DELTA RISK MANAGEMENT STRATEGY

INITIAL TECHNICAL FRAMEWORK PAPER

GEOMORPHIC RESPONSE TO DELTA ISLAND LEVEE FAILURE

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Geomorphic Response to Delta Island Levee Failure

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Foreword

The purpose of the Delta Risk Management Strategy (DRMS) Initial Technical Framework (ITF) is to guide the analysis of specific technical topics as they relate to assessing potential risks to Delta levees and assets resulting from various potential impacts (e.g., floods, earthquakes, subsidence, and climate change). These ITFs are considered "starting points" for the work that is to proceed on each topic. As the work is developed, improvements or modifications to the methodology presented in this ITF may occur.

Over the last 150 years, the Delta landscape has been transformed by levee building. The consequent land subsidence has created a potential increase in the volume below high-tide level, or "accommodation space," within the Delta system on the order of 5,000 cubic kilometers (km^3). This compares with the total current volume of the entire San Francisco Bay of about 7,000 km^3 (EPA 1989).

Therefore, a series of levee failures affecting even a small part of the Delta would not only directly affect the whole Delta landscape, but also the erosional and depositional processes that influence how the Delta and the estuary downstream will respond and evolve over the DRMS planning time frame. The effect of these levee failures would be superimposed on other changing processes that influence the evolution of the Delta's morphology, including sea-level rise, reduction in sediment supply, and continued subsidence. This changing morphology will affect hydrodynamics, wave exposure, habitat distribution, levee stability, and groundwater seepage over time scales of 2 to 200 years.

This ITF paper outlines a methodology to provide predictions of the geomorphic response to levee failure that can be used to develop snapshots of Delta morphology at different planning horizons. We anticipate that this information will be used by the hydrodynamics, ecosystem, and levee integrity teams. This methodology can also be applied in later stages of the project to inform future proactive planning scenarios intended to provide sustainable ecologic functions and human uses of the Delta, in support the Delta Visioning Process.

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1.0 INTRODUCTION

Over the last 150 years, the Delta landscape has been transformed by levee building. The consequent land subsidence has created a potential increase in volume below high-tide level, or “accommodation space,” within the Delta system on the order of 5,000 cubic kilometres (km^3). This compares with the total current volume of the entire San Francisco Bay of about 7,000 km^3 (EPA 1989).

Therefore, a series of levee failures affecting even a small part of the Delta would not only directly affect the whole Delta landscape, but also the erosional and depositional processes that influence how the Delta and the estuary downstream will respond and evolve over the Delta Risk Management Strategy (DRMS) planning time frame. The effect of these levee failures will be superimposed on other changing processes that influence the evolution of the Delta’s morphology, including sea-level rise, reduction in sediment supply, and continued subsidence. This changing morphology will affect hydrodynamics, wave exposure, habitat distribution, levee stability, and groundwater seepage over time scales of 2 to 200 years.

The key erosional processes that need to be considered are the potential increase in tidal channel scouring and the potential increase in wind-wave erosion. The key depositional processes are the capture of flood-borne alluvial sediments from upstream and tidally dispersed estuarine sediments from downstream due to the creation of efficient sediment “sinks” in the flooded islands. In addition, organic accretion can occur in low-energy subtidal environments and wherever tule marshes can colonize in the intertidal zone.

The net effect of erosion and deposition will be to significantly alter the sediment budget of the estuary and potentially cause long-term impacts on estuarine morphology downstream. In particular, long-term sediment discharge from the Delta could play an important role in sustaining offshore mudflats in Suisun and San Pablo Bay. Here, mudflat area has been diminishing over the last 50 years due to net loss of sediment (Cappiella et al. 1999). Further lowering of these mudflats would significantly reduce habitat and accelerate shoreline erosion.

This Initial Technical Framework (ITF) paper outlines a methodology to provide predictions of the geomorphic response to levee failure that can be used to develop snapshots of Delta morphology at different planning horizons. We anticipate that this information will be used by the hydrodynamics, ecosystem and levee integrity teams. This methodology can also be applied in later stages of the project to inform future proactive planning scenarios intended to provide sustainable ecologic functions and human uses of the Delta, in support the Delta Visioning Process.

