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memorandum

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cc

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subject SAFER Bay Project – Tidal Marsh Evolution and Blue Carbon Assessment Technical Memorandum – FINAL

1 Introduction

This technical memo, prepared in support of the San Francisquito Creek Joint Powers Authority's (SFCJPA) Strategy to Advance Flood Protection, Ecosystems, and Recreation along San Francisco Bay Project (SAFER Bay Project or Project), presents an assessment of how Ponds R1/R2 and nearby existing tidal marshes are expected to evolve over time with sea level rise. The analyses include:

1. sediment accretion modeling,
2. mapping sedimentation across the areas of interest to model bed elevation change,
3. likely habitat types associated with increasing bed elevations, and
4. blue carbon stocks and greenhouse gas sequestration.

The results of this technical memo will inform design elements of proposed Ponds R1 and R2 tidal wetland restoration to meet the Project's multiple objectives, which include flood protection and habitat restoration, ultimately creating a project with net ecological lift.

2 Sedimentation Modeling

The remnant marsh plain in Ponds R1 and R2 is subsided and generally too low in elevation to support tidal marsh vegetation once tidal inundation is restored. Over time, estuarine deposition will raise site elevations, and if deposition exceeds the rate of sea level rise, tidal vegetation can establish. ESA assessed marsh sedimentation to evaluate the potential for the restored site to convert from tidal mudflat to vegetated marsh over time.

2.1 MARSH98 Model

Sediment accretion in tidal marshes results from suspended sediment deposition and organic matter accumulation within bed sediments once vegetation is established. Sediment deposition dynamics within a tidal estuary setting are influenced by a wide array of factors, such as suspended sediment quantity and composition, physical and

chemical properties within the water column, and regional and local-scale hydrodynamic and wave conditions. For full representation in multi-decade computational modeling, all these processes require substantial data inputs and computation time.

We used an approach based on Krone (1985) that leverages simplifying assumptions about the key processes to distill them into an accretion model that estimates bed elevations changes over time with sea level rise. This computational model developed by ESA, called MARSH98, is then calibrated to observations at existing reference sites. This approach, tested at multiple San Francisco Bay restoration sites, has demonstrated its validity and utility over several decades of restoration practice (Orr et al. 2003, Stralberg et al. 2011).

The MARSH98 model was applied in two steps:

1. The model was calibrated by performing a set of model runs to select input parameters that best reproduce observed historic sediment accretion rates at San Francisco Bay tidal marsh restoration sites near the Ravenswood Pond Complex.
2. The model was run using the calibrated parameters to forecast bed elevations at Ponds R1 and R2 and nearby existing marshes with anticipated sea level rise from 2030 to 2100. (Discussed in Section 3)

2.2 Model Input Parameters

MARSH98 requires several input parameters, such as tide water levels, organic accretion rate, sea level rise scenario, and ambient suspended sediment concentration. Most parameters were selected based on available local measurements and typical regional values. The suspended sediment concentration was selected based on results of the calibration, discussed further in the next section.

Table 1 summarizes the key input parameters used for SAFER Bay’s MARSH98 model.

Table 2 provides sea level rise by decade for San Francisco from the California Ocean Protection Council (OPC) (2024). The Intermediate (INT) Scenario, considered by OPC to be an upper bound for the most likely future conditions, was used for the base case assessment, following OPC guidance for restoring natural infrastructure. The Intermediate-High (INT-HIGH) Scenario is considered in the sensitivity assessment (see Section 4.2).

TABLE 1
SUMMARY OF MARSH98 INPUT PARAMETERS

Parameter	Value	Explanation
Tide Water Level	Full range of Bay water fluctuations	Used water level data collected by the City of Mountain View on the outboard side of Inner Charleston Slough's tide gates because differences in tidal datums between SAFER Bay and Charleston Slough have negligible effects on model results over the timescale investigated.
Sea Level Rise	3.1 ft NAVD by 2100	Based on OPC (2024) for the Intermediate Sea Level Rise Scenario. See Table 2.
Model Start Date	Year 2030	Approximate year Ponds R1 and R2 will be restored.
Organic Accretion Rate	0 mm/yr	Assumed no accretion. ^a
Bed Bulk Density	560 kg/m ³	Comparable to values measured by Callaway et al. (2013) in vegetated marshes at restored Pond A21 and consistent with bulk density used by Orr et al. (2003).
Settling Velocity Coefficient	0.00019 m ⁵ /kg ^{4/3} /s	Observed settling velocity in South San Francisco Bay, just offshore of Inner Charleston Slough, which is near the project site (Manning and Schoellhamer 2013).
Representative Suspended Sediment Concentration	75 mg/L	Calibrated value that resulted in the best match to observed bed elevations in reference sites, as described below in Section 2.3.

NOTES:

- a. Organic accretion occurs once vegetation has established. See Section 4.2 for discussion of why assuming no accretion is expected to have only a small effect on results.

TABLE 2. SEA LEVEL RISE SCENARIOS

Year	Intermediate (INT)	Intermediate-High (INT-HIGH)
2020	0.2	0.3
2030	0.4	0.4
2040	0.6	0.7
2050	0.8	1.0
2060	1.1	1.5
2070	1.4	2.2
2080	1.8	3.0
2090	2.4	3.8
2100	3.1	4.8

SOURCE: Ocean Protection Council (2024)

NOTE: Sea level rise is measured from Year 2000.

2.3 Calibration

The representative suspended sediment concentration, a key parameter for the sediment accretion model, was calibrated for use in the model. It represents the sediment concentration available within the water column that can settle onto the bed as net accretion and causes bed elevations to increase. Actual suspended sediment concentrations, as collected by the United States Geologic Survey (USGS) and others, vary with location and fluctuate across multiple time scales, such as tides, seasonal variations, wave and rain events, and multi-year trends such as El Niño and regional droughts. It is beyond the scope of this analysis to simulate all the spatial and

temporal variability in suspended sediment concentration; instead, the MARSH98 model uses a representative constant suspended sediment concentration selected to reproduce observed rates of sediment accretion.

ESA calibrated the MARSH98 model with an appropriate suspended sediment concentration that represents conditions at Ponds R1/R2 and vicinity. To select this calibrated suspended sediment concentration, ESA ran MARSH98 for a range of suspended sediment concentrations. Results were compared to observed rates of bed elevation change based on monitoring reports at the following nearby restoration sites: Ravenswood Open Space (Cooley Landing) and South Bay Salt Pond Restoration Ponds A21 and A6 (ESA et al. 2011, Callaway et al. 2013). Figure 1 shows the locations of the reference sites with respect to the project. Figure 2 shows a series of historic aerial photos of Cooley Landing showing the emergence and evolution of vegetated tidal marsh since the site's breaching in 2000. Figure 3 and Figure 4 shows similar photo-series for Ponds A21 and A6, respectively. Pond A21 was breached in 2006. Pond A6 was breached in 2010 and has accreted almost three feet of sediment in the first five years after breaching. Since Pond A6's bed elevation was relatively low, the site had not yet accreted enough sediment for vegetation to establish as of the time of the most recent monitoring data in 2013. Aerial photographs of Pond A6 from the last few years show marsh vegetation starting to establish on the eastern portion of the site. We also considered the Bair Island and Moseley Tract restorations as potential calibration sites. The Bair Island Monitoring Reports, however, had limited data that could be used to quantify sediment accretion (United States Fish and Wildlife Service (USFWS) 2024). No monitoring is available for the Moseley Tract site. Although these two sites do not have sufficient data for MARSH98 calibration, aerial photographs indicate that both sites have evolved enough geomorphically for robust marsh vegetation to establish on the former mudflats.

