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Adapting to Rising Sea Levels in San Francisco Bay: The Potential for Thin Layer Sediment Application to Enhance Tidal Marsh Resiliency through This Century

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This Master's Project

ADAPTING TO RISING SEA LEVELS IN SAN FRANCISCO BAY: THE POTENTIAL FOR THIN LAYER SEDIMENT APPLICATION TO ENHANCE TIDAL MARSH RESILIENCY THROUGH THIS CENTURY

by

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Abstract

The research here focuses on two projected century sea-level rise scenarios (100 and 180 cm/century) and the potential to offset elevation loss to sea-level rise by supplying deteriorating tidal marsh habitat with a thin layer of dredge sediment via high-pressure spray disposal within San Francisco Bay. This adaptation strategy is then analyzed for potential integration into the Bay's long term management plan for dredge material disposal. The Marsh Equilibrium Model (Morris, 2012) is used to evaluate elevation deficits for existing tidal marsh habitat around San Pablo Bay against future century sea-level rise scenarios and model marsh resiliency following elevation enhancement.

This research shows that applying a 15 to 20 cm thin layer of dredge sediment onto deteriorating tidal marsh habitat is optimal for improving marsh habitat function. The model indicates that enhancing existing tidal marsh habitat elevations could be necessary around the year 2045 under the high century SLR scenario. Maintaining tidal marsh elevations at this time shows enhanced resiliency for 15 to 25 years. Modeling 100 cm/century SLR, existing marsh habitat elevations will need enhancement around the year 2060 in which resiliency is maintained for more than 40 years. Based on this research, the potential for thin layer spray disposal to enhance marsh elevation in San Francisco Bay is promising. However, to achieve these prescribed layer placement depths, spray disposal is limited to distances of 70 meter thus requiring multiple spray locations to cover larger areas of deteriorating tidal marsh habitat.

The potential for thin layer spray disposal to enhance future LTMS goals is promising based on recent amendments to the Bay Plan and willingness of the LTMS agencies to consider new methods to reduce climate change related impacts. However, policy impediments in Section 404 permitting regulations for wetland fill need adjusting to account for climate change adaptation strategies in order to preserve existing tidal marsh habitat through the century. Planning and budgeting for future adaptation strategies is urgent now to ensure resiliency in tidal marsh habitat and overall shoreline resiliency for San Francisco Bay through this century.

Acronyms and Abbreviations

Bay Plan	San Francisco Bay Plan
BCDC	Bay Conservation and Development Committee
CDFW	California Department of Fish and Wildlife
CWA	Clean Water Act
cm	centimeters
cy	cubic yards
EPA	Environmental Protection Agency
ha	hectares
HWRP	Hamilton Wetland Restoration Project
IPCC	Intergovernmental Panel on Climate Change
LTMS	Long Term Management Strategy
m^3	cubic meter
mcy	million cubic yards
MEM	Marsh Equilibrium Model
Mm^3	million cubic meters
MHW	Mean High Water
MHHM	Mean Higher High Water
MLW	Mean Low Water
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
NAVD88	North American Vertical Datum of 1988
NERR	National Estuarine Research Reserve
RCD	Sonoma Resource Conservation District
RWQCB	Regional Water Quality Control Board
SFBRWQCB	San Francisco Bay Region Water Quality Control Board
SF-DODS	San Francisco Deep Ocean Disposal Site

SLR	Sea Level Rise
SSC	Suspended Sediment Concentration
U.S.	United States
VE	Value Engineering
USFWS	U.S. Fish and Wildlife Services
USEPA	U.S. Environmental Protection Agency
USACE	United States Army Corps of Engineers

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1. Introduction

Invaluable tidal marsh habitat along the San Francisco Bay shoreline is at risk of disappearing if the projections for sea level rise in the latter half of this century are proven accurate (Schile et. al 2014 and Stralberg et. al 2011). The compounding effects of habitat loss would not only be catastrophic to sensitive wildlife but also poses a threat to coastal communities. Tidal marsh habitat in the Bay is home to endemic and endangered species such as the salt marsh harvest mouse, the California clapper rail and the delta smelt and serves as a critical point along the Pacific Flyway for migratory birds (Swanson et al. 2013 and Goals Project 2015). When tidal marshes start disappearing so too will wildlife that depend on this habitat. In addition, this loss of marsh habitat will reduce shoreline resiliency in the ability to sufficiently buffer coastal communities against extreme storm surges. As a result, efforts to preserve this habitat in the San Francisco Bay is being widely discussed in the conservation and regulatory community. The impact from extreme weather events and rising sea levels to low lying coastal areas has the potential to adversely affect the balance on the tidal marsh system to the point where marsh platform elevations can no longer support productive vegetation (Schile et. al 2014 and Stralberg et. al 2011). This increase in sea level rise will result in tidal marsh habitat transitioning into a subtidal mudflat before the end of this century unless adaptation strategies are implemented.

The San Francisco Bay Estuary (the Bay) is the largest on the U.S. Pacific coast and is home to ninety percent of the remaining wetlands in California. Coastal wetlands are noted in combination as being some of the most vulnerable and economically vital ecosystems on Earth, supporting a wide range of invaluable services (Kirwan and Megonigal, 2013). The Earth's changing climate over the next century is projected to severely impact the San Francisco Bay's coastal shoreline habitat (i.e. Baylands), specifically with accelerated rates of sea level rise (SLR) and coinciding reductions in sediment supply from rivers and tributaries (USACE et al. 2013 and Goals Project 2015). The Bay shoreline serves 270,000 people and $62 billion of development at risk of becoming inundated if SLR continues to escalate over the next century as projected (Cloern et al. 2011). The Baylands tidal marshes serve to sequester carbon from the atmosphere, enhance water quality, buffer storm surges and diminish flooding of surrounding infrastructure as well as provide critical habitat refuge for specialized and endemic species (Stralberg et al. 2011). Predictions of SLR of within the Bay over the next century indicate shoreline habitat may be particularly vulnerable to extreme inundation in which these low lying tidal marsh coastal zones will be first to encounter the potential affects (Cayan et al. 2008).

The National Research Council is projecting regional sea-level rise for San Francisco Bay upwards of 61 cm by 2050 and has much as 166 centimeters by the end of this century (Goals

Project, 2015). Rising sea-levels have had a strong influence in the San Francisco Bay as observed through a marked increase (by 20-fold) in extreme events over the last century, driven by oceanic processes such as El Niño and the Pacific Decadal Oscillation (PDO) (Cayan et al. 2008 and Goals Project, 2015). It is anticipated over this century these extreme events will become more commonly observed as sea-levels continue to rise which will only compound the effects to tidal marsh habitat along the San Francisco Bay shoreline (Cayan et al. 2008). Sediment inputs to the Bay have declined over the last century and are predicted to continue a downward trend into the future (Schile et al. 2014). The Bay's inter-tidal zone is particularly vulnerable to the stressors and limitations from reduced sediment availability (Goals Project, 2015). The continual decline in sediment supply worsens the issue for future tidal marsh resiliency as sea-level rise continues to rise because tidal marshes rely on sediment inputs from rivers and tributaries to support processes in marsh migration, erosion control and vertical accretion that help stabilize marsh function.

Although mean sea level has risen over last few decades roughly 2.2 mm/year (Cayan et al. 2008), marsh platform elevations relative to sea level have remained stable indicating they are naturally adapting to current increases of annual sea level rise. However, with SLR projections over the next century ranging from 20 – 200 cm, uncertainty looms around the longevity of coastal habitats in the Bay (Stralberg et al. 2011). SLR and marsh accretion rate modeling indicate over the next century, mean sea level rise will become too overbearing for tidal marshes to keep pace through natural vertical accretion mechanisms leading to eventual drowning of the marsh (Schile et al. 2014). It is not a question of whether tidal marshes will be able to maintain healthy marsh platform elevation (i.e. productive vegetation platform), but rather what is the threshold for when marsh habitat will begin to lose elevation from increasing rates of annual SLR before the marsh transitions to subtidal mudflat. With these changing conditions in mind, practical and effective methods are needed to offset marsh elevation loss relative to increases in mean sea level during this century.

One potential method to offset the effects from marsh elevation loss is to artificially supply the marsh with a thin layer of dredge sediment, as a sediment slurry via high-pressure spray disposal, to help build and sustain marsh elevation. This technique for enhancing marsh elevations may reduce the stress from prolonged inundation with future SLR and restore balance in the tidal hydrologic regime for future tidal marshes to sustain through the century. Dredge sediments from the Bay have typically been reused to supply wetland habitat restoration projects in diked baylands, for levee maintenance or sent to shoreline rehandling facilities to be used as landfill cover (USACE et al. 2013). High-pressure spray disposal of dredge sediment originated as a disposal management technique in Louisiana for dredging canals through tidal marsh plains for navigation to drilling sites. Spraying a thin layer of sediment slurry across the marsh platform was used to minimize spoil build up along dredge canals that degraded wetland function leading to marsh habitat loss throughout the Louisiana coastal zone. Several field studies have been conducted on the effects to the tidal marsh ecosystem from thin layer spray disposal in the Atlantic and Gulf Regions. It is undetermined whether thin layer spray disposal in San Francisco Bay would be a practical application and sea-level rise strategy for maintaining existing tidal marsh habitat. As well, the Bay's long term management plan for dredge material sets the guidelines for effective disposal management in which thin layer placement alternatives for marsh enhancement would need to similarly support the Bay's overall plan.

The United States Army Corps of Engineers (USACE), is responsible for maintaining adequate depths of federal navigation channels for safe and reliable passage. These channels accumulate sediment over time which in turn requires maintenance dredging to provide safe and reliable transportation of commerce and to accommodate national security needs (URS Group, Inc. 2014). Historically in the early 1970's, disposal of dredge material occurred at few select sites within the Bay (e.g. near Alcatraz island), which over time raised concern about the environmental impacts related to in-Bay disposal alternatives. As a result, in 1990, a multi-agency cooperative consisting of the United States Environmental Protection Agency (USEPA), the USACE, the San Francisco Bay Regional Water Quality Control Board (SFRWQCB), the San Francisco Bay Conservation and Development Commission (BCDC) and the State Water Resources Control Board (SWRCB) joined forces to improve how dredge material is managed in the Bay. In 1996, this interagency group began developing a long term management strategy plan (LTMS) for the disposal of dredge material in the San Francisco Bay region which published in 2001. The LTMS serves to provide guidance on the most economically and environmentally suitable disposal options, enhance permit review processes and maximize beneficial reuse of dredge material (USACE et al., 2001). Understanding the potential sediment budget needed to support beneficial reuse alternatives in maintaining of existing tidal marsh habitat will be important for future planning. Managing dredge material for beneficial reuse is challenged by high costs due in large part to transporting material to a specific alternative reuse site. A design strategy for an Aquatic Transfer Facility is being considered in San Pablo Bay as part of the Hamilton Wetland Restoration Bel Marin Keys expansion project. The strategy focuses on enhancing the management for reusing dredge material helping to reduce some of the current efficiency constraints imposed on beneficial reuse projects.

The attention of this research will focus on assessing the potential to use high-pressure spray disposal for thin layer placement of clean dredge material within the inter-tidal zone of the San Francisco Bay shoreline to enhance marsh resiliency against projected rates in SLR over this century. The motivation for this research comes through the need to conserve and maintain invaluable tidal marsh habitat for the many species of wildlife that depend on it throughout the

Bay as well as enhancing shoreline resiliency to protect the adjacent communities. If tidal marsh habitat continues to decline as a result from climate change impacts, threatened and endangered species will become extinct. Equally, preserving and maintaining tidal marsh habitat will ensure a more resilient shoreline to protect against more frequent and more intense flooding episodes that are projected as a result of future climate change. The research presented here focuses on considering thin layer sediment application to enhance marsh platform elevations in the Bay as a potential adaptation strategy to increase marsh resiliency against projected rates of century SLR. As necessary, this research will consider the potential in thin layer placement for marsh enhancement projects to be included within the LTMS plan for the Bay.

1.1 Physical Setting of San Francisco Bay and Research Focus Area

The Bay Estuary-Watershed is composed of interconnected river networks, estuary and coastal ocean that is bound by the Sierra Nevada and Cascade mountains (Cloern et al. 2011). Five thousand years ago the Sacramento River channel running through the Bay to the Golden Gate straight became inundated with rising sea levels (Barnard et al. 2013). As a result, tidal wetland habitat developed in the Bay due to increasing sea levels that flooded what is now the Bay (Stralberg et al. 2011). At the head of the estuary, freshwater enters from the Sacramento and San Joaquin Rivers converging into the Sacramento-San Joaquin Delta.

Prior to the Gold Rush in 1849, the Bay received sediment inputs primarily from the Delta, which delivered roughly 1.5 Mm^3 of sediment deposits each year and the remaining sediment input was attributed to local tributaries (Barnard et al. 2013). Between 1849 and 1914, a 9 fold increase in sediment supply was observed entering the Bay from hydraulic mining activities in the nearby mountain ranges. More than 850 Mm^3 in sediment deposits entered the Bay, which ultimately developed into 220,000 ha of tidal marshes and mudflats throughout the Bay (Barnard et al. 2013 and Stralberg et al. 2011). Over time the Sacramento and San Joaquin Rivers supplied sediment loads to the bay which helped to maintain tidal marsh habitat against annual increases in SLR (Stralberg et al. 2011).

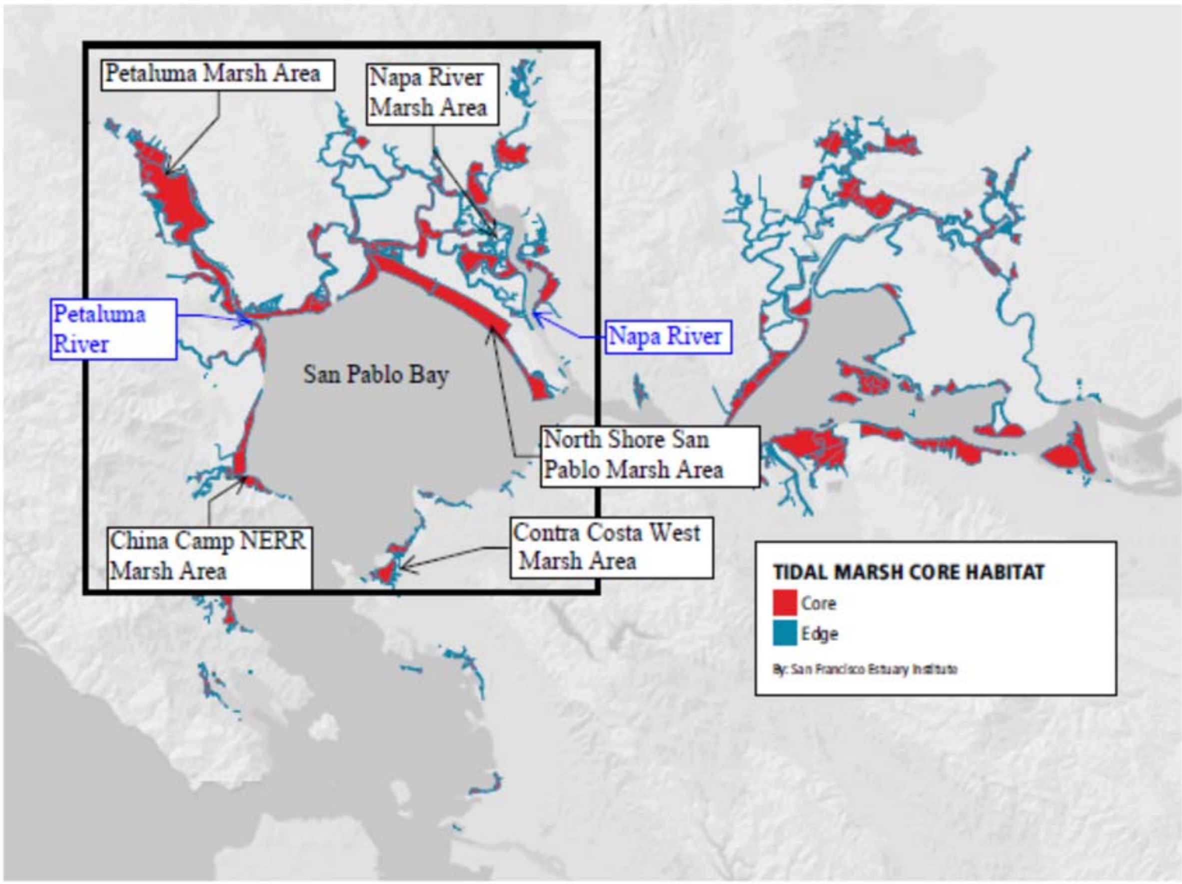
At the entrance of the Bay, tides sinuously roll through the Golden Gate to the Delta causing an influx of sea water intruding on freshwater river flow creating the tidal salt and brackish marshes of the Bay-Delta complex. Salinity intrusion to the Bay is determined by sea level height and river inflow (Cloern et al. 2011). Sea level height oscillates between highs and lows over the lunar cycle. The Bay has a mixed semi-diurnal tide cycle which is to say the Bay exhibits two high tides (mean high water (MHW) and mean higher high water (MHHW)) and similarly two low tides each with varying degrees in size each lunar day. During the winter and spring, outflow from reservoirs along with rain and runoff from snow pack reduce salinity levels in the Bay while increases in salinity concentrations are observed during summer and fall due to reduced influx of freshwater (Stralberg et al. 2011).