2.0 OBJECTIVE

The objective of the proposed work is to provide the following information at different temporal and spatial scales:

- Short Term: Local Scale
  - Response of downstream tidal channels [x,y,z]
  - Maximum potential breach size

- Long Term: Landscape Scale

- Response of tidal channel system [x,y,z], identifying if potential future channel dimensions impinge on existing levees
- Potential sedimentation rates in flooded islands
- Long term changes in hypsometry and habitat zones relative to future tidal frame at either island or regional scale [coordinated with the Subsidence White Paper and Ecosystem-Response White Paper]
- Generalized estimate of change in sediment budget within the Delta
- Projected impact of change in sediment budget on mudflat and shoreline erosion rates in Suisun and San Pablo Bays.

3.0 PHYSICAL SYSTEM/PROBLEM

The historic Delta evolved over the last 4,000 to 6,000 years at the inland margin of a transgressive estuary as two interlocked geomorphic units. The Sacramento Delta, comprising about 30% of the total area was influenced by the interaction of rising sea level and river floods, creating an inland "crow's-foot delta" system of distributary channels, natural levees, and marsh plains. In contrast, the 100,000-hectare (ha) San Joaquin Delta formed as an extensive freshwater tidal marsh dominated by tidal flows and organic accretion (Atwater and Belknap 1980).

As sea level rose, marsh vegetation kept pace, creating extensive marsh plains at approximately MHHW (Simenstad et al. 2000). As these freshwater tidal marshes expanded inland, a dendritic tidal channel system developed, feeding into the tidal San Joaquin "River," or slough, where it joined the Sacramento River at Antioch (Figure 1). The morphology or dimensions of the channel system equilibrated with the tidal prism upstream (Allen 2000).

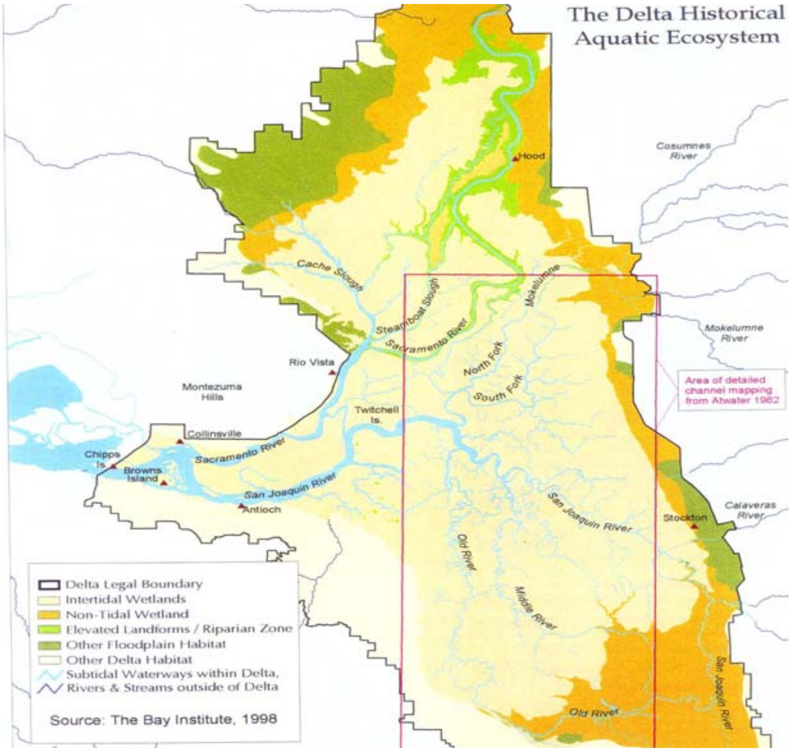


Figure 1. The Delta Historical Aquatic Ecosystem

Freshwater tidal marsh vegetation can colonize and persist to elevations below MLLW, occupying the entire intertidal elevation zone. This means that unlike in the brackish and saline parts of the estuary extensive mudflats did not form and wind-wave fetches were limited to slough channel reach lengths.