MARSH98 calibration results are shown in Figure 5. From comparing the modeled trajectories with observed elevation changes at the reference sites, ESA identified 75 mg/L as a representative suspended sediment concentration for forecasting accretion within R1 and R2. The calibrated value results in modeled bed elevations that track the mid to lower end of observations for all reference sites, so it is less likely to overstate future accretion. See Section 4.2 for discussion of how potential future changes in suspended sediment concentration may affect the model results.

Note that the reference sites include a range of initial bed elevations, starting from the lowest initial elevations in Figure 5a, and progressing to the highest initial elevation in Figure 5e. Therefore, even though the reference data spans at most a decade at each site, when these five panels are viewed together, the modeled results cover a range of elevations, implying fidelity to observations corresponding to multiple decades of accretion. As another point of reference, 15-minute and daily average suspended sediment concentrations observed at Dumbarton Bridge (USGS Gage #373015122071000) are plotted in Figure 6. The data exhibits substantial variability caused by processes beyond the scope of this analysis. However, these data show that the suspended sediment concentration selected for the MARSH98 modeling, 75 mg/L, is generally consistent with typical daily average observations.

3 Mapping Bed Elevation Change

After input parameter selection and calibration, MARSH98 was used to forecast bed elevation change at Ponds R1/R2 and for nearby marshes along the levee footprint to assess habitat evolution and resilience to sea level rise. Figure 7, inset B, shows modeled sediment accretion trajectories for initial bed elevations ranging from -2 ft¹ to +12 ft, under the Intermediate Sea Level Rise Scenario. The 75 mg/L calibrated suspended sediment

¹ All elevations presented in this technical memo are based on North American Vertical Datum 1988 (NAVD88) unless otherwise stated.

concentration was used to assess sediment accretion trajectories starting from 2030, the assumed start date for restoration (approximate). Select tidal datums and habitat thresholds are plotted on Figure 7, inset B, for reference (discussed in Section 4.1 below).

Based on the trajectories in Figure 7, inset B, sedimentation is sufficient to raise areas of Ponds R1/R2 even as low as -2 ft to elevations high enough to support marsh vegetation. The apple green line on the plot signifies the threshold above which tidal marsh vegetation is expected to colonize. At Ponds R1/R2, elevations of the remnant marsh plain are approximately 4 ft (typical) and the borrow ditch beds are 0 ft (typical). For the existing marshes along the levee footprint—Faber Tract, Laumeister Marsh, and Ravenswood Open Space (Cooley Landing)—modeled sedimentation is sufficient to maintain vegetated conditions. These existing marshes start higher in elevation. The model indicates that existing marshes will sustain as vegetated marsh through 2100, though they will be slightly lower in the tidal frame.

The modeled sediment accretion trajectories were applied to a digital elevation model (DEM) of Ponds R1 and R2 with 1-ft horizontal resolution. The DEM was created from a combination of aerial (i.e., Light Detection and Ranging (LiDAR)) and bathymetric surveys. LiDAR data was obtained from a 2023 flight survey conducted by Towill, Inc. ESA performed a supplementary bathymetric survey of large channels within the site using real-time kinematic global positioning system (RTK GPS) and an echosounder in March 2024. For all survey data, the horizontal datum is North American Datum 1983 (NAD83) with a projected coordinate system of NAD83 (2011) StatePlane California III Federal Information Processing Standards 0403 (U.S. ft). The vertical datum is the North American Vertical Datum of 1988 (NAVD88). The supplementary bathymetric data, along with proposed levee breach and habitat island grading, were added to the Towill LiDAR surface in AutoCAD Civil3D and exported to ArcGIS Pro.

The combined DEM was used as the 2030 starting year for projecting sediment accretion to 2100. For each cell within the DEM, sediment accretion was assigned according to the MARSH98 modeled accretion trajectory with the same starting elevation (Figure 7, inset B). By combining each cell's trajectory, DEMs were created for 2030, 2040, 2050, 2060, 2080, and 2100, which were then used to estimate tidal marsh evolution, as described in the next section.

4 Tidal Marsh Habitat Evolution

4.1 Habitat Projections

Coastal wetland habitats can be generally characterized based on the elevation of the land relative to tidal datums, with tidal datums serving as a surrogate for the frequency and duration of tidal inundation. At the site, the lowest areas are subtidal, followed by intertidal mudflat, vegetated tidal marsh, upland transition, and upland.

Dumbarton Bridge gage tidal datums summarized in Table 3 were used to determine the upper and lower elevation limits used for mapping habitat types in Table 4. The estimated vegetation colonization elevation is consistent with those provided for San Francisco Bay by Williams and Orr (2002) and H. T. Harvey & Associates and PWA (2005). ESA identified non-borrow ditch areas with bed elevations below 2.0 ft as corresponding to tidal channels, which are assumed not to accrete sediment due to scouring by concentrated tidal flows.

The habitat types are overlaid on the expected accretion trajectories from Figure 7, inset B. For predicting future habitat evolution, these habitat elevation ranges are assumed to increase over time at the same rate as sea level rise. This assumption is based on the understanding that the habitat range for tidal wetland vegetation is largely

determined by the tides and the resulting inundation frequency and soil moisture. Thus, starting elevations for 2030 are incremented by 0.4 ft to account for sea level rise between 2000 (the approximate timeframe for tidal datum and vegetation threshold data collection) and 2030.

The habitat elevation ranges in Table 4, escalated with the corresponding amount of sea level rise, were used to map likely habitat evolution across the future DEMs. Figure 8 shows the forecast spatial extents of tidal marsh habitats for 2030, 2040, 2050, 2060, 2080, and 2100. Table 5 tabulates the total area within each habitat type for 2030 and future conditions. Since the mapping methods are not able to resolve the smaller marsh channels (they map as marsh), we adjusted the marsh area down by 8% and added 8% to the subtidal habitat type. The table's distribution of evolving habitats is also plotted in Figure 9.

Note that the methods used to produce the maps in Figure 8 and tabulated areas in Table 5 and Figure 9 show habitat bands based on tidal elevation and do not account for the time required for vegetation colonization. Since vegetation will take time to establish once the colonization elevation threshold is reached, it is appropriate to apply a time lag to the habitat evolution. Based on monitoring of similar sites, low marsh generally takes 10 years to cover an area once the appropriate elevations are reached (Phyllis Faber, pers. comm., ESA PWA et al. 2011, H. T. Harvey & Associates and PWA 2005).²

Table 6 tabulates the total area within each habitat type for 2030 and future conditions with the application of a 10-year time lag.