1.1.1 Historical Tidal Marsh Loss in San Francisco Bay

The destruction of wetland habitat over the past century can be attributed to anthropogenic activities in filling, building dams and levees and induced land subsidence from development. These actions have resulted in less than 10 percent of historic tidal marsh habitat remaining around the Bay (Stralberg et al. 2011). The Goals Project (2015) reported that historical diking and filling activities are responsible displacing over 150,000 acres of tidal marsh habitat between 1800 and 1998. In 1965 the State of California was urged to prevent further destruction of wetlands in the Bay and signed the McAteer-Petris Act, the first 'no net loss of wetlands' legislation in the United States. As a result, marsh habitat loss eventually slowed due to the protection of threatened parcels. The declining trend in habitat loss was reversed during the 1990's through the effort of early restoration activities and dredge material management planning (Goals Project, 2015). Much of the early restoration effort focused on restoring former tidal marshes (i.e. diked tidal marshes). The first restoration project occurred in 1972, restoring 32-ha Faber Tract in the South Bay. Presently in the Bay, the remaining tidal marsh habitat fringes on the river margins and the majority are positioned adjacent to levees along urban and agriculture land. Tidal marsh restoration efforts in the Bay have been expansive over the past two decades with hundreds of millions of dollars invested towards conserving this invaluable habitat (Stralberg et al. 2011). As a result of these conservation efforts, the Bay has regained nearly 5,000-ha of tidal marsh habitat, having gone through decades of investigative research and overcoming challenges presented through interdisciplinary authorizing agencies and stakeholders. While these restoration efforts are critically necessary for bringing back historic tidal wetlands to the Bay, an equal effort is needed for maintaining existing tidal marshes to prevent future loss in the face of century SLR projections.

1.1.2 Focus Area: North Bay Tidal Marsh Habitat Overview

In the North Bay (San Pablo Bay; Study Area), fragmented marsh habitat exists in large marsh patches composed primarily of wide marsh areas linked to narrow fringing marsh (Goals Project, 2015). The San Pablo Bay tidal marsh area contains the largest average marsh patch size (205 acres) as well as the largest contingent of core marsh habitat in the bay encompassing 17,461 acres (Figure 1) (Goals Project, 2015). Table 1 presents the existing marsh acreage surrounding San Pablo Bay broken down into distinct marsh habitat areas. Existing marsh acreage was estimated using Wetland Mapper (here: http://www.fws.gov/wetlands/data/mapper.HTML). Marsh habitat characteristics for each identified locale are summarized below. Generally speaking, the mid to high marsh zone is characterized by dominate pickleweed (*Sarcocornia pacifica*). The broad fringing low salt marsh along tidal creeks typically supports native stands of cordgrass species (i.e. Pacific Cordgrass, *Spartina foliosa*) (Baye, 2012)



Goals Project. 2015. The Baylands and Climate Change: What We Can Do. Baylands Ecosystem Habitat Goals Science Update 2015 prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. California State Coastal Conservancy, Oakland, CA .

Figure 1: North San Pablo Bay Core Marsh Habitat

Table 1: North San Pablo Bay Existing Marsh Habitat Acreage

Existing Tidal Marsh Habitat Locale	Acres [1]
China Camp to Petaluma River	1,300
Petaluma Marsh Area	4,100
North Shore San Pablo Bay Marsh [2]	3,800
Napa River Marsh Area	2,800
Point Pinole to Carquinez Strait	390

Notes:

1 Individual marsh area acreage estimated from USGS Wetland Mapper : (available at http://www.fws.gov/wetlands/data/mapper.HTML).

2 Includes Mare Island marsh habitat.

China Camp NERR to Petaluma River

On the west side of San Pablo Bay in Marin County, China Camp State Park (China Camp) contains about 240 acres of undeveloped historic tidal marsh positioned adjacent to Gallinas Creek flowing into San Pablo Bay. China Camp is a National Estuarine Research Reserve (NERR), considered a living laboratory and used as a reference site for healthy marsh habitat which is operated under the National Oceanic and Atmospheric Administration (NOAA). China Camp is characterized by extensive stands of historic salt marsh vegetation developed on a prehistoric salt marsh platform containing a sinuous network of tidal creek channels (Baye, 2012). The mid to high marsh zone is dominated by pickleweed. The broad fringing low salt marsh along tidal creeks supports extensive native stands of Pacific cordgrass (Baye, 2012). Spanning north from China Camp, roughly 1,000 acres of existing marsh habitat fringes the shoreline converging at the mouth of the Petaluma River. The existing fringe tidal marshes along this stretch serve as valuable shoreline protection in flood control for the city of Novato and other local communities that live adjacent to the shoreline. Several large scale restoration projects have been undertaken including the completed 750 acres of wetlands on the former Hamilton Air Force Base and future restoration of 1,700 acres at Bel Marin Keys property (Goals Project, 2015).

Petaluma Marsh Area

Following the Petaluma River northwest inland of San Pablo Bay lies the Petaluma Estuary, located in Sonoma County. Fringing marshes line the river extending towards the Petaluma marsh which encompasses roughly 4,000 acres of tidal marsh habitat. Owned and managed by the California Department of Fish and Wildlife, this marsh area includes brackish and salt marsh habitat supporting a great diversity of native plant species. The Petaluma Estuary is rich in sediment availability as evident by the extensive high and mid-marsh plains and predominant tidal sloughs under minimal influence from wave energy as the marsh extends inland away from the Bay (Goals Project, 2015). The San Antonio Creek, Adobe Creek and Petaluma River each supply freshwater inputs through the system feeding San Pablo Bay. Adjacent to the Petaluma River on the east side are several completed restoration projects in Leonard Ranch as well as several planned projects in the Sonoma Baylands Salt Marsh Restoration and Sears Point Restoration Project. Only few existing marshes remain fringing the eastern portion along the north shore of San Pablo Bay, evident by the extensive inter-tidal mudflat habitat due to land impediments disrupting the hydrologic patterns and preventing marsh migration upland (Goals Project, 2015).

North Shore San Pablo Bay Marshes

San Pablo Bay National Wildlife Refuge marsh is located on the north shore of San Pablo Bay. The extent of this existing marsh habitat is vast, covering three counties in Sonoma, Solano and Napa, under the authority of U.S. Fish and Wildlife Services. Most notable along the north shore of San Pablo Bay, there is a 1,400 acre existing marsh strip spanning to Mare Island Strait. It is one of the larges intact marsh systems in the Bay and one of the most ecologically significant tidal marshes in San Pablo Bay (Takekawa et al. 2013 and Goals Project, 2015). Sonoma Creek cuts the marsh in two segments, a western portion and an eastern portion. The entire span of existing tidal marshes along the north shore of San Pablo Bay is influenced by wave energy and local tidal regimes as they are openly exposed to the Bay. The north shore salt marsh habitat contains dominant pickleweed and cordgrass strands throughout their respective mid and low marsh zones (USGS, 2013). There is roughly 3,800 acres of existing marsh habitat positioned around the north shore of San Pablo Bay. Extensive mudflat characterizes the low elevations extending into the Bay (Goals Project, 2015).

The surrounding land area of this marsh is mostly undeveloped with areas of agriculture land intermixed. Tidal marsh restoration efforts have been exhibited around the north shore marsh area including Tolay Creek and Lower Tubbs Island which have seen both subtidal and marsh-upland transition zones restored to improve hydrologic function as well as restoring native plants within the transition zone. Several large scale projects are planned including at Skaggs Island, Sonoma Creek and Sears Point. Highway 37 runs parallels the Bay shoreline inland and consequently crosses through adjacent low lying marsh habitat. As such, the tidal marsh habitat on either side of Highway 37 is impeded hydrologically (Goals Project, 2015). As a result, excess flooding on the bay side is causing marsh habitat to become degraded where stands of pickleweed die-off is causing transition to mudflat (Takekawa et al. 2013). This area is a distinct marsh type characterized by a high marsh terrace sustained by wave action and irregular sediment deposition (Goals Project, 2015). The Mare Island high marsh terrace located further down the shoreline is reported by the Goals Project (2015) to be among the most resilient marshes to SLR over this century. This marsh can be used as a guideline reference marsh to model resiliency for nearby marsh sites that may need future elevation enhancement.

Napa River Marsh Area

Currently much of the Napa River area is still undeveloped with managed ponds dominating the Rivers west side landscape. Portions of the Napa River Marsh complex have undergone extensive restoration exampled by the Napa-Sonoma Marsh Restoration Project where nearly 10,000 acres of wetlands and other habitats have been restored (Goals Project, 2015). However, historical brackish tidal marshes in both Fagan Slough Marsh and Coon Island marsh still remain intact along the Napa River. Each of these marshes are within the limits of Napa County and managed by the California Department of Fish and Wildlife. Fagan marsh is surrounded by private property, evaporation ponds and small upland areas where Coon Island contains adjacent salt pond restoration sites of the Napa Sonoma Marshes Wildlife Area (Goals Project, 2015). The Napa River marsh area contains about 2,800 acres of existing tidal marsh habitat in which portions of tidal marsh habitat fringe the levees that border the managed ponds.

Point Pinole to Carquinez Strait

As described by the Goals Project (2015), the landscape along the east shore of San Pablo Bay is highly developed where tidal flats remain within their historic distribution and several sandy barrier beaches and lagoons persist. The shoreline running north form Point Pinole up to the Carquinez Strait contains relatively few patches of existing marsh habitat mostly found within small coves and at the entrances of adjoining creeks. The nearly 390 acre expanse of tidal marsh habitat is directly exposed to the Bay waters and thus have high saline conditions, and experience high-energy wave action (Goals Project, 2015). The adjacent upland area along the shoreline is highly urbanized with limited inputs of sediment supporting the tidal marsh system. Consequently, marsh migration is restricted in the area and increasing wave action from SLR will likely cause the small remaining fringe tidal marshes to erode (Goals Project, 2015).

Special Status Species of San Pablo Bay Marshes

The existing marsh habitat encompassing San Pablo Bay all have similar vegetation characteristics as previously mentioned, and the same is true for the sensitive wildlife that depend on tidal marsh habitat in the Bay. Bay tidal marshes host several state and federally listed threatened and endangered species. The California black rail (i.e. Black rail), the salt marsh harvest mouse and Ridgway’s rail (i.e. California clapper rail) are all known to exist throughout the Bay tidal marshes (Takekawa et al. 2013). Significant populations of Ridgway's rail and Black rail have been found within the Napa River Marsh complex (Goals Project, 2015). San Pablo Bay Marsh is a significant stopover on the Pacific Flyway providing critical habitat for migratory and wintering habitat for shorebirds (USGS, 2013). As well, the San Pablo Bay National Wildlife Refuge had once reported the largest population of salt marsh harvest mouse until recent vegetation die back occurred form prolonged inundation over the marsh plain as a result of artificial drainage impediments (Takekawa et al. 2013). Spawning Chinook salmon have been observed in Sonoma Creek and steelhead trout are known to frequent Gallinas Creek at China Camp as well as Wildcat and Pinole Creeks in the Contra Costa area of San Pablo Bay (Goals Project, 2015). Intertidal and shallow subtidal areas around Point Molate and Point Pinole also support extensive eelgrass, oyster and macroalgal beds in the Bay. Each of these sensitive species inhabiting in and around these existing marshes will directly influence how and when thin layer disposal can be applied to the marsh area and present a significant challenge when considering the potential of using thin layer spray disposal to enhance marsh resiliency.

1.2 Statement Problem and Environmental Management Relevance

The threat of rising sea levels over this century is a concern for existing tidal marsh habitat around the Bay as marshes may not be able to naturally adapt. Compounding factors in declining trends of sediment supply to the Bay as well as restricted landward marsh migration along the shoreline adds to the concern for tidal marsh sustainability in the face of SLR over this century. Ecological function will begin to deteriorate if marshes are unable to naturally build elevation at a similar rate to SLR. The resulting marsh elevation loss relative to mean sea-level will lead to downward shift in marsh habitat zonation (i.e. mid marsh transition to low marsh to eventual subtidal mudflat) which could potentially have irreversible effects on the special status species inhabiting these Bay tidal marshes. In order to maintain longevity through this century, we need to understand and consider adaptive management strategies that are effective at reducing the risk against accelerated rates of future SLR. Future increases in annual sea level rise in conjunction with declining sediment supply to the bay are the fundamental problems facing tidal marsh survival through the century (Goals Project, 2015). Marsh accretion modeling has been exhibited for such scenarios to estimate the threshold for when vegetated marsh platforms will begin transitioning into subtidal mudflat habitat. From a management prospective, we need to understand how best to combat the initial impacts with a plan in place ready to act accordingly. This will require a different way of thinking from how current management and policy regulate impacts to wetlands.

The aim in my research is to present the potential for thin layer placement to enhance marsh platform elevations for beneficial reuse of dredge material to sustain marsh habitat in the face of sea level rise over this century. The goal for this research is to highlight the urgency in planning for future maintenance of existing tidal marshes, which will require allocated budgets with necessary funding. In particular, this research will provide high level volume estimates required to maintain existing marshes in the North Bay against future SLR scenarios. The required dredge volume will be compared to availability and compatibility with current maintenance dredging and disposal projects. The results from my research will hope to benefit future planning against SLR threats and management of dredge sediment towards beneficial reuse for tidal marsh habitat enhancement in the Bay.

1.3 Research Objectives and Report Overview

The main objective of this research is to understand the potential for thin layer sediment applications to enhance tidal marsh resiliency along the San Francisco Bay shoreline against projected rates of century SLR. Accordingly, this research will examine how thin layer disposal projects can be included within the LTMS plan as an adaptation strategy for future climate change impacts. Specifically this research seeks to answer the following questions that will support understanding the potential for thin layer disposal to be effective in the Bay for maintaining tidal marsh habitat through the century:

- What are the limits of thin layer spray disposal working to enhance marsh elevations and are elevations maintained long term? What are the potential impacts from thin layer spray disposal to existing marsh habitat and the surrounding ecosystem?
- If thin layer disposal can work to offset marsh elevation loss effectively, when is the critical implementation period and for how long is marsh resiliency maintained against future increases in SLR?
- As an adaptation strategy against future SLR threats in the Bay, how will alternative reuse options in thin layer placement for marsh habitat enhancement integrate with the LTMS to support future goals for dredging and disposal management in the Bay?
- How much sediment is required to maintain elevations of existing marshes in North San Pablo Bay through the century?

The following sections describe the research on the potential for replenishing marsh platform elevation using this layer sediment application. Section 2 describes the research approach and methods used in the investigation. Section 3 touches on the climate change impacts and SLR projections over this century and tidal marsh sustainability concerns. Section 4 provides case study analyses of thin layer spray disposal and marsh habitat response including effects on the physical and biological processes determining limits of practical use. The Marsh Equilibrium Model is utilized for two century SLR scenarios (100 and 180 cm/century), where marsh elevation deficits are projected and future target elevations are assumed for achieving healthy marsh platforms. The required layer depth of dredge sediment needed to achieve target elevations is analyzed accordingly. Section 5 analyzes dredging and disposal management in the Bay and current policy associated with dredge disposal and protection of marsh habitat. The focus is on whether thin layer placement of dredge material can be considered as "beneficial reuse" in habitat enhancement for the future maintenance of existing tidal marsh habitat. Specifically, the Bay's maintenance dredging projects are assessed for the potential to support alternatives in thin layer placement for marsh enhancement projects around San Pablo Bay. The projected sediment demand for maintaining San Pablo Bay marsh habitat under future SLR scenarios is compared to typical disposal volumes generated from maintenance dredging projects. Section 6 discusses the results and findings from this research. Management recommendations are presented in Section 7. Section 8 contains all referenced literature.

2. Reseach Methodology

The research presented here is a qualitative assessment to identify the potential for thin layer spray disposal to effectively enhance marsh elevation and maintain resiliency long term against projected increases in SLR over the next century. Using case study analysis, I will assess the physical and biological impacts associated with thin layer spray disposal comparing both in the near and long term response effects. Additionally, previous field investigations will be used to understand the long term response with respect to maintaining improved elevations following thin layer placement. The evidence will suggest whether thin layer sediment application to tidal marsh habitat can work to enhance overall marsh resiliency against future increases in SLR. The physical and biological considerations will account for potential impacts to both above and below ground dynamic functional processes, included existing vegetation response, benthic community composition effects and the response of soil characteristics following placement of dredge sediment onto the marsh platform. Lastly, I will consider the potential effects from thin layer spray disposal to threatened and endangered species that are endemic to the Bay marshes.

Furthermore, I will analyze how thin layer spray disposal to enhance marsh resiliency can support the LTMS future goals in San Francisco Bay as an adaptation strategy to SLR. The analyses will be measured through least environmental impacts or where the benefits heavily outweigh the side effects as well as cost and funding considerations which are main drivers in determining alternative disposal options. I will qualitatively assess the current dredging and disposal operations in the Bay to identify the challenges already facing beneficial reuse alternatives and determine whether thin layer disposal projects can be implemented effectively to support the LTMS goals. The critical factors in this analysis will be shown through available maintenance dredge material compared to what is required based on high level estimates for maintaining existing marshes around San Pablo Bay. Equally, cost and funding considerations for reusing dredge material to enhance marsh resiliency at alternative placement sites will be analyzed using current beneficial reuse associated project costs for comparison.

Marsh Equilibrium Modeling: Vertical Accretion Rates and Sea-Level Rise

Several marsh accretion model exist that indicate how marshes responds to increases in SLR. The Wetland Accretion Rate Model of Ecosystem Resilience (WARMER) and the Marsh98 model each simulate marsh elevation response to increases in SLR factoring both physical and biological marsh characteristics that aim to capture the interworking accretion rate process (Swanson et al. 2013 and Stralberg et al. 2011). The other alternative model, and the one used for this research is the Marsh Equilibrium Model (MEM or the model) developed by J.T. Morris (2010). The Marsh Equilibrium Model was also developed to address how tidal marsh habitat will respond to projected increases in SLR over the next century. The MEM utilizes extensive field investigation data and models how marsh elevations influences plant productivity that in turn effect vertical accretion rates of the marsh platform under century SLR scenarios. The model incorporates both inorganic and organic inputs to project marsh accretion at a given elevation over the century. The input parameters include starting elevation and current SLR rate, mean sea level, MHW, suspended sediment concentrations (SSC) and as well the projected SLR rate over the century. The model also accounts for biotic factors in minimum and maximum marsh vegetation elevation, peak above ground biomass. MEM factors plant productivity bound by upper and lower elevation input as the optimum growth elevation across the tidal flux (Schile et al. 2014). The MEM was chosen due to user friendly model interface and broad array of applicability. The MEM is available at: http://jellyfish.geol.sc.edu/model/marsh/mem.asp.

