U.S. Army Corps of Engineers®

San Francisco District

COUNTY OF MARIN

Strategic Sediment Pulse Delivery

USACE Floodplain Management Services Program

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USACE San Francisco District

Marin County Department of Public Works

Table of Contents

TABLES

FIGURES

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Executive Summary

This report describes the outcomes from a collaborative investigation conducted by the U.S. Army Corps of Engineers (USACE) San Francisco District's (SPN) Floodplain Management Services Program[1] and Marin County Department of Public Works (Marin County) from August 2023 to November 2024. The study explores Strategic Sediment Pulse Delivery (SSPD), a novel, nature-based approach to managing flood risk in tidal flood control channels and surrounding communities, as an alternative to traditional dredge methods (e.g. cutterhead, mechanical) for maintenance dredging. Conventional dredge methods and ancillary vessels (e.g. scows and tugs) are not always operationally feasible in narrow and shallow-draft tidal channels and present a high-cost and environmental impact. The SSPD addresses the specific issue of maintenance dredging of shallow, limited, or low-draft tidal flood control projects that are silted in and out of compliance due to the prohibitive costs for dredging and disposal.

SSPD proposes the use of hydrodynamic dredge methods to fluidize and mobilize sediment at the tidal channel bed, leveraging natural processes (e.g., ebb tidal velocities and fluvial flows) to transport material downstream into the San Francisco Bay sediment supply system and naturally nourish mudflats and marshes. Hydrodynamic dredge technology has been successfully used in the East Coast of the U.S. and Europe for Engineering with Nature (EWN) purposes. This pilot study evaluates the approach for a West Coast EWN context at Gallinas Creek in Marin County, CA. The primary goals of SSPD are to:

1) Reduce flood risk in San Francisco Bay Area tidal channels that have silted in.
2) Contribute sediment supply to downstream marsh and mudflat habitats for marsh resiliency under both current and future sea level rise conditions.
3) Improve small draft vessel navigation that had historically been available up these tidal channels.
4) Propose a dredge method with a lower carbon and greenhouse gas (GHG) impact.

Using a regional Adaptive Hydraulics (AdH) computer model developed by the USACE Engineering Research and Development Center (ERDC), the study evaluated SSPD's potential during winter and summer conditions to mobilize the upper several inches of the tidal channel bed and allow the natural forces of waves and tides to transport these sediments downstream. The Project Delivery Team (PDT) convened a Technical Working Group (TWG) composed of interdisciplinary experts in regional hydrodynamics and sediment transport, wetland science, food web ecologists, civil engineering and dredging, and other topics to provide feedback on key questions pertaining to feasibility. Guided by feedback provided by the TWG, the PDT evaluated the costs, environmental benefits, and potential environmental impact of implementing SSPD (TWG meeting notes are in Appendix A).

Modeling results indicate that SSPD effectively mobilized sediment from the tidal channel bed of Gallinas Creek downstream into San Pablo Bay, where it was ultimately transported to the China Camp Marsh complex and other fringe marshes. The next step in this pilot effort is to communicate findings to environmental resource agencies and seek funding opportunities to

[1] The Floodplain Management Services (FPMS) program was first authorized in Section 206 of the Flood Control Act of 1960, offers technical assistance in floodplain management. Funding for this project comes from the FPMS Program.

support design of an in-situ pilot project and comprehensive monitoring plan to evaluate observed benefits and impacts.

1. Study Background

Problem Definition

Sedimentation in tidal channels poses a flood safety problem and a compliance problem for the local entities that maintain them. Typically, traditional dredge methods have been used to remove sediment from these channels. However, costs for dredging across the nation have increased substantially in recent decades (USACE, 2024). This is particularly true in San Francisco Bay and its tributaries where dredging costs are among the highest in the Nation. This has a direct impact to the USACE design flood control projects in San Francisco Bay that were designed assuming recurring maintenance dredging by the local flood control entity on a regular basis to maintain channel depths and widths.

High dredging costs and extended environmental permitting schedules have made this maintenance dredging within the tidal floodplain cost-prohibitive for many local entities. As a result, many of these channels are out-of-compliance with flood control project requirements related to channel depth (e.g. increased safety concerns with flood risk and small boat navigation). Major factors that contribute to escalated dredging costs in San Francisco Bay include:

1) increased fuel and construction costs
2) permitting fees and mitigation costs
3) permitting restrictions that constrain dredging projects to a narrow window of several months in the calendar year
4) restrictions on the dredge technology/equipment (i.e. hydraulic dredging) and finally,
5) a lack affordable sediment disposal locations.

At the same time, sediment is a valuable resource needed to sustain tidal marshes in San Francisco Bay in the face of both sea level rise (SLR) and the decline in sediment supply (Schoellhamer, 2011; Goals Project, 2015). This realization has prompted a focus on the role of dredged sediment to restore and enhance tidal marsh resiliency especially in the face of accelerated SLR (Dusterhoff et al, 2021). There has also been increased awareness in recent years of the benefits of working with natural processes and a focus on EWN as an important goal for both the USACE (OASACW, 2024) and the professional design community. Broadly speaking, working with natural processes can both enhance resiliency of estuarine habitats and reduce costs.

The USACE SPN Operations and Maintenance (O&M) dredging program currently funds most of the dredging activities that occur in San Francisco Bay. The choice of where to place dredged material is a primary driver of overall dredging costs. Placement in San Francisco Bay is the typically most economically efficient location to place dredged material. Disposal sites in the Pacific Ocean (approximately 50 miles offshore for SFDODS) offer a more intermediate cost, whereas placing dredged materials at upland (or wetland) sites are often the most expensive option. Upland (wetland) sites are permitted locations that typically use dredged sediment to raise subsided grades to make these locations more suitable for tidal wetland restoration.

Federal law requires has required the USACE to select the least cost, technically feasible, and environmentally acceptable alternative.[2]

To increase the beneficial use of dredged material, additional funding from federal, State, or local sources will be required to supplement the O&M dredging program. The Water Resources Development Act (WRDA) 2020 Section 125a specifies the incremental cost above the Federal Standard, or base plan, for the beneficial use of dredged material can be cost-shared at 65 percent federal/35 percent non-federal given the benefits justify the additional cost. In addition, the USACE is exploring the viability of increasing beneficial use of dredged material through a regional plan. The Regional Dredged Material Management Plan (RDMMP) accomplishes this objective by offsetting the higher costs of beneficial use placement with increased in-bay placement and hydraulic dredging methods (i.e., cheaper methods of dredging and placement) on the regional scale.

However, the federal O&M dredging program implemented by the USACE in San Francisco Bay does not currently include dredging of shallow draft tidal channels like those investigated in this project, since these channels are typically owned by local entities (e.g. Marin County, Alameda County) and used for small boat navigation, rather than navigation and shipping. Yet, these tidal channels are a critical component of the coastal floodplain. The channels enable flood and stormwater drainage for local watersheds and deliver tidal flows and sediment into tidal marshes. Siltation within the tidal channels prevents gravity drainage from storm drain systems, which exacerbates backwater flooding in communities. Tidal channels are integral for functional flood protection to hundreds of thousands of people who live in the areas within the influence of tidal flooding.

In many locations, the USACE was the original designer of flood control channels, assuming recurring maintenance dredging by local entities to maintain depths for flood protection within the coastal floodplain. However, local flood agencies are consistently overburdened by the substantial monetary costs and permitting needs associated with maintenance dredging. This has led to an existing norm where most tidal flood control channels are out of compliance (e.g. reduced channel depth and conveyance) and unable to be dredged, which impedes recreational access to the creek for the local community. Additionally, the resultant loss of flood protection due to decreased channel capacity will only worsen under future SLR conditions.

[2] It is USACE policy to regulate the discharge of dredged material from its projects to assure that dredged material disposal occurs in the least costly, environmentally acceptable manner, consistent with engineering requirements established for the project (33 CFR 336.1(c)(1)).

Figure 1. Flood Risk Impacts by Silted-in Tidal Channels (Gallinas Creek)

The realization that costs for dredging and beneficial reuse of dredged sediments along with the need to evaluate projects holistically, including their carbon footprint, is a primary motivation for the project to evaluate this new EWN approach proposed by Marin County Flood Control (Leventhal 2021) to O&M dredging of tidal flood control channels in San Francisco Bay evaluated in this study. The goal of the study is to evaluate if this potentially lower-cost and low-carbon approach to dredging of tidal flood channels, that are not currently being dredged due to the reasons described above, can provide flood protection and navigation benefits for an example site in Marin County, CA (Figure 2).

Figure 2. Map of Marin County in San Francisco Bay

Proposed Approach – Strategic Sediment Pulse Delivery (SSPD)

The Marin County Department of Public Works (Marin County) and the USACE San Francisco District are investigating the potential for Strategic Sediment Pulse Delivery (SSPD) to support flood risk management within tidal flood control channels while also providing sediment into the bay system to nourish marshes and mudflats. This year-long study is funded by the USACE FPMS program[3].

SSPD proposes the use of hydrodynamic dredge methods to disturb and entrain sediments from the channel bottom during naturally elevated turbid conditions (e.g., prior to an extreme event or high wind conditions) and allowing natural processes at the channel (e.g., ebb tidal velocities and fluvial flows) to transport sediments downstream to the San Francisco Bay.

This approach is proposed as an alternative to using a traditional dredge approach under non-turbid conditions, which also includes mechanical piping and transport of sediment in barges for disposal. The efficacy of SSPD is evaluated for the tandem goals of flood risk reduction and regional marsh/mudflat resiliency using a regional Adaptive Hydraulics (AdH) model developed by the USACE Engineer Research & Development Center (ERDC). The pilot site selected for evaluation in the study is at Gallinas Creek in Marin County, although a framework and criteria for feasibility are developed and discussed in this report.

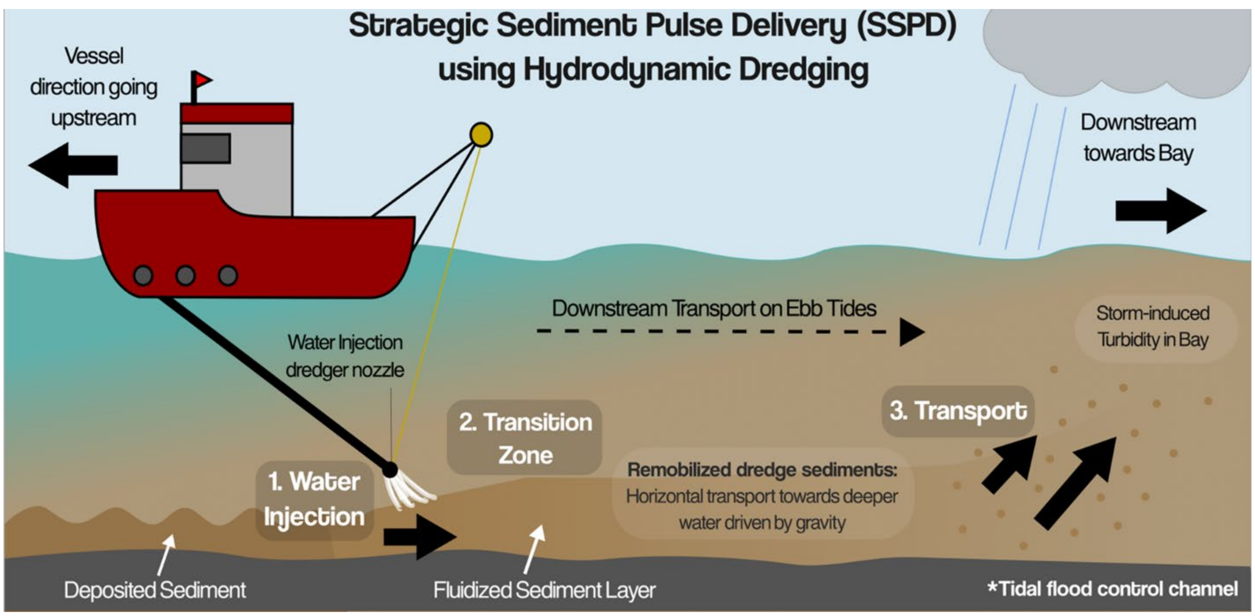

Figure 3. Conceptual schematic of Sediment pulse dredge

Rising sea levels and more severe storm flooding because of climate change are impacting Marin County, CA. Marin flood control channels, like many other tidal flood control channels around San Francisco Bay, were designed to rely on inexpensive dredging. Presently, these channels experience excessive deposition and shoaling. Climate change impacts, including

[3] FPMS is not a grant program and does not lead to detailed design or construction projects; implementation is the non-federal partner’s responsibility. More information on the USACE FPMS program can be found here: https://www.usace.army.mil/Missions/Civil-Works/Technical-Assistance/FPMS

SLR and extreme precipitation, threaten to exacerbate the risks to low-lying communities. For (smaller) tidal channels (order of 40 feet or less), a new dredging approach is needed because traditional dredging techniques are too expensive for typical Public Works agencies, including Marin County Public Works, and difficult to permit. To support coastal/fluvial flood risk management in Marin County, this study investigates a potential dredging approach proposed by Marin DPW staff called SSPD for tidal flood control channels that are infrequently dredged and are in essence “mud locked.”

USACE Programmatic Background

Floodplain Management Services (FPMS)

Flood risk management (FRM) is one of the USACE’s primary mission areas, and encompasses the development and communication of approaches, technologies, and solutions which reduce the risk of riverine flooding and coastal storm impacts. The FPMS program serves as a tool to help achieve the USACE FRM mission by addressing the needs of people who live and work in floodplains, and the actions they can take to reduce property damage and prevent the loss of life caused by flooding.

Through the FPMS program, the USACE provides information on flood hazards to local interests, state agencies, Tribal Nations, and other federal agencies to guide development of the floodplains and flood-prone areas of the United States. The program’s objective is to foster public understanding of the options for dealing with flood hazards and promote prudent use and management of the Nation’s floodplains and flood -prone areas. The FPMS program provides a full range of technical services and planning guidance needed to support effective floodplain and flood risk management[4].

Engineering With Nature (EWN) in the USACE San Francisco District

The USACE SPN EWN program[5] supports the intentional alignment of natural and engineering processes to address flooding hazards efficiently and sustainably while also delivering economic, environmental, and social benefits. As an EWN Proving Ground, the San Francisco District is committed to the broad integration of EWN principles and practices into all business lines in the form of constructed projects. Proving Grounds are places where innovative ideas are assessed on the ground, throughout USACE missions.

EWN encompasses a broad category and continuum of approaches across natural contexts (e.g. fluvial, coastal) that seek to harness natural processes to provide ecosystem and human benefits. These approaches range from natural (e.g. restoration) to natural enhancements to more traditional engineering approaches (e.g. manufactured) such as seawalls (see Figure 4).

[4] USACE Floodplain Management Services Program (FPMS) webpage can be accessed at: https://www.usace.army.mil/Missions/Civil-Works/Technical-Assistance/FPMS/

[5] Additional information on the USACE Engineering With Nature (EWN) program can be accessed at: https://ewn.erdc.dren.mil/

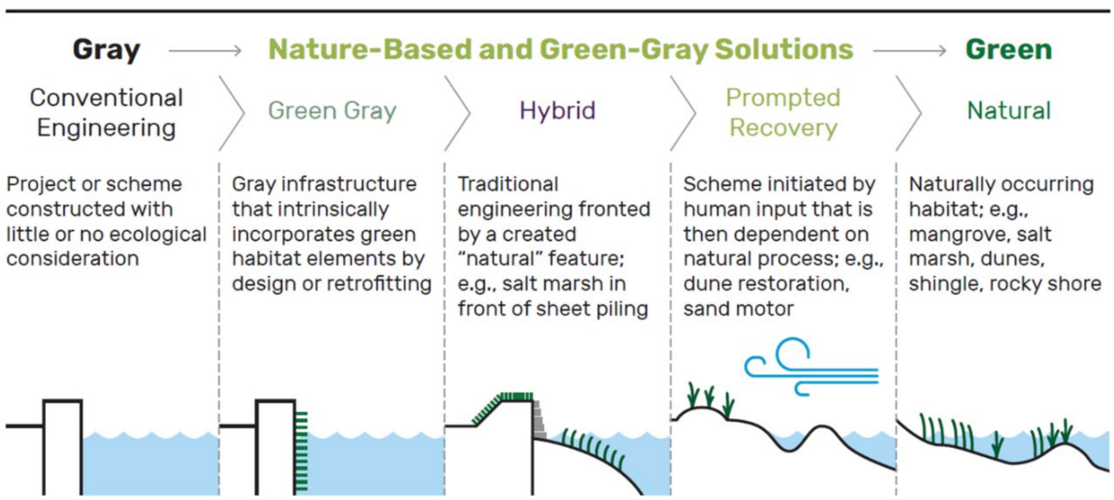

Figure 4. Grey-to-Green Spectrum of Engineering with Nature Measures (SAGE 2017)

Sediment pulse dredging, the focus of this study, can be categorized as being closer to the natural end of the EWN spectrum and as such provides the benefits from working with natural processes but with the increased uncertainty inherent in working only with natural processes. This understanding is critical to the proper evaluation of this approach and its context in the variety of EWN approaches.

Beneficial Reuse of Dredged Material in San Francisco Bay

USACE defines beneficial reuse of dredged material as "productive and positive uses of dredged material, which cover broad use categories ranging from fish and wildlife habitat development to human recreation, to industrial/commercial uses" (USACE Beneficial Uses of Dredged Material, Engineer Manual 1110-2-5026). Maximizing the beneficial reuse of dredged sediment is a key goal of the Long-Term Management Strategy (LTMS) program for dredged material from the San Francisco Bay Area. According to the Dredged Material Management Office's (DMMO) most recently published annual report, only 19% of the total volume of dredged material (approx. 420,000 cubic yards (CY)) was beneficially reused or placed upland in 2021. A total of 96% of the dredged material that was beneficially reused was from dredging of the larger Ports and Marinas and received by either the Montezuma Wetlands Restoration Project or the Cullinan Ranch Restoration Project, located in Suisun Bay and San Pablo Bay, respectively. As noted above, there is little to no dredging of these tidal flood control channels in the SPN maintenance dredging program.