TABLE 3
TIDAL DATUMS (DUMBARTON BRIDGE)

Tidal Datum	Elevation, 1983 – 2001 tidal epoch (ft NAVD88)	Elevation, adjusted to 2030 (ft NAVD88)
Highest Astronomical Tide (HAT)	9.0	9.4
Mean Higher High Water (MHHW)	7.4	7.8
Mean High Water (MHW)	6.8	7.2
Mean Sea Level (MSL)	3.5	3.9
Mean Lower Low Water (MLLW)	-1.2	-0.8
Lowest Astronomical Tide (LAT)	-3.4	-3.0

Source: NOAA Station 9414509 Dumbarton Bridge datums, 1983-2001 epoch.

Note: Added 0.4 ft to account for sea level rise between the 1983-2001 tidal epoch and construction in 2030.

² At the Cooley Landing/Ravenswood Preserve (ESA PWA et al. 2011), the initial marsh plain elevation was 5.5 ft (typical), or approximately 0.7 ft above the assumed colonization elevation. 60% vegetative cover was observed 10 years after breaching, sufficient for salt marsh vegetation to be the dominant cover type on the marsh plain. At the Island Ponds Pond 21, (H. T. Harvey and PWA 2005), the initial marsh plain elevation was approximately 1.1 ft above the assumed colonization elevation. Imagery (Google Earth) indicates that more than half of Pond A21 was vegetated in approximately 8 years. Of note at the Island Ponds is that the presence of gypsum would have initially slowed seedling establishment. On the other hand, the Island Ponds would have experienced faster accretion due to higher sediment concentrations. At Moseley Tract, examination of Google Earth imagery suggests that vegetation rates are consistent with those for the other site. Complicating factors at Moseley Tract are that the (unplanned) breach occurred in approximately 2003 but did not substantially enlarge until approximately 2008, and the marsh plain required some amount of time to accrete to colonization elevations.

TABLE 4
TIDAL MARSH HABITAT ELEVATIONS (APPROXIMATE)

Habitat Type	Lower Limit	Upper Limit	Elevation, adjusted to 2030 (ft NAVD88)
Upland	Above HAT+1 ft	-	Above 10.4
Transition Zone	MHHW + 1 ft	HAT + 1 ft	8.8 to 10.4
Vegetated Marsh	MSL+1.3 ft	MHHW + 1 ft	5.2 to 8.8
Mudflat	MLLW	MSL + 1.3 ft	-0.8 to 5.2
Subtidal	-	MLLW	Below -0.8

NOTE: Added 0.4 ft to account for sea level rise between the 1983-2001 tidal epoch and construction in approx. 2030.

TABLE 5
PROJECTED PONDS R1 AND R2 HABITAT AREAS, INTERMEDIATE SEA LEVEL RISE

Habitat Type	Habitat Area (acres)					
	2030	2040	2050	2060	2080	2100
Upland	1.9	1.9	1.1	0.7	0.0	0.0
Transition Zone	1.0	0.8	1.2	1.5	1.9	0.2
Vegetated Marsh	6.6	287	460	482	487	489
Mudflat	519	216	30	5.9	0.3	0.0
Subtidal	46	68	82	84	84	85
Total	574	574	574	574	574	574

SOURCE: ESA analysis.

NOTES: No time lag for vegetation establishment. Areas include approx. 1.8 acres of seabird nesting islands. Totals may not match the sum of values above due to rounding. Relatively small areas of mudflats along the edges of channels are expected but are not included in the table.

TABLE 6
PROJECTED PONDS R1 AND R2 HABITAT AREAS WITH TIME LAG FOR VEGETATION ESTABLISHMENT, INTERMEDIATE SEA LEVEL RISE

Habitat Type	Habitat Area (acres)					
	2030	2040	2050	2060	2080	2100
Upland	1.9	1.9	1.1	0.7	0.0	0.0
Transition Zone	1.0	0.8	1.2	1.5	1.9	0.2
Vegetated Marsh	0.0	6.6	287	460	486	488
Mudflat	525	497	202	28	1.2	0.8
Subtidal	46	68	82	84	84	85
Total	574	574	574	574	574	574

SOURCE: ESA analysis.

NOTES: 10-year lag for vegetation establishment. Areas include approx. 1.8 acres of seabird nesting islands. Totals may not match the sum of values above due to rounding. Relatively small areas of mudflats along the edges of channels are expected but are not included in the table.

4.2 Sensitivity Analysis

A sensitivity analysis was conducted to assess the model's sensitivity to the primary calibration parameter, suspended sediment concentration, and to a higher sea level rise scenario. Results are shown in Figure 7.

Sensitivity to suspended sediment concentration. Model results indicate that, for a point on the marsh plain starting at 4 ft (typical), this point will evolve to support vegetated marsh for all suspended sediment scenarios. For the higher suspended sediment concentration (100 mg/L) scenario, this point crosses the vegetation threshold between 2035 and 2040, or about 5 years sooner than for the base case (75 mg/L). For the lower suspended sediment concentration (50 mg/L) scenario, accretion raises this same point above the vegetation threshold between 2060 and 2070 after which accretion barely outpaces sea level rise through 2100, indicating a sensitivity to lower suspended sediment concentrations. Existing mature marshes in the vicinity—which are high in the tidal frame (about 7 ft) and already vegetated—are predicted to remain vegetated through 2100, even for the lower suspended sediment concentration scenario. However, accretion for the lower suspended sediment concentration begins to fall behind sea level rise later in the century, suggesting that Ponds R1/R2 and nearby existing marshes could convert to mudflat and subtidal habitats after 2100.

Sensitivity to higher sea level rise. While the INT Sea Level Rise Scenario is considered by OPC to be an upper bound for the most likely future conditions, ESA modeled the INT-HIGH Scenario to assess sensitivity of the model results to higher rates of sea level rise. Model results for the INT-HIGH Sea Level Rise Scenario indicate that areas in Ponds R1/R2 starting at 0 ft and 4 ft reach the marsh vegetation threshold only slightly later than in the INT Sea Level Rise Scenario, lagged by less than a decade. This suggests that evolution of tidal habitats is relatively insensitive to the higher sea level rise scenario through the end of the century. By 2100, however, all sedimentation trajectories for the INT-HIGH Scenario are lower in the tidal frame than for the INT Scenario and closer to the threshold at which marsh may convert to mudflat. Existing marshes are predicted to remain vegetated through 2100, even for the higher sea level rise scenario.

For the combined low suspended sediment concentration (50 mg/L) and INT-HIGH Sea Level Rise Scenario, model results for Ponds R1/R2 indicate that accretion would be too slow relative to sea level rise to result in widespread conversion of mudflat to tidal marsh. A typical point on the remnant marsh plain at 4 ft does not reach the vegetation colonization elevation. In the combined low suspended sediment and INT-HIGH Sea Level Rise Scenario, accretion for existing marshes begins to fall behind sea level rise later in the century. This combined scenario would have implications for marsh sustainability for San Francisco Bay as a whole, not just Ponds R1/R2.

Because organic accretion was omitted from the model, actual deposition rates after vegetation colonization would be higher than modeled. Stralberg et al. (2011) estimate a rate of 1 mm/yr for the project area. Since the base case model (75 mg/L suspended sediment concentration and Intermediate Sea Level Rise Scenario) indicates that vegetation, once established, persists through the modeled timeframe (2100), adding 1 mm/yr of organic accretion would not change the habitat outcome. Assuming vegetation establishes between 2040 and 2050, as in the base case, including organic accretion of 1 mm/yr would raise the marsh plain by approximately 0.2 ft by 2100, a small effect.