To highlight how models have been used to project marsh response to increases in SLR, in 2013 the USGS used the WARMER model to assess future response of existing marshes in the Bay, including China Camp Marsh, San Pablo Bay Marsh, Petaluma Marsh and Fagan Slough Marsh. Although each are relatively resilient marshes as indicated by their functioning characteristics, the results for each of these existing marshes indicate gradually lose elevation relative to MHW after the year 2030, experience more dramatic loss after 2060 and is projected to be under mean sea level by 2080 or before the end of this century. As evident from these model predictions, SLR effects on existing marsh habitat presents a serious problem for which adaptive management strategies are needed effectively preserve the balance of this invaluable tidal marsh ecosystem.

Using the MEM, I will quantitatively evaluate marsh elevation loss for existing tidal marsh habitat surrounding San Pablo Bay against projected future SLR scenarios of 100 cm and 180 cm/century. These century SLR rates are being used to represent a moderate and extreme SLR scenario which are consistent within previous studies applied century SLR projections (Schile et al. 2014). Using an estimated acreage of existing marshes in association with the model projected elevation deficits for each century SLR scenario, sediment volume requirements will be estimated to achieve target marsh platform elevations suitable for productive marsh vegetation to be resilient through the century.

The MEM will be calibrated for China Camp Marsh National Estuarine Research Reserve to assess elevation loss against each SLR scenario. The results will be projected to all existing core marsh habitat around San Pablo Bay. It should be noted here that even though marsh habitat within the Study area may have varying physical and biological input parameters based on their position around the bay, generally speaking, this research assumes that existing marsh habitat response to future SLR with respect to marsh elevation loss will not significantly differ. However, when assessing marsh elevation loss to determine appropriate or required disposal depths to reach target elevations, site specific evaluation is required. This research is intended to present a rough estimate of elevation loss to project high level volume requirements for maintaining existing marsh habitat around San Pablo Bay. These projections should be viewed as a starting point for understanding the level of effort in future planning and budgeting to preserve this habitat and maintain shoreline resiliency.

The research presented here aims to determine the potential for thin layer spray disposal to enhance marsh elevations in the Bay as an adaptation strategy against future SLR threats. Identifying the opportunities within the LTMS for thin layer placement of dredge sediment on to marsh platforms as alternative beneficial reuse options is another goal for this research. Understanding the limits of thin layer placement and marsh response related to physical and biological processes of the tidal marsh system will give an indication for the opportunities and constraints within the confines of the LTMS. Understanding future marsh elevation deficits against future SLR scenarios will be valuable information for future planning and management of supplying sediment to offset the effects from SLR and maintain healthy marsh platforms through the century.

3. Tidal Marsh Sustainability and Future Sea Level Rise Projections

Tidal wetlands are dynamic ecosystems in the low lying coastal zone at the interface between marine and land environments. The flux between tide cycles transitions between submerged and exposed habitat, each of which have variable soil conditions comprised of distinct vegetation types and regulated through this hydrologic regime. Tidal wetlands contain transition zones across its relatively flat topography. Tidal mudflats transition into low marsh containing vegetation of cordgrass species, then transitions to dominant pickleweed species in the mid to high marsh habitat. Tidal marsh habitat provides critical refuge for wildlife including threatened and endangered species endemic to the Bay marshes. Equally, tidal marshes are able to sequester carbon from the atmosphere as well as maintain shoreline resiliency through buffering extreme storm surges (Stralberg et. al, 2011).

Ecology of Tidal Marsh Habitat – Elevation Adaptation Processes

Tidal marshes naturally build elevation through two processes in surface sediment deposition and subsurface expanse of rooting vegetation and decaying plant matter (i.e. organic matter) (USGS, 1997). Although accumulation of organic matter is an important contributor if elevation accretion for tidal marshes, inorganic sedimentation is the primary process for tidal marshes to accrete vertically with rising sea levels (Goals Project, 2015). As marshes transition lower in the tidal frame, increased inorganic sediment deposits take place as a result of increased inundation depth over the low marsh zone, effectively reducing accumulation of organic matter. Tidal marshes function across a transition gradient through interactions between sea level, land elevation, primary production and sediment accretion to maintain a balance in elevation relative to mean sea level (Morris et al. 2002). With adequate sediment supply, the marsh builds to an elevation high within the tidal frame, typically around mean higher high water (MHHW) (Zedler et al. 2008 and Stralberg et al. 2011). Plants are able to colonize just above MHW for which established vegetation initiates marsh formation. Plant shoots work to slow water flow which allows sediment to settle and roots and rhizomes work to stabilize the sediment subsurface (Zedler et al. 2008). Marsh stability is achieved through biophysical feedbacks among vegetation and soil (mineral sediments and organic matter) that allow marsh platforms to establish a position within the intertidal zone (Kirwan and Megonigal, 2013).

Sea Level Rise Threats and Existing Tidal Marsh Sustainability

Tidal marsh stability is maintained through balance between mean sea level and sediment inputs supporting marsh accretion at a rate similar to increases in mean sea level over time (Ravit and Weis, 2014). Tidal marshes exhibit natural biological and physical processes that aid in building elevation within the tidal regime through root and rhizome productivity and natural sediment inputs accreting on the marsh platform. The balance between frequency and duration of inundation along with a healthy sediment supply, plays a critical role in how tidal marshes self-sustain a healthy platform elevation relative to mean sea level. Janousek and Mayo, 2013 report that marsh vegetation growing at depths between 25 and 50 cm below MHHW resulted in up to 72 percent less shoot mass compared to plant grown at shallower depths. The marshes ability to maintain a healthy vegetated platform relative to tide regime is essential for maximizing function and resiliency. The ability for the marsh to migrate landward and adapt naturally to the changes in environmental conditions is equally important being resilient to climate change related impacts such as accelerated rates in SLR. Unfortunately around the Bay today, much of the shoreline is highly developed, restricting marsh migration landward creating a major impediment for marsh habitat to naturally adapt and persist through increasing rates of SLR.

Century SLR projections span a wide range due to several contributing factors in greenhouse gas emissions warming the ocean and the rate at which glacial ice is melting (Cayan et al. 2008). Projections of global sea level rise are expected to be a close index for the California coast (Cloern et al. 2011). The Intergovernmental Panel on Climate Change (IPCC) in 2013 report that global mean sea level rise could be in the high range of 53 – 100 cm by the end of this century. Additionally, projections in SLR over the next century have a wide range, anywhere from 20 – 180 cm which brings great uncertainty in the future sustainability of coastal marsh habitat (Schile et al. 2011). Historical trends of SLR over the last few decades in the Bay have been roughly 20 cm/century in which tidal marsh elevation has shown to maintain balance through natural accretion mechanisms (Schile et al. 2011). Sediment supply to the Bay has been on the decline since 1884 when hydraulic mining diminished. Factors impeding sediment supply to the bay include dams that trap sediment and levees built for flood protection which divert sediment supply to adjacent floodplains (Schoellhamer et al. 2013). As a result of this massive anthropogenic disturbance over time, the natural sediment supply to the Bay is projected to decline continually into the foreseeable future and as a result, the demand for sediment in order to preserve marsh habitat is increasing (Kirwan and Megonigal, 2013). Due to the close relationship among dynamic feedbacks between marsh platform and tidal regime, accelerated rates of SLR in conjunction with reduced sediment inputs over this next century will ultimately disrupt the balance of existing marsh habitat (Barnard et al. 2013).

Under these future SLR projections, tidal marsh habitat function is at risk of losing balance and becoming unstable ecosystems over the next century. To exacerbate this matter, Cayan et al. (2008) investigated the relationship between SLR and future extreme events and found as sea level continues to increase, impacts of high tides and storm surges worsen. The frequency and magnitude of extreme events (i.e. astronomical tides and El Nino events) compared to the present is expected to be more pronounced as the rate of sea level rise increases over this century (Cayan et al. 2008). The fact that tidal marsh habitat interfaces between water and land, this habitat will be among the first to experience the effects of SLR over the next century.

Tidal marsh habitat is particularly vulnerable to increases in mean sea level having potential to succumb to drowning and eventual loss (Schile et al. 2011). More specifically, the high marsh habitat is particularly susceptible to initial loss where landward migration is impeded by developed shoreline. Long term stability of tidal marshes depend on available space to migrate and naturally adapt to environmental changes. Tidal marsh habitat also depend on vegetation productivity to help maintain a balanced marsh platform elevation relative to mean sea level (MSL) (Morris et al. 2002). Current marsh accretion rate modeling against future SLR provides insight on how tidal marsh function will respond over this century. In the face of SLR over this century, the time scale for which marsh habitat is projected to start transitioning is a critical component for adaptive management over this century. As the rate of SLR is expected to sharply increase in the latter half of the century, marsh elevation relative sea level rise is at risk of becoming unbalance such that mean sea level will drive changes in marsh habitat function (Cloern et al. 2011).

The concern and uncertainty with SLR projections and tidal marsh sustainability over the next century, is the rate of SLR predicts to be faster than marshes will be able to naturally build elevation and maintain balance relative to the tidal regime. In principle, at a minimum, tidal marsh platforms must increase elevation at a rate equal to the rate of SLR to survive (Kirwan and Megonigal, 2013). Tidal marsh vegetation is a critical component in regulating the marsh platform and maintains balance through the marshes ability to migrate with changes in sea level (Schile et al. 2014). As tides rise and inundate the marsh platform, mineral sediments contained in the water column settle out. Sediment deposits are greater in lower elevation marsh zones due to longer periods of inundation compared to upland marsh elevations (Schile et al. 2014). It is important to note, the dynamics of vertical accretion mechanisms in tidal marshes will be not always be equal. Variations among inorganic sediment inputs and organic matter depend on where the marsh is located within the Bay (Schile et al. 2014). Maintaining marsh elevations in anticipation of accelerated rates in annual SLR will be critical for the survival of marsh habitat and its dependent species that are adapted to the tide regime of the marsh system (Swanson et al. 2013). This will require climate change adaptation strategies to be implemented during this century for which policy regulations will need to be addressed. The Goals Project (2015) suggest sediment could be placed as thin-layer deposits (i.e. placement), or placed on adjacent mudflats to be re-suspended and then dispersed by tidal action through creek networks into the interior marsh plains. This research focuses on thin layer sediment application via high-pressure spray disposal as an adaptation strategy to enhance existing tidal marsh habitat elevations around San Pablo Bay when increases in SLR threaten marsh habitat integrity.

4. Thin Layer Sediment Application and Tidal Marsh Elevation Enhancement

This section examines the technique of high-pressure spray disposal for applying a thin layer of dredge sediment to enhance existing tidal marsh elevations. The objective here is to determine if supplying dredge sediment to a deteriorating marsh can successful enhance platform elevations with sustained long term benefits. In California, thin layer sediment application for marsh elevation enhancement is currently being pilot tested at the Seal Beach National Wildlife Refuge in Orange County where the project is designed to improve habitat quality for the endangered light-footed Ridgeway's rail. Most field studies related to thin layer disposal center on the Louisiana's coastal zone due to its wide application for dredging channels through marsh plains. Follow up studies have been performed on marsh habitat in North Carolina capturing long-term marsh response to thin layer placement of dredge sediment. As such, the findings from past investigations will be used to infer how tidal marshes in the Bay might respond to thin layer placement using high-pressure spray techniques. Finally, I will use the MEM to assess marsh elevation deficits against moderate and high projections of century SLR to determine when thin layer sediment additions will be necessary for enhancing tidal marsh elevations and for how long resiliency is maintained through this century.

4.1 Overview Thin Layer Spray Disposal and Environmental Background

In the Louisiana coastal zone, canals are commonly dredged across tidal marshes for navigation, pipeline construction and access to oil and natural gas drilling sites (Cahoon and Cowan, 1988). Historically, upland spoil banks were created alongside the canal channel from conventional bucket dredging methods. This practice was suspected in causing wetland loss by converting tidal marsh habitat to open water and altering the hydrologic system. Low pressure hydraulic dredges dates back to the 1930's as a management technique used to minimize environmental impacts where dredge material is sprayed across the marsh and away from the canals edge which prevents the formation of spoil banks (Wilbur, 1993). As technology of early bucket dredging improved, it was generally found to be more cost effective and preferable method compared to hydraulic dredging (Wilbur, 1993). Placing dredge material in marshes received eventual backlash as it became realized that wetlands outside the disposal area were subject to severe impacts (Weber, 1993). The observed wetland loss was a priority concern for the state. As such, federal and state regulatory agencies sought the need for better management of disposal methods in order to reduce the impacts associated with spoil bank formation. In response, the concept of high-pressure spray disposal (thin layer disposal) of dredge material was first developed as a way to minimize dredging related impacts on Louisiana's coastal wetlands

(Cahoon and Cowan, 1988). This method allows dredgers to spray dredge material several hundred feet away from the channel banks. The expectation is that a uniform layer will be deposited over the marsh platform without leading to habitat elevation based changes. Material is sprayed as a sediment slurry of thoroughly mixed sediments (80% water, 20% sediment). Uniform distribution of soil size particles across the marsh area is expected due to coarse and fine soils being well mixed (Ford et al. 1999).

The term "thin layer disposal" as originally developed had multiple definitions, depending on its intended use. Wilber (1992) of the U.S. Army Engineer Waterways Experiment Station, investigated how thin layer disposal was driving regulatory projects and identified the following four factors to consider when defining this concept for consistent terminology. Clearly defining thin layer disposal separates it from alternate dredging practices such as those used for habitat creation or restoration (Wilber, 1992). First, the definition should be independent of the technique used to achieve a thin even layer, as this can limit the practicality of the definition with future advances in dredging technologies. The second factor to consider in defining thin layer disposal is that significant elevation based habitat alterations should not result from the layer of dredge sediment placed over the disposal area. Small elevation changes via thin layer placement is more appropriately associated with habitat improvement rather than wetland formation (Wilber, 1992). The third consideration calls to thoughtfully assess distributing dredge material in a particular fashion rather than allowing to chance or exclusively natural dispersive forces. The final consideration when defining thin layer disposal is to not be associated with a particular environmental effect, as that definition has potential to be open ended. Incorporating these four factors into the definition of thin layer disposal is important for understanding the potential advantages and disadvantages associated with this method.

Challenges are presented when trying to understand what layer thickness of dredge material can be placed without altering existing elevation based habitat functions. Wilber (1992) raises the question, how much can natural elevations in tidal wetlands be altered such that new habitat not created? Certain tidal marsh habitats may be more accommodating to greater thickness of thin layer placement without changing its habitat type. Therefore, the actual thin layer placement depth will be relative to the projects objective and is dependent on a case by case examination.

All taken into consideration, high-pressure spray disposal for thin layer placement can be defined as: *Disposing of dredge material in a purposeful manor, such that the placement is carefully planned to a thickness believed to maintain natural system processes and functions without causing elevation based habitat alterations.*

Technical Characteristics: High-Pressure Spray Disposal

Thin layer spray disposal is commonly referred to in the context of subtidal placement or marsh nourishment with layers in thickness ranging from 0.5 to 3 feet (Ray, 2007). Investigative studies on the effects from thin layer spray disposal have analyzed sediment additions ranging in depth from a couple millimeters to more than thirty centimeters (Cahoon and Cowan, 1988; Wilber, 1992). High-pressure spray nozzles allow for controlled directional movement and so are not restricted to deposit material continuously in a single area. Controlling the direction for material placement is conducive for avoiding sensitive habitat areas. Furthermore, high-pressure spray of sediment slurry is capable of spreading to distances as far as 100 meters across the marsh platform and can deposit as little as several inches (Cahoon and Cowan, 1988). Achieving a uniform thin layer across a marsh platform can alternatively be done through pumping the sediment slurry through pipes to evenly distribute sediment across the marsh platform. Pumping slurry through pipes onto the marsh platform may cover larger distances, but layer depth may not be as evenly distributed compared to high-pressure spray disposal. Cahoon and Cowan (1988) describe how the material is sprayed in that spoil deposits spread in a fine rain-like mist, cascading down on the marsh platform in a relatively thin uniform layer. This dynamic functionality in using high-pressure spray disposal for thin layer sediment application distinguishes it from alternative dredging disposal technique (e.g. conventional bucket dredging or pumping and piping). Additionally, we begin to see the opportunity for high-pressure spray disposal and thin layer placement to be utilized for enhancing tidal marsh elevations as an adaptation strategy against future SLR impacts.

4.2 Physical Processes: Tidal Marsh Response to Thin Layer Sediment Applications

Several important factors need consideration prior to supplying dredge sediment onto the tidal marsh platform for the purpose of enhancing elevations. First, understanding the potential target elevation using local marsh reference sites and calculated disposal depth based on site capacity (i.e. elevation deficits relative to MSL) will influence the volume of dredge material to be disposed of for enhancing marsh elevation. Understanding the limits of placement layer depth on to the marsh is critical for successful marsh enhancement using thin lay sediment application. Based on marsh vegetation productivity influencing the stability of a marshes platform, it can be inferred that any successful enhanced or sustained elevations following thin layer placement of dredge sediment would indicate healthy and productive marsh vegetation response.

When considering the potential for thin layer sediment application to enhance marsh elevation, it’s important to understand how physical factors of unconsolidated dredge sediment respond and change over time following placement. The question here is whether thin layer placement of dredge sediment can enhance marsh platform elevations and maintain function over time. There have been limited studies investigating whether thin layer sediment application specifically works to enhance marsh elevation but rather investigated the range in layer placement depths to evaluate the effects on existing marsh habitat and associated physical and biological process.