Beneficial reuse can be achieved through a range of dredge material handling/placement methods, the optimal method being influenced by placement location characteristics, desired outcomes from placement, costs, etc. The two projects described above (along with the SPN Hamilton Wetland project) represent bulk fill approaches to the mechanical dredging transport and pumping of large volumes of dredged sediment into former Baylands that have subsided due to diking and consolidation of bay muds or peat soils. This approach requires major engineering and construction work to mechanically dig the sediment, place into barges, push these barges miles to the disposal location and then pumping of large volumes of water to reslurry the sediment to a low enough percent solids concentration to allow for pumping into the disposal location. This bulk fill process is both overly expensive as well as massively carbon and greenhouse gas producing.

The SPN EWN Program offers a 'toolbox' of approaches for the beneficial reuse of dredge sediments, providing flexibility based on specific project needs (Figure 5). Among these, bulk fill approaches, such as those employed at Cullinan, Montezuma, and Hamilton, have proven effective for large-scale dredging and placement. These methods are well-suited for managing the extensive volumes of sediment—ranging from hundreds of thousands to millions of cubic yards over time—that must be dredged to maintain navigability of federal navigation channels to authorized depths as mandated by Congress.

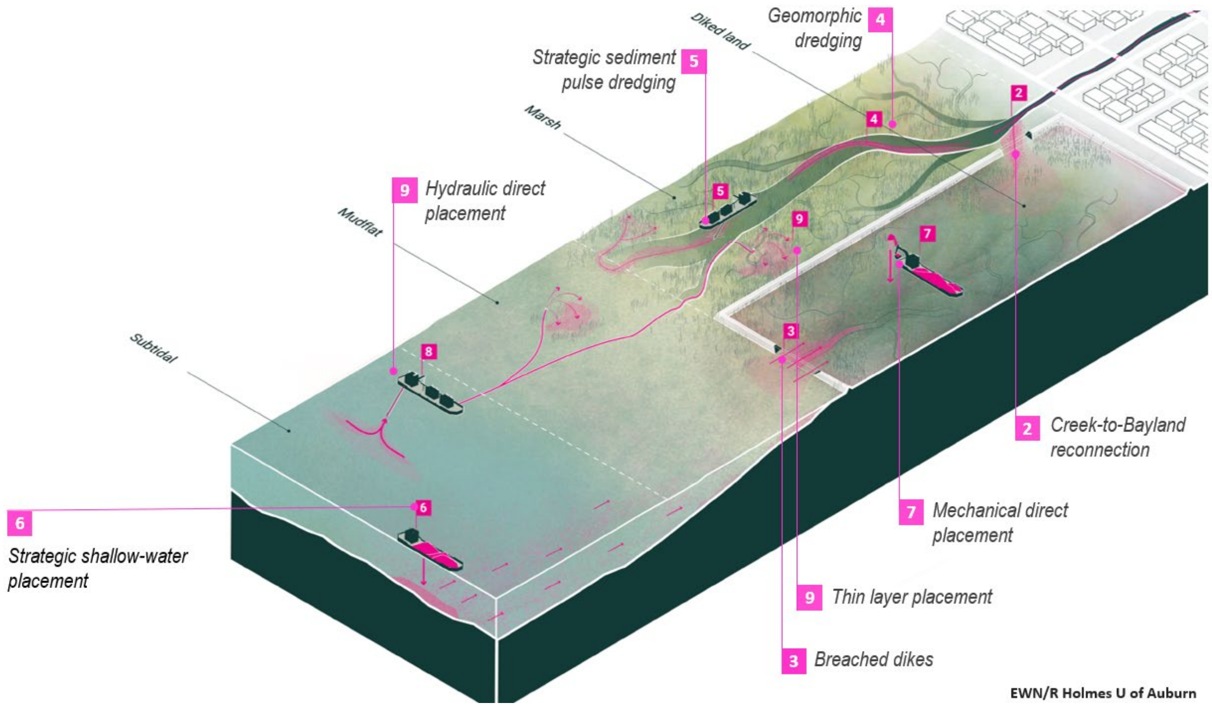

Figure 5. Beneficial use opportunities across the tidal profile (Source: EWN/R. Holmes, University of Auburn)

In 2021, SPN started work to permit the Section 1122 Strategic Shallow Water Placement pilot offshore of Eden Landing by Hayward, CA for implementation over Winter 2023/2024. In December 2023, the shallow water placement pilot project placed 90,000 CY of clean dredged sediment in the San Francisco Bay in the shallows offshore of Hayward, CA, where tides and wave energy are anticipated to move this sediment onto the marsh at Eden Landing Ecological Reserve (Figure 6). While the effectiveness of this approach for marsh sediment deposition is still being evaluated (monitoring is ongoing through December 2024), preliminary results most relevant to this study show minimal and short duration turbidity spikes during sediment placement and no adverse impacts to aquatic species at the time of this report preparation. While the costs for this pilot project were in the order of a typical bulk fill project, it is anticipated that additional experience would reduce this cost over time.

Figure 6. Strategic shallow water placement pilot offshore of Eden Landing Ecological Reserve, Hayward, CA (December 2023)

Goals and Objectives

This pilot study aims to assess the feasibility, costs, limitations, and ecological impacts and benefits at a planning-level, of implementing SSPD at a tidal flood control channel in Marin County and the potential applicability to tidal flood conveyance channels all around San Francisco Bay.

The goals for this study are as follows:

1. Develop the original proposal by Marin DPW (Leventhal 2021) for a sediment pulse dredging approach to a fully developed project in the South Fork of Gallinas Creek in Marin County. The project would be developed enough to allow for hydrodynamic modeling and assessment of impacts and costs to assess the feasibility of this approach to the maintenance dredging of tidal flood control channels.

2. Develop a pilot project and associated monitoring program to assess the costs and effectiveness of a field program.

3. Prepare a road map for the next implementation phase of the project and seek funding for pilot study.

Caveats and Assumptions

This study is based on available data and state-of-the-science hydrodynamic and sediment transport modeling tools available at the time of preparation. There are significant unknowns and uncertainties inherent in an innovative proposal for a new type of dredging application, although the study does review existing applications of hydrodynamic dredge technology elsewhere in the continental U.S. and Europe. There are limits on what a single study or model simulation can tell us about the effectiveness and costs for actual implementation. Based on the outcomes of this year-long study, the team presents recommendations for future efforts. A field pilot study is highly desirable for ground-truthing modeled hydrodynamic and sediment transport processes to provide results more definitively.

Technical Working Group

To support feasibility of the SSPD approach from a scientific and engineering perspective, this study incorporates input from a Technical Working Group (TWG) comprised of representatives from organizations such as USGS Pacific Coastal and Marine Science Center and San Francisco Estuary Institute (SFEI), as well as dredge experts from industry. The TWG members provided feedback individually and through group discussion over the study at three meetings: September 2023, March 2024, September 2024.

Appendix A contains the meeting minutes from the technical working group sessions. In general, the TWG members were supportive of the project approach and had ideas for improvement incorporated by the design team. The TWG members saw no flaws or unacceptable impacts from the proposed project and had useful suggestions especially in the design of a monitoring program to assess impacts to aquatic organisms.

2. Technical Background

Bay Area Hydrodynamics and Sediment – Physical Context

The San Francisco Bay-Delta estuary is a major urban estuary along the West Coast of North America, draining freshwater flows from the Sacramento and San Joaquin rivers while exposed to the Pacific Ocean through the Golden Gate Strait. The region's climate is Mediterranean, characterized by distinct wet and dry seasons. Water levels in San Francisco Bay are influenced by astronomic tides, freshwater inflows, and lower-frequency ocean fluctuations (e.g. El Niño–Southern Oscillation); tidal signals generally follow a mixed semi-diurnal regime.

San Francisco Bay is composed of four sub-embayments: San Pablo Bay, Suisun Bay, Central Bay, and South Bay. As this study is focused primarily on a pilot in Marin County, located on the western edge of San Pablo Bay, the discussion of hydrodynamics and sediment transport will center on San Pablo Bay and, where appropriate, San Francisco Bay as a whole. For a comprehensive overview of regional hydrodynamic patterns across the San Francisco Bay and its sub-embayments, the reader is referred to Barnard et al (2012).

San Pablo Bay is the northern embayment of the San Francisco Estuary (90 square miles), receiving drainage from the Central Valley and major rivers and creeks in Marin, Napa, and Sonoma Counties. Extensive mudflats and shallow subtidal habitat cover San Pablo Bay, apart from the deepwater shipping channel. (maintained by USACE). Average depths within the bay are < 6 ft (2 m) at Mean Lower Low Water (MLLW), with wide mudflat complexes fringing around the northern and northeastern sides (Bever and MacWilliams, 2013). Winds in San Pablo Bay arrive predominantly from the northwest. Meteorological conditions in San Pablo Bay influence regional hydrodynamics, including the formation of a gyre which rotates clockwise around the bay, influencing wave energy and sedimentation patterns along the bay edge. Wave energy in San Pablo Bay is notably higher than in other embayments due to its orientation relative to wind and fetch distance. Schoellhamer et al. (2008b) observed significant wave heights of approximately 1.5 feet and periods of 4 seconds by the channel. Sediment transport from tidal streams is hypothesized to be driven by upstream advection of sediment during flood tide, followed by deposition during slack water and downstream advection during ebb tide (Ganju et al., 2004).

Historic studies of San Pablo Bay have shown that freshwater discharge and sediment concentration are key drivers of sedimentation in the tidal flats. Human-driven activities in the Sierra Nevada, a mountain range in California, and other areas of the state, have altered sediment delivery to the bay over the 19th and 20th centuries. Hydraulic mining in the Sierra contributed large volumes of fine sediment flowing to the San Francisco Bay, building up intertidal mudflats and fringing tidal marshes, as shown in Figure 7 below. Schoellhamer et al (2011) identified a decreasing trend in sediment yields from the Sacramento and San Joaquin Deltas, resulting in a deficit of suspended sediment concentration in the San Pablo and San Francisco bays. Major sub-embayments within San Francisco Bay have been shown to become net erosional (Schoellhamer & Drexler, 2013).

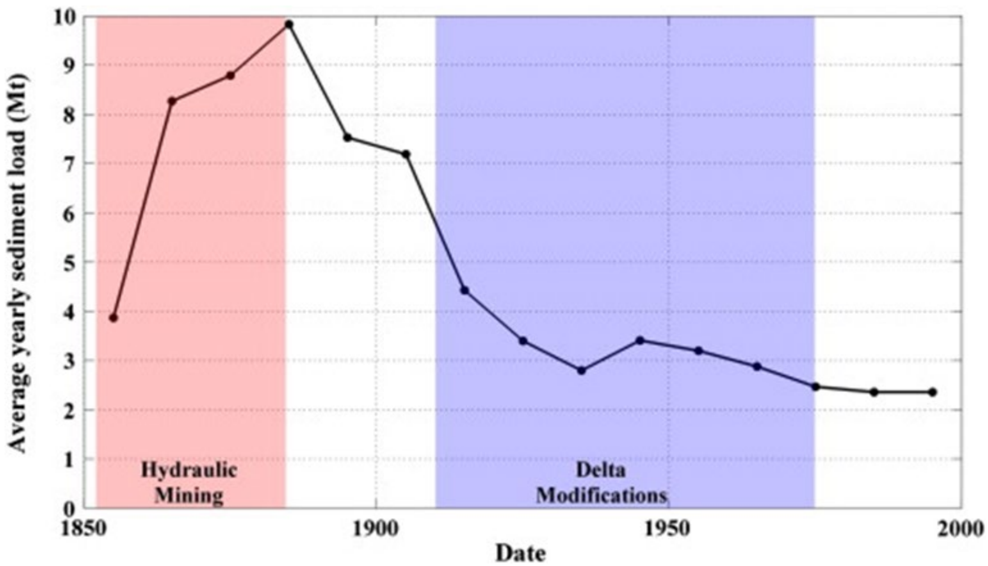

Figure 7. Historical Sediment Supply for San Francisco Bay (Source: Wright & Schoellhamer 2004)

Sediment aggradation is also driven by the loss of tidal prism from urban development on former tidal baylands. The daily flow of tidal prism maintains tidal channel depths in natural systems. When this tidal prism is removed, the creek narrows and shallows as a geomorphic response to this loss of daily tidal flows. Dusterhoff et al (2021) estimates that approximately 5 to 10% of sediment supply is in tidal creeks feeding San Francisco Bay, confirming prior research from McKee et al (2012) that small, urbanized watersheds may dominate local contributions to sediment supply. The timely release of these sediments is key to feeding the system and allowing for marsh deposition.

Impacts from Climate Change

Currently, San Francisco Bay has a long-term historical average sea-level-rise (SLR) rate of approximately 0.08 inches (2 mm), per year, which is within the range of values that natural marshes can typically keep pace with. Figure 8 shows the projected SLR curves from USACE (2013) and NOAA (2022) for San Francisco Bay Area. The rise in tide levels has been mitigated along the Pacific Coast due to atmospheric pressure forces that have dampened water levels. However, SLR is expected to accelerate sometime mid-century in response to a global rise in water levels and a lessening of the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) pressure forces. This will likely lead to a rapid drowning of tidal marsh habitats and loss of both habitats as well as the wave damping benefits of vegetated tidal marshes.

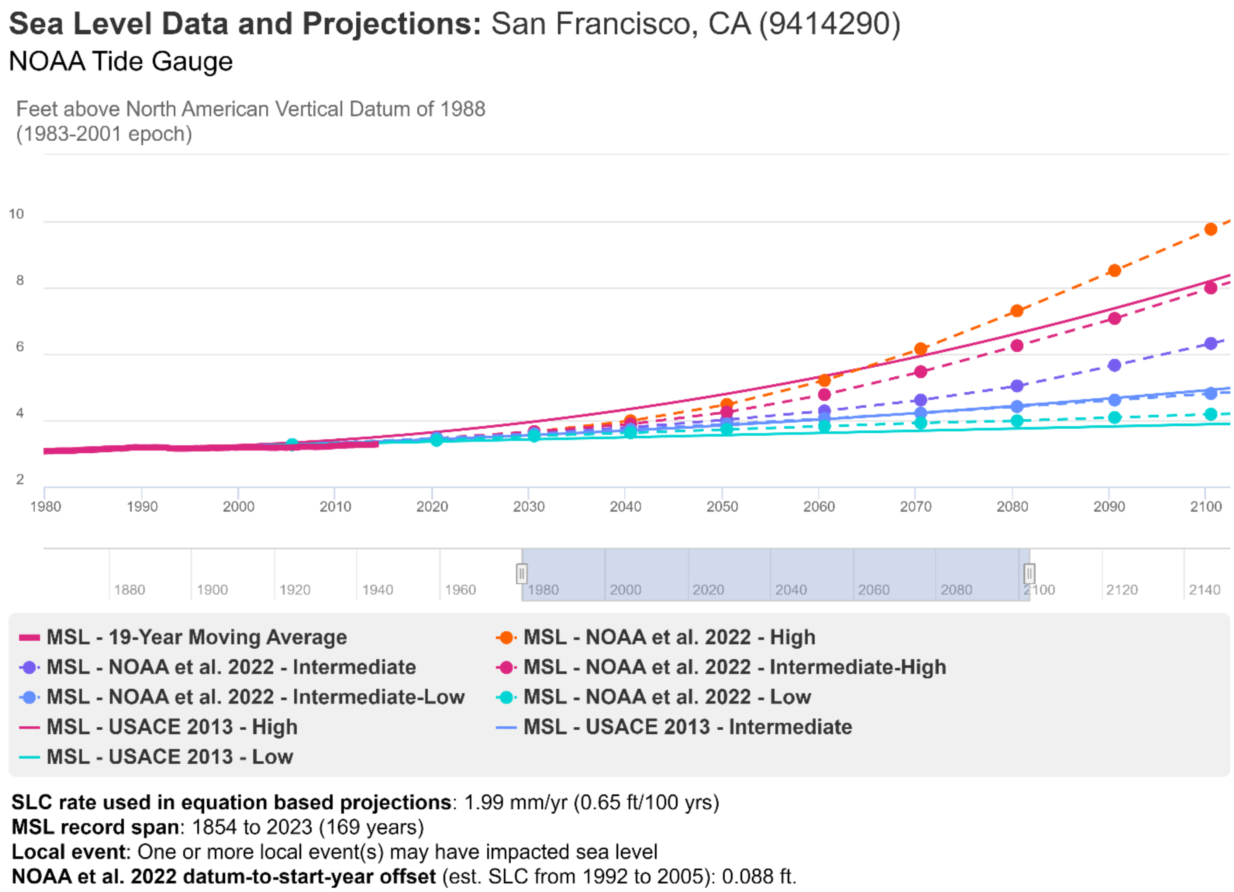

Figure 8. USACE Sea Level Change projections for San Francisco Bay, CA through 2150 (Source: USACE Sea Level Assessment Tool)

As local sea levels rise due to climate change, the hydrodynamic processes, namely wave-driven erosion, contributing to marsh edge erosion (scarping) are likely to accelerate, leading to marsh block slump failure and loss of marsh habitat. Previous studies in San Francisco Bay Area tidal marshes (e.g., Corte Madera Creek, Marin County) have shown that mudflat habitat in front of marsh complexes work to dampen wave energies, thereby helping to sustain the marsh-mudflat system. Adequate sediment supply to marshes and mudflats will strengthen the resiliency of the estuarine coastline to SLR.

Marsh/Mudflat Response to Storms

As estuarine ecosystems, tidal marshes are significantly shaped by both terrestrial and ocean processes. Specifically, marsh accretion processes are driven by the surface deposition of sediment and accumulation of organic material. Flooding by tides and extreme water levels transport suspended sediment from local water bodies onto the marsh plain, supporting deposition (McKee et al 2013). With respect to SLR, a marsh may “drown” and convert to mudflat habitat if the rate of local marsh accretion does not keep pace with the rate of SLR. Similarly, mudflat complexes (which are typically located adjacent to marsh) are predicted to convert to shallow subtidal as local water levels rise. To maintain ecosystem function, marsh and mudflat accretion rates must keep pace or exceed local SLR rates.