5 Blue Carbon Stock Assessment

Coastal wetland protection and restoration have come into focus as strategies for reducing greenhouse gas (GHG) emissions and their contribution to climate change. Greenhouse gas reduction strategies focused on coastal ecosystems, including salt marshes, have earned the label “blue carbon,” distinguishing these more recent strategies from already-established “green” (e.g., forestry) and “gray” (e.g., industrial) carbon. Coastal ecosystems act as carbon sinks and long-term carbon reservoirs.

To better understand the effects of the SAFER Bay Project on coastal blue carbon resources, ESA quantified changes in blue carbon stocks due to project activities. We considered the SAFER levee footprint and Ponds R1/R2 restoration site and how they will change over time with sea level rise.

5.1 Stock and Sequestration Quantification Methods

Tidal marshes contribute to GHG reductions by storing carbon within the plant aboveground biomass and in the soils. Carbon stock refers to the quantity of carbon held within a specific carbon pool (or reservoir) at a given time, such as the carbon stored in marsh vegetation and soils. Carbon sequestration,³ or removal, is the rate of change in carbon stock.

This assessment applies methods consistent with the Intergovernmental Panel on Climate Change (IPCC) guidance from the 2013 Wetlands Supplement to the 2006 accounting guidelines (IPCC 2014) to calculate greenhouse gas (GHG) emissions and removals from tidal coastal wetlands. The IPCC GHG accounting framework uses the following equation:

$$Emissions = - Sequestration = Activity Data * Emissions Factor$$

Where:

- *Emissions* are releases of GHG into the atmosphere.
- *Sequestration* is a negative emission.
- *Activity data* in this context refer to changes in land cover—such as changes in tidal habitat—over time.
- *Emissions factors* are the rates of GHG emissions and removals associated with the activity data.

In this study, the relevant *emissions factor* is for carbon dioxide (CO₂). While methane (CH₄) and nitrous oxide (N₂O) fluxes are often considered for changes in land use, salt marshes are not a meaningful source of these gases (see Section 5.1.4).

5.1.1 Carbon Stocks

IPCC (2014) identifies three carbon stocks important to calculating CO₂ removals in coastal wetlands (this also applies to other vegetated land cover types): biomass (aboveground and belowground), soil carbon, and dead organic matter. In the blue carbon context, dead organic matter is relevant to mangrove forests. When aboveground mangrove biomass dies, the decomposition of wood is slow, and much of the material is buried and

³ The terms “sequestration” and “removal” are synonymous. “Sequestration” is used more often in the wetland carbon context, while “removals” is more common when considering a broader range of activities.

accumulates as soil organic matter. Dead organic matter is not significant for coastal salt marshes and has not been included (ESA 2023).

To calculate CO₂ removals, each land cover type is assigned a biomass carbon area density and soil carbon sequestration rate factor to each land cover type. And when applied over habitat area, carbon stock changes can be tracked through time as sea level rises and wetlands evolve. For example, when land is covered with vegetation, there is a carbon stock in the plant biomass and soil. The soil carbon increases according to the soil sequestration rate of the habitat due to the incorporation of organic matter back into the soil. When a habitat converts to another habitat (e.g., from mudflat to salt marsh), aboveground biomass changes (may increase or decrease) due to the different type of vegetation. Soil sequestration continues, but at the rate of the new habitat type. With restoration, when mudflats convert to marsh, aboveground biomass develops, and soil sequestration begins.

5.1.2 Aboveground and Belowground Biomass

When vegetation is established, carbon in the form of CO₂ is sequestered from the atmosphere to build aboveground biomass. The size of the carbon stock depends on the vegetation type and density. If the vegetation type changes, the amount of aboveground biomass will change as well. Furthermore, roots contribute to belowground biomass in varying degrees (e.g., grasses have low belowground biomass, while marsh has high belowground biomass). Biomass carbon factors used are listed in Table 7.

5.1.3 Soil Carbon Sequestration

Carbon also accumulates in the soil, especially in wetlands. As more soil layers are deposited, the soil carbon is buried and sequestered. Soil carbon sequestration rates used are listed in Table 7.

5.1.4 Methane and Nitrous Oxide Emissions

Methane (CH₄) emissions are produced when microorganisms in wet, poorly aerated soils, such as in freshwater marshes, decompose organic matter. High salinities reduce methane production and coastal wetlands with salinities greater than 18 ppt are considered to have negligible methane emissions (Beers and Crooks 2022).

Nitrous oxide (N₂O), a potent GHG, is emitted as a by-product of the conversion of ammonia (contained in fish urea) to nitrate. In areas with aquaculture, N₂O emissions should be included in the GHG accounting. In the case of SAFER, aquaculture land use does not apply, so nitrous oxide emissions are not included (ESA 2023).

TABLE 7
BIOMASS AND REDUCTION FACTORS

Habitat Type	Total Biomass Carbon (Mg C/ha)	Reference/Assumptions	Soil Carbon Sequestration Rate (g C/m ² /yr)	Reference/Assumptions
Upland and Transition Zone	5.5	IPCC 2006 V4 Chap 6 - p6.29 & Table 6.4 (for cold temperate - wet regions)	9.0	Kroodsma and Field (2006) value for non-rice annual cropland
Vegetated Marsh	15.9	Beers and Crooks (2022) (for saline estuarine emergent wetlands)	76.6	Beers and Crooks (2022) (for saline estuarine emergent wetlands)
Mudflat	0.0	Assumed no vegetation because habitat type is below the vegetation colonization elevation threshold	0.0	Assumed no vegetation because habitat type is below the vegetation colonization elevation threshold
Subtidal	0.0	Assumed no vegetation because habitat type is below the vegetation colonization elevation threshold	0.0	Assumed no vegetation because habitat type is below the vegetation colonization elevation threshold

5.2 Results and Discussion

5.2.1 Ponds R1/R2

Changes in habitat areas and associated carbon sequestration for restoration of Ponds R1/R2 are shown in Table 8 and Table 9, respectively. Restoration results in cumulative 39,000 tonnes CO₂ equivalents sequestered by 2100.

TABLE 8
CHANGE IN PROJECTED PONDS R1 AND R2 HABITAT AREAS (COMBINED) FROM BASE CASE (WITHOUT PROJECT)

Habitat Type	2030, immediately pre-breach (acres)	Change from Base Case (acres)					
		2030, immediately post breach	2040	2050	2060	2080	2100
Upland and Transition Zone	2.9	0.0	-0.2	-0.6	-0.7	-0.9	-2.7
Vegetated Marsh	0.0	0.0	+6.6	+287	+460	+486	+488
Mudflat	0.0	+525	+497	+202	+28	+1.2	+0.8
Subtidal	571	-525	-503	-489	-487	-487	-487

NOTE: Intermediate Sea Level Rise Scenario. Time lag for vegetation establishment (from Table 6). Total net change for all habitat types for each year shown may not sum to zero due to rounding.