Tidal marshes in Louisiana and North Carolina have shown healthy marsh platforms following thin layer placement depths up to 15 cm measured several years after thin layer application from high-pressure spray disposal (Wilber, 1993). In 1996, 0.5 ha subsided salt marsh in coastal Louisiana received dredge sediment via high-pressure spray disposal. In this study, dredge material consisting of river sand sediment was placed to a depth of 2.3 cm on a cordgrass dominate salt marsh. Twenty months following placement, Ford et al. (1999) observed similar vertical accretion rates and coinciding elevation changes at both the placement site and nearby reference site over a year's time. Surface elevation change was greater at both disposal site and reference site compared to accretion rates suggesting subsurface soil processes improved biomass production or pore water storage capacity (Ford et al. 1999). By 1998, vertical accretion contributed to 6.2 cm of sediment accumulation. This example demonstrates how improved marsh platform elevations are able to maintain natural processes over time. The applied layer depth was thin enough to maintain existing marsh habitat characteristics without causing habitat based elevation changes and therefore exhibits how thin layer disposal applied onto marsh habitat can successfully enhance and maintain healthy productive marsh platform elevations.

Thin Layer Placement and Marsh Substrate Physical Processes

Assessing the physical changes of dredge sediment across a range of initial layer thickness, Reimold et al. (1978) found initial postplacement thickness of dredge material had been reduced 10 to 40 percent (based on initial disposal depth on 8 – 91 cm) after ten days with little variation between dredge material type (sand, silt, clay concentrations). Conversely, standard engineering analyses show grain size does influence consolidation mechanisms (Wilbur, 1993). Investigations also suggest that percent consolidation of dredge material could reach as much as 66 percent (Wilber, 1993). Complete consolidation typically occurs within a year post-disposal, although hydrodynamics and sedimentation processes (e.g. soil permeability, water table elevation and evaporation effects) imposing on consolidation will be specific to the marsh site (Wilbur, 1993). When considering enhancing marsh platform elevations to reach a desired target elevation, incorporating post-consolidation sedimentation factors into the initial layer placement depth should be planned. Based on the nature of dredge material being a sediment slurry mix when applied to the marsh, the volume of dredge material to be sprayed can be four to seven times greater than in-situ dredge material volumes depending on soil characteristics (Wilber, 1993). Since in-situ sediment volumes and solids concentration (i.e. bulk density) are known for the dredging site, estimates of the total sediment mass to be disposed can be acquired to achieve target marsh elevation. It should be noted, unless otherwise mentioned, thin layer sediment depths mentioned in this paper assume post-consolidation established layer depth.

The physical and chemical properties of dredge sediment are important factors corresponding to effective elevation enhancement following thin layer sediment applications. In the natural system, inorganic sediments distributed over the marsh work to build and maintain marsh platform elevation over time. Marsh vegetation dynamics in above ground sediment trapping and subsurface soil processes regulate the rate at which marsh elevation changes over time (USGS, 1997). Three distinct soil processes in vertical accretion, subsurface compression and sediment consolidation influence how marsh platform elevations respond to thin layer sediment application (Cornu and Sadro, 2002). To highlight how marsh soils respond to thin layer dredge sediment applications, Slocum et al. (2005) found benefits in greater bulk density and increased elevation under moderate thin layer depths ranging from 2 – 12 cm across the marsh area. These benefits degraded over time, however, the marsh platform maintained improved elevations and sufficient bulk density properties offsetting the effects of subsidence for more than 11 years. Finally, Leonard (1999) observed increases in oxidation reduction potential with sediment layer depths of 10 cm which improved overall vegetation canopy (e.g. cordgrass species). This moderate elevation increases of the marsh platform reduced flooding effects and improved soil aeration allowing the rooting zone to benefit leading to increased vegetation productivity.

The evidence provided above demonstrates how physical processes of applied thin layers of dredge sediment function to support improved platform elevations. As balance in relative marsh elevation is restored to the system, we begin to see the role of marsh vegetation functioning to maintain enhanced marsh platform elevations. Therefore, it’s important to understand how marsh vegetation and other biological processes respond to thin layer sediment application.

4.3 Biological Considerations: Thin Layer Sediment Application

In tidal marsh systems, the hydrologic regime controls the physical and biological processes and therefore directly influences surface elevations which in turn effects vegetation productivity (USGS, 1997). Cahoon and Cowan (1988) report that layer thickness is a driving factor influencing how marsh vegetation will respond to thin layer applications. Successful enhancement of marsh habitat depends on how vegetation responds and adapts to sediment slurry additions via high-pressure spray disposal. It is recognized that tidal marshes are naturally adapted for responding to extremes in storm surges which can deposit excess sediments on to the marsh surface (Ray, 2007). Under a balanced hydrologic regime, biological process and elevation gradients function in unison as vegetation plays a critical role in trapping sediments and providing organic matter inputs above and below ground (Stralberg et al. 2011).. Marsh vegetation response to thin layer placement of dredge sediment both immediately following spray disposal and over the long term will attest the potential for enhancing marsh resiliency through maintaining improved elevation. As such, understanding appropriate disposal depths that maximize vegetation productivity with little overall impact on biological function is vital for thin layer spray disposal to be effective at long term marsh resiliency.

Vegetation Response to Thin Layer Placement via High-Pressure Spray Disposal

Vegetation productivity plays a governing role in regulating marsh platform elevation changes relative to sea level through above and below ground biological interactions. With respect to effects on marsh vegetation from thin layer sediment application, several studies have been conducted to identify how marsh vegetation will respond to a range of sediment layer thickness. The most observable impact on marsh vegetation from thin layer spray disposal is the smothering and even slaying of above ground plant canopy (Cahoon and Cowan, 1988). While this immediate response might be thought to have irreversible effects moving forward, Wilber (1993), generally found that recovery of vegetation from this initial post-placement impact requires successive growing seasons to reach expected vegetation densities for a healthy functioning marsh habitat. Correlating this finding with applied layer thickness, Reimold et al. (1978) found that plant shoots of cordgrass species are able to endure disposal depths of up to 23 cm for which successful recovery was observed following two consecutive growing seasons. Reimold et al (1978) also noted disposal depths greater than 60 cm permanently restricted cordgrass productivity. The evidence further suggests that shoots were better able to emerge from sandy and silty-sand material compared to the silty material but conversely, plant shoot biomass was greater in the silty material (Reimold et al. 1978). The observed enhanced shoot biomass within the silty material as suggested by the authors may be a result of increased nutrient content or less competition for nutrients from reduced shoot abundance. Based on this evidence, thin layer placement of dredge sediment can enhance both above and below ground plant productivity at appropriate disposal depths not exceeding 23 cm for tidal marsh habitat with cordgrass dominate species.

Cahoon and Cowan (1988) examined thin layer placement of silty clay dredge material at layer depths ranging from 10 to 38 cm up to 80 meters away on two brackish marshes in Louisiana. Most of the above ground vegetation was smothered by dredge material after initial placement. They found that limited recolonization of both cordgrass and pickleweed species after one year and saltgrass species were apparent. Midway through the second growing season, vegetation cover increased but remained less than pre-placement conditions. It was noted that some marsh area receiving thin layer depths towards the upper range (i.e. 18 – 38 cm) had converted to upland habitat. Six years later upon returning to each marsh site, healthy stands of vegetation including both cordgrass and pickleweed species were observed (LaSalle, 1992). Species distributions and abundances were similar to nearby reference sites at one site but conversely, the other site was predominately comprised of cordgrass and pickleweed marsh vegetation compared to its reference site dominated by saltgrass, needlerush and cordgrass (Wilber, 1993). This example provide evidence that several marsh vegetation species are capable of successful recovery in response to thin layer placement of dredge sediment at layer depths around 10 – 20 cm. Although vegetation recovery differed to a nearby reference site, marsh habitat was improved and benefited from thin layer placement sediment application.

Looking at the long term response of a thin layer placement to cordgrass marsh habitat, Tong et al. (2013) report that above and below ground vegetation productivity do not follow similar recovery rates. After seven years following thin layer sediment application of layer depths ranging from 8 – 15 cm, above ground plant biomass was comparable to reference sites whereas subsurface vegetation biomass was still significantly lower (Tong et al. 2013 and La Peyre et al. 2008). However, even though below ground plant biomass was not comparable to the reference site, Tong et al. (2013) report that below ground plant biomass had increased over time as bulk density of dredge sediment layer (i.e. top 10 cm) gradually decreased over the seven years. Slocum et al. (2005) investigated thin layer placement effects after seven years and similarly reported that layer depths of 5 – 15 cm were able to maintain greater vegetation function compared to those sites that received more than 20 cm of dredge sediment. As suggested by Tong et al. (2013), moderate placement depths appear to provide the most benefit to cordgrass dominate marsh habitat. Based on this evidence, there is potential to enhance tidal marsh elevation over the long term using thin layer sediment application with layer depths around 15 cm.

4.4 Modeling Marsh Elevation Loss Under Century SLR Projections

The 2015 Baylands Ecosystem Habitat Goals investigated the priority sites that need to be addressed in the near future (i.e. the next 30 years or mid-century when SLR is expected to accelerate significantly). In the North Bay this includes inter-tidal habitat between Point San Pablo and the Carquinez Bridge (i.e. Contra Costa West). All other North Bay sub-regions including the Napa River Area, north shore San Pablo Bay, Petaluma Marsh area and North Marin are expected to have sufficient habitat elevations and adequate sediment supply through the mid-century, however these areas will require habitat maintenance over the latter half of this century in order to maintain balance from the effects of increased rates in SLR.

Projections of century SLR for the latter half of this century have been reported as high as 180 cm and 200 cm (Schile et al. 2014 and Stralberg et al. 2011). In 2013, the USGS modeled century SLR response for 124 cm and found that 95.8 percent of existing marshes in the Bay would lose marsh plant communities and transition to mudflat habitat by 2100. The following marsh equilibrium modeling analysis uses century SLR rates of 100 cm and 180 cm. The model was calibrated for China Camp Marsh NERR obtained from Schile et al. (2014) and Swanson et al. (2013) and presented in Table 2. The model output will be representative of existing marshes within the North Bay study area. In 2013, the USGS investigated SLR effects on existing marsh habitat around the Bay and showed similarly, that existing marsh habitat will be resilient during the mid-century mark however, and by the end of this century marshes will become fully submerged transitioning to mudflat. For this analysis, I will assume that existing marshes around San Pablo Bay will respond similarly to projected century rates of SLR.

Table 2: Marsh Equilibrium Model Calibration Inputs

Table 2
Marsh Equilibrium Model Inputs: Calibration
MEM 3.4 (Morris, 2010)

Physical Inputs	Existing Marsh Habitat [1]	Units
Mean High Water	177	cm
Mean Sea Level	106	cm
Lunar Nodal Amplitude [2]	3.1	cm
Initial Rate SLR	0.24	cm/yr
SSC [3]	50	mg/liter
Marsh Elevation [4]	170	cm
Biological Inputs		
Maximum Vegetation Elevation	195	cm
Minimum Vegetation Elevation	70	cm
Maximum Peak Biomass	1200	g/m^2
OM Decay Rate	-0.3	l/time
Root & Rhizome:Shoot Ratio	2.5	g/g
BG Turnover	1	$year^{-1}$
Refractory Fraction (kr) [5]	0.1	g/g
Maximum (95%) Root Depth	20	cm

Notes:

cm	centimeter
cm/yr	centimeter per year
g/m^2	gram per square meter
g/g	gram per gram
mg/liter	miligram per liter
OM	organic matter
SLR	Sea Level Rise
SSC	Suspended Sediment Concentration
$year^{-1}$	per year
1	MEM calibrated to China Camp Marsh NERR obtained from Schile et al. (2014). Mean High Water obtained from Swanson et al. 2013.
2	Lunar Nodal Amplitude simulates the osscilation of tidal flux.
3	Suspended sediment concentration represent moderate levels of current sediment supply into the next century.
4	Marsh elevation based on peak biomass elevation or mid marsh platform
5	(kr) The fraction of the belowground production that is eventually incorporated into stable soil carbon.
MEM 3.4	availabile at http://jellyfish.geol.sc.edu/model/marsh/mem.asp

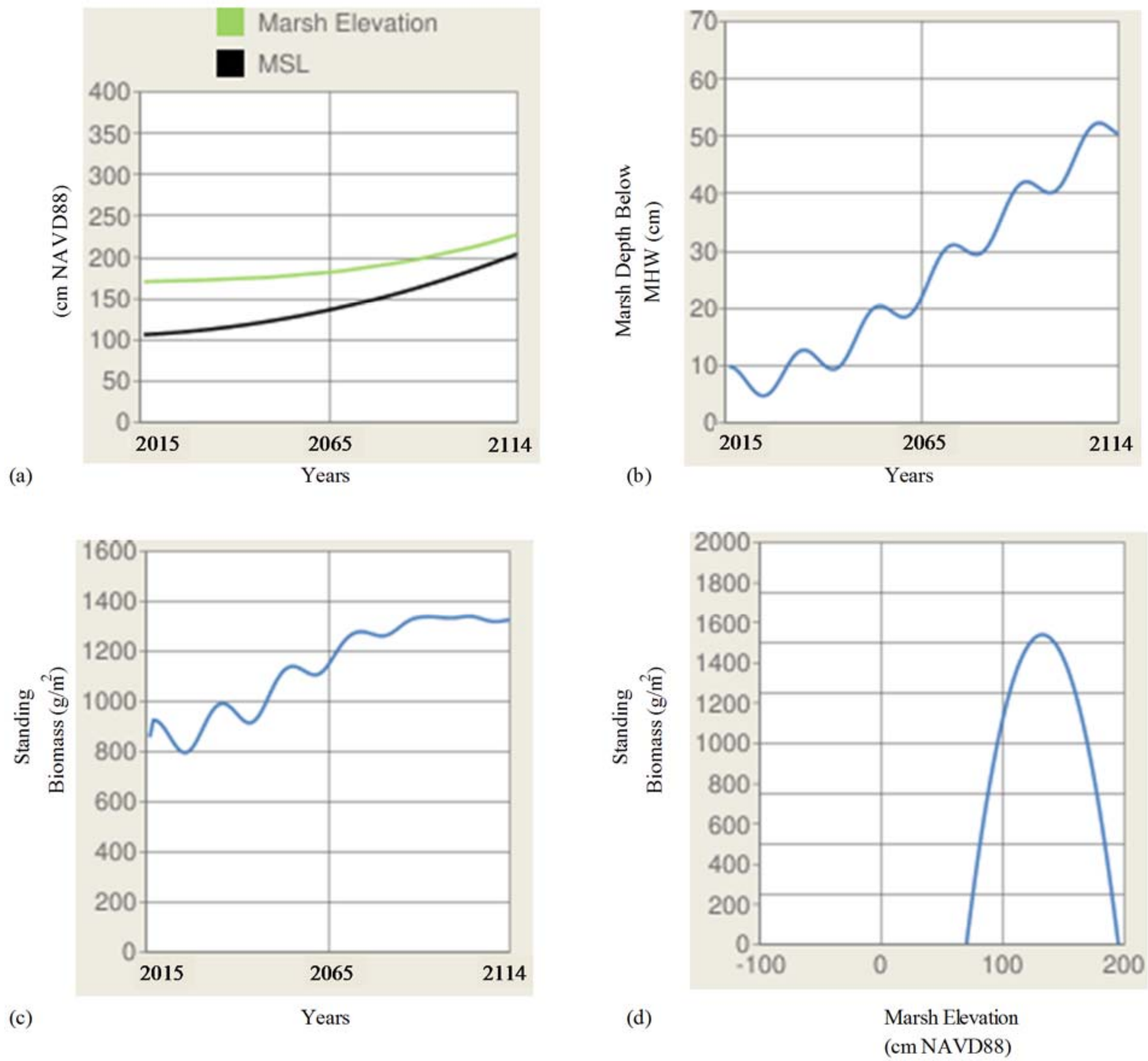
MEM Analysis and Marsh Elevation Deficit: Thin Layer Sediment Application Evaluation

100 cm/century SLR Scenario

The model outputs under 100 cm/century SLR representing existing marshes in San Pablo Bay are shown in Figure 2 below. Table 3 below presents the data results of marsh elevation change over the century and required thin layer depths to achieve healthy vegetated marsh target elevations. The model output shows marsh elevations will remain above MSL through this century. Under this scenario, the model indicates that the marsh platform is losing elevation to relative to MSL over the century but remains above MSL. However, over time the standing vegetation biomass starts to flatten out around the year 2075 nearing its peak threshold as the marsh continues to experience elevation loss to MSL.

Evidence for thin layer sediment application working to enhance marsh elevation indicates that upper limits for successful elevation enhancement is around 15 cm (post-consolidation depth). Peak vegetation biomass on the marsh platform is typically positioned around MHW (Schile et al. 2014) and can be considered target elevations for enhancing marsh habitat. Existing marsh elevation in the North Bay are around 170 cm NAVD88 and roughly average about 64 cm above MSL. Tidal marshes are currently maintaining elevation similarly to the annual rate of SLR (2.1 mm/year) (Swanson et al. 2013). Using this balanced steady state, marsh elevation deficit can be projected using modeled marsh elevations along with the elevation difference between marsh surface and MSL derived from the model. Marsh target elevations can then be estimated according to this elevation loss. It should be noted when planning projects designed for thin layer sediment application, such variables will need to consider site specific conditions to evaluate target elevations for a particular marsh area rather than interpolating based on averages or generalizations.

Understanding the limits of layer depth and knowing target elevations is critical in successful marsh elevation enhancement. We can then calculate the required thin layer depth to achieve target elevations and project the year when thin layer sediment additions will be needed to sustain long term. Under the 100 cm/century SLR scenario, thin layer sediment application will be needed around the year 2060 in order to preserve marsh habitat into the next century. At this time, tidal marsh habitat around the North Bay will require 16 cm thin layer sediment application across the marsh platform to reach target elevations. Looking ahead in the year 2075, tidal marsh elevations would be close to 30 cm below MHW requiring around 23 cm of dredge sediment across the marsh to get back to healthy platform elevations. Using the model to predict marsh resiliency over time, maintaining North Bay marsh habitat between the years 2060 and 2075 would reduce future SLR threats and enable marsh habitat function to persist into the next century before having to reapply another thin layer of sediment. If we do not maintain marsh elevation until 2100, the necessary applied layer depths would be upwards of 35 cm to reach target elevations. As such, multiple disposal episodes would have to account for this elevation deficit, likely spanning several years from one to the next in order for sufficient vegetation growth to stabilize the new sediment surface. Having to go through multiple episodes of thin layer disposal to reach desired elevations reduces project efficiency. Logistically, this delay would inherently incur additional costs to the project having to re-plan years after and repeat disposal episodes. Based on the practical and logistical considerations for planning marsh enhancement projects in the North Bay, maintaining marsh habitat against future SLR under this scenario should occur around the year 2060 to ensure successful elevation enhancement for improved resiliency into the next century.



