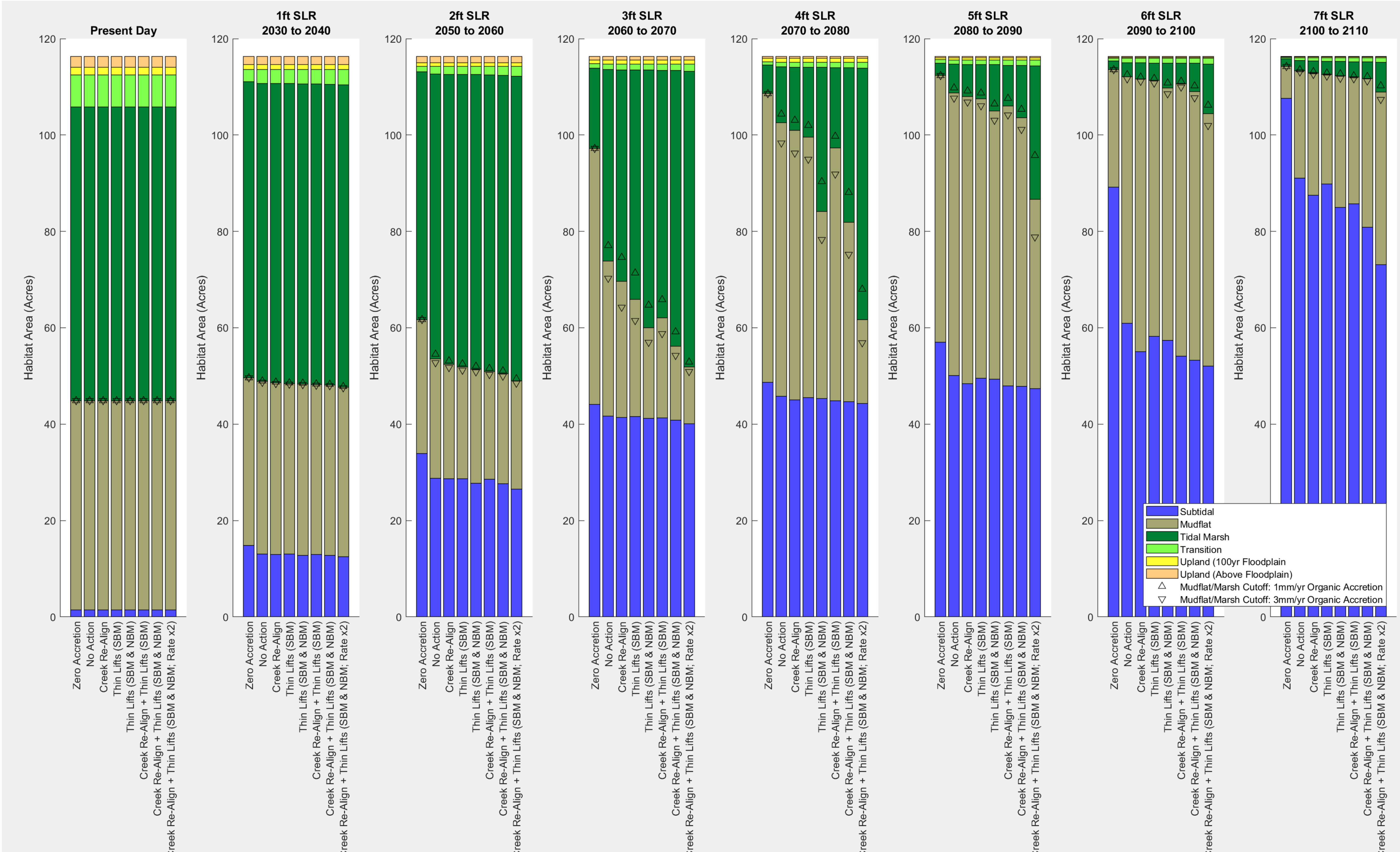
The sensitivity to different assumed constant organic productivity rates is presented graphically with symbols (open triangles) indicating the change in estimated distribution of area between tidal marsh and mudflat habitat for the lowest (1 mm/y) and highest (3 mm/y) organic productivity rates.