ASSUMPTIONS: Assume change in upland and transition zone immediately after breaching is negligible (set to zero).

TABLE 9
PROJECTED PONDS R1 AND R2 BLUE CARBON STOCK CHANGES FROM BASE CASE (WITHOUT PROJECT)

Habitat Type	a. Net Biomass (tonnes CO ₂ equivalents)					
	2030	2040	2050	2060	2080	2100
Upland and Transition Zone	0.0	-1.3	-5.1	-5.8	-7.6	-22
Vegetated Marsh	0.0	157	6,795	10,879	11,504	11,550
Mudflat	0.0	0.0	0.0	0.0	0.0	0.0
Subtidal	0.0	0.0	0.0	0.0	0.0	0.0
Total	0.0	156	6,790	10,874	11,497	11,528

Habitat Type	b. Net cumulative soil carbon sequestered (= GHG Sequestration) (tonnes CO ₂ equivalents)					
	2030	2040	2050	2060	2080	2100
Upland and Transition Zone	0.0	-0.1	-0.6	-1.5	-3.7	-8.5
Vegetated Marsh	0.0	38	1,708	5,956	16,714	27,794
Mudflat	0.0	0.0	0.0	0.0	0.0	0.0
Subtidal	0.0	0.0	0.0	0.0	0.0	0.0
Total	0.0	38	1,708	5,954	16,710	27,786

Habitat Type	c. Net CO ₂ equivalents sequestered, Biomass and Cumulative Soil Carbon (tonnes CO ₂ equivalents)					
	2030	2040	2050	2060	2080	2100
Upland and Transition Zone	0.0	-1.4	-5.8	-7.3	-11	-31
Vegetated Marsh	0.0	195	8,503	16,835	28,218	39,344
Mudflat	0.0	0.0	0.0	0.0	0.0	0.0
Subtidal	0.0	0.0	0.0	0.0	0.0	0.0
Total	0.0	194	8,498	16,828	28,207	39,314

NOTES: All values are net change from the base case (without Project). 2030 values represent conditions immediately after Project construction and breaching. Upland/transition zone conversion to tidal habitat with restoration results in negative biomass and sequestration compared to the base case. Assume no soil carbon sequestered in 2030 because insufficient time for vegetation to establish. Use a ten-year lag for vegetation establishment. Totals may not match the sum of values due to rounding.

Entries in Table 9c are the sum of corresponding entries in Table 9a and Table 9b.

5.2.2 Existing Marshes

Removing portions of existing marshes to construct the SAFER flood protection levee results in cumulative 2,400 tonnes CO₂ equivalents released to the atmosphere by 2100. Table 10 summarizes carbon emission results.

Comparing Table 9 and Table 10, carbon sequestration through Ponds R1 and R2 restoration greatly offsets carbon emissions from levee construction, resulting in net cumulative 36,600 tonnes CO₂ equivalents sequestered by 2100 through the Project.

TABLE 10
PROJECTED EXISTING MARSH CARBON STOCK CHANGES FROM BASE CASE (WITHOUT PROJECT)

Habitat Type	a. Net Biomass (tonnes CO ₂ equivalents)					
	2030	2040	2050	2060	2080	2100
Vegetated Marsh - Directly Impacted	-362	-362	-362	-362	-362	-362
Vegetated Marsh - Indirectly Impacted	-194	-194	-194	-194	-194	-194
Total	-556	-556	-556	-556	-556	-556

Habitat Type	b. Net cumulative soil carbon sequestered (= GHG Sequestration) (tonnes CO ₂ equivalents)					
	2030	2040	2050	2060	2080	2100
Vegetated Marsh - Directly Impacted	0	-174	-348	-522	-871	-1,219
Vegetated Marsh - Indirectly Impacted	0	-93	-186	-280	-466	-652
Total	0	-267	-535	-802	-1,336	-1,871

Habitat Type	c. Net CO ₂ equivalents sequestered, Biomass and Cumulative Soil Carbon (tonnes CO ₂ equivalents)					
	2030	2040	2050	2060	2080	2100
Vegetated Marsh - Directly Impacted	-362	-536	-710	-885	-1,233	-1,581
Vegetated Marsh - Indirectly Impacted	-194	-287	-380	-473	-660	-846
Total	-556	-823	-1,091	-1,358	-1,893	-2,427

NOTE: All values are net change from the base case (without Project).

Directly impacted refers to habitat replaced by the SAFER levee, while indirectly impacted refers to habitats affected by ancillary levee construction effects (e.g., isolation from tides).

2030 values represent conditions immediately after Project construction. Assume no soil carbon sequestered in 2030 because insufficient time for sequestration to occur immediately after construction.

Assume all stored carbon in affected habitats is released to the atmosphere.

Assume no net change in upland/transition zone compared to base case and thus no net change in carbon stock. Mudflat and subtidal habitats are excluded as they do not support vegetation. Managed wetlands that are inboard of the current and proposed levee are not included in the carbon accounting.

Totals may not match the sum of values above due to rounding.

Entries in Table 10c are the sum of corresponding entries Table 10a and Table 10b.

6 Limitations and Uncertainties

Overall, this analysis suggests that if Ponds R1/R2 are restored to full tidal inundation around 2030, substantial marsh establishment is likely after one to two decades and approximately 480 acres of tidal marsh vegetation is likely to establish within three decades. This assessment is supported by three factors: First, in the last two decades, tidal restorations at multiple nearby reference sites have demonstrated the capacity for sediment accretion and extensive vegetation establishment when starting from mudflats. Second, the primary calibration parameter, suspended sediment concentration, was chosen to replicate observed bed elevation changes at several reference sites and marsh establishment still occurs even when the suspended sediment concentration is only 50 mg/L, or 66% of the calibrated value. Finally, the Intermediate Sea Level Rise Scenario used in the model provides, according to OPC (2024), “a reasonable upper bound for the most likely range of sea level rise by 2100.” If the actual sea level rise is lower, less bed accretion will be needed for marsh vegetation to establish.

While this assessment indicates that extensive marsh establishment is likely with full tidal restoration, the analysis presented herein does have limitations and uncertainties which should be considered when interpreting these results.

1. This analysis does not model sediment transport dynamics in detail. MARSH98 models a constant “effective” sediment supply based on calibration with other sites and simulates a constant, uniformly distributed deposition rate on the mudflat/marsh surface. In reality, marsh sediment supply is highly variable and sediment transport within the site varies based on hydrodynamics and proximity to sediment supply. While erosion of sediments due to wind-waves and tidal currents are not simulated directly, the model is calibrated to account for the effect of erosion to the extent that these processes influenced net accretion rates at the reference sites. Any additional effects of erosion not captured in the calibration are not expected to significantly affect the long-term distribution of marsh vegetation.
2. This analysis does not model vertically varying sediment consolidation within the bed. The MARSH98 model represents the soil column as having uniform composition and constant density. As such, the bed bulk density should be viewed as an average value representative of the upper portion of the soil column. If compaction results in higher bed bulk density and corresponding lower bed elevations, marsh establishment may take slightly longer but is still anticipated to occur.
3. This analysis assumes that conditions and processes which influenced the calibration sites’ accretion rates will persist into the future. The calibration data periods vary by site but generally cover the period from 2000 to 2015.