MEM output for 100 cm/century SLR scenario projected on existing tidal marsh habitat of San Pablo Bay.

(a) shows marsh elevation relative to mean sea level over the century, (b) shows the relative distance between marsh surface and MHW, indicating marsh elevation deficit to SLR, (c) shows vegetation productivity over the century and (d) shows how vegetation productivity influences marsh elevation change.

Figure 2: 100 cm/century SLR Scenario Model Output

Table 3: 100 cm/century SLR Scenario: Prescribed Thin Layer Placement Criteria

Year	MSL (cm NAVD88)	Sea-Level Rise (cm)	Marsh Elevation (cm NAVD88)	Elevation Deficit (cm) [1]	Marsh Surface Depth below MHW (cm)	Target Elevation Marsh Platform (cm NAVD88) [2]	Prescribed Thin Layer Placement Depth (cm) [3]
2015	106	--	170	--	7	--	--
2030	111	5	172	3	10	175	3
2060	132	26	180	16	23	196	16
2075	148	36	189	23	30	212	23
2100	181	75	210	35	42	245	35

Notes:

cm	centimeter
MSL	Mean Seal Level
MHW	Mean High Water
NAVD88	North American Vertical Datum of 1988
--	Not relevant

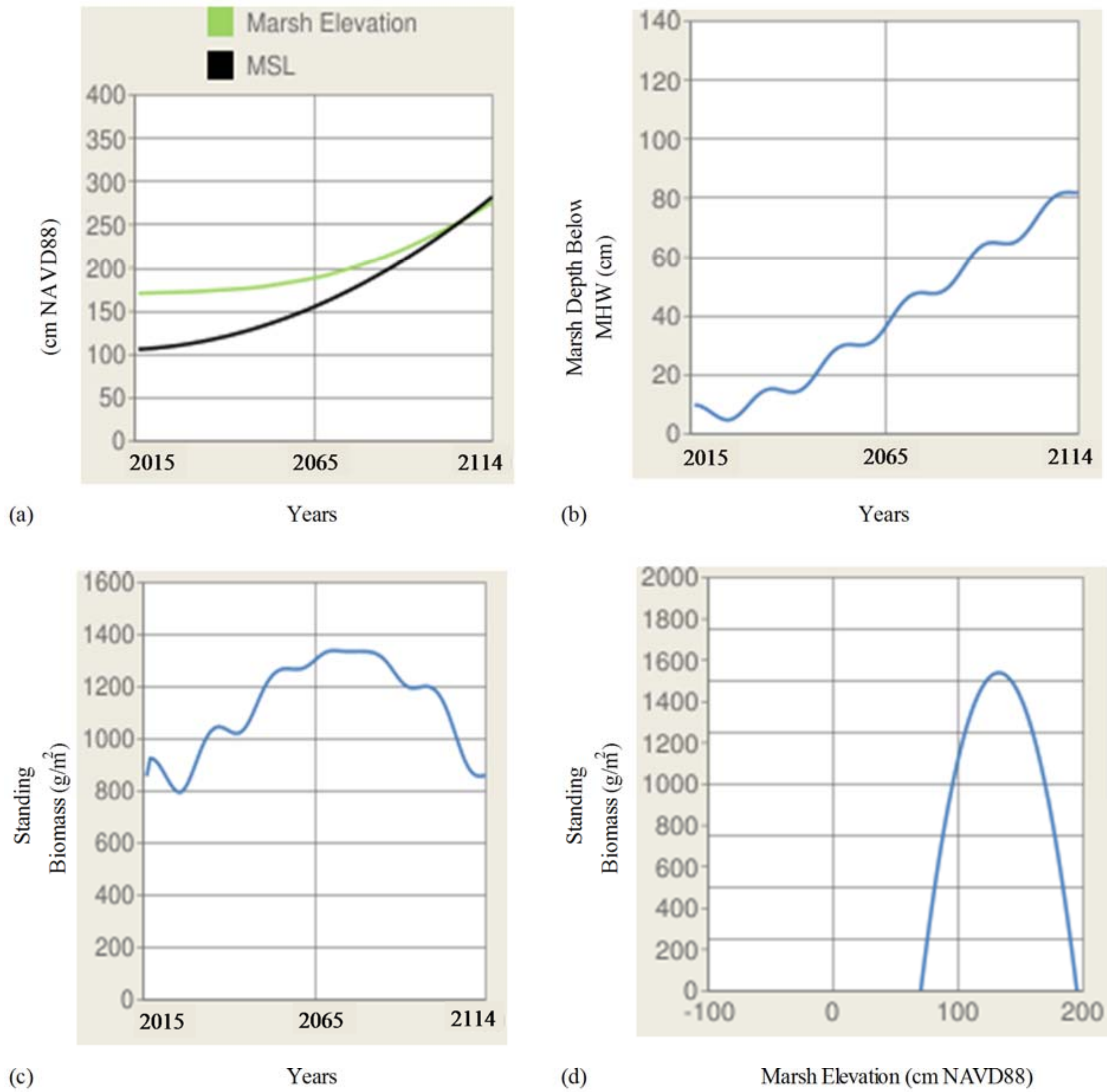
1 Elevation deficit is the difference between marsh elevation relative to MSL compared to the starting year (2015) relative marsh elevation of 64 cm NAVD88.

2 Marsh elevation plus the elevation loss to reach healthy platform elevation relative to MSL.

3 Post-consolidation depth to reach target marsh elevation.

180 cm/century SLR Scenario

Figure 3 below presents the model output under 180 cm/century SLR scenario projected on existing marsh habitat around San Pablo Bay. The four pictorial graphs illustrate the relationship between marsh platform elevations and increasing SLR over this century. Table 4 below shows the projected criteria in thin layer sediment depths over this century based on the model output. The model run under 180 cm/century SLR scenario indicates that around the year 2080, marsh platform will no longer be able to support vegetation due to excessive inundation leading to marsh habitat transitioning into mudflat. Under this high SLR scenario, the model indicates at the end of this century marsh elevations will be near equal to MSL if no action is taken to enhance platform elevations. Based on the model outputs, maintaining marsh elevations would be critical before the year 2060 at which point the elevation deficit prescribes a thin layer placement depth of. 27 cm. This layer depth is beyond the proven limits for successful marsh enhancement for a single disposal episode. If this high projection is proven accurate, thin layer sediment application for maintaining marsh elevations through this century would need to occur around the year 2045. At this time, the prescribed thin layer depth about 15 cm within optimal range for successful habitat enhancement.



MEM output for 180 cm/century SLR scenario approximated to existing tidal marsh of San Pablo Bay

(a) shows marsh elevation relative to mean sea level over the century, (b) shows the relative distance between marsh surface and MHW, indicating marsh elevation deficit to SLR, (c) shows vegetation productivity over the century and (d) shows how vegetation productivity influences marsh elevation change.

Figure 3: 180 cm/century SLR Scenario Model Output

Table 4: 180 cm/century SLR Scenario: Prescribed Thin Layer Placement Criteria

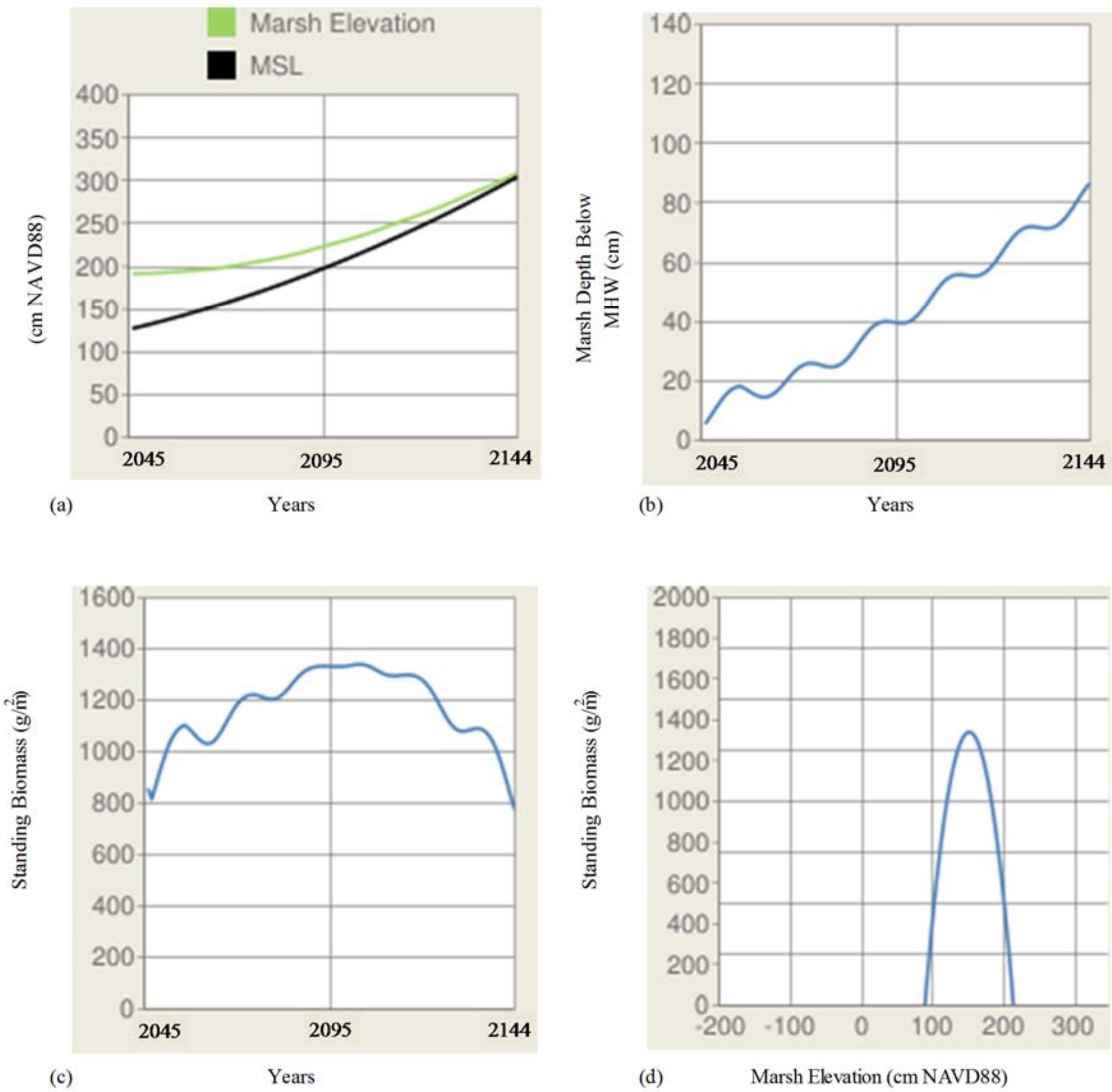
Year	MSL (cm NAVD88)	Sea-Level Rise (cm)	Marsh Elevation (cm NAVD88)	Elevation Deficit (cm) [1]	Marsh Surface Depth below MHW (cm)	Target Elevation Marsh Platform (cm NAVD88) [2]	Prescribed Thin Layer Placement Depth (cm) [3]
2015	106	--	170	--	7	--	--
2030	113	7	172	5	12	177	5
2045	127	21	176	15	22	191	15
2055	140	34	182	22	29	204	22
2060	148	42	185	27	34	212	27
2075	176	70	201	40	47	240	40
2100	239	133	243	60	67	303	60

Notes:

cm	centimeter
MSL	Mean Seal Level
MHW	Mean High Water
NAVD88	North American Vertical Datum of 1988
--	Not relevant
1	Elevation deficit is the difference between marsh elevation relative to MSL compared to the starting year (2045) relative marsh elevation of 64 cm NAVD88.
2	Marsh elevation plus the elevation loss to reach healthy platform elevation relative to MSL.
3	Post-consolidation depth to reach target marsh elevation.

Thin Layer Sediment Application and Enhanced Marsh Resiliency

Using the model we can further project how resilient the marsh will be following thin layer sediment application over the century. Under the 100 cm/century SLR scenario, the model indicates that improving marsh elevations will enhance tidal marsh resiliency for at least 40 years and lasting through this century before a second 16 cm thin layer application is necessary. Here, I have chosen to describe tidal marsh resiliency under the high 180 cm/century SLR scenario as the example. As illustrated below in Figure 4, the model indicates after supplying tidal marsh habitat with a 16 cm layer of dredge sediment in the year 2045, resiliency is improved for 15 - 25 years before having to maintain elevations again between the years 2060 and 2070 (Table 5). The annual rate of SLR increase during this time in nearly 10 times that of marsh accretion rates and reason why multiple thin layer applications over the course of this century will be necessary to maintain resiliency under this high SLR scenario.



MEM output for 180 cm/century SLR scenario following 15 cm thin layer sediment application in the year 2045.
(a) shows marsh elevation relative to mean sea level over the century, (b) shows the relative distance between marsh surface and MHW, indicating marsh elevation deficit to SLR, (c) shows vegetation productivity over the century and (d) shows how vegetation productivity influences elevation change.

Figure 4: 180 cm/century SLR Scenario Following Marsh Elevation Enhancement

Table 5: Thin Layer Placement Criteria Following Marsh Elevation Enhancement

Year	MSL (cm NAVD88)	Sea-Level Rise (cm)	Marsh Elevation (cm NAVD88)	Elevation Deficit (cm) [1]	Marsh Surface Depth below MHW (cm)	Target Elevation Marsh Platform (cm NAVD88) [2]	Prescribed Thin Layer Placement Depth (cm) [3]
2045	127	--	192	--	7	--	--
2060	145	18	195	15	22	210	15
2070	159	32	200	23	30	223	23
2075	166	39	204	27	34	231	27
2100	209	82	231	42	49	273	42

Notes:

cm centimeter
MSL Mean Seal Level
MHW Mean High Water
NAVD88 North American Vertical Datum of 1988
-- Not relevant

1 Elevation deficit is the difference between marsh elevation relative to MSL compared to the starting year (2045) relative marsh elevation of 64 cm NAVD88
2 Marsh elevation plus the elevation loss to reach healthy platform elevation relative to MSL.
3 Post-consolidation depth to reach target marsh elevation

This finding demonstrates that thin layer sediment application under future high SLR projections can enhance tidal marsh resiliency through this century. However, multiple episode of thin layer sediment application is needed about every 15 years in order to maintain resiliency through the latter half of this century as a result of accelerated SLR rates dominating marsh accretion rates.

4.5 Practical and Logistical Perspective

While the concept of thin layer spray disposal was initially developed and implemented as a dredge disposal management alternative to common conventional dredge disposal methods, this concept equally may be suited to enhance marsh resiliency against impacts from SLR over the next century. Based on the observed benefits to deteriorating marsh habitat, seen through improved marsh elevations supported by successful response in vegetation productivity, the concept of thin layer sediment application can be viewed as an adaptation strategy to counter effects from SLR and maintain existing marsh habitat in the Bay through this century.

The response of marsh habitat to thin layer placement with respect to layer depth has been demonstrated on Louisiana's coast marsh zone as well in North Carolina on salt and brackish tidal marsh habitat. In the Bay, both cordgrass and pickleweed species are the dominant salt marsh vegetation within their respective intertidal zone, but pickleweed in the mid to high marsh covers a much greater extent compared to the cordgrass species (Josselyn, 1983). Cordgrass covers the narrow fringing low marsh area or stands lining edges of channels. Each function similarly as main drivers for below ground vegetation productivity in their roots and rhizomes supporting vertical marsh accretion although cordgrass is more productive than pickleweed (Woolfolk and Labadie, 2012 and Swanson et al. 2013). Based on these characteristics, similar responses to thin layer sediment application among pickleweed and cordgrass can be inferred due to the inherent nature for each to promote and stabilize marsh platform via root zone vigor (Woolfolk and Labadie, 2012). Additionally, the limited available evidence indicates pickleweed species are able to recover from layer depths of 10 – 20 cm with improved marsh elevation maintained six years following initial placement of dredge sediment. In the Bay, invasive species control is a major concern where in relation to thin layer placement, the response has yet to be investigated and warrants further research.

Tidal marsh habitat experiencing initial subsidence, to the extent where the vegetated marsh platform begins to deteriorate, may consider thin layer sediment application to improve platform elevation. In the face of future SLR, marsh accretion rate modeling indicates existing marsh habitat will begin to experience initial subsidence effects in the latter half of this century. Based on the previous studies investigating marsh response to high-pressure spray disposal, opportunities and constraints for adapting to future threats of century SLR can be assessed for the Bay.

While it can be recognized that thin layer disposal can work to enhance marsh resiliency, the area to which it's applied is relatively small. High-pressure spray disposal is limited to depositing sediments to an area less than 100 meters away from the spray equipment but is able to uniformly distribute an even mixed slurry across the marsh area. The spray distance becomes reduced when thicker disposal depths is required for the area (i.e. disposal depths of 10 – 15 cm thick is achieved up to 70 meters away). For a marsh site receiving thin layer sediment application, the marsh platform needs sufficient slope to assure water flows off the marsh and doesn't get trapped. While there is considerable control in targeting specific disposal areas with high-pressure spray techniques, water quality impacts area a concern to local aquatic habitat supporting longfin delta smelt, eelgrass meadows or oyster beds. When assessing the potential for thin layer disposal onto a marsh and considering surrounding sensitive areas, control measures need to be implemented such as a silt curtain containment to minimize turbidity and sedimentation effects to outside habitat. The tidal marshes of San Francisco Bay support numerous threatened and endangered species that need to be worked around which ultimately threatens the potential for considering high-pressure spray disposal on to marsh habitat. More pilot project studies similar to what's happening at the Seal Beach National Wildlife Refuge are needed to investigate and monitor how sensitive species residing in marsh habitat respond to high-pressure spray disposal.