The main historic and modern source of inorganic sediment to the Delta is Sacramento River floods (Wright and Schoellhamer 2004). A portion of this sediment is captured on Delta marsh plains but most bypassed the Delta and was deposited in Suisun and San Pablo Bays. A large portion of these deposited sediments are resuspended by wind-wave and tidal action and recirculated into the estuarine system (Krone 1979). A significant portion of these estuarine sediments migrate up-estuary along the channel bed, driven by the vertical baroclinic residual estuarine circulation. This process creates a turbidity maxima zone within the water column that migrates from San Pablo Bay to the western Delta depending on the magnitude of river flows and tidal forcing.

Human activities have significantly altered the Delta landscape and processes that had sustained the Delta morphology. Of most significance to assessing future conditions are the following anthropogenic effects:

1. Creation of Accommodation Space

Until the construction of dikes in the 19th century all of the Delta's accommodation space was filled by organic and inorganic sediment accretion (Mount and Twiss 2005). Diking and consequent subsidence has fundamentally altered the Delta landscape. The potential anthropogenic accommodation space created to date is up to 5 times the current tidally influenced volume of the Delta, as shown in the attached hypsometric curve (Figure 2) (EPA 1989). Levee breaches can return a significant portion of this accommodation space to tidal action altering bathymetry and hydrodynamics throughout the northern reach of the estuary. Over longer time scales the size of this accommodation space changes as determined by subsidence rates (see subsidence ITR paper), sedimentation rates, and sea-level rise.

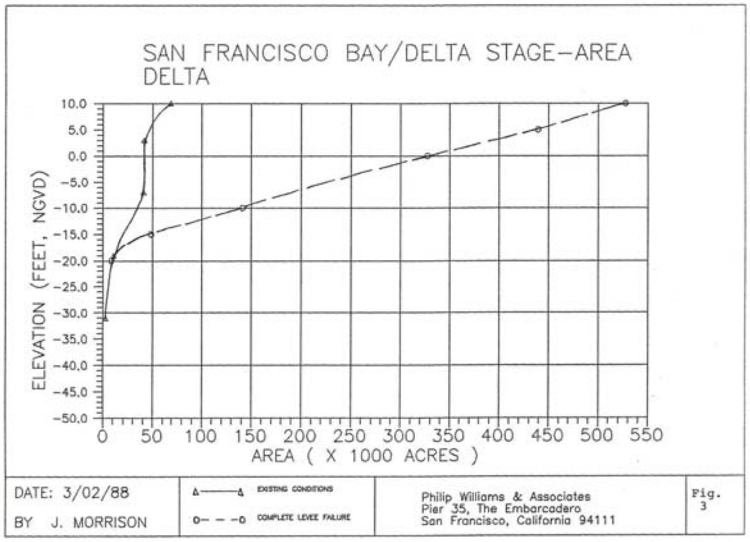


Figure 2. Hypsometric Curves for Existing Conditions and Levee Failure

2. Change in Tidal Prism and Channel Geometry

With island flooding the tidal prism increases, which, in turn, increases tidal current velocities and accumulated average boundary shear stresses. Because the channel banks are unarmored they adjust to these increased shear stresses by deepening. Over time, as channels deepen, their banks can become over-steepened causing channel widening. Eventually, the channel cross section equilibrates to the new tidal prism.

A crude but illustrative example of the maximum range of potential change is shown in Figure 3. This shows the scale of potential response of the San Joaquin River channel depth at Antioch if all Delta levees were to fail, increasing the potential tidal prism at this location by an order of magnitude.

Larger and deeper channels affect hydrodynamics, salinity distribution and sediment dynamics within the Delta. Wider channels may also affect levee stability downstream of a breached island. Deeper channels can increase groundwater transmissivity and increase seepage in adjacent islands.