An active area of research in San Francisco Bay and other major urban estuaries is the role of episodic, storm-driven events in maintaining and increasing marsh elevations through sediment deposition. These types of landscape-scale disturbances are linked with extreme water levels from storm surge and fluvial flooding, which can significantly influence geomorphic processes at the marsh.

Studies from Venice, Italy (Pannozzo et al 2023) as well as locally in San Pablo Bay (Thorne et al 2022) demonstrate through long-term monitoring methods (deep rod Surface Elevation Table and feldspar marker) that storm-driven events result in the most natural sediment deposition to marshes, as extreme water levels would maximize amounts of suspended sediment delivered to the marsh. Thorne et al (2022) monitored sediment accumulation rates, elevation change, and flooding at five (5) tidal marsh sites, across San Pablo Bay, Suisun Bay and the Sacramento River. The sites, which ranged from riverine- to ocean-dominated, were monitored during the January/February 2017 atmospheric river events, which brought record-setting precipitation to California. The study characterized geomorphic landscape by the following parameters: elevation, tide range, salinity, distance to San Pablo Bay, distance/size of nearest channel, size of nearest major watershed.

Of the 5 monitored sites, San Pablo Marsh is located closest to the Marin County side of San Pablo Bay. While the San Pablo Bay marsh did not exhibit an immediate response to the storm, surface elevation gain was observed the following measurement period after the storm which indicates local processes post-storm (e.g., wind-wave resuspension) likely transported fine-grained sediment from the mudflat onto the marsh. Ruhl et al (2004) found that shallow areas functioned as “storage” for suspended sediment that had been transported downstream by freshwater pulse events, where wind could then resuspend sediments. Other recent studies in estuarine morphodynamics (Lacy et al 2020) affirm that moderate wave action in the summer season was a significant contributor to annual accretion in the marsh transition zone, even more so than winter wave conditions.

Dredging and Sediment Disposal or Reuse in San Francisco Bay – Comparison between Traditional Methods and the SSPD Approach

Dredging and disposal are traditionally two separate parts of any dredging project that while connected can be performed in different combinations. This section describes the typical (aka "traditional") approaches to dredging and disposal in the San Francisco Bay and compares these approaches to the SSPD dredging approach which is uniquely a single combined dredging and reuse approach.

Traditional Dredging and Disposal in San Francisco Bay

Maintenance dredging in San Francisco Bay typically involves the following steps:

1. Sediment Quality Testing: Sediment sampling is conducted, and results are reviewed by the DMMO to determine if the sediment is suitable for aquatic or upland placement.
2. Excavation: Removing recently shoaled sediment from the dredging site.
3. Transportation: Moving dredged material via scows, hopper dredges, or pipelines to the placement site.
4. Placement and Management: Depositing and managing dredged material at designated sites or transferring it to another permitted location for use.

Typical methods of maintenance dredging include hydraulic or mechanical dredging (Figure 9). Hydraulic dredging involves hopper dredges (a ship with a hopper bin to store and transport material) or suction/cutterheads attached to hydraulic pipelines that convey the dredged material to a scow or directly to a placement site. Mechanical dredging involves bucket or clamshell dredges, which scoop material from the channel bed and place it directly into a scow for transport to a placement site. The various methods of dredging and equipment used are discussed below.

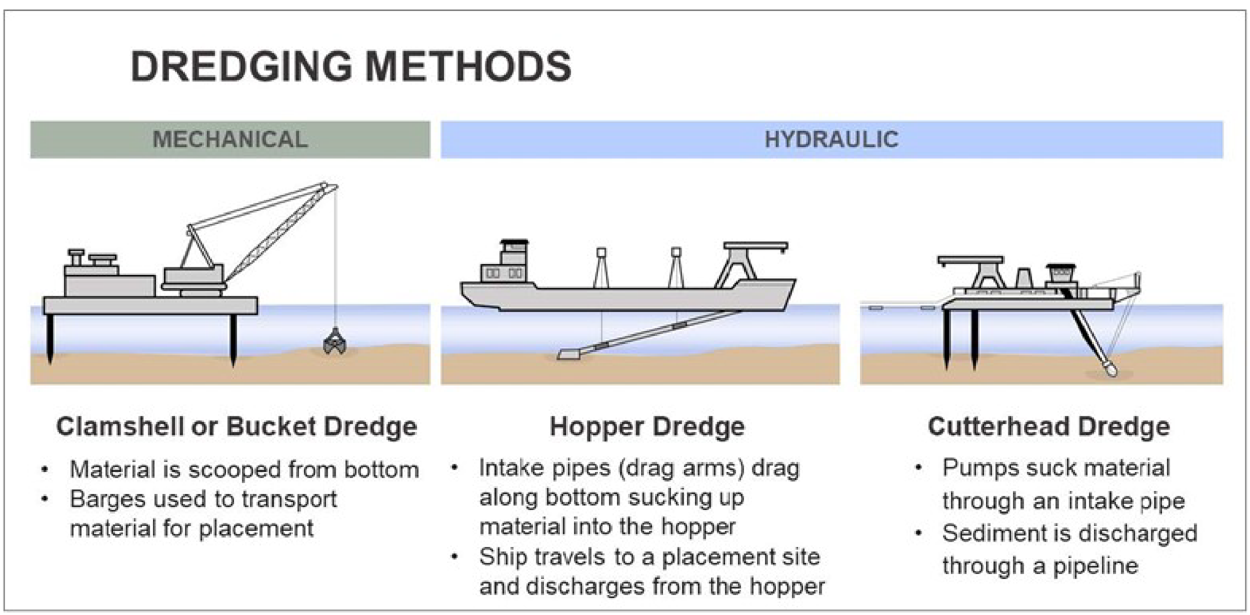

Figure 9. Traditional dredge equipment

The most common dredging method in San Francisco Bay is mechanical clamshell dredging which uses a sediment excavator to dig, lift, and place sediment into barges for transport to the disposal site. Hydraulic cutterhead dredging is another common dredging approach around the world that tends to be at a lower cost but is usually prohibited in San Francisco Bay due to concerns over fish and aquatic species entrainment. This blanket restriction is unique to San Francisco Bay proper and is allowed at most other SPN O&M locations that also have fish and aquatic species. Within San Francisco Bay proper, the most common dredging method, especially for the ports and marinas (most dredge locations), utilize clamshell dredging and placement into barges that are then pushed and guided by tugboats to the disposal location. In most locations, the implementation process of dredging and transport of sediments and disposal is powered by diesel engines and fuel, resulting in a large pollutant and GHG footprint.

For narrow flood control channels, a common desilting (similar to dredging) method is digging of sediments from the channel banks and transport by trucks to the disposal site(s). This approach is limited by the digging distance from the top of bank to the channel. This approach is more properly called desilting than dredging, a term typically reserved for water-based equipment, not land-based. Where feasible, digging sediments using typical land-based equipment may be less expensive because the equipment is more readily available and the number of contractors able to do this kind of work is much larger than the smaller number of marine dredging contractors, however as noted below the disposal costs may be higher because the sediment have to be truck transported unless there is a disposal site immediately adjacent to the dredge site.

Hydrodynamic Dredge Methods

The SSPD approach utilizes a newer and potentially environmentally preferable dredging approach known as hydrodynamic dredging. Hydrodynamic dredge methods are defined as dredging techniques that rely on natural forces (e.g., waves and tides) to transport suspended sediments within the water column. Sediments are suspended using methods such as agitation dredging and water-injection dredging (WID), which are described below. Compared to a mechanical or hydraulic dredge, hydrodynamic dredging keeps dredging activities completely below the water surface and removes the need for above-water handling and placement.

Richardson (1984) defines agitation dredging as: “the removal of bottom material from a selected area by using equipment to raise it temporarily in the water column and currents to carry it away.” The success of the operation is dependent on currents transporting sediment out of the dredge reach. If material is suspended, but redeposited shortly afterwards in the same location, only agitation has been achieved and not necessarily agitation dredging. The recent deployment of a water agitation dredge (Tiamat) in Harwich Harbor, UK is a successful case study application of the technology for harbor maintenance.

WID is defined as dredging that pumps water at high-velocity and adjustable bed jet pressures through a series of flow nozzles into the channel bed, which erodes and fluidizes sediment from the bed and creates a near-bottom density current which carries the sediment downstream with the tides (Tyler et al 2022; Welp et al 2017). The production rate, or volume moved by the dredge process, is influenced by the channel and sediment parameters (e.g., grain size, channel slope, channel geometry). As compared to traditional dredge methods, WID operations require less time to achieve a desired production rate, which results in lower overall costs, interference to navigation, and disturbance to the local environment (Fuller et al 2024).

Current Use Cases in Continental U.S. and UK

Within the continental U.S., WID has been used by the USACE to dredge federal navigation channels since 1992 (Wilson, 2007) primarily in various locations along the Mississippi River. Key waterway projects include the Michoud Channel and Mississippi River Gulf Outlet (MRGO) in 2002 and 2003, respectively. These case studies were all conducted as dredging in a deepwater context and with coarser sediments (sandier) compared to the estuarine context proposed in this pilot study. For the 2003 MRGO case study, WID was shown to be highly effective, with a dredge period of 96 hours (about 8 days) and approximately 350,000 CY of material removed (production rate: 3,645 CY/hour), which corresponds with a production rate of 3,645 CY/hour and a unit cost of $0.28/CY. Table 1 summarizes known case studies of WID in the continental U.S. and a case of agitation dredging in the UK. The reader is further referred to Fuller et al (2024) for additional detail on U.S. case studies of hydrodynamic dredging.

Table 1. WID Dredge Use Locations and Characteristics

Location	*Year*	*Dredge Characteristics*	*Comments*
Michoud Channel	2002	WID applied for maintenance dredging of federal navigation channel (deepwater)	232,235 CY removed over 96 h. 2,419 CY/hour production rate. Median grain size of 0.06 mm.

Mississippi River Gulf Outlet	2003	WID applied for maintenance dredging of federal navigation channel (deepwater)	350,000 CY removed over 96 h.3,645 CY/hour production rate. Similar grain sizes to Michoud Channel.
Port of Wilmington, NC - North Carolina State Ports Authority (NCSPA)	2022	Custom-built WID for harbor maintenance dredging	71,000 CY removed from permitted dredging area. 2,450 CY/hour production rate. Monitoring conducted by USACE ERDC.
Harwich Harbor, UK	2023	Tiamat agitation dredge	2,875 – 5,875 CY/hour production rate. Shown to be effective in removing silty sediment from navigation channels.
Tuttle Creek Lake	2024	WID for reservoir sediment management	Proposed pilot project is undergoing public comment and environmental review

Despite examples of successful use, currently no WID or hydrodynamic dredge equipment is known to be available to projects within the San Francisco Bay Area or West Coast, nor does the existing technology service shallow-draft areas. Discussions with subject matter experts in the dredging industry indicate that the potential for adapting the dimensions of the dredge equipment to shallow depth applications is high and that there are a wide range of additional use cases for such technology in similar sediment management projects (e.g., reservoir sediment management, small ports/harbors). The proposed effort would be the first application (as far as the authors know) of hydrodynamic dredge equipment for a shallow tidal creek.

Dredged Material Placement Options in San Francisco Bay

Dredged material placement most often represents the largest cost in dredging projects. Placement costs usually exceed the dredging costs (of course, depending on many factors, so all costs are every project specific). Traditional disposal options in the Bay, especially from port and marina dredging, has been at one of the following locations:

- *In-Bay Placement at Designated Sites* - There are four permitted disposal sites in San Francisco Bay that are limited to certain, usually smaller maintenance dredging project sites. The major in-bay disposal sites are SF-9, SF-10, SF-11, and SF-16. These sites are not suitable for the larger dredging projects and are difficult to permit tidal flood control channels due to limitations on volume. This disposal option still requires clamshell dredging methods that are slow, costly and may not fit within smaller and lower draft channels.

- *Placement at Permitted Placement Sites* – As noted previously, there are two permitted placement sites located in the Bay that are available for beneficial sediment placement, the Cullinan and Montezuma placement sites. Both sites are on diked former baylands that have subsided by several feet and thus require a large volume of sediment to bring them up to elevations suitable for breaching the sites and re-establishment of wetland vegetation and habitat. These sites operate by charging a tipping disposal fee for barges of dredge sediments seeking to place their sediment for beneficial reuse. Additionally, the former Hamilton AFB was a USACE project completed in 2014, known as the Hamilton Wetlands Restoration Project. The project placed approximately 6 million cubic yards to raise grades to those suitable for tidal restoration. This disposal location is most applicable for larger projects where there is an economy of scale for placement of hundreds of thousands to millions of yards into the site. This type of placement likely requires construction of a new offloader facility and equipment. Cullinan will likely be completed (filled) in FY 2024, leaving only one permitting site accepting material until others can come online, which may be several years.

- *Ocean Disposal* – The least-cost placement option for multiple channels for many years has been the San Francisco Deep Ocean Disposal Site (SF-DODS) located approximately 55 nautical miles offshore of the Golden Gate bridge. The sediments are bottom dumped into the ocean. In recent years, there has been push back from environmentalists and agencies to reduce or eliminate ocean disposal in favor of more expensive beneficial use of these sediments. In recognition of the value of dredged material, and therefore waste associated with ocean disposal, recent policy changes, including cost-sharing opportunities, have allowed SPN to direct more material to beneficial use sites instead of SF-DODS. The Water Resources Development Act (WRDA) 2020 Section 125(a) authorizes cost-sharing for the beneficial use of dredged material at 65 percent federal/35 percent non-federal, given the benefits justify the additional cost. The added risk of rising sea levels due to climate change has also heightened the awareness of the need to keep Bay sediment within the Bay system is critical to sustain our marshes and wetland habitats in the era of SLR and accelerated SLR expected to happen mid-century.

In addition to the traditional approaches, there are newer approaches that are being promoted by many local agencies and environmental groups.

Newer Approaches to Dredge Sediment Beneficial Reuse Options

- *Thin-Lift Sediment Placement* – Thin-lift placement refers to the hydraulic placement of dredged sediments to a depth of approximately 10 to 20 cm thickness. on a low-elevation tidal marsh. This fill depth is suitable for natural vegetation to grow through mimicking the natural episodic deposition of sediment following storm events and subsequent vegetation regrowth. This approach has been used more extensively in the Gulf and East Coasts, especially by the USACE, and has been shown to be effective. This approach has been used at Seal Beach in Southern California by the USFWS and with some lessons learned has been shown to be effective. In San Francisco Bay, Marin DPW pioneered this on a small scale for the 2016 and 2020 maintenance dredging of Novato Creek. Subsequent monitoring by DPW has shown extensive vegetation regrowth in the areas where sediment was placed. While thin-lift placement is an important approach that should be promoted, it still requires a hydraulic cutterhead dredge with its local impacts and fish entrainment concerns as well as HDPE (oil based) pipelines and a higher use of diesel fuels. However, it does not require barges and tugboats and significant transport distances to move sediment and as such is environmentally more beneficial than the traditional dredging and disposal options described above. This approach also has an added ecological benefit of engineering the natural connectivity of local watersheds to local marshes when the thin-lift placement occurs in the same watershed.

- *Shallow-Water Strategic Placement* – As noted previously, the San Francisco District has conducted a pilot project implementing shallow water strategic placement using clamshell dredging and transport by smaller scows (lower draft). Dredged sediment is transported to locations adjacent to mudflats and marshes for bottom dumping sediment into the bay with the goal of sediment movement and dispersal onto marshes by the tides. In December 2023, 90,000 CY of clean dredged material was transported and placed in shallow mounds offshore of Eden Landing Ecological Reserve (Hayward, CA). The pilot is undergoing monitoring through calendar year 2024. This approach removes some of the large transport distance and tipping fee costs required for the currently permitting bulk fill locations described above. However, in many areas, the placement location may still be miles away from the nearest marsh due to depth limitations preventing scows which typically draw ten (10) plus feet of draft when loaded with sediments and thereby unable in many locations from getting close enough to the marshes to be resuspended by wind-waves and transported toward shore.

  Another example of shallow water placement is the Mud Motor project implemented on the Wadden Sea coast in the Netherlands, which successfully added elevation to a nearby salt marsh. This is a method developed from the Netherlands that was used to strengthen and elevate salt marshes by placing mud upstream (tidally) from the marsh area and harnessing natural tidal flows to distribute the fine-grained sediments (there is a corresponding sand motor for sand placement).

- *Marsh Adjacent Hydraulic Pipeline Placement* – The USACE has also shown in figures the concept of hydraulic dredging and placement of the pipeline discharge immediately adjacent to the marsh. This concept has not been further developed past the concept figure stage and would need to be evaluated for impacts such as increased shoreline erosion due to outlet pipe velocities as well evaluations of how much marsh nourishment would be accomplished as well as turbidity impacts in these localized areas subject to large scale sediment placement to the marsh area. This alternative does not appear to offer many (or any) benefits over the thin-lift direct placement onto the marsh described above. A recent example of this type of approach is use of dredged material at Nummy Island, New Jersey for marsh rehabilitation. The dredging at this location uses a hydraulic cutter-head dredge connected to a floating pipeline, which sprays the mixture of fine sand and mud onto the marsh surface, creating a favorable substrate for marsh recovery and allowing natural processes to facilitate the growth of marsh grasses.

Differences and Pros/Cons Between Engineered Sediment Placement Options and the SSPD Natural Sediment Dredging Approach

As discussed above, in San Francisco Bay, by volume the primary engineered placement of sediment has been by far the bulk fill placement in subsided former diked baylands. Newer sediment reuse approaches such as thin-lift sediment placement have been used on small scale on the East and Gulf coasts but have had little application within San Francisco Bay. To-date, the only application of thin-lift placement has been by Marin Flood Control in the Deer Island Basin in the Novato Baylands, and this was for a very small amount of sediment, of approximately 15,000 CY. While there is much agency interest in promoting the beneficial reuse of dredged sediments, costs have been prohibitive for flood control agencies who do not have revenue-generating mechanisms like such as (commercial) ports. Additionally, the prohibitive testing/sampling, monitoring, and reporting requirements of thin-lift placement have been a barrier to widespread use of this approach in San Francisco Bay.

Table 2 summarizes the pros and cons for three of the most used sediment placement options and compares against the SSPD approach being evaluated as part of this study.