In Orange Country the U.S. Fish and Wildlife Service have designed a thin-layer salt marsh sediment augmentation pilot project on the Seal Beach National Wildlife Refuge. The project purpose is to improve habitat quality for the endangered lightfooted Ridgway's rail (formerly known as the light-footed Clapper rail). The project will be evaluated as a sea-level rise adaptation strategy for preserving tidal marsh habitat along the shorelines. This is the first pilot project for thin layer placement of dredge sediment on to degraded marsh habitat in California. The dredge volume will be upwards of 13,500 cubic yards of clean dredged sediment to be placed over ten acres of degraded cordgrass habitat. This will result in a 20 to 25 cm layer depth settling across the marsh platform. Natural revegetation of the site is expected to occur over a two-year period. The dredged sediment will be transported to the receiving site by a containment barge or slurry pipeline; sediment will be applied across the receiver site using a rainbow sprayer or pipeline. Pre- and post-sediment application monitoring of physical and biological responses to the project will occur over a five year period, in order to evaluate the effectiveness of sediment augmentation to enhance salt marsh habitat. The project also includes mitigation measures that require restoration of salt marsh habitat to pre-project conditions should natural reestablishment of cordgrass fail to occur after sediment augmentation. In this example, we begin to see the level of effort currently required for thin layer sediment applications on to marsh habitat.

5. Dredge Material Management in the Bay

One of the drivers in determining the potential for marsh habitat enhancement via thin layer sediment application is the volume of dredge material required and how this will impact dredge disposal management in the Bay. This section examines dredge disposal management strategy in the Bay to understand how thin layer sediment application can be implemented as a future SLR adaptation strategy for maintaining existing marsh habitat. Contextual background, policy implications and economic aspects related to thin layer sediment application are reviewed. As well, the annual maintenance dredging program is discussed in terms of current federal placement sites including beneficial reuse and the relationship to thin layer placement for marsh habitat enhancement. The objective here is to assess the potential for such future projects to be integrated within the LTMS based on practical and logistical aspects within the confines of maintenance dredging projects around San Pablo Bay.

5.1 Background and Regulatory Setting

Historically, 80 percent of dredge material was disposed of in the Bay (primarily at the Alcatraz site) and 20 percent went to the ocean or upland reuse. As a result, there was immense public concern over what the future might hold for San Francisco Bay if such activities continued. Stemming from this concern in 1965, the McAteer-Petris Act came into law and created the Bay Conservation and Development Commission (BCDC). The BCDC was tasked to organize a comprehensive and enforceable plan for conserving the Bay and associated development of its shoreline. In 1969, the San Francisco Bay Plan (Bay Plan) was completed, reviewed and approved by California Legislature. At this time, the McAteer-Petris Act was revised to include the findings and policies of the Bay Plan. From this point, the BCDC was designated as the agency responsible for governing the policies of the Bay Plan set forth to preserve and protect the Bay and its shoreline.

The Bay's Long Term Management Strategy plan (LTMS) was established in 1990 and set clearly defined goals to manage the disposal of dredge material which are: 1) to manage dredge operations in the most environmentally and economically feasible manor, 2) to maximize the beneficial reuse of dredge disposal through alternative placement sites and 3) to have a coordinated permit application review process for dredging and disposal projects. Soon after the initial LTMS plan was published in 1998, the Basin Plan (the San Francisco Bay Region Water Quality Control Plan) and the BCDC's Bay Plan were adopted in leading to the final LTMS document being published in July 2001. The primary objectives of this LTMS plan are to reduce in-Bay disposal and maximize beneficial reuse of dredge sediment. Over a 12-year transition period the LTMS was specifically designed to reduce in-Bay disposal volumes to not exceed

1.25 mcy per year by the end of 2012. The decided overall collective strategy was to limit in-Bay disposal to 20 percent, have 40 percent sent to deep ocean disposal and put 40 percent towards beneficial reuse, considered the *40-40-20* plan.

The Clean Water Act (CWA) under Section 404, disallows the discharge of materials into wetlands or open waters of coastal zones, a direct result of historical land alterations in filling and levee diking activities for urban development, which displaced more than 90 percent of former tidal marsh habitat in the Bay (Stralberg et al. 2011). Section 404 gives duel regulatory responsibility to both the USACE and USEPA for authorizing permits under Section 404 to allow discharge of soil or sand material (discharge material) into wetlands or open water. Section 404 has been an important regulatory tool guiding provisions in compensatory mitigation for any wetland impacts on coastal restoration projects. A distinguishing note however, is that Section 404 regulation was not specifically intended to protect wetlands, rather as a way to manage the discharge of fill material into wetlands (Ravit and Weis, 2014). In the face of accelerated SLR over the next century, supplying sediment to marshes will be required to maintain existing habitat unless alternative elevation enhancement methods are brought forth, tested and proved more effective with less overall habitat impact. In order for thin layer sediment application to be permitted under Section 404 regulation, the rule defining “discharge of fill material” should be amended to consider wetland replenishment with appropriate fill material to enhance marsh resiliency against future threats of accelerated SLR as suggested by Ravit and Weis (2014). In the case of thin layer sediment applications on to deteriorating tidal wetland marshes, using dredge ‘fill’ material has shown to ultimately enhance habitat function marshes through improved marsh platform elevations.

As was described earlier, the USFWS thin-layer salt marsh sediment augmentation pilot project at Seal Beach examples the potential for such an adaptation strategy to be implemented for the purpose of maintaining tidal marsh habitat and shoreline integrity against future SLR impacts. The project will place clean dredged sediment to restore salt marsh habitat and will knowingly incur initial short term impacts in vegetation smothering at the project site. As governed, the project includes mitigation measures including to restore salt marsh habitat to pre-project conditions in the event cordgrass marsh vegetation fails to reestablish productivity over time. The project includes adaptive management and mitigation measures, construction best management practices, and an extensive monitoring program. The project will also fall under the allowable use, alternatives, mitigation, and other tests contained in the wetland fill policy of the California Coastal Management Program (CCMP; Coastal Act Section 30233(a) and (b)). We can take from this short project highlight the multifaceted layering of logistical planning and approval process required to implement this 10-acre pilot project for critical habitat enhancement. Additionally, associated costs are expected to be high and could affect the project coming through to fruition.

A recent approved in-Bay disposal project has been for the Middle Harbor Enhancement Area (MHEA) project of the formerly dredged Oakland Middle Harbor. In 2014, 180 acres of shallow water habitat was restored using 5.2 mcy of dredge sediment. As governed, the project includes monitoring requirements over time to determine whether success criteria is being met for the established project goals. The findings from this project will guide future unconfined aquatic disposal projects seeking to enhance habitat of natural resources in Bay waters such as thin layer sediment application for marsh enhancement against future increases in SLR.

In 2002 as part of the MHEA project, the Bay Plan amended its Policy No. 11 related to dredging, which outlines requirements for the approval of using dredge material to enhance natural resources of the Bay waters. In part, the policy states determination be based on whether 1) the project provides substantial net improvement of habitat for Bay species; 2) no feasible alternatives to the fill exist to achieve the project purpose; 3) the project would only use clean suitable material for unconfined aquatic disposal; 4) results will not exhibit a net loss of Bay surface area or volume; and 5) dredge material shall not be placed in areas of high value such as tidal marsh unless the material would be needed to protect or enhance the habitat. Based on the analysis of thin layer sediment application and associated effects exhibited on marsh habitat from improved elevations, these policy requirements would be met for consideration and approval by the BCDC. However, other stipulations with in these requirements calls for consultation with the CDFW, National Marine Fisheries Services (NMFS) and the USFWS in which at least one agency needs to support the project. Finally, monitoring requirements for the project must demonstrate habitat is not adversely impacted from disposal activities. Current policy stipulates that in-Bay disposal should not be authorized for habitat enhancement until full evaluation of disposal effects on Bay natural resources including final evaluation of the post monitoring for the MHEA project. The amendment to the Bay Plan shows good promise for thin layer sediment application to enhance tidal marsh habitat. Ultimately however, a more definitive understanding for potential effects to surrounding Bay habitat is needed to support future policy decisions regarding thin layer sediment application for marsh habitat enhancement.

5.1.1 Dredge Material Suitability Determinations for Reuse Alternatives

When considering thin layer sediment application to marsh habitat, the dredge material needs to undergo physical and biological quality testing for to determine whether the material is suitable for reuse at a particular site. The quality testing results are then reviewed by the DMMO to make a determination of suitability for disposal alternatives which are: 1) open-water disposal (unconfined in-Bay aquatic disposal), 2) confined disposal (upland disposal or diked areas near shore), or 3) beneficial reuse sites. In regards to thin layer placement alternatives, the potential to reuse dredge material at a marsh site for habitat enhancement presents a unique situation falling under two categories in unconfined aquatic disposal and as beneficial reuse in marsh habitat enhancement. Therefore, dredge material applied to existing marsh habitat for enhancement would require standards pertaining to the SUAD (suitable for unconfined aquatic disposal) testing requirements following the Inland Testing Manual guidelines and the suitability criteria developed by the SFBRWQCB following wetland surface and wetland foundation material guidelines (USACE et al. 2001).

As it stands, unconfined aquatic in-Bay disposal has no correlation to beneficial reuse. Beneficial reuse of dredge material focuses on reusing dredge material with a beneficial purpose, as described in the LTMS as habitat improvement (restoration projects), creating in-Bay habitat, to stabilize levees and for capping and liner material at landfills (USACE et al. 2001). The question then becomes whether the potential for thin layer disposal for maintaining marsh elevation platforms can be considered a beneficial reuse. Based on the current understanding of marsh response to thin layer placement, this applications does provide lasting benefits in terms of improved habitat and so the case can be made that thin layer sediment application to enhance marsh habitat against future increases in SLR is a type of beneficial reuse in unconfined aquatic placement sites.

5.1.2 Thin Layer Placement and Opportunities for Beneficial Reuse Alternatives

Three important aspects center on whether dredge sediment for reuse is deemed beneficial for a project site. First, identifying ‘a need’ for the certain reuse project must be exemplified, secondly, the proposed benefits clearly must outweigh any potential impacts to the environment and third, understanding that any impacts will be fully mitigated by the project (USACE et al. 2013). Any project satisfying these fundamental logistics is suitable for LTMS consideration. Beneficial reuse of dredge material is broadly defined by the USACE (2001) as being all productive and positive uses of dredge material, including for example developing habitat for fish and wildlife and supporting both human recreation and industrial practices. Within the definition of thin layer disposal as developed for the USACE (Wilber, 1992), thin layer disposal does not align with beneficial use of dredge material as thin layer placement does not associate with a particular environmental effect. This definition stems from thin layer disposal being characterized as a dredge disposal management technique with the only intent to reduce spoil piles along the canals edge impacting wetland function. In time, field investigations have shown supplying a relatively thin layer of dredge sediment to a subsided or deteriorating tidal marsh will increase vegetation productivity and sustain function long term.

In 2011 the Bay Plan was amended to update the old sea level rise findings and policies in the plan by adding a new section that more broadly characterizes climate change impacts to the Bay and adaptation to SLR threats. Projects will continue to be evaluated on a case by case basis, however, policy now encourages enhancing habitat in suitable low-lying areas. Even though project approval takes considerable time with many logistical layers to get through, the changes to the Bay Plan enhance opportunity for the future projects requiring thin layer sediment application for marsh habitat enhancement. The DMMO would need to evaluate the proposed deteriorating marsh habitat site to determine suitability criteria and guidelines for placing dredge material within existing marsh.

As part of a 12-year review (USACE et al. 2013), future changing conditions and adaptive management needs were evaluated. The agencies recognized that in addition to significant reduction in sediment inputs from the Sacramento-San Joaquin Rivers, low lying areas of the Bay are in jeopardy of being inundated from rising sea levels or extreme storm surges. These environmental changes threaten existing tidal marsh habitat which puts shoreline integrity at risk. The LTMS acknowledges the need to preserve existing marsh habitat as well as the need to potentially supply sediment to the inter-tidal zone in order to combat future threats of increasing SLR. The LTMS is willing to consider new measures for achieving increased beneficial reuse allocation from USACE maintenance dredging projects that meet the federal standard.

Recent agency investigations have been focused on whether unconfined in-Bay disposal can be managed effectively so to benefit shorelines, mudflats and tidal wetland habitat (USACE, 2013). The opportunity for thin layer sediment application for marsh habitat enhancement as an alternative reuse is apparent but meeting the federal standard remains to be a challenge. The issue of dredging site versus placement site location and the associate high costs related will hinder future maintenance of existing marsh habitat in the Bay. However funding constraints may be reduced if projects have support through non-federal sponsors using incentives such as carbon tax credits for maintaining tidal wetland habitat against impacts from future threats of accelerated SLR.

5.1.3 Environmental Work Windows and Dredging Projects

Threatened and endangered species occupying marsh habitat presents a major obstacle when considering the potential to artificially supply a thin layer of sediment to a marsh site in the Bay. Established under the Endangered Species Act (ESA), the CDFW, the National Marine Fisheries Service, and the USFWS set ‘environmental work windows’ specific to the dredging or disposal site with respect to sensitive species that are known to inhabit the area. Throughout the Bay, federally endangered California clapper rail and salt marsh harvest mouse depend on tidal marsh habitat. Clapper rail take to low marsh cordgrass where they establish nesting grounds, and the salt marsh harvest mouse relies on dense stands of pickleweed habitat for food supply, protection from predators and nesting as well (Swanson et al. 2013). In this regard, bay-wide areas in and around salt marsh habitat require consultation with wildlife agencies at any point during the year to thoroughly assess any potential negative impacts to these species associated with the dredging activity. Additionally, both the Napa and Petaluma Rivers dredging is limited to strict work windows from August through October 15 for steelhead trout and from August through January for the endangered delta smelt. Work conducted outside of the work windows would require written approval from the appropriate agencies. As a result, dredging projects associated with thin layer sediment application will likely incur delays and or increased project costs for implementing avoidance mitigation measures.

Threatened and endangered species occupying tidal marshes around the Bay present a major challenge facing thin layer sediment applications for marsh habitat enhancement. Although thin layer spray disposal has the potential to avoid sensitive habitat areas when being applied, it would be challenging to justify avoiding impacts to these endemic marsh wildlife species. We know that initial impacts from placing dredge material on to marsh platforms will burry marsh vegetation leading to temporary changes in marsh habitat characteristics. The response of sensitive species to such a change has yet to be investigated and warrants further research field studies. If no action is taken to enhance marsh resiliency in during the latter half of the century, these species would be equally susceptible to marsh habitat loss from accelerated rates in SLR during this century.

5.2 USACE Dredging Projects and Thin Layer Placement Alternatives

The USACE is responsible for maintaining the deep- and shallow-draft channels throughout the Bay, for which routine maintenance dredging is required to allow safe navigable transportation for the maritime industry. In the Bay there are 11 federal navigation channels under the USACE's maintenance dredging program, six of these channels are dredge annually (Richmond Inner and Outer Harbor, San Francisco Harbor – Main Shipping Channel, Pinole Shoal, Suisun Bay Channel, and Oakland Inner and Outer Harbor), and the other five (Napa River Channel, Petaluma River Channel, San Rafael Creek Channel, San Leandro Marina and Redwood City Harbor) cycle dredging episodes ranging every 4 – 10 year based on funding and priority. Table 6 below presents the breakdown of eight USACE maintenance dredging projects and associated maintenance dredge volumes (URS Group Inc. 2014) that could locally support maintaining marsh habitat around San Pablo Bay.

Table 6: USACE Federal Navigation Channels Maintenance Dredging Projects

USACE Federal Navigation Channel [1]	Dredge Frequency (years)	Dredge Volume Low Range (cy)	Dredge Volume High Range (cy)	Average Dredge Volume (cy) [2]	Federal Standard Placement Site [3]
Richmond Inner Harbor	1	11,000	631,000	390,000	SFDODS
Richmond Outer Harbor	1	78,000	318,000	190,000	SF-11 (alcatraz)
San Rafael Creek	4-7	87,000	150,000	83,000	SF-11 (alcatraz)
Pinole Shoal [4]	1	80,000	487,000	146,000	SF-10
Napa River Channel	6-10	140,000	140,000	140,000	Upland (Sponser provided)
Peteluma River Channel	4-7	150,000	150,000	150,000	Upland (Sponser provided)
Suisan Bay Channel	1	41,000	423,000	159,000	SF-16
Oakland Inner and Outer Harbor	1	122,000	1,055,000	330,000	SFDODS
Channel Volume Totals:		**709,000**	**3,354,000**	**1,588,000**	

Notes:

cy cubic yards

USACE U.S. Army Corps of Engineers

1 Maintenance dredging projects relatively local to San Pablo Bay.

2 Average dredge volume per year since 2000.

3 The federal standard is defined as the least-costly dredge material disposal or placement alternative consistent with sound

4 Channel also include Mare Island Strait but dredging data not presented as dredging is not planned in the foreseeable future.

Reference: URS Group, Inc. (on behalf of U.S. Army Corps of Engineers and Regional Water Quality Control Board) 2014. Draft Environmental Assessment/Environmental Impact Report. Maintenance Dredging of the Federal Navigation Channels in San Francisco Bay, Fiscal Years 2015-2024. December 2014.