SOURCE: ESA Analysis

Bothin Marsh Adaptation Project

Figure 3
Habitat Areas at 1ft SLR Intervals
Low Risk Aversion SLR Projection



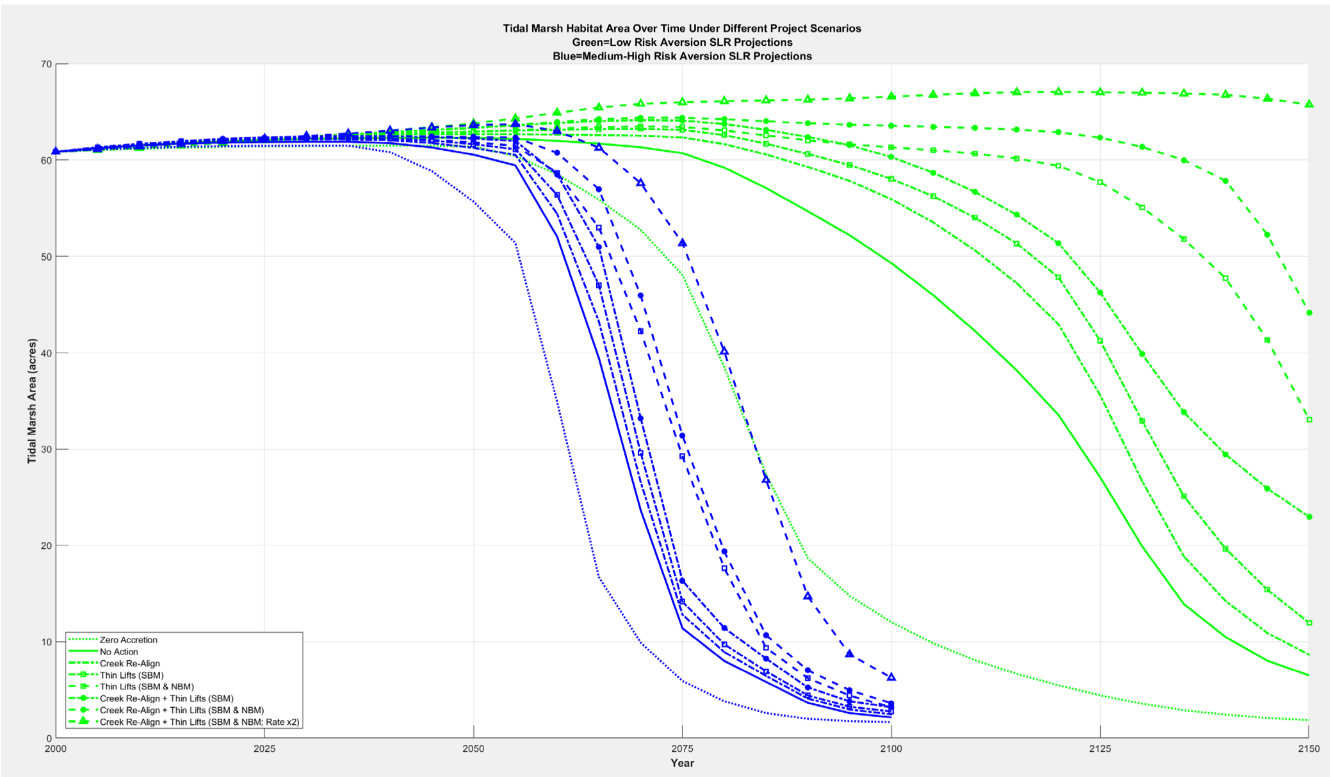
SOURCE: ESA Analysis

Bothin Marsh Adaptation Project

Figure 4
Habitat Areas at 1ft SLR Intervals
Medium - High Risk Aversion SLR Projection

Change Tidal Marsh Habitat Extents over Time

Figure 5 shows the change in tidal marsh habitat area over time under the different project scenarios (indicated by line and marker type) and for the two sea-level rise projections (indicated by line color).