Historic records for San Francisco Bay indicate that conditions can change rapidly over relatively short time scales due to anthropogenic activities in the Bay, upland watersheds, and climate factors. Even over the time period shown in Figure 6, there appear to be inter-annual trends in suspended sediment concentration. Over longer time frames, studies of historic suspended sediment concentrations in San Francisco Bay indicate that the estuary experienced a period of very high sediment yield from the Delta and local watersheds beginning during the Gold Rush (mid-1800s) and continuing through approximately the 1930s as sediments mobilized by hydraulic mining in the Sierras and coast ranges made their way into to the Bay. This pulse is believed to have largely worked its way through the Bay and the regional estuarine sediment supply has been declining since the late 1990s (Schoellhamer 2011). Although a

detailed assessment of historic and future trends in suspended sediment that could be available to the SAFER study area is beyond the scope of this study, recent nearby restoration sites show continuing accretion, even after the 1990s suspended sediment decline, and the sensitivity analysis for suspended sediment concentration indicates that even 66% of the calibrated suspended sediment would still lead to marsh formation in Ponds R1/R2 and maintain sustainable marshes through 2100.

4. There is broad consensus among the scientific community that the Earth’s climate will experience changes over the coming century due to the accumulation of greenhouse gases in the atmosphere. Most significant for marsh establishment, sea level rise means that bed elevations will need to be ever higher to catch up to and pace the tidal thresholds for marsh vegetation establishment. As noted above, the Intermediate Sea Level Rise Scenario used in the model (3.1 ft by 2100) provides a reasonable upper bound for the most likely range of sea level rise by 2100 (OPC 2024). If the actual sea level rise is lower, marsh vegetation would establish more quickly and sustain higher in the tidal frame. Conversely, if sea level rise is higher, vegetation would take longer to establish and be lower in the tidal frame by 2100. Sensitivity modeling for a higher sea level rise scenario (4.8 ft by 2100) suggests that for a suspended sediment concentration of 75 mg/L, marsh will establish and sustain in Ponds R1/R2 through 2100.

The rate of sea level rise increases with time, so if tidal restoration occurs several decades past the assumed 2030 start date, the bed will be subject to faster rates of rise, which could compromise marsh vegetation establishment.

Climate changes could also affect other processes related to marsh growth. For example, changing precipitation patterns may alter the supply of sediment to the Bay. The analysis of the potential impacts of climate change and related effects on bed accretion and habitat evolution is beyond the scope of this analysis, but it must be acknowledged that a changing climate will likely influence the growth and accretion of tidal marshes over the coming century and that such effects are not reflected in this analysis.

5. Blue carbon is extremely variable, and the carbon assessment presented is a high-level estimate. It is intended to be illustrative of the potential for GHG reduction and should be used for planning purposes only.

To address the above limitations and uncertainties with respect to habitat evolution, the SAFER Bay Project could use an adaptive management approach. This would consist of monitoring marsh conditions and preparing for interventions such as thin layer sediment placement if sea level rise and/or sediment supply results in slow marsh formation or marsh die-off.

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8 Figures

Figure 1. Project and Reference Site Locations

Figure 2. Cooley Landing Reference Site Aerial Imagery

Figure 3. Pond A21 Reference Site Aerial Imagery

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Figure 6. Suspended Sediment Concentration (SSC) at Dumbarton Bridge

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Figure 8. Pond R1/R2 Projected Habitat Extents

Figure 9. Pond R1/R2 Projected Habitat Distributions



SOURCES: Basemap (County of Santa Clara 2022; Maxar 2022)

D211919.00 SAFER Bay Project

Figure 1
Project and Reference Site Locations



SOURCE: Google Earth (2017)

NOTE: Cooley Landing site first breached in 2000, and an additional breach was added in 2005.

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Figure 2
Cooley Landing Reference Site Aerial Imagery

2007



2011



2014



2017



SOURCE: Google Earth (2017)
NOTE: Pond A21 site breached in 2006.