On average, maintenance dredging projects produce 1.6 mcy of dredge material from in and around San Pablo Bay with designated placement sites based on the federal standard. Through the establishment of alternative disposal sites, including San Francisco Deep Ocean Disposal Site (SF-DODS) and beneficial reuse alternatives (i.e. habitat improvement via restoration and levee rehabilitation projects), more than 10 million cubic yards (mcy) of dredge material was diverted from in-Bay disposal from 2001 to 2013 (USACE et al, 2013). The interagency Dredge Material Management Office (DMMO) has been successful in streamlining the permit application process to expedite the implementation of dredging and disposal projects (USACE et al., 2001). Unfortunately, since the 2008 recession, dredging and disposal projects in the Bay have been dramatically impacted, seen through higher project costs and reduced available funding (USACE et al, 2013). The USACE has been challenged to fund maintenance dredging projects as their annual budgets have failed to increase appreciably over the past 12 years which poses a major constraint managing dredging in the Bay while meeting the long term goals of the LTMS (USACE et al. 2013). This challenge will be ongoing until budgets and funding are realigned. Currently, maintenance dredging projects are relying more on deep ocean disposal (SF-DODS) rather than beneficial reuse alternatives due to lower costs. This is a concern for projects seeking to reuse available dredge sediment and impedes the LTMS from maximizing beneficial reuse of dredge material. Similar cost relationship dynamics would be expected to impact thin layer sediment application alternatives. However, as the need arises, the choice will either be to fund such beneficial reuse projects or risk losing invaluable tidal marsh habitat before the end of this century.

Over the past four years (2011 – 2014), annual dredge volume for the Bay range from 2.1 to 3.3 mcy, having differences of a million cubic yards between years (Table 7). Most recently in 2014, the DMMO (2015) reported 57 percent (1.21 mcy) was placed at designated in-Bay sites, roughly 6 percent (130,000 cy) was transported to SFDODS and about 36 percent (777,618 cy) went to beneficial reuse or upland disposal projects (Table 7).

Table 7: Recent Dredging Volumes in San Francisco Bay

Year	Total Dgredge Volume (mcy) [1]	Disposal Alternative	Placement Volume (percent)
2011	3.3	in-Bay	1.66 mcy (51)
		SFDODS	641,821 cy (19)
		Reuse	971,368 (30)
2012	2.6	in-Bay	808,953 cy (31)
		SFDODS	630,486 cy (24)
		Reuse	1.17 mcy (45)
2013	3.2	in-Bay	987,268 cy (31)
		SFDODS	1.63 mcy (52)
		Reuse	544,000 (17)
2014	2.1	in-Bay	1.21 mcy (57)
		SFDODS	130,000 cy (6)
		Reuse	777,618 (36)

Notes:

cy cubic yards

mcy million cubic yards

1 Main Ship Channel (MSC) dredge volume not included; outside limits of LTMS program area. DMMO (2011, 2012, 2013, 2014).

Due to the inter-annual variability of total dredge material volume, suitable material for reuse will similarly vary year-to-year and so projecting future availability of dredge material specific for enhancing marsh habitat against SLR is uncertain. As well, approved beneficial reuse alternative placement sites are available and currently waiting to accept clean dredge material. Accordingly, the future potential for thin layer sediment application alternatives will require assigning prioritization under the LTMS. Although suitability determinations ultimately determine where dredge material can be appropriately placed, the total volume of clean dredge material required to maintain marsh habitat can be projected through this century under each SLR scenario. Based on the findings presented Section 4, we can calculate high level volume estimates using the applied thin layer depth and presumed acreage of existing marsh habitat around North San Pablo Bay. The volume analysis is presented in the following section comparing the sediment demand for maintaining existing marsh habitat to the average annual dredge volumes in and around the North Bay to understand the potential volume budget for reusing dredge material to enhance marsh habitat resiliency against future threats from accelerated SLR.

Century Sea-Level Rise Scenarios and Volume Demands for Marsh Habitat Enhancement

Future SLR Scenarios and Projected Volume Requirements

Table 8 below shows the required volume of dredge sediment to maintain marsh platform elevations around San Pablo Bay against the projected century SLR scenarios. The required volume is based on the calculated thin layer depth to reach target marsh platform elevation for the given year and does not account for dredge material consolidation.

Table 8: Required Sediment Volumes Projected Against Century SLR Scenarios

(a)

Thin Layer Placement Marsh Area (acres)	100 cm/century SLR Scenario		
	Placement Depth of 16 cm (2060) Volume (cy)	Placement Depth of 23 cm (2075) Volume (cy)	Placement Depth of 35 cm (2100) Volume (cy)
West Shore China Camp to Petaluma Marsh Area (1,300)	1,102,727	1,585,169	2,412,214
Petaluma Marsh Area (4,100)	3,477,830	4,999,381	7,607,753
North Shore San Pablo Bay Marsh (3,800)	3,223,355	4,633,572	7,051,088
Napa River Marsh Area (2,800)	2,375,103	3,414,211	5,195,539
Contra Costa County Point Pinole to Carquinez Strait Marsh Area (390)	330,818	475,551	723,664
Reuse Volume Totals:	10,509,832	15,107,884	22,990,258

(b)

Thin Layer Placement Marsh Area (acres)	180 cm/century SLR Scenario			
	Placement Depth of 15 cm (2045) Volume (cy)	Placement Depth of 27 cm (2060) Volume (cy)	Placement Depth of 39 cm (2075) Volume (cy)	Placement Depth of 60 cm (2100) Volume (cy)
West Shore China Camp to Petaluma Marsh Area (1,300)	1,033,806	1,860,851	2,687,896	4,135,225
Petaluma Marsh Area (4,100)	3,260,466	5,868,838	8,477,210	13,041,862
North Shore San Pablo Bay Marsh (3,800)	3,021,895	5,439,411	7,856,927	12,087,580
Napa River Marsh Area (2,800)	2,226,659	4,007,987	5,789,314	8,906,638
Contra Costa County Point Pinole to Carquinez Strait Marsh Area (390)	310,142	558,255	806,369	1,240,567
Reuse Volume Totals:	9,852,968	17,735,342	25,617,716	39,411,871

Notes:

SLR Sea Level Rise
cm centimeters
cy cubic yards

These requirements are relatively high compared to average annual dredge volume in the Bay and taking into consideration the 'unknown' percentage of suitable dredge material for marsh placement. The required volumes area likely greater than what will be available for reuse during the implementation time period. In the North Bay, average annual maintenance dredging volumes around San Pablo Bay have potential to yield about 1.5 mcy of dredge material which may potentially be diverted to marsh enhancement projects if deemed suitable. Assuming one million cubic yards are suitable for reuse each year starting around 2060 under 100 cm/century SLR, it would take over a decade of annual marsh habitat maintenance to reduce impacts from increasing rates of SLR. Under the high end projection of 180 cm/century SLR, we can see that the high volume demand to maintain marsh habitat occurs 15 years earlier around the year 2045. Thin layer sediment application for the purpose of enhancing tidal marsh habitat would benefit the LTMS goals in both reducing in-Bay disposal and maximizing beneficial reuse of dredge sediments. However, to the benefits would not be realized until the latter half of this century when the need arises for maintaining tidal marsh habitat. As well, future dredging projects in the Bay are not exactly certain due to budget constraints as current project cuts have previously been observed.

Under these two century rates of SLR, the required volumes to maintain existing marsh habitat is large, but this is in part due to the vast area of core marsh habitat likely to experience impacts in marsh elevation loss to SLR. Granted, while some tidal marshes around San Pablo Bay are projected to be more resilient to increases in SLR, marsh accretion rate modeling indicates that even the more resilient marshes will not be able to keep pace if accelerated rates of century SLR become real. Although we can estimate required volumes needed for maintaining marsh platform elevations, understanding what is potentially suitable for reuse is moot until criteria are established for placing dredge material on to existing marsh habitat. If there is not enough suitable dredge material available to enhance marsh elevations, alternative approaches need to be sought for preserving such critical habitat through the century. Therefore, further research is needed to investigate the suitability of dredge material for reuse marsh elevation enhancement in the Bay.

5.3 Economic Considerations: Maintaining Existing Marsh

Economic considerations for maintaining marsh habitat over this century will center on understanding who the stakeholders are and determining how project costs will be provided. The existing marsh habitat around San Pablo Bay has a range of stakeholders including CDFW, San Pablo Bay National Wildlife Refuge, State Parks, County land trusts, and City and transportation authority. On any one project, multiple stakeholders can be involved through the implementation process where projects costs and contracts are thoroughly vetted. In 2011, the USACE performed a Value Engineering (VE) study on dredge material management in part to identify inefficiencies leading to high costs and recommend strategy for improvement. Even though strategy is actively being sought to improve dredge material management costs, funding beneficial reuse projects will continue to present constraints in the future unless non -federal sponsors have incentive to support projects through completion.

To reiterate, the principle objectives of the LTMS are to reduce the overall in-Bay disposal and to maximize beneficial reuse alternatives in the most cost effective pursuit. Fact of the matter is beneficial reuse projects are more expensive compared to in-Bay disposal or even Deep Ocean. Once dredging projects meet their requirements for disposal (as mandated in their permits), their objective turns to the least costly disposal alternative for any remaining material. Unfortunately, beneficial reuse is challenged by the federal standard disposal alternative due to the associated higher costs. Placing dredge material at a designated beneficial reuse site has associated off-loading fees as well as increased costs for transporting the dredge material to the disposal site.

To understand the potential costs for marsh elevation enhancement related to dredge material transport and placement disposal costs, the Hamilton Wetlands Restoration Project (HWRP) provides good reference for analysis. The California Coastal Conservancy sponsored the project, however dredging and offloading was paid for through federal maintenance dredging projects along with sponsored material from the Port of Oakland Harbor 50 Foot Deepening Project. The federal maintenance portion of dredging and off-loading costs associated with the project ranged from $19 to $22.75 per cubic yard. Utilizing these project costs for maintenance dredging and disposal as a baseline reference, we can project costs for marsh elevation enhancement projects around San Pablo Bay. Table 9 below presents the associated costs for under the 180 cm/century SLR scenario. The 100 cm/century SLR scenario associated dredging and off-loading costs are not presented as they are comparable based on prescribed placement depths, however implementation would occur later during this century (i.e. 16 cm layer depth in 2060 and 23 cm layer depth in 2075).

Table 9: 180 cm/century SLR Scenario: Dredging and Thin Layer Placement Costs

Thin Layer Placement Marsh Area (acres)	180 cm/century SLR			
	Thin Layer Depth of 15 cm (2045)		Thin Layer Depth of 27 cm (2060)	
	Volume (cy)	Costs	Volume (cy)	Costs
West Shore China Camp to Petaluma Marsh Area (1,300)	1,033,806	$23,519,090	1,860,851	$42,334,362
Petaluma Marsh Area (4,100)	3,260,466	$74,175,591	5,868,838	$133,516,064
North Shore San Pablo Bay Marsh (3,800)	3,021,895	$68,748,109	5,439,411	$123,746,596
Napa River Marsh Area (2,800)	2,226,659	$50,656,501	4,007,987	$91,181,702
Contra Costa County Point Pinole to Carquinez Strait Marsh Area (390)	310,142	$7,055,727	558,255	$12,700,309
Totals:	9,852,968	$224,155,018	17,735,342	$403,479,033

Notes:

cy cubic yards

cm centimeters

1 Individual marsh habitat area breakdown to represent patch size.

Volume cy $= m^3 * 1.31 cy/m^3$

Costs based on $22.75/cy for maintenance dredging and placement only; projected using the HWRP disposal fees.

We know that beneficial reuse of dredge material is a costly endeavor, primarily due to transporting material and associated disposal fees. Regionally, San Francisco Bay has the highest dredging related costs per cubic yard and it may be uncertain whether these high costs can be sustainable for beneficial reuse projects in to the future. In this example, in order to maintain tidal marsh habitat through this century, hundreds of millions of dollars will need to be invested in funding projects on about a 15 – 20 year cycle. Costs for reusing material should come down, comparable to other less expensive alternatives such as deep ocean disposal. While serving as a great 'safety net' for maintaining in-Bay disposal limits, the relatively lower costs detract from having material go towards beneficial reuse projects. Moving forward the federal standard needs to make exceptions for habitat improvement adaptation processes so high costs do not deter from marsh elevation enhancement alternatives.

6. Findings and Discussion

The focus of this research was to understand the potential for whether high-pressure spray disposal for thin layer placement can be effective in San Francisco Bay to maintain marsh elevation against projected rates of increased SLR over this century. I set out to answer the following questions:

1. What are the limits of thin layer spray disposal working to enhance marsh elevations and are elevations maintained long term? What are the potential impacts on existing marsh habitat and to the surrounding ecosystem?

2. If thin layer disposal can work to offset marsh elevation loss effectively, when is the critical implementation period and for how long is marsh resiliency maintained against future increases in SLR?

3. As an adaptation strategy against future SLR threats in the Bay, how will alternative reuse options in thin layer placement for marsh habitat enhancement integrate with the LTMS to support future goals for dredging and disposal management in the Bay?

4. How much sediment is required to maintain elevations of existing marshes in North San Pablo Bay through the century and what are the associated costs for maintaining tidal marsh habitat through this century?

High-pressure spray disposal was initially developed in the Louisiana coastal zone to reduce impacts from spoil piles being placed on the canals edge leading to wetland loss. Looking forward, thin layer placement of dredged sediment via high-pressure spray offers an opportunity to enhance surface elevations on subsided or deteriorating existing marsh habitat in the face of future impacts from accelerated rates in SLR. Most of the research investigating the effects of thin layer spray disposal on marsh habitat has been conducted in the Gulf and Atlantic coast region studying the effects of layer placement depths and tidal marsh response rather than habitat enhancement. There have been relatively few studies on the West coast regions. The following subsections detail my findings from this research and describe the potential for thin layer sediment application via high-pressure spray disposal to enhance existing marsh habitat resiliency in San Francisco Bay through this century against future projected increases in SLR.

6.1 Effectiveness of Thin Layer Spray Disposal for Enhancing Marsh Elevations and Improving Habitat Resiliency Through This Century

Based on the analysis of thin layer sediment application via high pressure spray in conjunction with the model analyses for enhanced marsh resiliency, the evidence suggests there is good potential for this technique to be an effective SLR adaptation strategy. However, challenges remain with inefficiencies through limited spray distance and marsh coverage area. Table 10 below highlights the key findings of the potential for thin layer sediment application to enhance tidal marsh resiliency through this century. A detailed discussion of each key finding is presented thereafter.

Table 10: Key Findings for Effective Thin Layer Sediment Application

#1	The layer depth of applied sediment is the driving factor for successful marsh recovery. Thin layer depths around 15 to 20 cm demonstrate optimal tidal marsh vegetation (cordgrass and pickleweed species) recovery in abundance and percent cover with improved elevations maintained long term. Further research is needed to understand potential impacts to sensitive species and adjacent aquatic habitat ecosystems.
#2	Supplying the marsh with a thin layer dredge sediement around 15 - 20 cm could be necessary for implementation as soon as the year 2045. 100 cm/century SLR scenario: 16 cm necessary in the year 2060 180 cm/century SLR scenario: 15 cm necessary in the year 2045
#3	Supplying the marsh with a thin layer dredge sediement around 15 - 20 cm thinck would enahance resiliency. 100 cm/century SLR scenario: 40 - 55 years resilient 180 cm/century SLR scenario: 15 - 25 years resilient
#4	Spray disposal limited to distances of 300 feet across the marsh platform. Thin layer sediment applications of 15 cm may only reach 70 meters away from the spray location.

Key Finding #1:

The layer depth of applied sediment is the driving factor for successful marsh recovery. Thin layer depths around 15 to 20 cm are the upper limits for optimal tidal marsh vegetation (cordgrass and pickleweed species) recovery in abundance and percent cover with improved elevations maintained long term. Further research is needed to understand potential impacts to sensitive species and adjacent aquatic habitat ecosystems.

The research presented here examined how thin layer placement of dredge sediment onto subsiding tidal marsh habitat can enhance marsh function. A key consideration is balancing the hydrologic regime and marsh vegetation productivity while raising platform elevations against sea-level rise. The layer depth of applied sediment is the driving factor in successful marsh recovery. Improved marsh habitat can be realized if vegetated marsh platforms recover to similar conditions of nearby reference sites or pre-subsidence conditions lasting years following initial placement.

To achieve a desired target elevation at the marsh site, post-consolidation of dredge material needs to be factored into the placement volume. Standard engineering analysis indicate disposal volumes typically account for post-consolidation reduction of 10 – 40 percent depending on grain size but may be as high as 66 percent. Consolidation rates vary with layer depth over time and through percent reduction. Shallower layer depths will consolidate less but full consolidation will occur sooner compared to thicker layer depths experiencing greater percent reduction taking longer to stabilize. Full consolidation of material may take up to a year depending on site specific hydrologic regimes and sedimentation influences.

Analysis in this report show that thin layer depths ranging from 5 – 23 cm achieving target elevation can reliably yield ecological benefits with the least impact to existing marsh function. More specifically, sediment layer placement depths of 5 – 15 cm were able to maintain greater vegetation function compared to those sites that received more than 20 cm of dredge disposal material after seven years. Undoubtedly, marsh vegetation will be smothered when applying sediment via spray disposal. However, shoots and rhizomes of cordgrass and pickleweed species observed recovery in vegetation densities similar to reference areas occurring after two consecutive growing seasons with lasting productivity observed four years following the disposal episode. Recolonization by seedlings will take considerably longer if too many shoots and rhizomes are destroyed upon initial impact assuming elevation is maintained. Benthic infauna are able to recover and or recolonize the newly applied dredge sediment layer via migrating across the layer profile in opportunistic fashion. As such, it can be viewed that long term impacts to benthic infauna are not observed from thin layer placement depths within the optimal range. Based on this research, the potential for thin layer spray disposal to enhance marsh elevation in San Francisco Bay is promising. However, further research is needed to understand the potential impact to sensitive species and adjacent aquatic habitat ecosystems. In the Bay, control of invasive marsh plant species is of high concern and further research is needed to understand how invasive species might respond to thin layer sediment applications as well.

Key Finding #2:

If 100 cm/century SLR projections become real, existing tidal marsh habitat around San Pablo Bay will require between 15 to 20 cm sediment applications starting around the year 2060.