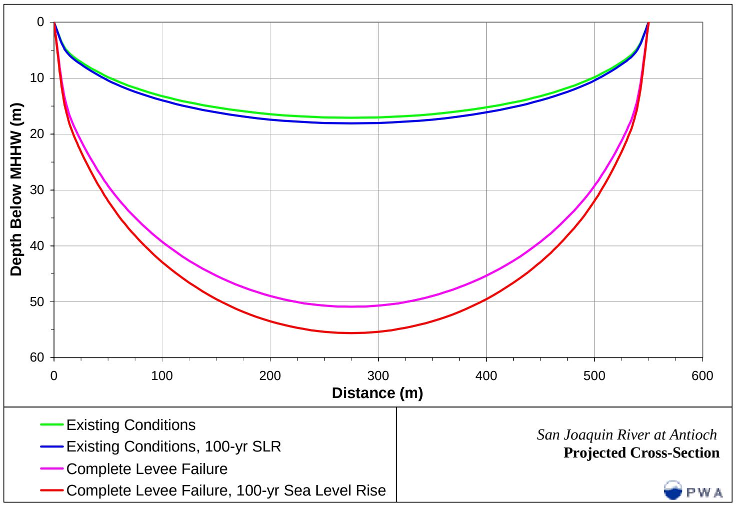


Figure 3. Projected Cross Section of San Joaquin River at Antioch with a Complete Levee Failure

3. Accelerated Sea-Level Rise

Accelerated sea level rise has a lesser direct effect on the hypsometry and accommodation space in the Delta than failure of levees and island flooding (see Figure 2). However, sea-level rise will also affect levee stability, change hydrodynamics (EPA 1989), change habitat area, and increase wind fetches.

4. Creation of Extensive Wind Fetches

Wind fetches will at first be limited by the scale of individual flooded islands. However, with the combined effects of continued subsidence of abandoned levees, wind-wave erosion and sea-level rise, wind fetches could increase over longer planning horizons as successive levees erode and/or are submerged.

5. Changes in Fluvial Sediment Delivery

With climate change, sediment delivery to the Delta during flood events would change, altering sedimentation patterns and habitat evolution in some of the flooded islands.

6. Increase in Sediment "Sinks"

Most flooded islands will become efficient sediment traps, creating large new sediment sinks within the estuarine system. In many locations island floors are deeper than adjacent channels and will preferentially divert sediment that might be dispersed downstream. Gross trap efficiency and sedimentation rates will be limited by wave scour. For most islands' wind fetches, this means that subtidal depths will be limited to about 1-2 m below MLLW, lower than tule marsh colonization elevations, as is illustrated by the bathymetry of Franks Tract.

7. Changes in Estuarine Sediment Dynamics

The creation of large sediment sinks combined with changes in hydrodynamics will alter the movement and distribution of sediment within the estuary. These changes in turn will affect the sediment budget and future bathymetry of the Delta, Suisun Bay and San Pablo Bay (Williams 2001).

8. Changes in Hypsometry Relative to the Tidal Frame

Small changes in Delta and Suisun Bay bathymetry can have significant impacts to Delta hydrodynamics and hence salinity transport through the Delta. With expected low sedimentation rates, the tidal prism and tidal volume of breached islands could increase over time due to subsidence that will continue in flooded islands – although at slower rates than farmed islands. Remnant levees will subside at faster rates, reducing the extent of riparian and fringing tule marsh. With sea-level rise the tidal frame will move upwards causing further reductions in supratidal and intertidal habitat.

4.0 ENGINEERING/SCIENTIFIC MODELS

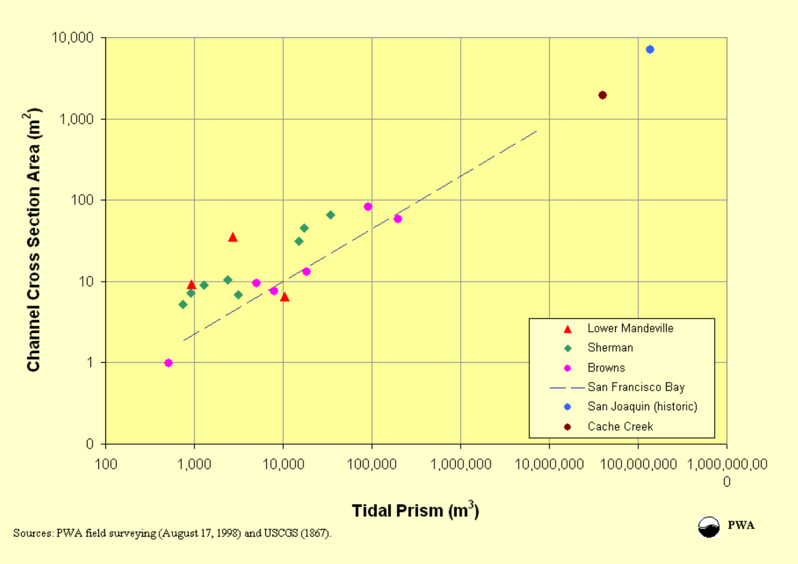
The following three interacting analyses are proposed:

1. Predicting Channel Geomorphic Response Using Hydraulic Geometry

Empirical hydraulic geometry relationships are a practical geomorphologically based method for predicting the depth, width, and cross-sectional area of tidal channels as functions of contributing tidal prism. They have successfully been used in a variety of ways, such as design tools in the planning of tidal wetland restoration projects (Williams et al. 2002). Here we propose using the relationships to predict channel erosion responses to increases in upstream tidal prism caused by levee failure. Figure 4 illustrates a data set we have previously developed for Delta channels.

The proposed methodology comprises four main steps.

Step 1 will refine the hydraulic geometry relationships using existing surveys and historical information on tidal prism and channel cross section for natural channels within the Delta. Figure 5 provides an example on Cache Slough of how additional data can be developed to characterize channel response to increase in tidal prism due to flooded island levee failure.



Sources: PWA field surveying (August 17, 1998) and USCGS (1867).

Figure 4. Hydraulic Geometry Relationships to Calculate Depth and Width of Delta Channels Under a Range of Upstream Tidal Prisms

Figure 5. Effect of Liberty Island Levee Breech on Channel Geometry at Cache Slough

Step 2 will estimate tidal prism downstream of projected levee failures in one of two ways: approximate estimates of potential tidal prism based on island hypsometry and assumed tidal range, or outputs of average gross tidal flux from hydrodynamic models.

Step 3 will apply these relationships to scenarios of multiple levee failure, using estimates of tidal prism change to predict equilibrium channel depth.

Step 4 will use these predictions of channel depth in different locations to construct longitudinal thalweg profiles and cross-sectional areas.

Step 5 will highlight locations where large changes in cross-sectional area could take place with the potential to undermine adjacent levees.

2. Predicting Morphologic Response and Habitat Changes Using Hypsometric Analysis

The tidal prism of a flooded island is controlled by sedimentation rates, subsidence rates, and sea-level rise. These changes can be represented by a set of hypsometric curves which describe the elevation/area relationship for an island, a group of islands, or for the whole Delta. The change in shape between curves is therefore an estimate for the loss or gain of habitat at different elevations relative to the tidal frame. This task will estimate changes in hypsometry due to sedimentation, subsidence and sea level rise on the distribution of four identified habitat zones (supratidal, intertidal, shallow subtidal and deep subtidal) (Figure 6).

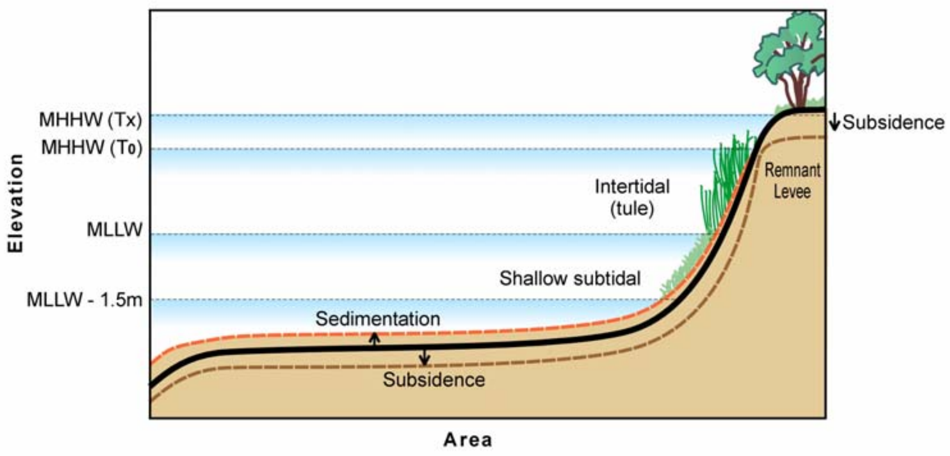


Figure 6. Diagrammatic Representation of Hypsometry of a Flooded Island and Relationship to Habitat Zones

The proposed task is divided into three steps.