SOURCE: ESA Analysis

Bothin Marsh Adaptation Project

Figure 5
Projected Changes in Total Tidal Marsh Habitat Area

Tables 8 and 9 list the time and amount of sea-level rise associated with loss of 25%, 50%, 75 and 90% of the existing tidal marsh habitat area at Bothin Marsh for the Low and Medium-High Risk Aversion sea-level rise projects, respectively.

TABLE 8
ESTIMATED TIME-HORIZON FOR TIDAL MARSH HABITAT LOSS

SLR Projection	% of Existing Tidal Marsh Habitat Lost	Value	No Accretion	No Action	Creek Re-Align	Thin Lifts (SBM)	Thin Lifts (SBM & NBM)	Creek Re-Align & Thin Lifts (SBM)	Creek Re-Align & Thin Lifts (SBM & NBM)	Creek Re-Align & 2x Thin Lifts (SBM & NBM)
Low Risk Aversion	25%	Estimated Date	2077	2107	2119	2123	2142	2126	2152	*Beyond 2170*
		Change Relative to No-Action (Years)	-30	0	12	16	35	19	45	
	50%	Estimated Date	2084	2123	2128	2131	2154	2138	2163	*Beyond 2170*
		Change Relative to No-Action (Years)	-39	0	5	8	31	15	40	
	75%	Estimated Date	2094	2133	2138	2146	2167	2166	*Beyond 2170*	*Beyond 2170*
		Change Relative to No-Action (Years)	-39	0	5	13	34	33		
	90%	Estimated Date	2117	2155	2162	2171	2175	2177	*Beyond 2170*	*Beyond 2170*
		Change Relative to No-Action (Years)	-38	0	7	16	20	22		
Medium-High Risk Aversion	25%	Estimated Date	2055	2062	2064	2066	2069	2067	2070	2078
		Change Relative to No-Action (Years)	-7	0	2	4	7	5	8	16
	50%	Estimated Date	2060	2068	2069	2070	2075	2071	2076	2084
		Change Relative to No-Action (Years)	-8	0	1	2	7	3	8	16
	75%	Estimated Date	2066	2073	2074	2075	2081	2076	2082	2090
		Change Relative to No-Action (Years)	-7	0	1	2	8	3	9	17
	90%	Estimated Date	2075	2085	2086	2087	2091	2089	2092	2101
		Change Relative to No-Action (Years)	-10	0	1	2	6	4	7	16

Conclusions

The analysis presented in this study demonstrates the expected effects of different project measures on the future distribution and extents of habitats within the Bothin Marsh Preserve. Within the limits of this studies assumptions and uncertainties, this analysis supports the following findings:

- Under the No Action scenario, the majority of the tidal marsh habitats in the Preserve are expected to convert to mudflat or open water habit. The timing of this tidal marsh habitat loss depends on the selected SLR projection, with significantly more rapid habitat loss expected under the Medium-High risk aversion projections compared to the Low risk aversion projections.
    - Actions beyond the scope of the Bothin Marsh Preserve Adaptation Project that slow the rate of sea-level rise (eg. reductions in greenhouse gas emissions) are expected to provide significant benefits to the resilience of the tidal marsh habitats at the Preserve.
- All of the Proposed Project Action scenarios are expected to extend the lifespan of the tidal marsh habitats relative to the No Action scenario. The magnitude of this habitat preservation depends on the selected SLR projection, and combination of project measures.
- The "Creek Re-Align" scenario, which only uses natural processes to improve marsh resilience (eg. no beneficial re-use), provides the least benefit to tidal marsh resilience of all of the project scenarios evaluated. This scenario extends the life of the tidal marsh by 2 to 12 years[2], depending on the selected SLR projection.
- This analysis shows that combinations of measures which deliver greater quantities of sediment to the tidal marshes are expected to result in greater increases to the resilience of the tidal marsh habitats, but that the benefit of these measures will still be highly sensitive to the rate of sea-level rise.
    - The best performing combination of measures evaluated, the "Creek Re-Align & 2x Thin Lifts (SBM & NBM)" scenario, extends the life of the tidal marsh by more than 63 years under the low risk aversion SLR projection, but only extends the life of the marsh by 16 years under the medium-high SLR projection.