SAFER Bay Project. D201100919.04

Figure 3
Pond A21 Reference Site Aerial Imagery

2011



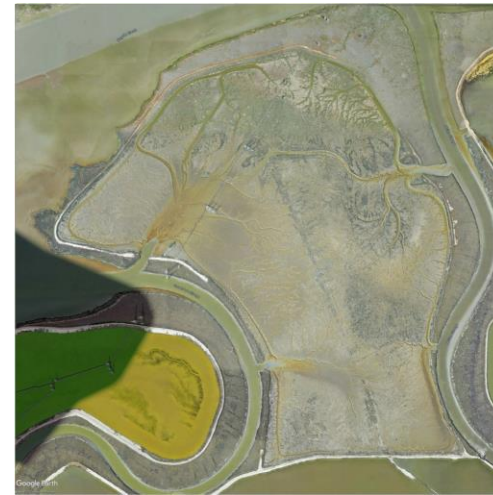
2014



2018



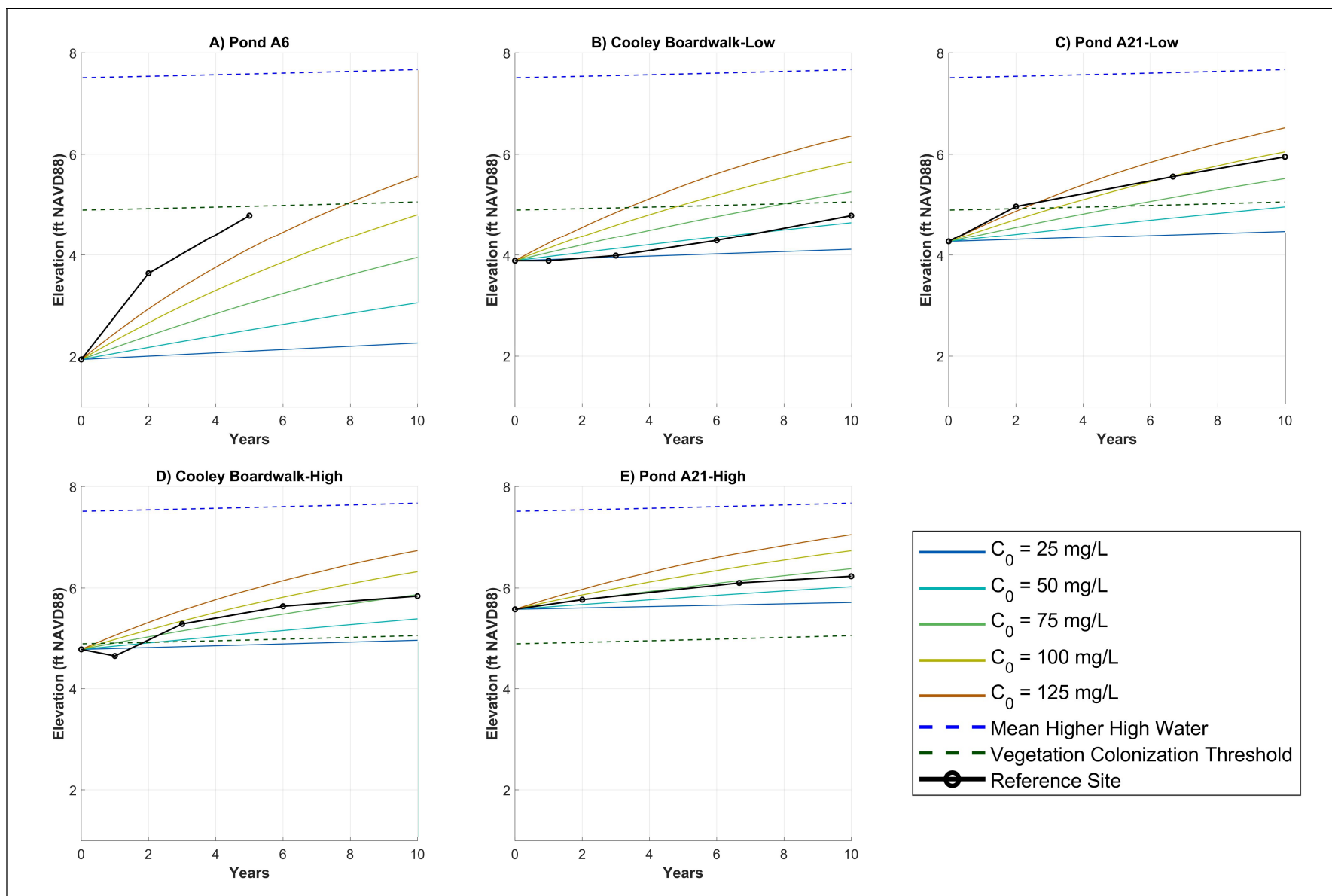
2022



SOURCE: Google Earth (2017)
NOTE: Pond A6 site breached in 2010.

SAFER Bay Project. D201100919.04

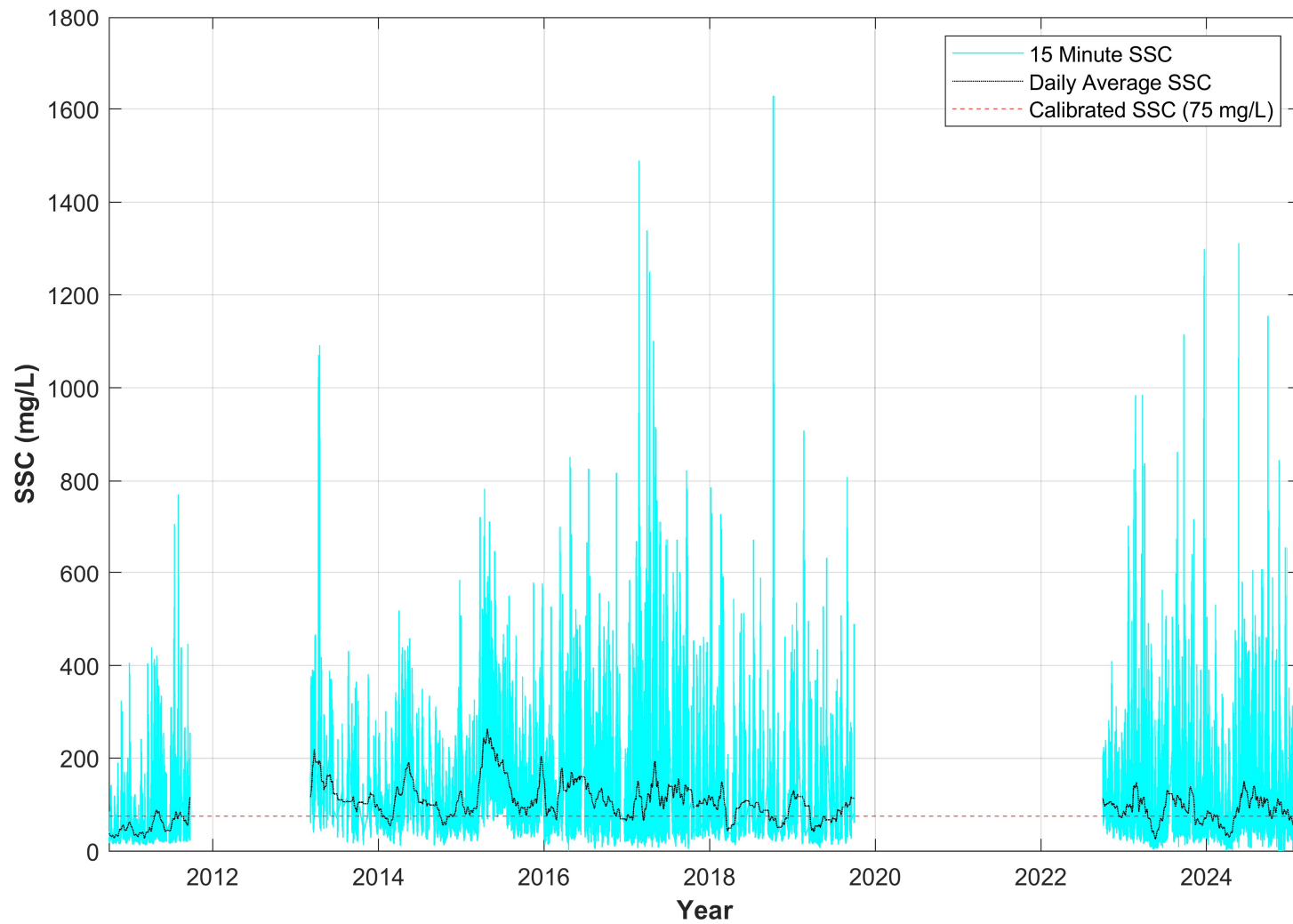
Figure 4
Pond A6 Reference Site Aerial Imagery



SOURCES: ESA analysis.