Step 1 will describe the existing hypsometry of both individual flooded islands and provide a cumulative assessment of the area-elevation relationship.

Step 2 will superimpose the sedimentation, subsidence, sea-level rise parameters on to the hypsometry.

Step 3 will translate the changes in hypsometry into projected changes in the area occupied by habitat zones, with assumptions made regarding the colonization elevation of tule marsh. The results of this task will also feed back information on tidal prism into the hydraulic geometry analysis.

3. Projecting Changes in Sediment Budget That Influence Bathymetry and Habitats in Suisun and San Pablo Bays

A sediment budget is an accounting of the sediment fluxes through a fixed boundary in space and time to estimate the net accumulation or loss of sediment within the boundary. Quantifying the sediment budget of the rivers feeding the Delta, the Delta itself and, using monitoring information of gross sediment fluxes, downstream in Suisun and San Pablo Bays (McKee et al. 2002) is important to understand how they will respond to a change in environmental conditions.

This proposed part of the work will outline our conceptual understanding of the existing sediment budget, exploring source, supply, storage areas and suspended sediment fluxes between these areas. This understanding will be used to assess how the sediment dynamics will change after levee failure, and what impact this change will have on bathymetry and habitat response in Suisun Bay and San Pablo Bay. For example, flooded islands are very efficient sediment traps with the potential to reduce sediment supply to both these Bays. In addition, island flooding has the potential to increase suspended sediment concentrations in the Delta by drawing-in the turbidity maximum from its existing position in Suisun Bay. In order to assess the sensitivity of the system, we will look at two extreme cases to "book-end" the potential range of impacts.

5.0 PROBABILISTIC APPROACH

The three main components of the geomorphic response of the Delta system to levee failure outlined above each have there own set of uncertainties.

1. The prediction of channel geomorphic responses using hydraulic geometry are estimates based on empirical data and not detailed morphological modeling. Figure 4 illustrates the error band of the limited amount of data accumulated to date. To reduce this uncertainty we propose to update the hydraulic geometry relationships by expanding the data set using readily available existing and historic channel surveys from the Delta. There is also uncertainty related to the amount of tidal prism affecting channel scour at different locations within the Delta. These uncertainties can be reduced by using average gross tidal fluxes to calculate tidal prism. Finally, there is uncertainty regarding the time frame of a response to sudden increases in tidal prism. The channel erosion trajectory can be better defined by examining historic channel cross-section surveys at Cache Slough and in other parts of the estuary.
2. Predicting the morphologic response and habitat changes using hypsometric analysis requires assumptions about accretion rates and subsidence rates. To enable a variety of scenarios to be tested around the best estimates, sensitivity analyses will be conducted to gauge the response of the system to increases or decreases in these parameters. In addition, the results of the hypsometric analysis will be strongly dependent on estimates of future sea-level rise. Recent published estimates will be used but there will be uncertainty inherent in the unpredictable nature of future global events.
3. Projecting changes in sediment budget that influence bathymetry and habitats in Suisun and San Pablo Bays has significant uncertainties related to the complexity of the physical processes operating in the system. We expect the largest uncertainties to be in estimating how changes in sediment dynamics will affect key terms in the sediment budget. In addition, although the magnitude and response of the salinity gradient to changes in Delta outflow can be fairly well established, the relationship of this gradient to suspended sediment load and turbidity maximum is less precise, particularly at low Delta outflows. Because of the large uncertainties and finite resources of the study we are proposing to develop sediment budget estimates that bracket the range of potential outcomes.

5.1 Assumptions, Constraints, Limitations

The details of our assumptions, constraints, and limitations that we anticipate in our methodology are described above (Section 5.0).