If 180 cm/century SLR projections become real, existing tidal marsh habitat around San Pablo Bay will require between 15 to 20 cm sediment applications starting around the year 2045.

Using the Marsh Equilibrium Model under projected century SLR rates, elevation deficit was calculated to determine appropriate thin layer placement depths to reach target elevations representative of healthy vegetation marsh platforms under current steady state conditions. The analysis shows that under 100 cm/century SLR, existing tidal marsh habitat around San Pablo Bay will require 16 cm of thin layer sediment application in the year 2060 to maintain healthy platform elevations relative to MSL. Similarly, under the projected 180 cm/century SLR scenario, existing tidal marsh habitat around San Pablo Bay will require 15 cm of thin layer sediment application in the year 2045 to maintain healthy platform elevations relative to MSL. If tidal marsh elevations are not maintained during the respective years, prescribed thin layer placement depths will be too much for existing marsh vegetation to optimally recover.

Key Finding #3:

Existing tidal marsh habitat resiliency is improved against future SLR impacts following thin layer sediment application to enhance platform elevations relative to MSL. If 100 cm/century SLR projections become real, thin layer sediment application around the year 2060 has the potential to offset the impacts of SLR for more than 40 years. If 180 cm/century SLR projections become real, thin layer sediment application around the year 2045 has the potential to offset the impacts of SLR for more than 15 years.

Using the model to project marsh resiliency through lasting effects from improved elevations under future SLR scenarios, under the 100 cm/century SLR scenario, thin layer sediment applications will improve tidal marsh resiliency for at least 40 years while lasting through this century before a second 16 cm thin layer application is necessary. Under the high scenario of 180 cm/century SLR, the model indicates that supplying tidal marsh habitat with a 15 cm layer of dredge sediment around the year 2045 will enhance resiliency for 15 to 25 years before having to maintain elevations again between the years 2060 and 2070. Based on this research, the potential for thin layer spray disposal to enhance tidal marsh resiliency against future increases in SLR over this century is promising.

Key Finding #4:

High-pressure spray disposal has limitations. Thin layer application is limited to distances of roughly 100 meters across the marsh platform area with layer depths correlating to spray *distance. Thin layer sediment applications of 15 cm may only reach 70 meters away from the spray location.*

The findings from this research indicate thin layer placement on to marsh habitat can be effective in San Francisco Bay for maintaining marsh elevations over time but there are still limits working against this technique being a suitable SLR adaptation strategy for maintaining tidal marsh habitat in San Francisco Bay. While it can be recognized that thin layer placement of dredge sediment can work to enhance marsh resiliency, the area to which it's applied is relatively small and is bound by disposal depth. High-pressure spray disposal is limited to depositing sediments to an area less than 100 meters away from the spray equipment but is able to uniformly distribute an even mixed slurry across the marsh area. The spray distance becomes reduced when thicker disposal depths become required for the area (i.e. disposal depths of 10 – 15 cm thick is achieved up to 70 meters away). Although thin layer disposal typically involves hydraulic dredging adjacent to disposal site area (in Louisiana as a way to simply spread dredge spoils), in the Bay high-pressure spray disposal for thin layer placement would require dredge material to be transported to the designated disposal site based on the regional differences between dredging practices. In the Bay due to the nature of routine dredging sites of federal navigation channels, dredge sediment slurry would be transported by pipeline or barge to the placement site (i.e. restoration sites receiving sediment slurry). Increased costs are associated with transporting material which limits the incentive for thin layer placement project alternatives. Finding sponsors to subsidize thin layer placement associated costs in the form of maintenance mitigation projects in return for green carbon credits, may provide more appeal to using thin layer disposal for maintaining marsh habitat over the next century.

For a marsh site receiving thin layer placement of dredge sediment slurry, there needs to be enough slope to assure water flows off the marsh and doesn't get trapped. While there is considerable control in targeting specific disposal areas with high-pressure spray techniques, local aquatic habitat supporting longfin delta smelt, eelgrass meadows or oyster beds are a concern due to sensitivity against turbidity and sedimentation disturbance. The tidal marshes of San Francisco Bay support numerous threatened and endangered species that need to be worked around which ultimately impacts the potential for considering high-pressure spray disposal on to marsh habitat. Additional pilot project studies—similar to those happening at the Seal Beach National Wildlife Refuge—are needed to investigate how sensitive species residing in marsh habitat respond to high-pressure spray techniques for thin layer placement.

6.2 Thin Layer Placement Alternatives and Dredge Material Management in the Bay

This research indicates that thin layer placement for marsh enhancement can be considered for alternative reuse as the need arises to supply marsh habitat with sediment to enhance elevations relative to sea level. However during the interim, additional pilot studies in the Bay are needed to fully evaluate the potential impacts of unconfined aquatic disposal to natural resources of Bay waters. This will take considerable time, on the order of decades to see these pilot projects to completion. As such, we need to use the time now to further evaluate the potential impacts using high-pressure spray disposal for thin layer placement to improve tidal marsh habitat in the Bay.

Federal regulations in Section 404 permitting currently impede the potential for implementing thin layer disposal projects due to the 'no discharge of fill' rule. Such policy constraints would need to amend as guidelines to support the discharge of appropriate fill material on to tidal marsh habitat for maintaining elevations when threatened by increased rates of SLR. At the very minimum, dredge material applied to existing marsh habitat would need to meet both the SUAD and the suitability criteria following wetland surface and wetland foundation material guidelines (USACE et al. 2001).Thin layer placement of dredge sediment for enhancing marsh elevation will be challenged by the federal standard placement site as this beneficial reuse alternative is more costly compared to in-Bay or Deep Ocean disposal. While thin layer sediment application for marsh elevation enhancement may not be the most cost effective disposal alternative, it currently stands as the only technique being considered for maintaining existing marsh elevations against future SLR impacts. In this regard, the federal standard placement site may need to take exception when the need for maintaining marsh elevations becomes realized. Table 11 below highlights the key findings of the potential for thin layer placement alternatives to integrate within and support future LTMS goals in the face of SLR over this century. A detailed discussion of each key finding is presented thereafter.

Table 11: Key Findings for LTMS Implementation and Volume Demand

#5	Thin layer sediment application for marsh elevation enhancement against future SLR impacts has good potential to support future LTMS goals based on recent amendments to the Bay Plan. Additionally, the LTMS inter-agency cooperative is willing to consider new methods to reduce climate change related impacts. Thin layer sediment applications for marsh enhancement can be considered as beneficial reuse of dredge material for USACE maintenance dredging projects.
#6	Under future SLR scenarios, it can be anticipated that around 10 mcy of clean dredge material will be needed to maintain existing tidal marsh habitat over the course of implementation. These volumes may be required as soon as the year 2045 if the high projections of accelerated SLR are proven accurate. Under high SLR projections, multiple episode of thin layer sediment application is needed about every 15 years in order to maintain resiliency through the latter half of this century. Maintain existing tidal marsh habitat around San Pablo Bay is projected to cost in the hundreds of millions of dollars over the course of implementation.

Key Finding #5:

The LTMS agencies understands the need to preserve existing marsh habitat as well as the need to potentially supply sediment to the inter-tidal zone in order to combat future threats of increasing SLR and are willing to consider new measures for achieving increased beneficial reuse allocation. Therefore, thin layer sediment application for marsh elevation enhancement against future SLR impacts has good potential to support future LTMS goals in maximizing beneficial reuse of dredge sediment for USACE maintenance dredging projects.

The amendment to the Bay Plan shows good promise for thin layer sediment application to enhance tidal marsh habitat. Ultimately however, a more definitive understanding for potential effects to surrounding Bay habitat is needed to support future policy decisions regarding thin layer sediment application for marsh habitat enhancement. In 2011 the Bay Plan update the old sea level rise findings and policies in the plan by adding a new section that more broadly characterizes climate change impacts to the Bay and adaptation to SLR threats. The LTMS understands the need to preserve existing marsh habitat as well as the need to potentially supply sediment to the inter-tidal zone in order to combat future threats of increasing SLR. The inter-working agencies are willing to consider new measures for achieving increased beneficial reuse allocation from USACE maintenance dredging projects that meet the federal standard.

Maintenance dredging projects around the Bay are compatible with thin layer sediment application for improving tidal marsh habitat due to the nature of the unconsolidated dredge material. Much of the current maintenance dredge material is already designated for specific federal standard placement sites and in 2014 1.2 mcy was designated for in-Bay disposal. This in-Bay disposal volume meets the LTMS goal (i.e. less than 1.25 mcy) and tidal marsh elevation enhancement projects may provide opportunity to reduce in-Bay disposal even more while maximizing beneficial reuse alternatives. Based on this research, the potential for thin layer spray disposal to enhance future LTMS goals is promising.

With that said, special considerations need to account for environmental dredging work windows related to threatened and endangered species and essential fish habitat protection. As a result, such measures will impose constraints for thin layer placement on to existing marsh habitat. In the Napa and Petaluma Rivers, endangered steelhead trout populations restrict dredging activity from August 1 – October 15. Even more hindering is the protection of California clapper rail and salt marsh harvest mouse, for which there is no approved work window to conduct dredging activities within areas of salt marsh habitat. Any potential activity must adhere to consultation and evaluation prior to being approved. As previously mentioned, the Napa marsh areas is known to support significant populations of salt marsh harvest mouse and the Petaluma Marsh area is home to a large population of Ridgeway's rail. These circumstances present hinder the potential when considering thin layer placement applied to these marshes. However, if tidal marsh elevations are not maintained through this century, these endangered species will equally lose as their critical habitat begins to disappear. To reduce impacts to sensitive species, additional project costs will be incurred for implementing avoidance mitigation measure in biological monitoring.

Thin layer placement for marsh enhancement as a beneficial reuse alternative could be considered as part of climate change adaptation strategy for habitat enhancement projects. The purpose would intend to reverse potential negative effects imposed by SLR. These projects will inherently require substantial funding which currently among the dredging projects in the Bay is a major impediment. Beneficial reuse of dredge material is a costly endeavor, primarily due to transporting material great distances and off-loading fees. As a result, many beneficial reuse projects are currently waiting to accept material to move the restoration project forward. Compounding the issue, equipment limitations pose a serious constrain on managing dredge material in the Bay. Currently, there is only one operating off-loader serving the entire west coast. As such, the off-loader dictates when beneficial reuse projects are able to receive material which is also based on the timing of maintenance dredging projects.

A Value Engineering Study (VE) was undertaken for the HWRP by the USACE which found concerns with the efficiency and logistics using an off-loader to transport dredge material. As a result, the California State Coastal Conservancy began addressing the potential for designing an Aquatic Transfer Facility (ATF) that would effectively transport dredge sediment to the designated reuse site. The current design ATF is a side project for the HWRP Bel Marin Keys Wetland Expansion (BMK) project. The design ATF is a 58-acre water basin located in San Pablo Bay, intended for stockpiling and transporting dredge sediments to the restoration site. If the ATF is approved and implemented, the results will provide insightful strategy for effectively supplying dredge sediment to maintain marsh habitat in the future. If successful, transfer facilities present an opportunity to stockpile dredge material which would alleviate the dependency from factors which constrain project efficiencies such as environmental work windows, testing requirements and federal budget uncertainties. Relating to the BMK project, utilizing a transfer facility is estimated to significantly cut project costs (from $302M to $119M) while serving to expedite the restoration construction by eight years. Considering marsh enhancement projects in the future will complicate matters in deciding who gets what and when for selecting beneficial reuse alternatives.

Key Finding #6:

Under future SLR scenarios, it can be anticipated that around 10 mcy of clean dredge material will be needed to maintain existing tidal marsh habitat. These volumes may be required as soon as the year 2045 if the high projections of accelerated SLR are proven accurate. Under high SLR projections, multiple episode of thin layer sediment application is needed about every 15 years in order to maintain resiliency through the latter half of this century. Maintain existing tidal marsh habitat around San Pablo Bay is projected to cost in the hundreds of millions of dollars over the course of implementation.

Based on the model output for the 100 cm/century SLR scenario indicating the need for thin layer sediment applications of 16 cm in the year 2060, an estimated 10.5 mcy of dredge material would be needed for maintaining existing tidal marsh habitat around San Pablo Bay. Under the high SLR scenario of 180 cm/century, nearly 10 mcy of dredge sediment would potentially be needed as soon as the year 2045. Based on the finding that tidal marsh resiliency is sustained for an additional 15 – 25 years under high SLR projections, multiple episode of thin layer sediment application is needed about every 15 years in order to maintain resiliency through the latter half of this century. Looking forward, if on an annual basis roughly 1 mcy of clean material goes towards enhancing marsh habitat, it would take around ten years to improve tidal marsh habitat elevations surrounding San Pablo Bay. Using these projections, the year 2060 and the year 2045 can be viewed as the target implementation period for each respective SLR scenario. We can see each scenario has capacity to delay thin layer placement projects for at least 10 years where prescribed thin layer placement depths will remain within the limits for successful marsh elevation enhancement (i.e. around 20 cm). However, if this 10 year buffer is utilized, the consequence would be seen in greater dredge volume requirements that may not be readily available.

Beneficial reuse of dredge material is a costly endeavor, primarily due to transporting material and associated disposal fees. This research shows in order to maintain tidal marsh habitat through this century, hundreds of millions of dollars will need to be invested in funding tidal marsh enhancement projects. Under high rates of century SLR, these costs will be needed on about a 15 – 20 year cycle. Accounting for inter-annual variability of dredge material that is SUAD, it is uncertain how long it will take to complete maintaining marsh habitat and likely a concern for future marsh habitat preservation. In addition, already approved beneficial reuse alternative placement sites are available and waiting to accept clean dredge material. Accordingly, beneficial reuse alternatives in tidal marsh habitat enhancement will require assigning prioritization under the LTMS. Although we can estimate required volumes needed for maintaining marsh platform elevations, understanding what is potentially suitable for reuse is moot until criteria are established for placing dredge material on to existing marsh habitat. If there is not enough suitable dredge material available to enhance tidal marsh elevations during the critical implementation period, alternative approaches need to be sought for preserving such critical habitat through the century. Therefore, further research is needed to investigate the suitability of dredge material for reuse marsh elevation enhancement in the Bay with respect to potential volume limitations.

7. Management Recommendations

Planning and budgeting for future adaptation strategies need to begin now to ensure resiliency in shoreline habitat for San Francisco Bay. Policy impediments in Section 404 permitting regulations for wetland fill should consider climate change adaptation needs. Developing purpose-dependent regulatory guidelines addressing climate change adaptation measures to guard against future impacts from SLR would benefit projects that aim to enhance shoreline resiliency such as maintaining tidal marsh elevations via thin layer sediment application. While the LTMS and amended Bay Plan now encourage enhancing habitat and flood management, the DMMO should focus efforts on suitability criteria and guidelines for placing dredge material within existing marsh as a potential alternative. Accounting for inter-annual variability of dredge material that is SUAD, the LTMS future goals should focus on diverting as much clean dredge material as possible to be designated for maintaining tidal marsh habitat on an annual basis. Additionally, the LTMS plan could suggest alternative beneficial reuse placement sites that consider unconfined in-Bay disposal for habitat enhancement and sustainability against SLR impacts through this century.

The LTMS plan through 2065 should include goals in separate beneficial reuse projects for the purpose of maintaining marsh habitat via thin layer placement alternatives. Investigations need to continue for understanding whether unconfined in-Bay disposal can be managed effectively so to benefit shorelines, mudflats and tidal wetland habitat. The opportunity for thin layer placement for marsh enhancement as an alternative reuse is apparent but meeting the federal standard remains to be a challenge. For thin layer disposal alternatives to be considered, future potential placement will need to be prioritized under the LTMS. Considering thin layer placement as an adaptation strategy for maintaining existing tidal marsh habitat being threatened by increases in SLR, the federal standard could adopt such criteria as the evidence shows environmental benefits outweigh the costs.

San Francisco Bay has the highest dredging related costs per cubic yard and it may be uncertain whether these high costs can be sustainable for beneficial reuse projects in to the future. Costs for reusing material should come down, comparable to other less expensive alternatives such as deep ocean disposal. Moving forward the federal standard needs to make exceptions for habitat improvement adaptation processes so high costs do not deter from marsh elevation enhancement alternatives. The LTMS acknowledges the need to maintain shoreline resiliency through preserving existing marsh habitat and including the need to supplement sediment to the inter-tidal zone in order to combat future threats related to the effects from a changing climate. Looking towards the future, management efforts should continue to focus on cost effective strategy for maximizing beneficial reuse alternatives as a priority. Alternative funding strategies such as offering carbon tax credits for sponsors may additionally need to be considered to further reduce the associated costs for thin layer placement marsh enhancement projects. Considering marsh enhancement projects in the future will complicate matters in deciding who gets what and when for selecting beneficial reuse alternatives. Designated project specific ATFs may be a solution to most appropriately manage dredge material for beneficial reuse. The potential for ATFs to enhance efficiency in dredge material management for beneficial reuse seems promising. To accommodate future demands in supplying clean dredge sediment to beneficial reuse projects, understanding the capacity for additional ATFs around San Pablo Bay needs to be investigated. Field studies examining thin layer placement on subsided marsh habitat in the Bay are needed to assess additional considerations for high-pressure spray disposal for this region such as sensitive species of concern.

When considering the time it takes to implement pilot projects, including follow-up monitoring efforts to assess long term response, seeking opportunity now to implement thin layer placement for elevation enhancement is important. These investigations should focus on sensitive species response to thin layer sediment additions as they are in part driving the need to preserve tidal marsh habitat. Equally, there is a need to understand what the effects are on native vegetation abundance and conversely, how invasive species respond in particular following thin layer sediment application using high-pressure spray disposal technique. We should use the time now to start budgeting and prioritize project planning as our ability to manage dredge material effectively in the future depends being prepared. As well, it's ever important now to begin implementing pilot studies in the Bay to acquire a more comprehensive understanding for how existing tidal marsh habitat responds to thin layer spray disposal with respect to protected species, control of invasive species and dredge material suitability.

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