Table 2. Qualitative Comparison of Selected Beneficial Reuse Sediment Placement Approaches to Tidal Marsh Nourishment

Approach to Marsh Sediment Addition	Type of Bayland	Major Pros	Major Cons
Bulk Sediment Placement	Subsided Diked Former Baylands	Bulk placement in a subsided basin allows for some cost-scale benefits Most suitable for large dredging projects where larger volumes are being placed	Costly and achieves most benefits at larger scale Suitable for highly subsided areas and less suitable for active marshes that requires regularly-occurring placement of sediment to maintain marsh elevations
USACE Strategic Placement	Shallow Waters Adjacent to Eroding Marsh/Mudflat	Pilot study by Eden Landing shows promise for in-bay placement of sediment at what may be at a lower cost than bulk sediment placement Useful as an O&M tool to maintain marsh elevations over time	Pilot costs were on the same order as larger beneficial reuse projects Placement is in the vicinity of marshes but in some locations with too shallow for standard scows, or without sufficient wind-wave energy to resuspend sediment. Still requires clamshell dredging and barge movement; however, no off-loading facilities needed
Thin-Lift Sediment Placement	Eroding Marsh	Where appropriate, it may be cost-effective and produce lower GHG emissions to move local sediment from creeks to adjacent marshes as part of marsh sustainability. Overcomes historic urbanization that diked off sediments from their historic marshes. Recreates a sediment connection from watershed to adjacent marshes through engineered pumping and placement of sediment.	Difficult to permit in San Francisco Bay, but Marin FCD is applying for permits for both active and inactive marshes. Agencies require mitigation unless tied to an immediate tidal restoration project that is not always possible given site elevations and funding. Results in both loss of elevation capital gained over repeated dredging events over time since most

			maintenance channel dredging events are small in volume Requires a hydraulic cutterhead dredging system that may entrain and kill fish and requires greater water depths for effective dredging and pumps and piping for placement Extensive monitoring and mitigation requirements that drive up costs and uncertainty and results in inflated costs and uncertainty that results in public agencies unable to undertake projects with elevated risk
Strategic Sediment Pulse Dredging	Tidal Channels	Much lower cost and lower carbon GHG emissions to achieve dredging benefits Dredging equipment is less environmentally impactful than standard dredging equipment. The dredging approach is under current study by the USACE ERDC program and a technology of interest for applications as proposed within this study. Impacts to aquatic species and fish should be much reduced as compared to hydraulic cutterhead dredging because of reduced fish mortality or fish entrainment into the dredge pipeline and stranding in the disposal site. SSPD mimics strong currents, which fish are likely to be adapted to.	Dredging technology and equipment is new and currently not commercially available in San Francisco Bay The timing of the proposed dredging approach is relatively new (on the West Coast) and may have different implementability and contracting challenges than standard dredging contracts. There are emergency response contracting vehicles that could be used for this purpose. Sediment reuse benefits are more difficult to quantify than direct placement, but implementation, mitigation and monitoring costs may be barriers to projects happening.

SSPD Logistical and Operational Feasibility Evaluations

This section describes the operational constraints and anticipated costs for the SSPD dredging approach versus more traditional dredging performed in San Francisco Bay. All costs are approximate and are presented to allow for comparison between approaches and are subject to change as potential pilot design is refined and when contractor bids are received.

SSPD makes use of dredging technology (WID) that has been proven effective for deep water harbor dredging in England and in an East Coast Port, so the effectiveness of this approach is known for deep-water dredging applications. What is being proposed for evaluation for this study and described in more detail in this section are operational modifications for use in San Francisco Bay in the dredging of shallow water tidal flood control channels.

1. Modification for Shallow Draft Tidal Channels – The WID dredge technology will be adapted for this application to the dredging of shallow draft tidal flood control channel with depths that tend to range to 4 to 6 feet at MHHW tides and lower under lower tide levels.

2. Timing of the dredging occurs around periods when the bay is in more turbulent condition and the forces of tides tend to move sediment around the bay into mudflats and marshes.

3. Control of the depth and movement of the created turbidity plume through dredge operations. The technology allows for some measure of control over the mixing depth and thickness of the turbidity plume through control of jet and boat angles.

Each of these operational constraints is discussed in more detail below. The proposed field pilot study will be able to test and refine each of these SSPD dredge parameters and the proposed monitoring program will assess its effectiveness in meeting multiple project goals.

Timing and Contracting

A core basis of the SSPD is that the dredge shall occur during periods when the wind-wave and tidal forces are higher and thus able to move disturbed sediments naturally to the various locations in the Bay where it naturally deposits such as mudflats and marshes. These are the periods when the bay is naturally turbid (Figure 10). This timing addresses agency concerns over turbidity impacts to various aquatic species. However, elevated turbidity during high wind and storm events is a natural state of San Francisco Bay during high wave and tidal force events and the various aquatic species have adapted to these periods of higher turbidity. This concern is one of the major reasons that dredging in San Francisco Bay is expensive and beneficial reuse is limited to large USACE-funded port dredging projects. Setting a single dredge window standard for all bay conditions is not scientifically valid and fundamentally misunderstands the variability and resilience of natural systems. A “design with nature” approach to all aspects of natural systems from dredging to wetlands relies on working with the forces of nature and not against them or setting artificial regulatory limits as if they do not exist.

Figure 10. Satellite imagery of San Francisco Bay during the winter season, when turbidity in the Bay is naturally elevated (January 25, 2019 imagery from the Copernicus Sentinel-2)

To this end, the next stage of the SSPD pilot proposes to evaluate the advantages or the need to schedule dredging around these states of elevated bay turbidity. This is no trivial matter as contracting for dredging on an unknown schedule is much more difficult and is not the typical engineering and environmental compliance standard.

Dredge Timing Alternatives

This section discusses the various alternatives for timing of the proposed SSPD. An in-the-ground pilot would provide real-world monitoring data that would help inform which of these alternatives might be most feasible and appropriate for the desired outcomes and logistical constraints:

1. **No Timing Limitations**. This alternative involves dredging without any contractual limitations on timing. However, permit restrictions such as work-windows may still apply, limiting the time available for dredging.

2. **Timing Around Winter Storm Events**. The SSPD would be implemented around winter storm events. The definition of “around” would need to be developed further during the next field pilot phase of the project. EWN involves some uncertainty due to the unpredictability of both natural forces and the output of natural systems. There is a trade-off in any dredging approach and working “around” winter storm events may mean a window of days/weeks both before/after a significant storm event. It does not mean implementation during a major event when safety considerations are paramount.

3. **Timing Around Summer Higher Wind Events**. During the TWG meetings, a USGS scientist pointed out that the consistently elevated summer winds also increase the wave and hydrodynamic conditions in San Francisco Bay suitable for performance of this dredging approach. Based on their research, these conditions may perform more

sediment transport "work" than even episodic winter storm events. USGS scientists have recognized the importance of higher summer wind events to sediment movement onto marshes. This may represent an opportunity to conduct dredging operations during non-winter periods.

Note that the next phase pilot study can ascertain if timing of dredging operations is needed to avoid turbidity impacts. Studies conducted by the USACE evaluating the Tiamat dredge in England showed almost no turbidity impacts for dredging conducted under non-storm or wind event conditions, therefore, it is not certain that this additional requirement is necessary to perform this dredging approach to avoid impacts to aquatic species. Summer months may be strongly preferred for SSPD, due to operational safety concerns and due to existing in-water work windows established by environmental regulatory agencies to protect species of concern. However, to the extent that water perturbation dredging can be timed with periods of higher wind-wave and tidal forces this will help to move sediments onto mudflats and marshes.

Shallow-Draft Operations

Another characteristic of the SSPD dredge approach is its application to narrower, shallow draft tidal flood control channels, which is a completely new operational endeavor. To-date, WID and hydrodynamic dredging (e.g. Tiamat) have been in deepwater ports.

The constraints on dredging of shallow draft are more intensive than those in deep waters. The dredge vessel requires a water depth of three to four feet minimum, which will limit dredging in many if not most tidal channels that may have bed elevations at or above MLLW. Therefore, it is likely that the SSPD dredge will be limited to approximately half the tide cycle on any given day. Note that the winter perigean spring tides, also known as king tides, occur during the days in December and January allowing for higher tide levels. These same water levels are also raised by stormwater outflows, which may allow for longer dredging periods during daylight hours.

The final determination of dredging depths and tide levels will depend on the pilot study as well as the practical limitations of dredge vessel construction for commercial dredging vessels which is still to be determined for the West Coast. The PDT has been working with ERDC dredge experts to evaluate potential options for shallow-draft dredge vessels that can navigate narrow channels.

Operational Safety

The planning of timing dredging around storm events of periods of elevated wind-wave conditions and/or increased freshwater flows requires careful safety requirements related to being on the water during periods of turbulence. Additionally, the timing of the dredge event may occur before or after a winter (seasonal) storm event. Sediment pulse dredging would not include operation outside of the typical range of marine operations for the winter season. Vessels in San Francisco Bay must navigate these conditions during winter periods every year and commercial dredging companies are trained to operate during these periods as well. As the sediment pulse dredge is being proposed for application in Marin County or elsewhere within the Bay, conditions are also anticipated to be calmer compared to an open ocean location (e.g., DODS) during typical dredge operations.

Costs

Costs for this study are separated into costs for the pilot study (Table 3) and costs for the SSPD dredge method as compared to two other traditional dredge methods clamshell and hydraulic cutterhead (Table 4). All costs are considered planning-level; values are approximate and provided for comparison purposes. Costs are subject to change during the time as planning and design of an in-the-ground pilot is refined during competitive bid conditions.

Pilot Unit Costs

Table 3 contains the anticipated costs for design, permitting, implementation and monitoring and reporting for the proposed pilot study in Gallinas Creek. Each cost is broken out by category with a unit cost, number of units and a total cost. A reference column describes the cost basis and source.

The anticipated approximate total cost for the pilot study is $1.8 million including fabrication of a pilot vessel, monitoring and preparation of a summary report and recommendations for next steps. Given draft limitations, the pilot (dredge) unit will be towed with a skiff with twin outboard engines suitable for use in depths of 3 to 4 feet of water.

Comparison to Traditional Dredge Methods

Table 4 compares the proposed SSPD dredge to the two most common other shallow water dredging methods known to occur in San Francisco Bay, clam shell loading into barges (or scows) and hydraulic cutterhead dredging. Clamshell dredging into barges is not commonly done because of the draft limitations of barges is typically greater than available in tidal channels except during periods of high tides and for small (hence more expensive) barge, 200 to 500 CY or smaller. These smaller barges lose the economy of scale and are not ocean-worthy, so this is best suited for in-bay disposal options,

Other Considerations

Dredging is an equipment and labor-intensive business which requires specialty training and expertise. The number of qualified contractors experienced in marine dredging is much fewer as compared to conventional land-based contracting. The upfront equipment costs are typically extremely high and therefore, dredging contractors are not going to make upfront investments in new equipment or even in the training for new dredging approaches without some assurances that there is going to be a market of projects to pay for the equipment. Therefore, widespread adoption of this innovative approach will require certainty in the permitting for these types of projects.

Table 3. Pilot Study – Two Week Field Deployment and Monitoring Effort

Design, Permitting and Bidding	#	Units	$/unit	Total ($)
Design	1	LS	$ 50,000.00	$ 50,000.00
CEQA	1	LS	$ 100,000.00	$ 100,000.00
Permitting	4	EA	$ 60,000.00	$ 240,000.00
Preparation of PSE	1	LS	$ 50,000.00	$ 50,000.00
Preparation of monitoring plan and program	1	LS	$ 40,000.00	$ 40,000.00
Bidding and Award	1	LS	$ 25,000.00	$ 25,000.00
			Sub-Total Design, Permitting and Bidding:	$ 505,000.00
Pilot Unit Design and Construction				
Design	1	LS	$ 60,000.00	$ 60,000.00
Fabrication	1	LS	$ 300,000.00	$ 300,000.00
Deployment and pre-ops testing	1	LS	$ 40,000.00	$ 40,000.00
			Sub-Total Pilot Design and Construction:	$ 400,000.00
Field Pilot Test – Est. Two Weeks				
Field mobilization	1	LS	$ 40,000.00	$ 40,000.00
Electrical connections	1	LS	$ 25,000.00	$ 25,000.00
Dredging	14	DAYS	$ 20,000.00	$ 280,000.00
Data collection monitoring	30	DAYS	$ 16,000.00	$ 480,000.00
Turbidity				
Benthic communities				
Suspended Sediment				
Demobilization	1	LS	$ 12,000.00	$ 12,000.00
Analysis of data	1	LS	$ 20,000.00	$ 20,000.00
Final report preparation	1	LS	$ 40,000.00	$ 40,000.00
			Sub-Total Field Pilot Study:	$ 897,000.00
				$ 1,802,000.00

Table 4. Cost Comparison – SSPD vs Traditional Dredge Methods

Item	Hydraulic Dredging w/ Local Thin-Lift Placement (1)	Clamshell and Barge to San Francisco-10 (2) Lower Reach Only (note 2)	Clamshell and Barge to Beneficial Reuse (Cullinan, Montezuma) (Lower reach only see note 3)	SSPD (4)	Comments
Dredging and Disposal					
Mobilization (lump sum)	$ 1,100,000	$ 700,000	$ 700,000	$ 500,000	
Dredging and disposal (per cubic yard)	$15 - $35/CY	$15 - $25/CY	$34 TO $44/CY	$6 - $10/CY	costs for SSPD to be confirmed following pilot study.
Monitoring and maintenance (total assume 7 years)	$ 1,000,000	$ -	$ -	$ 300,000	

Notes:

(1) Thin-lift costs from 2024 Environmental Science Associates memo to Marin County for Gallinas Creek to McInnis Dredge sediment placement. Assumes two mobilizations over two years. Note that staff believe the unit cost reflects uncertainties in the new approach, and it would be lower if this approach had more experience in San Francisco.

(2) Values from USACE costs table. Note that there is insufficient draft to dredge Gallinas Creek above the downstream confluence with Santa Margarita Island so this approach cannot meet goals for the Gallinas Creek project in the upper reaches

(3) Montezuma and Cullinan costs include monitoring. As noted above, clamshell and barging are limited to reaches below SM island.

(4) SSPD costs are approximate and based on engineering experience and discussions with TWG members experienced in use of this dredging technology

3. Pilot Site Selection and Criteria for Feasibility

Site Selection Process

The following Marin County creeks were discussed by the team as potential sites to progress further in modeling conducted for the pilot study. A summary of the creeks is provided below. Figure 11 shows the locations of the creeks.

- *Corte Madera Creek* – Corte Madera Creek is a tributary to San Francisco Bay and drains a watershed of approximately 24.4 square miles. At the downstream end, the creek is bounded by the town of Greenbrae to the north and Larkspur to the south. The Corte Madera Marsh State Park is a marsh complex immediately south of the outlet.

- *Coyote Creek*- Coyote Creek is a tidal flood control channel with a small watershed of approximately 4 square miles that has a high sediment load due to the erosive nature of the watershed geology. The Coyote Creek channel was built by the USACE and provided to Marin Flood Control in the 1964s but may be currently out of compliance due to unauthorized easements and a lack of freeboard capacity. The creek is short and is concrete lined in the upper steeper reaches and earthen levees in the lower reach where the slope flattens out. The proposed dredge could provide necessary flood risk relief and sediment boost to downstream wetlands at Bothin Marsh, which is presently eroding.

- *Gallinas Creek* – Gallinas Creek drains a 5.6 square mile basin between the Miller Creek and San Rafael watersheds on the southwestern corner of San Pablo Bay. The North and South Fork of Gallinas Creek join at the confluence by the low-lying community of Santa Venetia, built on a former mudflat. Two Marin County Flood Control Zones are located near Gallinas Creek: Zone 6 (San Rafael Meadows) and Zone 7 (Santa Venetia). Both flood control zones are at risk of flooding under SLR and elevated runoff volumes in the watershed from extreme precipitation. Marsh complexes, including the China Camp Marsh, which is maintained by the San Francisco Bay National Estuarine Research Reserve, flank both sides of the creek outlet into the Bay.

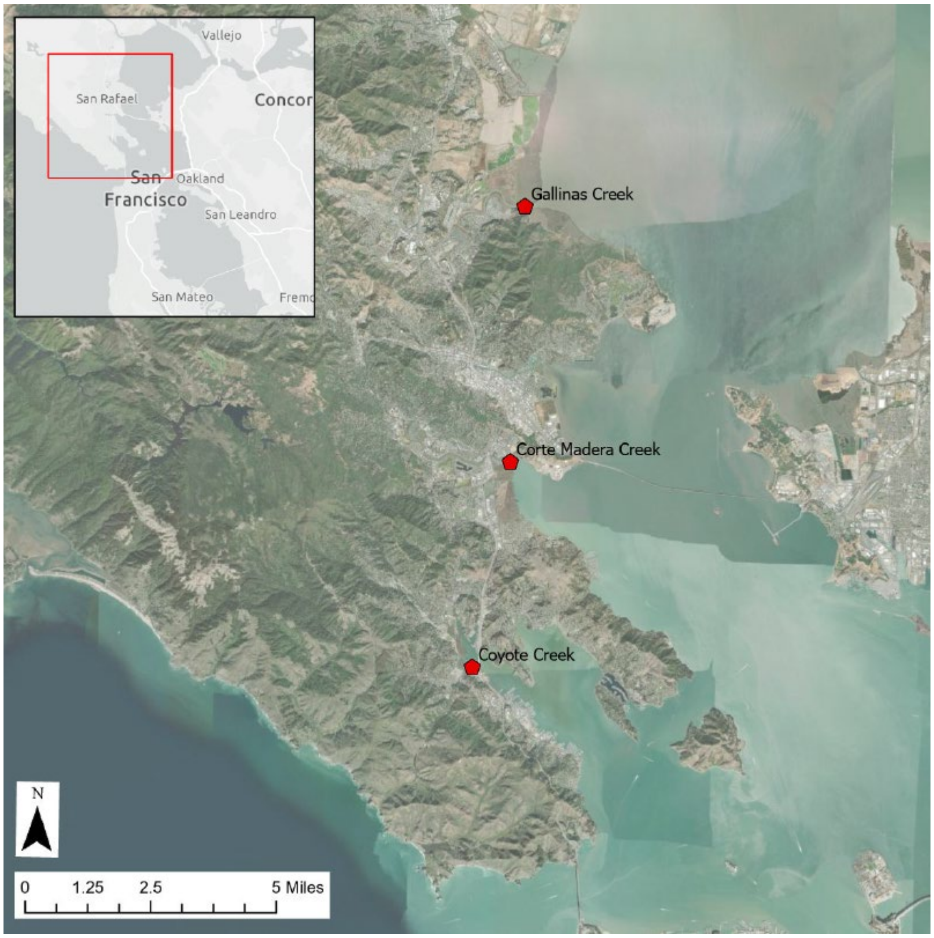

Figure 11. Marin County tidal creek locations

Table 5 summarizes the site selection parameters, including benefits and limitations, associated with each channel, based on team discussion and with the Technical Working Group through Fall 2023.