Limitations and Uncertainties

The following list summarizes the limitations and uncertainties associated with this study and its findings. Additional uncertainties and assumptions are also previously discussed in the methods section.

- The resilience of the tidal marsh habitats, and the relative benefits of the proposed project measures, is very strongly influenced by the rate of future SLR. The uncertainty related to projected rates of future SLR is unlikely to be resolved during the timeframe for project planning.
- The estimated rates of accretion associated with different physical processes and associated with specific project measures each are based on numerous simplifying assumptions and have inherent uncertainties, including:
    - Accretion from Open Estuary:

        - This study assumes that future estuarine suspended sediment concentrations will be similar to present day conditions. Future conditions may change, for example as rising sea-levels alter currents and wave conditions, changing patterns of erosion and deposition on nearshore mudflats, and changes to watershed sediment delivery to the greater San Francisco Estuary.
    - Accretion from Organic Productivity
        - This study assumes a constant rate of accretion associated with organic productivity.
        - Actual organic productivity can have significant variations, including variations due to frequency and duration of tidal inundation, specific plant communities, salinity and soil conditions.
        - More detailed analysis of organic productivity would require additional data collection and the selection of numerous additional model parameters.
    - Accretion from Watershed:
        - Accretion due to deposition of sediments from the adjacent Coyote Creek and Arroyo Corte Madera del Presidio watersheds is estimated based on studies by SFEI and Anchor. These studies have significant limitations and uncertainties.
        - Change in accretion rates due to changes in tidal and creek channel configurations has been informed by hydraulic modeling and sediment transport modeling by Anchor QEA (2021) which evaluated existing conditions and a single project scenario for South Bothin Marsh only.
    - Accretion from Beneficial Re-Use of Dredged Sediments:
        - Accretion from beneficial re-use of dredged sediments is based on an unspecified hypothetical approach for sediment placement that is assumed to result in a particular distribution of sediment across the different habitat types.
        - The actual spatial distribution and thickness of sediment placement due to a specific beneficial re-use project would vary and depend on methods used (eg. hydraulic slurry vs. overhead spray vs. mechanical placement and spreading).
        - There are likely to be significant regulatory hurdles that would need to be resolved before any beneficial re-use project at Bothin Marsh could proceed. Potential measures such as thin-lift slurry placement or mudflat augmentation have only been applied at a small number of pilot studies inCalifornia, with notable examples including Novato Creek (Marin County), Buttano Creek (San Mateo County) and Seal Beach (San Diego County). These methods may have significant temporary impacts to protected habitats and species. It is uncertain whether these measures would be permitted by local regulatory agencies.
    - Processes not evaluated:
        - Subsidence and Consolidation/Auto-compaction of soils are not evaluated in detail. For this study it is assumed that the bulk density of sediments throughout the study area is uniform and constant in time and equal to the bulk density of sediments measured in mature tidal marshes in the central bay region.
        - Coastal Erosion
- This study has not evaluated temporary ecological impacts associated with the proposed project measures. There may be adverse temporary ecological impacts associated with both creek re-alignment and thin lifts. The extent and duration of these temporary impacts have not been evaluated and would depend on the detailed design of each measure.

Potential Future Refinements

The following list summarizes potential additional studies and data collection that could support future refinement of this analysis through the resolution of uncertainties and evaluation of additional processes.

- Watershed sediment sampling to verify estimated watershed sediment yields that informed Anchor and SFEI watershed sediment estimates
- Additional Hydraulic and Sediment Transport Modeling:
  - ACMdP creek connection measures
  - Intermediate Coyote Creek connections such as one or more small connector channels
- Sediment cores to estimate accretion from organic productivity, variations in sediment bulk density, and sediment source.
- Geotech exploration to estimate rates of subsidence and consolidation
- Use of WARMER or similar model to evaluate a greater range of processes affecting organic productivity.
- Incorporation of estimates of habitat type conversion due to wave-induced erosion.

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