NOTE: NAVD88 = North American Vertical Datum of 1988

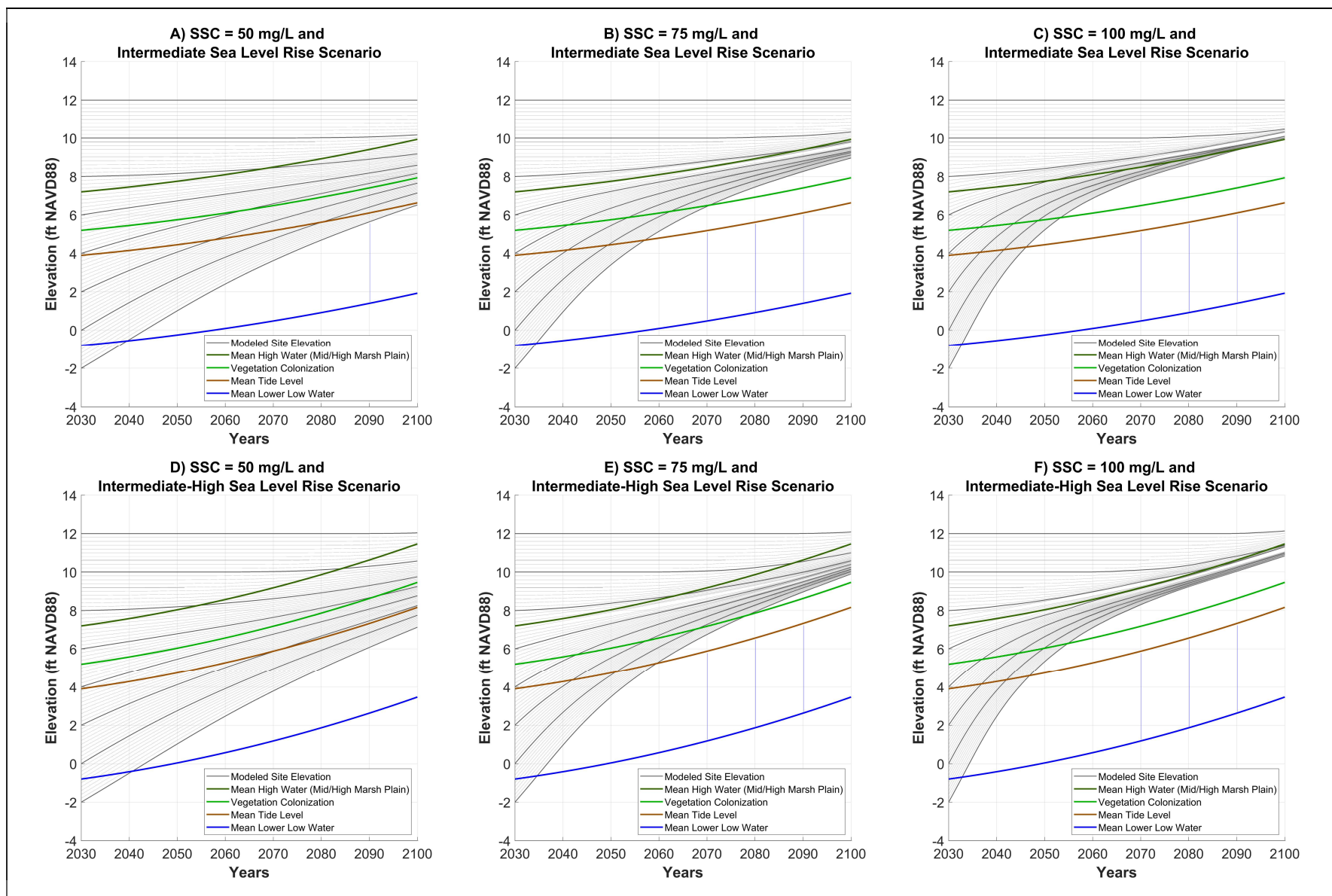
SAFER Bay Project. D201100919.04
Figure 5
 MARSH98 Calibration Results



SOURCE: United States Geologic Survey (USGS) Dumbarton Bridge, Gage #373015122071000
 NOTE: Data was unavailable from September 2011 to March 2013 and October 2019 to September 2022.

SAFER Bay Project. D201100919.04

Figure 6
 Suspended Sediment Concentration (SSC)
 at Dumbarton Bridge



SOURCES: ESA MARSH98 analysis. Sea level rise scenarios from the Ocean Protection Council (2024).
 NOTE: Assume Pond R1/R2 is restored in 2030 (approx.) The remnant marsh plain begins at a typical elevation of 4 ft NAVD88 (North American Vertical Datum of 1988).

SAFER Bay Project. D201100919.04

Figure 7
 Pond R1/R2 Marsh Plain Accretion Trajectories
 for Various Suspended Sediment Concentrations (SSC)
 and Sea Level Rise Scenarios



SOURCES: ESA analysis, Basemap (County of Santa Clara, 2022; Maxar, 2022)

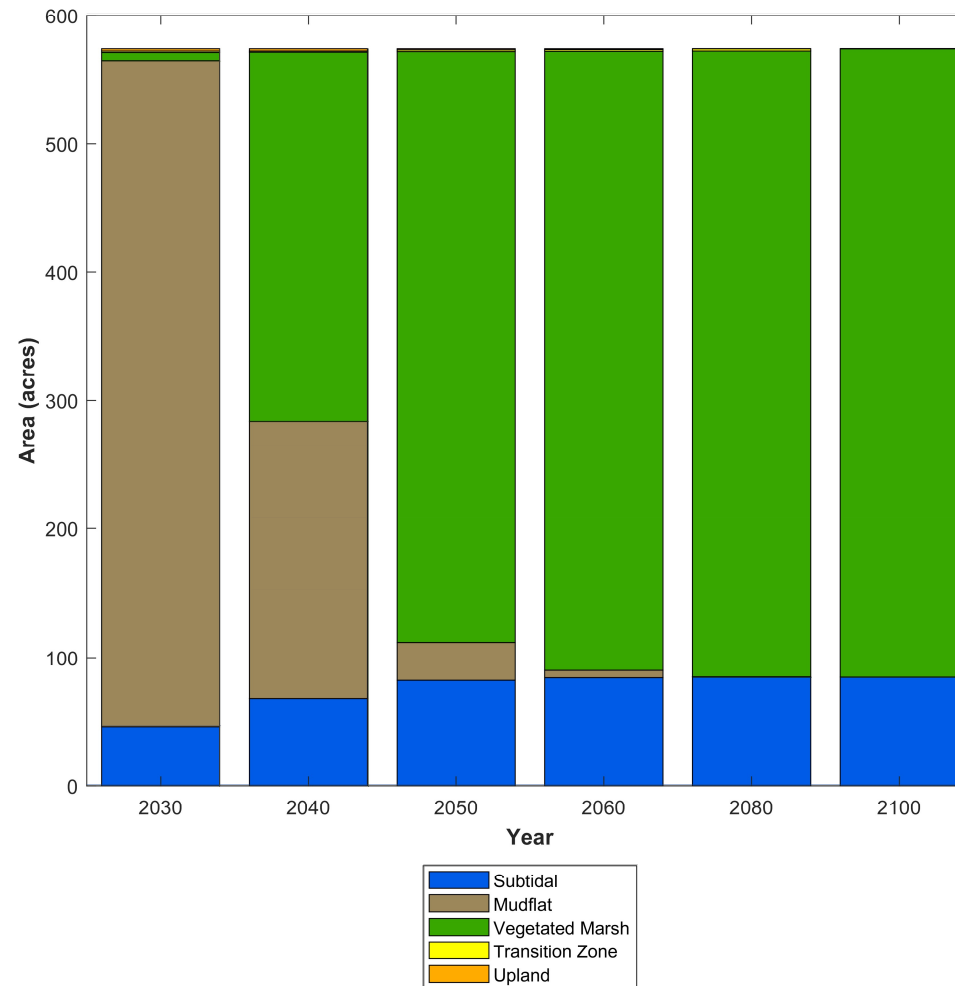
NOTE: Assumed Pond R1/R2 restored in 2030 (approx.).

Legend

- Subtidal
- Mudflat
- Vegetated Marsh
- Transition Zone
- Upland

D211919.00 SAFER Bay Project

Figure 8
Pond R1/R2 Projected Habitat Extents



SOURCE: ESA analysis

NOTES:

1. Assumed Pond R1/R2 restored in 2030 (approx.).

2. Upland and transition zone habitat areas are too small to be visible at this plot scale.

See Table 5 for values.

SAFER Bay Project. D201100919.04

Figure 9

Pond R1/R2 Projected Habitat Distributions