Table 5. Site Selection Parameters for Marin County Creeks

	Gallinas Creek	Corte Madera Creek	Coyote Creek
Data Availability for Creek and Downstream Marshes	The National Estuarine Research Reserve (NERR) maintains a full-time water quality sensing station at the mouth of Gallinas creek with real time water level and water quality parameters including salinity and turbidity. USGS has also collected data in the vicinity. The USACE and Marin County had both conducted hydrology and hydraulic modeling studies, and the County had recently resurveyed the creek in 2024.	USGS has collected data at Corte Madera marsh. Marin DPW maintains a network of rain and tide gauges for water level in the Creek and watershed.	Limited data availability. Marin DPW maintains a full-time water level sensor in Lower Coyote Creek and has conducted grab samples for suspended sediment during storm events.
Potential Flood Risk Reduction Benefits	Proximity to low-lying Santa Venetia community, which is actively affected by reduced conveyance	Would improve level of flood protection	Existing flood risk - out-of-compliance currently with freeboard
Potential Benefits to Marsh	Multiple opportunities to monitor and measure potential marsh benefits downstream of Gallinas	Multiple opportunities to monitor and measure potential marsh benefits at Bothin Marsh	Bothin Marsh is located downstream of Coyote Creek. Best opportunity to show how sediment resuspended higher up in system goes into marshes
Constraints	The creek has the smallest fluvial input than the other two creeks limited the outflow velocity. It represents a more conservative scenario than the other two creeks where higher fluvial outflows will move sediment further out into the system.	Less than one tidal excursion away from the marsh. Ebb-tide processes would transport sediment back into the channel and it will not find its way back to the marsh. Ferry terminal dredges at mouth so impacts to dredged channel would have to be mitigated.	Hydrodynamic dredge may only be feasible in a small reach between Highway 1 and the Bay Trail. Equipment may have to be transported to this reach by truck. Active restoration plans proposed for Bothin Marsh in-progress by Marin County, which may complicate logistics.

Given the proximity of the Santa Venetia community, which has experienced longstanding flood risk issues from severely reduced channel conveyance, as well as the potential to increase SLR resilience for the downstream marsh complexes which are well-studied (e.g. China Camp Marsh), Gallinas Creek was thought to be an optimal candidate to evaluate the SSPD approach. The selection of Gallinas Creek, out of the three Marin County tidal creeks discussed above, for further evaluation in the hydrodynamic and sediment transport modeling conducted for the study, does not preclude the applicability of a sediment pulse dredge approach elsewhere in the Bay.

Gallinas Creek

The Gallinas Creek watershed is 5.6 square mile basin on the eastern side of Marin County between the Miller Creek and San Rafael watersheds. It has two main drainage areas:

- **North Fork**. The North Fork is the larger of the two drainages. It flows from the western ridgeline through the Santa Margarita Valley and the community of Terra Linda to its confluence with South Gallinas Slough near McInnis Park.
- **South Gallinas Creek**. South Gallinas Creek is a tidal slough channel fed by several small tributaries that originate in the San Rafael Hills and San Pedro Ridge and flow through the highly urbanized communities of San Rafael Meadows and Santa Venetia. It extends inland as far as the lagoon below the Marin County Civic Center. Upstream of that were several intermittent tributaries draining the Santa Margarita Valley. Miller Creek also runs in Gallinas Valley, and it has a separate mouth at the northern edge of Gallinas Marsh.

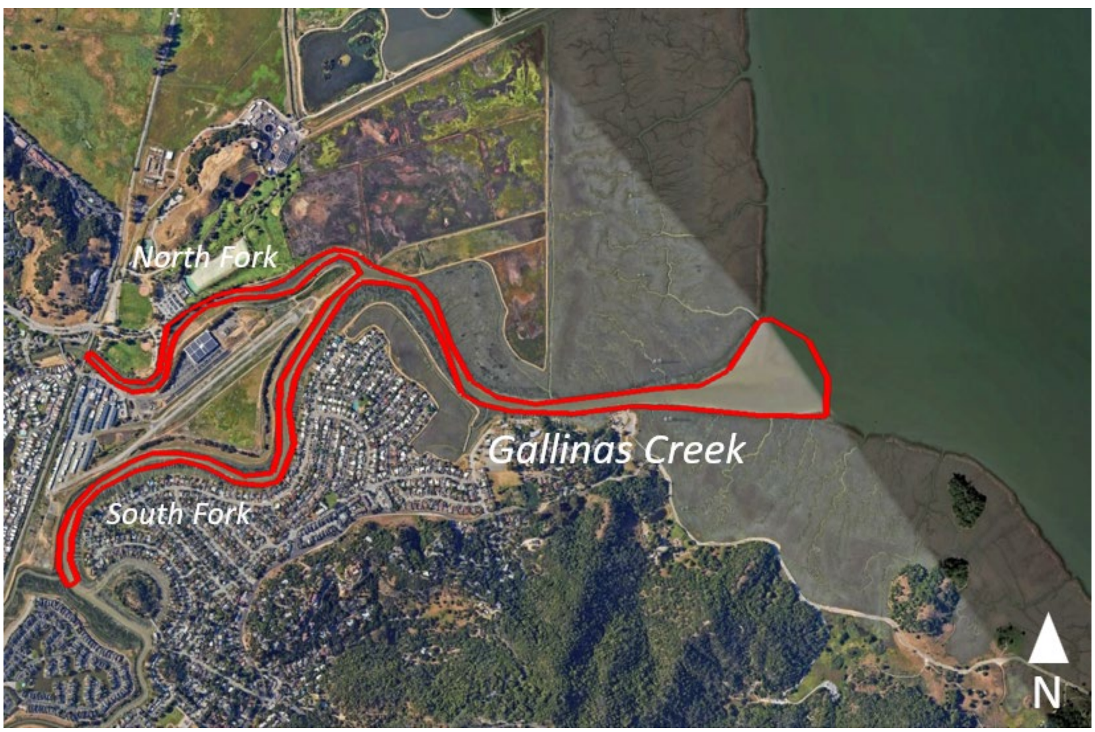

Figure 12. North and South Forks of Gallinas Creek

County Service Area #6 (CSA 6) (DPW) and consists of creek side properties along the south fork of the Gallinas Creek extending downstream to Bucks Landing off North San Pedro Road, including properties in the neighborhoods of Marin Lagoon and Santa Venetia. The Marin County Department of Public Works manage CSA 6. The primary purpose of CSA 6 is navigation and recreational boating. Due to a loss of historic tidal prism from developments such as Santa Venetia, the airport and Marinwood, the creek has narrowed and shallowed resulting in a loss of channel depth especially along the inner bend of Santa Margarita Island where the channel has filled above mean tide elevations and has seen vegetation (notably cordgrass) colonizing the aggraded mudflats resulting in increased sediment deposition. This has resulted in a high concern by the Creekside property owners, most of whom own docks that have silted in as the creek has been unable to be dredged. The lack of dredging may also exacerbate flooding of low laying areas.

There have been multiple H&H studies in the lower Gallinas Creek watershed mainly focused on flooding and ecological studies around the Santa Venetia development and the McInnis Marsh restoration project. The creek was surveyed in 2023/2024 by the County and used in the updated modeling work performed in this study. The PDT reviewed historic studies conducted by SPN and Marin County, including an existing HEC-RAS model of McInnis Marsh, to develop assumptions and fluvial inputs for the AdH model.

Event Selection

The concept of sediment pulse dredging assumes that the Bay is in an activated state (e.g., increased turbidity, higher winds) during or close to the time of implementation, such that sediment mobilized downstream from the dredge area would boost suspended sediment concentration in the "erodible pool." Ebb tide velocities, in combination with fluvial flows, must also be significant enough to move sediment that has been disturbed from the channel bed.

The following scenarios were determined to be representative of potential hydrologic and weather conditions where the sediment pulse dredge approach could be feasible:

- Pre/Post Winter Storm when operational conditions are safe
- Summer King Tides

The team decided to include a summer king tide scenario to assess the ability of ebb tidal velocities alone to transport sediment downstream after disturbance, which would provide a conservative evaluation of the method. More information on scenario assumptions and model input development can be found in Section 5: Hydrodynamic Modeling.

4. Environmental Considerations

Since the hydrodynamic dredging technology being considered is novel for San Francisco Bay, the environmental effects of SSPD are theorized based on studies conducted at other locations. On the other hand, the effects of traditional dredging in San Francisco Bay are well-characterized and understood and accepted ways. The USACE O&M dredging program complies with applicable regulations, including but not limited to those established in the National Environmental Policy Act (NEPA), Clean Water Act, Coastal Zone Management Act, and Endangered Species Act. Thus, the O&M program is implemented in an environmentally responsible manner.

Similarly, the implementation of SSPD would comply with all applicable regulations; however, SSPD is expected to have fewer environmental impacts than traditional dredging due to anticipated lower greenhouse gas emissions and reduced risk of harm to aquatic organisms. Should an SSPD pilot project be funded, full environmental documentation and compliance procedures would be undertaken to ensure all applicable regulatory requirements are met.

In traditional dredging, the environmental impact of greatest concern is typically entrainment of organisms, which is the incidental removal of organisms from their environment along with the dredged material. Organisms on or in the dredged material, such as snails, clams, or worms may be entrained, in addition to organisms in the water column near the dredging apparatus. Fish that are smaller, weaker swimmers, or often found near the bottom of the channel are more susceptible to dredging entrainment, which is defined as “the direct uptake of aquatic organisms by the suction field generated at the draghead or cutterhead” (Reine & Clarke, 1998; Technical Note DOER-E1). In addition, hydraulic cutterhead dredges may also physically damage and injure aquatic species as they are impacted by the cutterhead mechanism. Suedel et al (2019) documents the impacts on aquatic species from underwater sound generated by mechanical and hydraulic dredge equipment.

For SSPD, there is no entrainment, only the potential to disturb or hydraulically move organisms from their local habitat through the forces of the adjustable hydraulic jets. Suspension of sediment into the water column may also cause some species to move in response. However, during natural storm events, the entire water column is already turbid, so it is more likely species have evolved to adjust to short-term, storm-driven turbidity impacts. Any mobilized organisms would eventually settle where natural forces allow them.

Other potential impacts of SSPD include injury of organisms, smothering or burial of organisms, and increased turbidity. However, these impacts are considered less significant than entrainment. Recent case studies of WID and agitation dredge methods characterize them as virtually silent (Tiamat 2023 deployment; Fuller et al 2024).

It's also important to consider the natural context of the system. High-bed shear forces are a normal occurrence in fluvial and tidal systems during storm events. However, the dredge jets used in SSPD can be adjusted to minimize their impact. In this application, the jet forces will be set to a relatively low level, approximately 0.5 to 1 MN/m2, which corresponds to a pressure range of 58 to 100 psi. This low setting helps to reduce the potential for disturbance to the surrounding environment.

For the purposes of this study, the team chose to consider environmental effects in the near-field, defined as the immediate location where dredging would occur, and far-field, which encompasses areas downstream of the dredge segment and confluence with a larger body of water in the region.

Based on close discussion with the TWG and existing scientific literature, the team identified these key environmental considerations in the near-field pertinent to dredge activities, whether traditional (e.g., mechanical, hydraulic) or with a hydrodynamic dredge approach:

1. Impacts on Benthic Habitats and Aquatic Species
2. Water Quality
3. Contaminants –a site-specific parameter that will be considered for any proposed dredge location.
4. Community Rate of Recovery

As a relatively new technology, there is limited availability of scientific literature on the environmental impacts of hydrodynamic dredging. However, existing seminal papers on the topic seem to confirm that hydrodynamic dredge methods are more environmentally friendly. Based on discussion with the TWG, impacts to benthic habitat likely are the environmental consideration of greatest concern because benthic macroinvertebrates are generally concentrated in the top five centimeters of the sediment bed, which SSPD would directly disturb. Although, any form of dredging would disturb the top layer of sediment.

Pledger et al. (2020, 2021) studied the environmental effects of water injection dredging in a channel in England with depths of 1.6-9.8 ft. Their studies covered water quality (i.e., turbidity, salinity, dissolved oxygen, and pH) and community impacts (i.e., abundance, taxonomic richness, species diversity, and species dominance), which have not been well characterized for any form of hydrodynamic dredging. The statistically significant effects on water quality were increased turbidity, decreased dissolved oxygen, and decreased pH. However, these changes in water chemistry were short-term, usually returning to pre-dredge levels within an hour of dredging being ceased and comparable to changes due to tidal influence. For the community effects indicators, the upstream groups (control) were compared to the dredged and the downstream reaches. For fish, there were no significant effects on the dredged group; only the downstream group had significant immediate effects to taxonomic richness, diversity, and dominance. For benthic macroinvertebrates, there were significant effects across all indicators, but all effects were temporary since they recovered to control within the 5-month study period. For marginal macroinvertebrates, there were no significant effects except for a decrease in species dominance for the dredged reach.

Pledger et al. (2021) also found that health and mortality effects of water injection dredging were negligible; all 200+ fish that were captured during dredging were alive and showed no obvious signs of distress. They did find that 3% of the total catch had split or torn caudal fins, and these were all from the same, most-dominant species.

Near Field Effects

Water Quality

Studies by the USACE have shown that traditional dredging and placement methods do not cause substantial changes to salinity, temperature, or pH, and any minor changes are localized and short-lived. Dissolved oxygen (DO), the concentration of oxygen gas incorporated in water, can decrease during dredging. By suspending bed sediment, DO could decrease due to oxygen consumption of reducing substances in the newly exposed sediments or due to inhibition of photosynthesis from increased turbidity. Decreases in DO from traditional dredging are characterized as short-term (USACE and Regional Water Board, 2015). Similarly, any changes to DO due to SSPD are expected to be localized and temporary. Pledger et al. (2021) found that DO levels dropped during dredging but returned to ambient conditions in about three hours on average.

Suspended sediment

WID-generated density currents have a thickness varying between a few centimeters to a few decimeters. Their thickness is much smaller than that of the overlying water column, so the fluid mud's motion would not affect the upper water layer's motion.

WID-induced fluid mud layers may be eroded in the form of entrainment processes by the turbulent water column above, and Winterwerp et al. (2002) found that much of the WID-induced fluid mud layer in a flood-dominated estuary was entrained rapidly by the tidal flow and mixed efficiently over a major part of the river. Over half of the volume of the sediment mobilized was transported to the sea (one tidal excursion away from dredging site) during ebb tide and did not re-enter the river. Most of the sediment that remained in the estuary accumulated in the upstream area. After about one week, almost no sediment was traced in the water column.

Since SSPD is intended to be timed with a natural high-energy event, such as a winter storm or summer higher winds period, the fluidized mud layer likely would be eroded quicker than observed in published studies due to the increased turbidity, and the sediment would be suspended throughout the water column. The scale of the storm’s effect is expected to be much greater than that of WID’s suspension of sediment from the pilot site at Gallinas Creek.

The average turbidity at the Gallinas Creek NERR monitoring station, at which turbidity is measured every 15 minutes, during water year 2017 was approximately 77 NTU (n = 31,134, SD = 67 NTU). The average turbidity increases to 95 NTU (n = 2,976, SD = 75 NTU) for the month of January 2017, when atmospheric rivers occurred. The turbidity data can be visualized and downloaded at https://cdmo.baruch.sc.edu/dges/. Thus, species present at Gallinas Creek are accustomed to naturally occurring periods of elevated turbidity, and SSPD would not introduce new conditions.

Contaminant release

Dredging of all forms can disturb aquatic habitats and organisms by resuspending bottom sediments, thereby recirculating any toxic metals, hydrocarbons, pesticides, pathogens, and nutrients that may be present into the water column. Any toxic metals and organics, pathogens, and viruses, absorbed or adsorbed to fine-grained particulates in the sediment may become biologically available to organisms either in the water column or through food chain processes. Most contaminants, however, are not easily released during short-term resuspension because they are tightly bound in the sediments.

All dredging projects in San Francisco Bay must regularly evaluate sediments prior to dredging, and all dredging is conducted in compliance with water quality standards. On a channel-by-channel basis, the DMMO determines where dredged material can be placed based on sediment testing results. The sediment testing and suitability determinations prevent contaminant release from dredging activities in San Francisco Bay. At Gallinas Creek, previous testing and suitability determinations indicate that contaminant release would not be an issue.

Any potential short-term resuspension of contaminated sediments would have short-term effects and localized on aquatic species in contact with the resuspended contaminated sediments. That said, the SSPD approach would not be suitable for a channel with significant contaminants and is not proposed for these applications.

Impacts to Benthic Habitats and Aquatic Species

The SSPD can affect benthic habitats and the species they support by suspending the top layer of sediment. The magnitude of any effect would be determined by species presence, based on time-of-year, and recovery rates. While the effects cannot fully be anticipated, the currently anticipated potential effects to macroinvertebrates and fish are summarized in Table 6.

Table 6. Potential impacts and recovery times for aquatic species. Recovery times are not included for fish since they are mobile species that can leave and return to disturbed areas.