5.2 Information Requirements

Basic Data: Hydraulic Geometry and Hypsometry

We propose to carry out the hydraulic geometry and hypsometry analyses using available existing hydrographic and topographic surveys from the Delta. The basic data will include:

- Historic cross sections recorded by others such as DWR and USACE
- Historic maps published in the 19th and 20th centuries
- Pilot sites for resurvey of cross sections at Liberty Island (Figure 5) and Jones Tract
- Island elevation data from the DEM survey by DWR (we are assuming the recent LiDaR survey will be available as a single surface model with the most recent bathymetry data)
- Sedimentation rate data extracted from the results of BREACH I (Simenstad et al. 2000) which measured and compared vertical accretion rates and elevation change at “restored” and “natural” marsh sites.

Basic Data: Sediment Budget

The conceptual understanding of the sediment budget and its potential for change will need to draw together data from a wide variety of sources, which will be used in expert geomorphic assessment. These sources will include:

- Historic bathymetry surveys
- Flow and salinity data recorded by DWR
- Hydrodynamic and sediment dynamic measurements carried out by USGS and others
- Erosion and accretion data from Suisun and San Pablo Bays

5.3 Interface (Input) Requirements

Levee failure will result in impacts over different time scales. Short-term impacts will involve the rapid evolution of the breaches and tidal channels as a result of the initial levee failures. Longer term impacts will take place over 20, 50 and 100 year time horizons. The scale of these impacts will be controlled to a large extent by the number, location, size, and phasing of island breaches. The envisaged scenarios will be required as part of the interface (inputs) requirements. Other requirements will include:

- Subsidence rates: Estimates of subsidence rates beneath both submerged and non-submerged sites, and assumptions regarding subsidence of remnant levees will be provided by the Subsidence Team.
- Sea-level rise: Estimates of sea-level rise will utilize the most up-to-date available scenarios from the Climate Change Team.
- Habitat zones: The definition of habitat zones will be provided by the Ecosystem Team.
- Tidal processes: Data on tidal prism and tidal range will be provided by the Hydrodynamics Team.

5.4 Anticipated Outputs/Products

We anticipate the following deliverables in relation to various levee failure scenarios that will feed into the work of other teams within the DRMS:

1. We will provide the Levee Integrity Team with information on enlargement of Delta channels and potential pressure points in the system where levee integrity may be undermined.
2. We will provide the Hydrodynamics Team with estimates of change in channel morphology, maximum breach dimensions, hypsometry of Delta islands and future bathymetry in Suisun and San Pablo Bays.
3. We will provide the Ecosystem Response Team with estimates of change in the area of supratidal, intertidal, shallow subtidal and deep subtidal habitat zones across the Delta, and Suisun and San Pablo Bays

5.5 Resource Requirements

David Schoellhamer from the USGS and Denise Reed from the University of New Orleans have agreed to act as technical reviewers or advisors to our work, with exact roles to be determined by the DRMS Project Management Team. To carry out all our tasks, we require access to the DEM survey in GIS format.

5.6 Project Tasks

- Predicting Channel Geomorphic Response using Hydraulic Geometry
  - Refine the hydraulic geometry relationships using existing surveys and historical information
  - Estimate tidal prism downstream of projected levee failures
  - Apply these relationships to scenarios of multiple levee failure
  - Use these predictions of channel depth in different locations to construct longitudinal thalweg profiles
  - Highlight locations where large changes in cross-sectional area could take place with the potential to undermine adjacent levees
- Predicting Morphologic Response and Habitat Changes using Hypsometric Analysis
  - Describe the existing hypsometry of flooded islands
  - Superimpose the sedimentation, subsidence, sea-level rise parameters on to the hypsometry
  - Translate the changes in hypsometry into projected changes in the area occupied by habitat zones
- Projecting Changes in Sediment Budget that Influence Bathymetry and Habitats in Suisun and San Pablo Bays
  - Provide a conceptual understanding of the existing sediment budget
  - Apply this understanding to assess how budget changes will impact bathymetry and habitat response in Suisun Bay and San Pablo Bay
  - Sensitivity analysis to book-end the likely impact

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