Category and Example Taxa/Species	Potential Effect(s)	Presence Time of Year/Recovery Time
Benthic Macroinvertebrates: Amphipoda (e.g., *Ampelisca abdita),* Bivalvia (e.g., *Corbula amurensis*), Cumacea (e.g., *Nippoleucon hinumensis*), Nematoda, Ogliochaeta (e.g., tubificids), Polychaeta (e.g., *Streblospio benedicti*)	Displacement, burial, high suspended sediment concentrations	Present year-round. Rates of recovery are variable among both species and communities, but the most abundant species in San Francisco Bay tend to be early colonizers that invaded the estuary.
Benthic Fish: Arrow Goby (*Clevelandia ios*), Yellowfin Goby (*Acanthogobius flavimanus),* Starry Flounder (*Platichthys stellatus*)	Prey reduction	Present year-round; spawning December-July for gobies and November-February for starry flounder.
Pelagic Fish: Topsmelt (*Atherinops affinis*), Pacific Herring (*Clupea pallasii*), Northern Anchovy (*Engraulis mordax*)	Prey reduction, high suspended sediment concentrations (may cause health effects)	Topsmelt are present to spawn March-October. Pacific herring adults are present to spawn November-March, and juveniles are present in summer/fall. Northern anchovies are present and spawn throughout the year.

Benthic Invertebrates

Benthic habitats of San Francisco Bay are largely composed of invertebrates. These organisms that inhabit the bottom substrate play a key role in maintaining both water and sediment quality, and they are an important food source for fish, birds, and other predators.

The composition of benthic macroinvertebrate communities is strongly influenced by salinity levels and influenced to a lesser extent by other physical factors such as substrate grain size and temperature. Shallow mesohaline regions, such as the Gallinas Creek tidal channel, have predominately muddy, fine-grained sediment substrates. The macroinvertebrate communities in these regions are dominated by amphipods (primarily *Ampelisca abdita* and *Monocorophium acherusicum*), the clam *Corbula amurensis*, and tolerant taxa including the polychaete *Streblospio benedicti* and tubificids and are generally concentrated within the top five centimeters of substrate (Thompson et al. 2013; De La Cruz et al. 2020). All the aforementioned species are not native to San Francisco Bay, a highly invaded estuary (Cohen and Carlton, 1995).

Dredging of all forms would directly impact benthic communities through physical disruption and displacement of benthic organisms. Since the top five centimeters will be disturbed by SSPD, the benthic community will necessarily be impacted through displacement from original location, burial or smothering which can involve clogging of built tubes, or other health effects of high suspended sediment concentrations. These impacts can lead to mortality for benthic macroinvertebrates and are anticipated to result in changes at the community level. It is unknown whether the force of injected water would directly cause injury to invertebrates.

Based on the literature and input provided by the TWG, the general consensus is that following sediment-disturbing activities such as dredging or the placement of dredged material, disturbed areas are usually recolonized quickly by benthic organisms (Newell et al. 1998). The species that recolonize first are usually characterized by rapid growth and reproduction rates. Following dredging, disturbed areas are recolonized, beginning with mobile and opportunistic species (Oliver et al. 1977, Lenihan and Oliver 1995), which may or may not be the same species present prior to the disturbance. Studies have indicated that even relatively large areas disturbed by dredging activities are usually recolonized by benthic invertebrates within one month to one year, with original levels of biomass and abundance developing within a few months to between one and three years (Newell et al. 1998).

However, when comparing dredged and undredged areas in Central San Francisco Bay, in and adjacent to marinas, respectively, De La Cruz et al. (2020) found that macroinvertebrate biomass in dredged areas did not recover to the levels of adjacent undredged areas within one to three years after dredging. Interestingly, density, biomass, and energy content of the smallest macroinvertebrate size class (0–4 mm) increased closest to dredged areas, while larger macroinvertebrates (12–50 mm) had increasing biomass with increasing distance from a dredged area. The studied macroinvertebrate community metrics were used to estimate trophic (nutritional) support available for fishes in benthic habitats, and the total mean available energy was 40 to 50 percent less at dredged sites compared to undredged sites.

As noted previously, Pledger et al. (2021) found that benthic communities recovered quickly (within five months) following WID. It is possible that the quicker recovery rate can be attributed to better conditions following WID as opposed to traditional dredging. Although, other factors are important in determining recovery rates. As noted by De La Cruz et al. (2020), limited information exists about benthic community recovery from dredging in San Francisco Bay. The benthic macroinvertebrate community at Gallinas Creek is like that of the shallow, fine-grained sediment marinas studied by De La Cruz et al. (2020). Contrastingly, a sand mining study in deep-water channels in Central San Francisco Bay found no significant differences in number of taxa or abundance between control and mined areas after three years (Applied Marine Sciences Inc., 2009).

Fish

Increased suspended sediment concentrations could directly impact fish, but turbidity tolerance ranges for fish are species and life-stage dependent. Turbid environments are more optimal for some species and size groups of fish (planktivores and fish larvae) and less so for others (adult piscivore fish) as visual prey detection is affected. Turbidity and suspended sediments have been shown to impact gills of fish as well as clogging of fish gill rakers and gill filaments because of excess suspended material (Hess et al. 2015). While delta smelt are not expected to be present in the project area, Hasenbein et al. (2016) found that detrimental effects to late-larval delta smelt occurred at high turbidities of 120 and 250 NTU, likely due to elevated stress levels.

As noted previously, Pledger et al. (2021) found that fish were relatively unaffected by WID, and the same is expected for SSPD. Due to their mobile nature, it is reasonable to assume they will avoid any perceived threats.

Indirectly, foraging fish can be affected by SSPD through impacts to benthic macroinvertebrates because the top layer of sediment in shallow subtidal areas is an important foraging area. As described above, De La Cruz et al. (2020) found that impacts of traditional dredging on trophic support for fishes varied by macroinvertebrate size class; fish species that forage on the two smaller macroinvertebrates would experience the greatest potential impact, while fish that forage on small to intermediate prey size classes would experience less impacts.

In August 2024, Marin DPW hired Kleinfelder Associates (Kleinfelder August 2024) to conduct a habitat suitability assessment for Gallinas Creek for longfin smelt (*Spirinchus thaleichthys)* and this analysis determined that lower Gallinas Creek in the proposed project area is not suitable for longfin smelt due to salinity and substrate.

Physical Processes Framework and Metrics for Success

Far Field Effects

The far-field effects of SSPD would be determined by the fate of resuspended sediments. The injection of water and any associated short-term disturbances are not anticipated to directly affect downstream areas. The hypothesized fate of sediments mobilized by SSPD is the 'erodible sediment pool' in San Francisco Bay that was characterized by Schoellhamer (2011) as created by hydraulic mining and urbanization and depleted rapidly around 1999. Any larger grain sediments would settle out quickly, while finer material would remain in suspension longer, traveling further, and become resuspended again more easily. Thus, the magnitude of any impact of SSPD would decrease as distance from the pilot site increases.

Ideally, the long-term fate of the sediments mobilized by SSPD would be mudflats and marshes in San Francisco Bay. The TWG noted that mudflat habitat, which is crucial for migratory birds, is already very limited in San Francisco Bay. To keep pace with the current rate of SLR, mudflats and marshes around San Francisco Bay need about 2 mm of sediment per year, and excessive sediment deposition would lead to smothering of existing vegetation. Although, in all cases, the far field effects of SSPD are expected to be minimal and likely undetectable. For the San Francisco Bay Strategic Shallow-Water Placement Pilot Project that was implemented in December 2023, placement of 90,000 CY of clean dredged material was estimated to deposit up to 1 mm of sediment in the nearshore area about two miles away (USACE Section 1122 EA, 2023). Regardless of where the sediment ends up, marsh or ship channel, the resulting far field elevation changes are anticipated to be so small as to be difficult to measure.

5. Hydrodynamic Modeling

This section summarizes hydrodynamic and sediment transport modeling that was undertaken by the team during the pilot study to evaluate potential flood risk reduction benefits and sediment transport and fate resulting from the sediment pulse dredge.

Model Selection – Adaptive Hydraulics (AdH) with SEDLIB

Two-dimensional shallow water Adaptive Hydraulics (AdH-SW2D) coupled with the SEDLIB sediment transport library was used for this study. AdH coupled with SEDLIB allows for hydrodynamics and sediment transport processes to be calculated.

AdH is a finite element code that utilizes an unstructured mesh. AdH includes spatial and temporal adaptation, wetting and drying, and can model sediment transport processes when coupled with SEDLIB. The wetting and drying component makes AdH suitable for modeling shallow marsh environments and floodplains. AdH is developed and maintained by the Coastal and Hydraulic Laboratory (CHL) at ERDC.

SEDLIB is a sediment transport library that when coupled with AdH, is capable of simulating the transport of non-cohesive, cohesive, and mixed sediments. SEDLIB can solve for multiple grain classes, multiple bed layers, and calculate erosional and depositional bed processes.

Major Assumptions

A major assumption inherent in the pilot study’s model selection is that the version of AdH used is the depth averaged shallow water formulation of the two-dimensional Navier Stokes equations. The 2D model can capture storm effects, but it is limited in its ability to simulate processes driven by vertical variations in the water column. Regional hydrodynamic processes in the Bay, such as the San Pablo Bay gyre, may not be represented accurately without a 3D model. Representing 3D processes in AdH is possible yet computationally expensive and would exceed the constraints of project schedule and budget. For a preliminary assessment of the pilot, the team decided that a 2D-depth averaged model and parameterizing 3D processes would be sufficient. Where possible, the team includes discussion on how this assumption may affect model results and perceived efficacy of the sediment pulse dredge.

It should also be noted that no waves are included in these simulations. A coupled wave model would be necessary to appropriately model the fate of sediments within San Francisco and San Pablo bays. However, due to time and cost constraints this was not included, and the modeling approach is deemed sufficient for the feasibility phase of this project.

Another major assumption is the application of the shear stress boundary condition applied to simulate the effect of the hydrodynamic dredge. This forcing is applied directly to the bed when in reality, the dredge would be some distance from the bed surface. Therefore, the actual applied shear necessary from the dredge could deviate from the values modeled. The overall effect of the modeled dredge, in terms of displacement and generated suspended sediments, is what should be attempted to recreate for the pilot.

Also, hydrodynamic dredging is a complicated process that causes long term effects on the sediment bed. The modeling for this effort focuses on the immediate impact of the physical application of the hydrodynamic dredge at the sediment bed. Hydrodynamic dredging fluidizes the sediment bed, increasing the porosity of the upper layer and making it more susceptible to scouring or eroding at subsequent tides. This physical process is not being modeled for this effort. The immediate effect of the shear of the dredge on the sediment bed and the resulting suspended concentrations are what are being simulated for this effort.

Model Development

Figure 13 below displays the model bathymetry overlaid on a satellite image. The bathymetry was developed by merging the original AdH model bathymetry, interpolated from USGS DEM (Fregoso 2017), with the McGinnis RAS model bathymetry in the project area and multibeam surveys in Gallinas Creek provided by Marin County. The projection was UTM Zone 10, and the vertical datum used was NAVD88 meters[6].

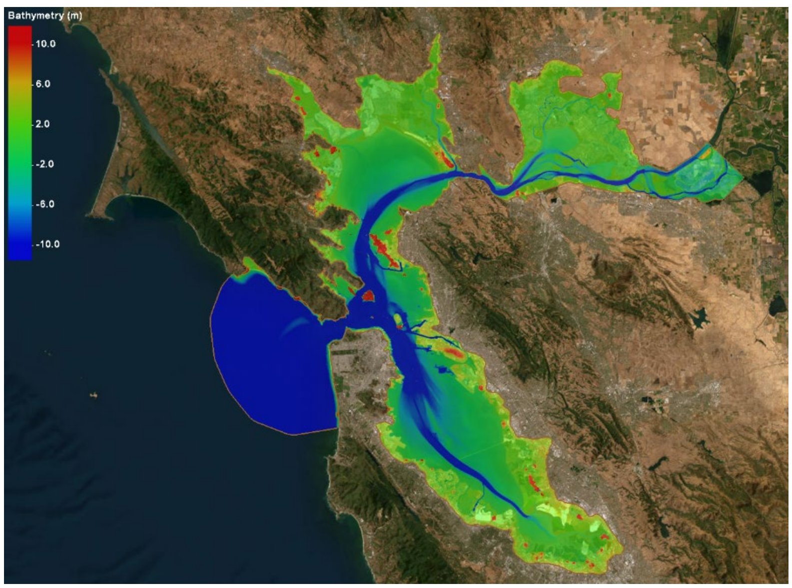

Figure 13 : Model bathymetry (m NAVD88) (Image reproduced with permission from Esri 2024. Powered by Esri.)

Figure 14 displays the model mesh overlaid on a satellite image and Figure 15 displays the zoomed in mesh to the project area with the local bathymetry. The mesh has 1,048,711 elements and 527,028 nodes. The maximum spacing was 1000 m along the ocean boundary and 2 m spacing along Gallinas Creek within the project area.

[6] AdH operates in metric units. All modeling analyses and outputs are presented in metric.

Figure 14 : Model mesh (Image reproduced with permission from Esri 2024. Powered by Esri.)

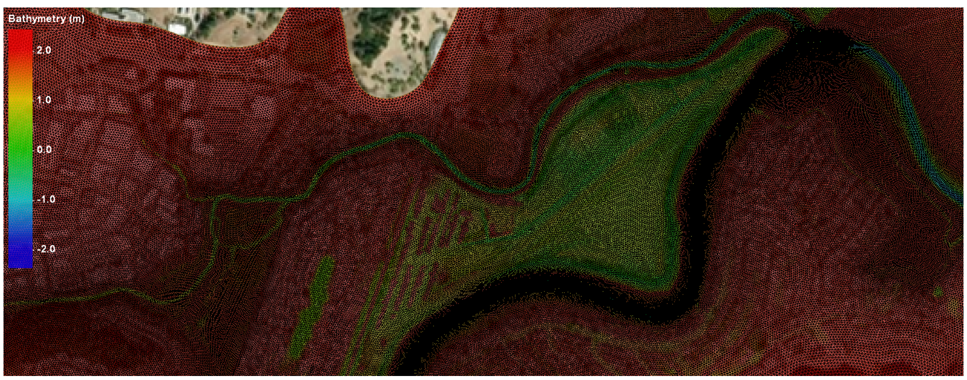

Figure 15 : Model mesh and bathymetry zoomed to project area (Image reproduced with permission from Esri 2024. Powered by Esri.)

Figure 16 and Figure 17 below illustrates the model materials used. shows the zoomed in materials in the project area with materials 7 through 24 delineating the dredge path along Gallinas Creek. Materials are used within AdH to define physical parameters such as friction, viscosity, diffusion, along with specific sediment bed definitions and properties.

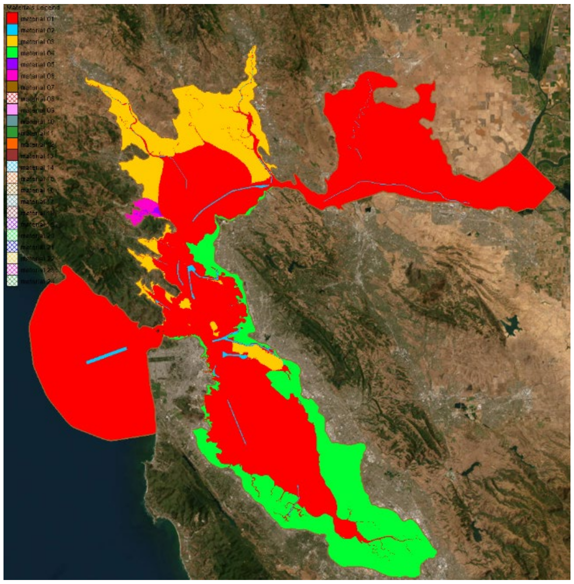

Figure 16 : Model materials (Image reproduced with permission from Esri 2024. Powered by Esri.)

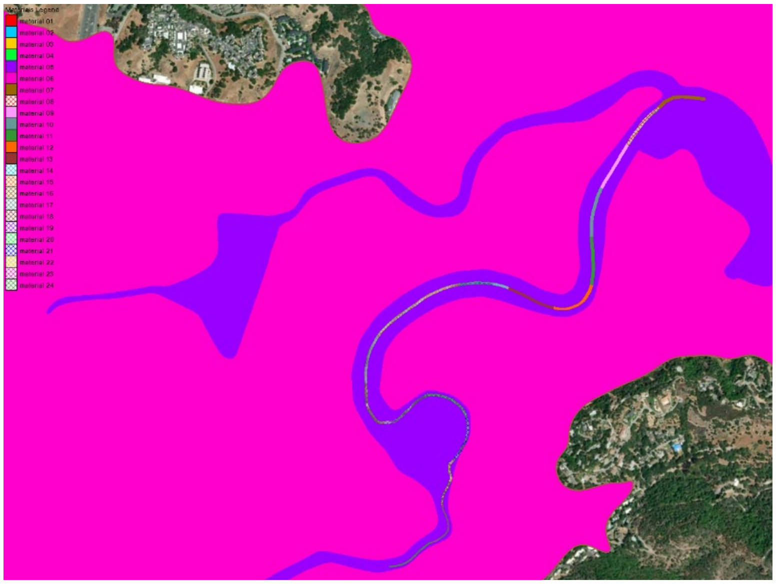

Figure 17 : Model materials zoomed to project area (Image reproduced with permission from Esri 2024. Powered by Esri.)

Boundary Conditions Development

Figure 18 and Figure 19 below display the time series of WSE from January and June 2017 applied to model tidal boundary. These values were derived from the San Francisco, CA NOAA gage 9414290.

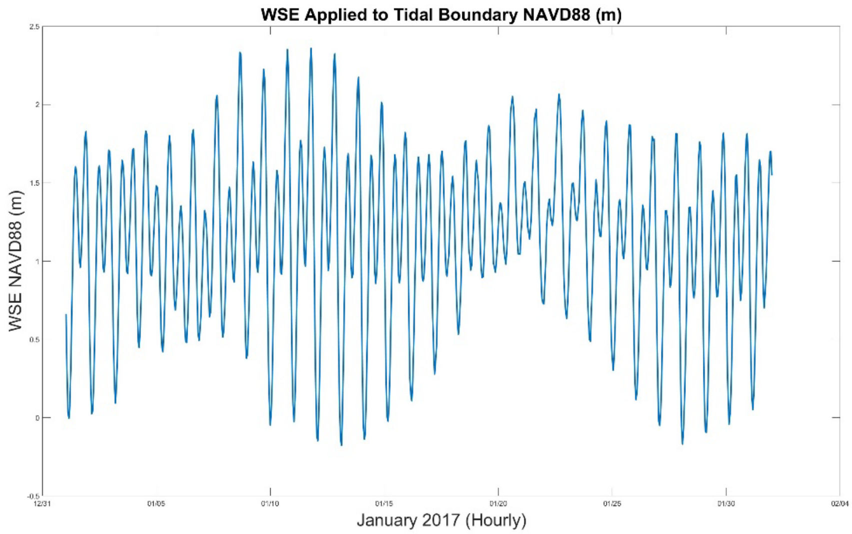

Figure 18 : Tidal boundary for January 2017

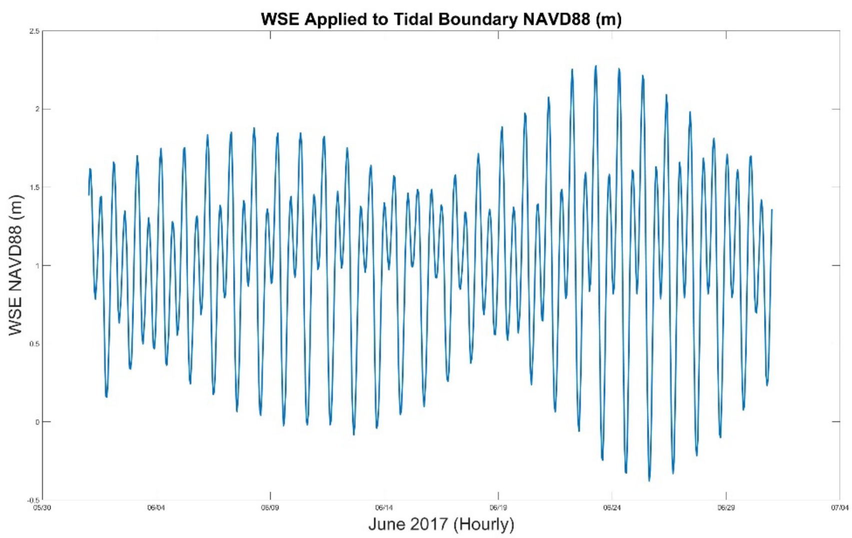

Figure 19 : Tidal boundary for June 2017

Figure 20 displays the 6 NOAA stations where time series of wind were taken and applied to the AdH model. These include Point Reyes, CA 9415020; San Francisco, CA 9414290; Martinez-Amorco Pier, CA 9415102; Richmond, CA 941 4863; Alameda, CA 9414750; and Redwood City, CA 9414523. Figure 21 displays the Novato NWS station where winds were also applied. The wind stresses were applied over the model domain using the Teeter method (the reader is referred to the AdH hydrodynamic manual V4.7.1 for further technical details).

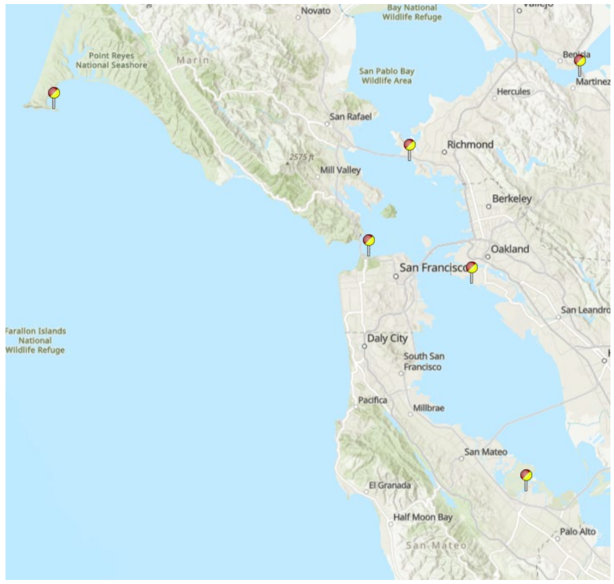

Figure 20 : NOAA stations where time series of wind forcings were applied

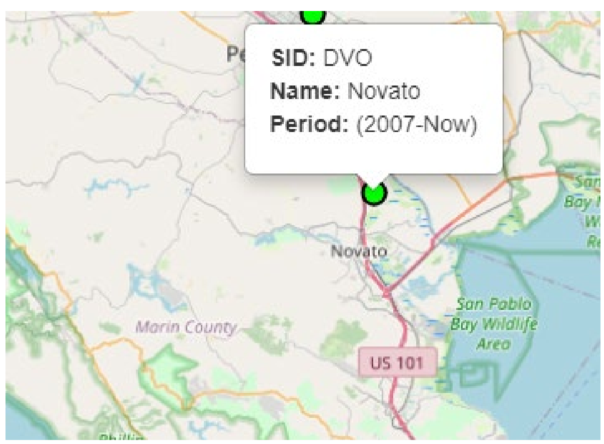

Figure 21 : Novato meteorological station used for wind

Freshwater inflows were also applied in North and South Gallinas Creek. A steady state flow was used in the June simulations and a 2-year, 10 year, and 100-year flow was applied for the January simulations.

Sediment Bed Development

Table 7 below displays the sediment grain class physical property definitions used in the 2D AdH model. Each grain class was duplicated to allow for the definition of unique Gallinas Creek sediments. This allowed for these sediments derived in Gallinas Creek to be easily measured and tracked. Table 8 shows the bed distribution definitions. The grain class percentages for Gallinas Creek were based on sediment borings described in the Sediment Characterization Sampling and Analysis Results (SAR) prepared by the firm CLE Engineering for the Department of Public Works Marin County. Model areas not in Gallinas were defined based on previously established AdH sediment models in the domain.

Table 7 : Sediment grain class definitions

Sediment Class	Diameter (mm)	Specific Gravity	Bed Porosity	Critical Shear (Pa)	Erosion Rate Constant	Critical Shear for Deposition (Pa)	Settling Velocity (m/s)
Gallinas Very Fine Sand	0.088	2.65	0.3	NA	NA	NA	NA
Gallinas Clay	0.001	2.65	0.5	0.05	0.00001	0.02	0.00005
Gallinas Very Fine Silt	0.005	2.65	0.5	0.05	0.00001	0.04	0.0003
Gallinas Fine Silt	0.011	2.65	0.5	0.05	0.00001	0.08	0.0005
Gallinas Medium Silt	0.022	2.65	0.5	0.05	0.00001	0.12	0.0007
Gallinas Coarse Silt	0.044	2.65	0.5	0.05	0.00001	0.2	0.0009
Very Fine Sand	0.088	2.65	0.3	NA	NA	NA	NA
Clay	0.001	2.65	0.5	0.05	0.00001	0.02	0.00005
Very Fine Silt	0.005	2.65	0.5	0.05	0.00001	0.04	0.0003
Fine Silt	0.011	2.65	0.5	0.05	0.00001	0.08	0.0005
Medium Silt	0.022	2.65	0.5	0.05	0.00001	0.12	0.0007
Coarse Silt	0.044	2.65	0.5	0.05	0.00001	0.2	0.0009

Table 8 : Sediment grain class distributions

Material Category	Gallinas Very Fine Sand %	Gallinas Clay %	Gallinas Very Fine Silt %	Gallinas Fine Silt %	Gallinas Medium Silt %	Gallinas Coarse Silt %	Very Fine Sand %	Clay %	Very Fine Silt %	Fine Silt %	Medium Silt %	Coarse Silt %
Gallinas Materials	5	13.5	13.5	22	24	22	0	0	0	0	0	0
Everywhere Else	0	0	0	0	0	0	5	19	19	19	19	19

Model to Field Comparisons

Figure 22 displays the NOAA gages utilized for WSE comparisons. These include San Francisco, CA 9414290; Richmond, CA 9414863; and Alameda, CA 9414750.

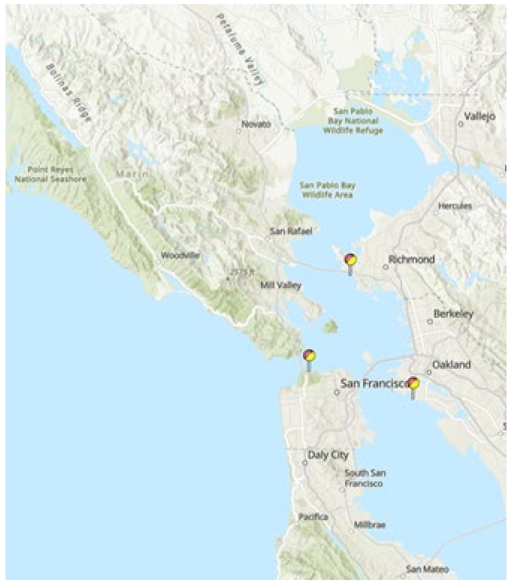

Figure 22 : NOAA comparison stations locations

Figure 23 through Figure 28 show model to field comparisons at the three chosen NOAA gages for the January and June simulations. The model compares well to field measurements.

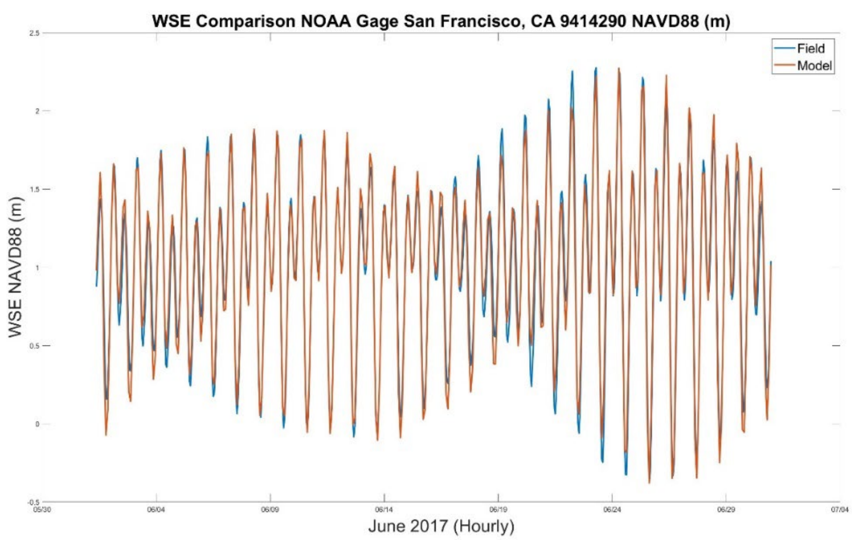

Figure 23 : June WSE comparison at San Francisco gage

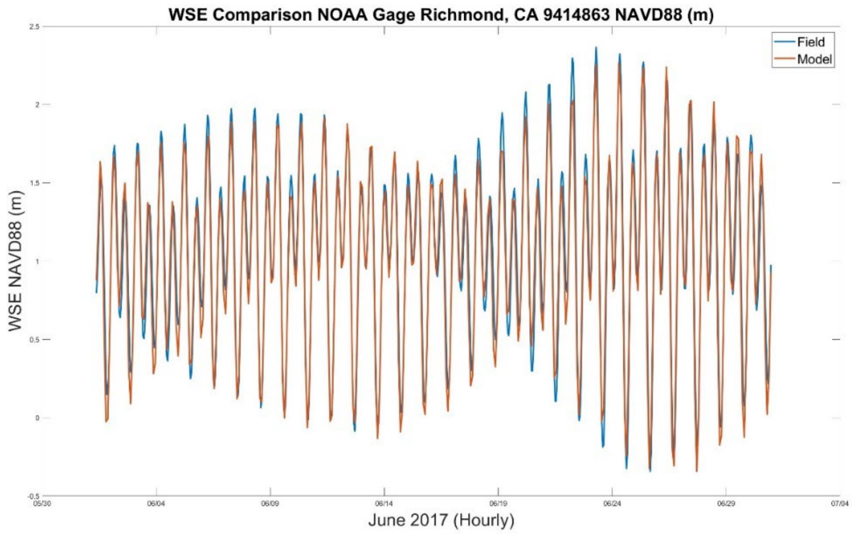

Figure 24 : June WSE comparison at Richmond gage

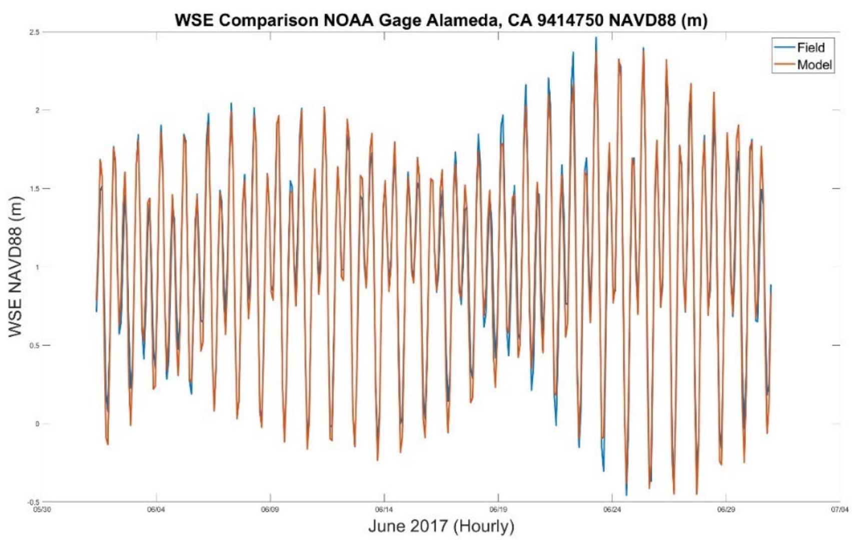

Figure 25 : June WSE comparison at Alameda gage

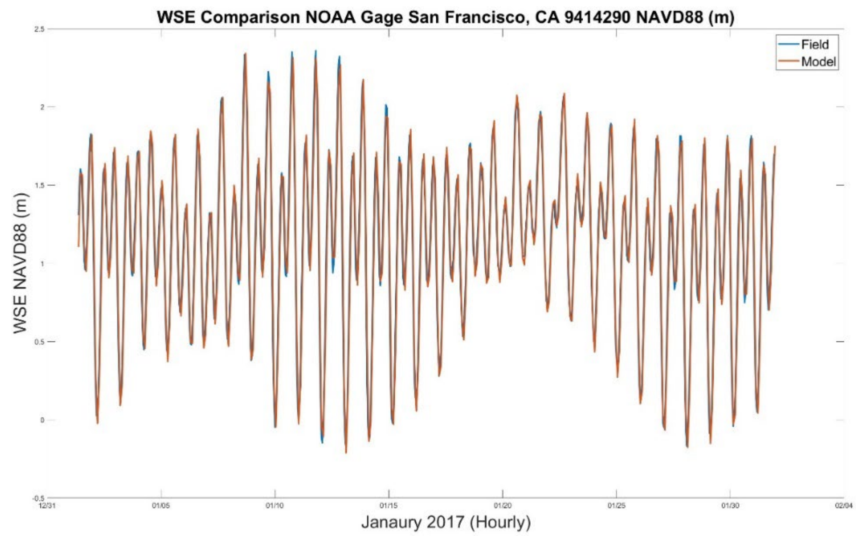

Figure 26 : January WSE comparison at San Francisco gage

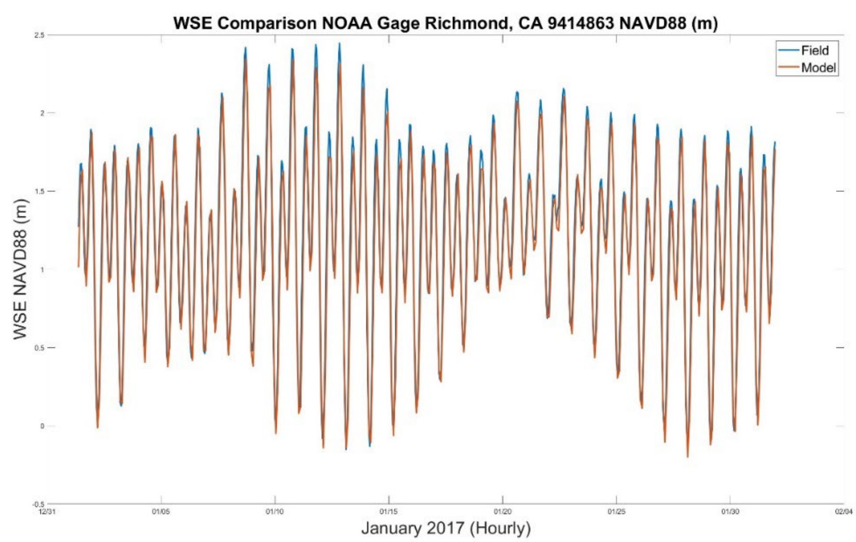

Figure 27 : January WSE comparison at Richmond gage

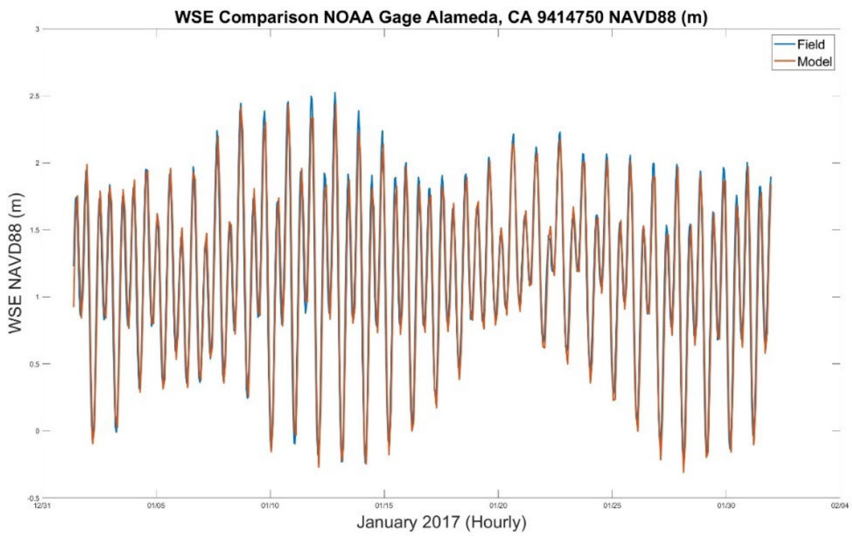

Figure 28 : January WSE comparison at Alameda gage

Table 9 displays the model performance and error metrics for all WSE comparisons shown above. The model performs well with high Nash and Willmott performance metrics (closer to one means better performance) and low error values.

Table 9 : Error metrics for WSE comparisons (Field vs Model)

NOAA Gage	San Francisco, CA 9414290 January 2017	San Francisco, CA 9414290 June 2017	Richmond, CA 9414863 January 2017	Richmond, CA 9414863 June 2017	Alameda, CA 9414750 January 2017	Alameda, CA 9414750 June 2017
Covariance	0.279	0.302	0.300	0.318	0.350	0.390
R^2	0.941	0.964	0.956	0.953	0.915	0.973
Standard Deviation	0.529	0.544	0.554	0.565	0.598	0.618
Standard Deviation	0.546	0.565	0.556	0.578	0.614	0.642
Variance	0.280	0.296	0.307	0.319	0.358	0.382
Variance	0.298	0.320	0.310	0.334	0.377	0.412
Mean	1.146	1.014	1.211	1.068	1.164	1.034
Mean	1.140	1.006	1.158	1.026	1.150	1.019
Median	1.198	1.074	1.279	1.107	1.196	1.054
Median	1.196	1.047	1.229	1.076	1.196	1.070
Maximum	2.360	2.277	2.436	2.366	2.497	2.465
Maximum	2.343	2.274	2.345	2.265	2.440	2.382
Minimum	-0.177	-0.379	-0.151	-0.325	-0.230	-0.458
Minimum	-0.212	-0.379	-0.200	-0.343	-0.308	-0.462
RMSE	0.133	0.107	0.128	0.133	0.180	0.107
Nash	0.937	0.961	0.947	0.945	0.909	0.970
Willmott	0.984	0.991	0.987	0.986	0.977	0.993

Figure 29 and Figure 30 display the SSC (mg/L) comparisons at the San Rafael Bridge USGS gage for January and June 2017. The model can simulate the overall trends of SSC over time. The model does not capture the peaks shown in the field data and this is due to the model not being coupled with a wave model which would recreate these maximum peaks of SSC.

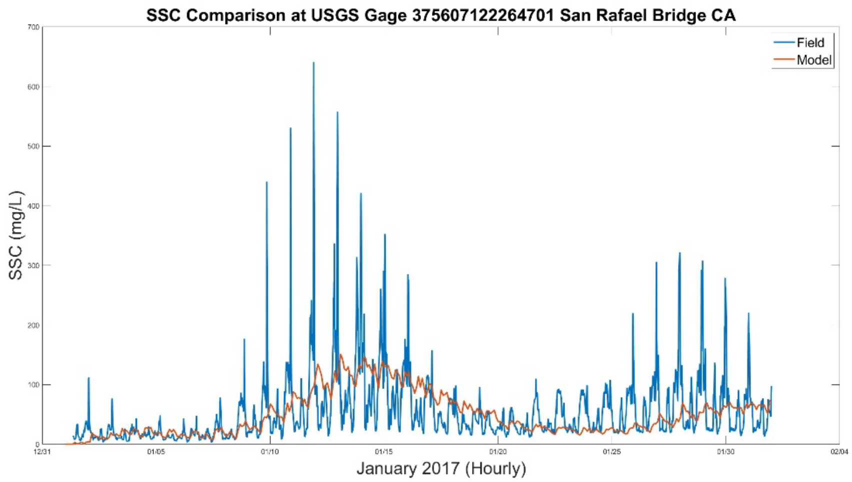

Figure 29 : SSC (mg/L) comparison at San Rafael Bridge, CA USGS Gage 375607122264701 January 2017

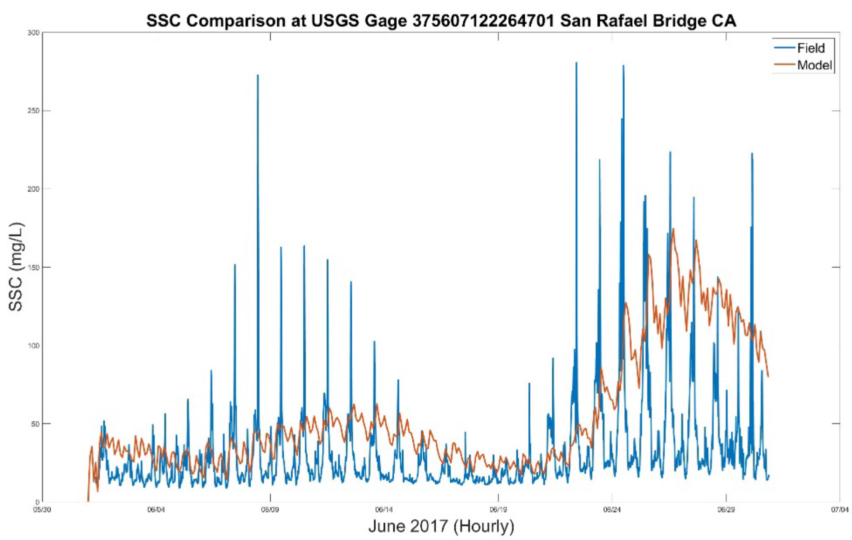

Figure 30 : SSC (mg/L) comparison at San Rafael Bridge, CA USGS Gage 375607122264701 June 2017

Simulating Dredge on Channel Bottom

The water injection dredge was parameterized within AdH by applying time series of pressures that were internally converted to shear stress that was applied to the sediment bed by material definition within the model. The maximum pressure was calculated based on the specifications for a similar injection dredge used as an example.

The dredge path was delineated using eighteen polygons. Each polygon was 180 meters long along the path and it was assumed that the dredge spent eight minutes in each polygon. This time was chosen based on dredging speed and the limiting model parameters such as timestep.

Each polygon was activated in series with the calculated shear stress applied to simulate the path of the boat and water injection dredge. Figure 31 shows the dredge path.

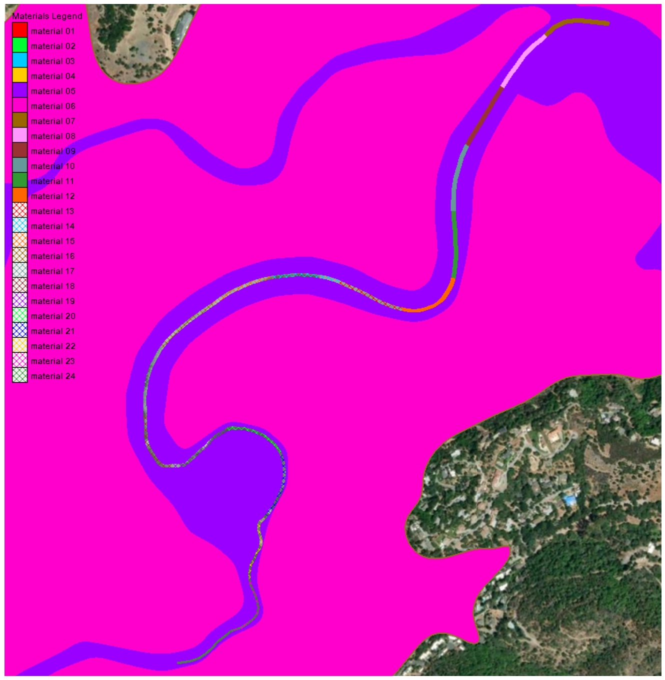

Figure 31 : Dredge path represented with model materials (Image reproduced with permission from Esri 2024. Powered by Esri.)

Sensitivity to Shear

Multiple time series of shear stresses were applied and evaluated. Due to constraints with the allowable amount of TSS leaving Gallinas Creek, it was determined that a shear of 10 Pascal (Pa) was appropriate for this effort. However, as discussed above in the assumptions, what shear is applied at the bed would differ when applying the hydrodynamic dredge due to the differences in the model formulation and actual practical applications. The model derived displacement compared to generated suspended solids are realistic estimates. If the dredge causes similar bed displacement, then these values for TSS can be expected. Figure 32 shows a comparison of bed displacement when applying 3.5 Pa and 10 Pa along the dredge path. Figure 33 displays the corresponding SSC generated by these time series of shear. The model is sensitive to the magnitudes of shear applied along the dredge path.

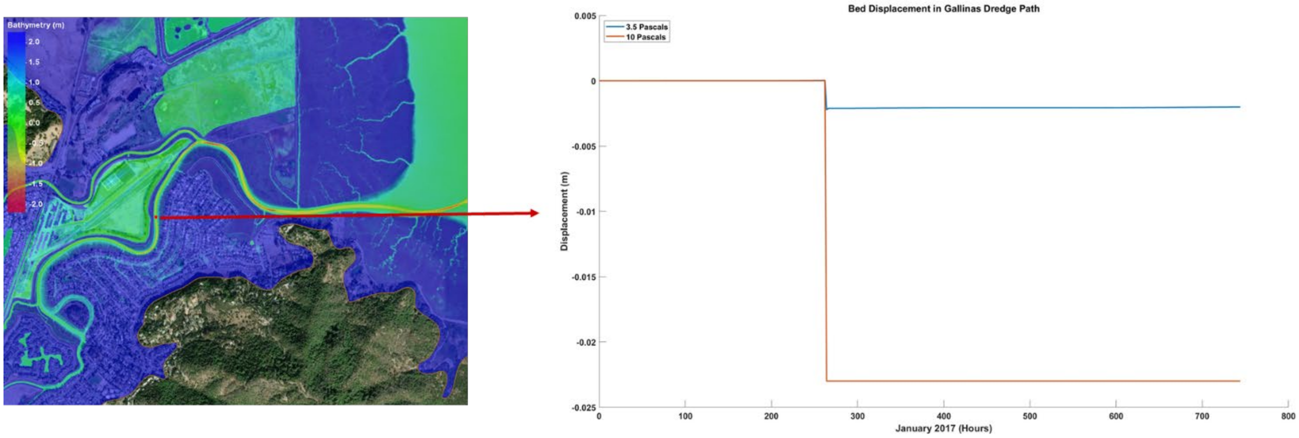

Figure 32 : Displacement (m) for applied shear stress (Image reproduced with permission from Esri 2024. Powered by Esri.)

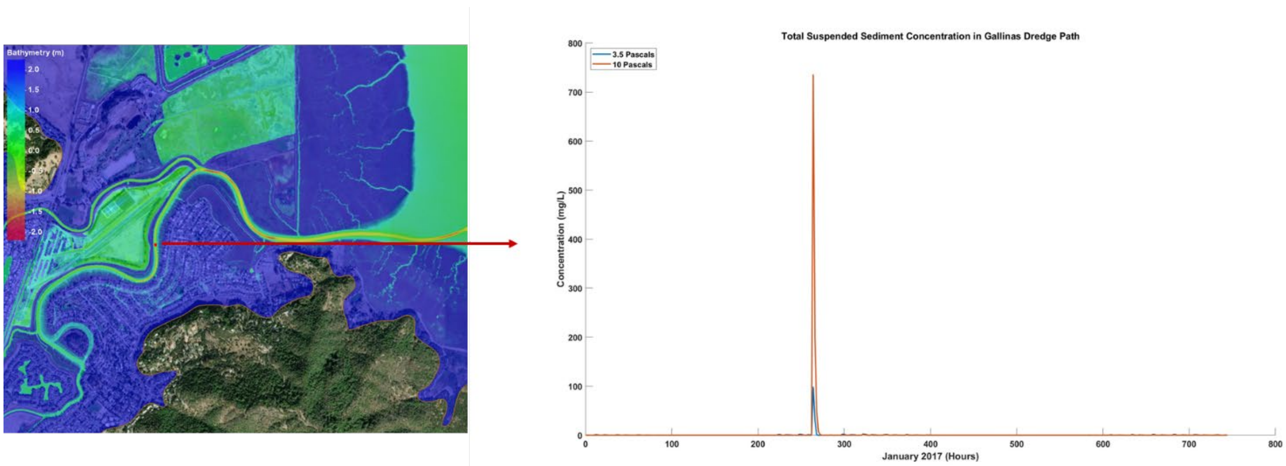

Figure 33 : SSC (mg/L) for applied shear stress (Image reproduced with permission from Esri 2024. Powered by Esri.)

6. Modeling Result Discussions and Implications for Pilot

Figure 34 through Figure 36 show velocity magnitude plots of Gallinas Creek for January 11th when the simulated dredge was applied for the 2-year, 10- year, and 100-year freshwater flows. Figure 37 shows the velocity magnitude plot of Gallinas Creek for June 22nd when the simulated dredge was applied. The January event is generally more energetic than the June event and shows higher velocities in the Creek. The velocities increase for January with increasing freshwater inflow magnitudes as would be expected. The 100-year inflow for January displays the largest velocities and most well distributed velocity laterally within the channel.

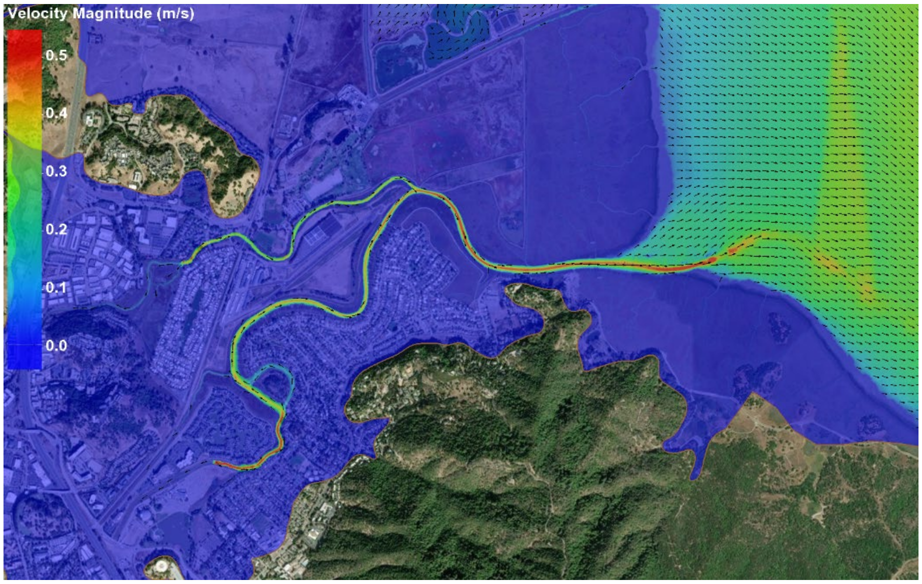

Figure 34 : Velocity magnitude on ebb tide January 11 during dredge event for 2-year inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

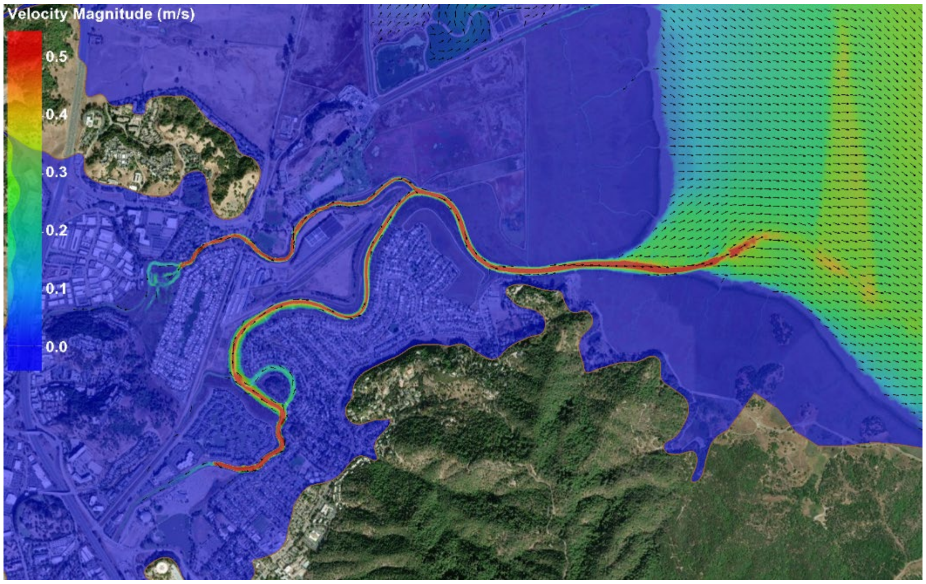

Figure 35 : Velocity magnitude on ebb tide January 11 during dredge event for 10-year inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

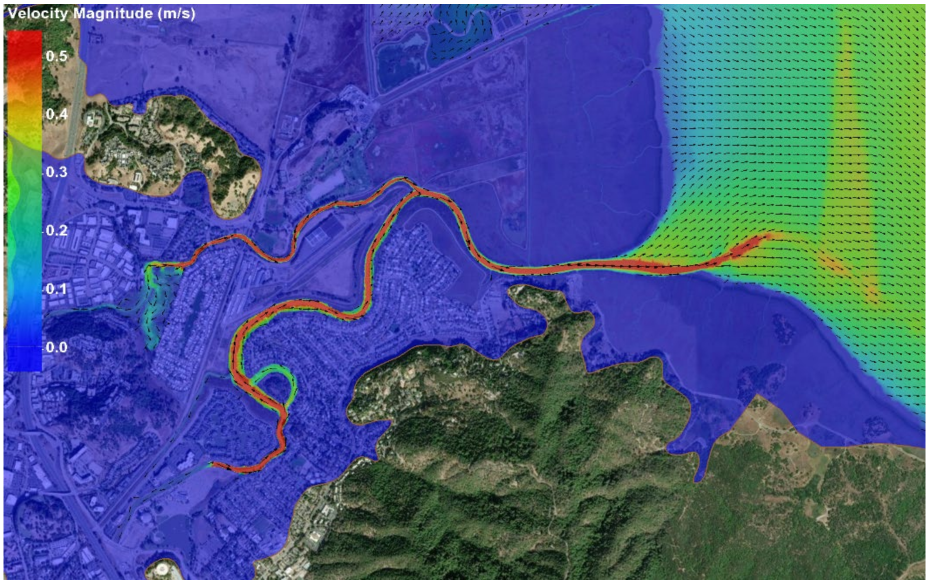

Figure 36 : Velocity magnitude on ebb tide January 11 during dredge event for 100-year inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

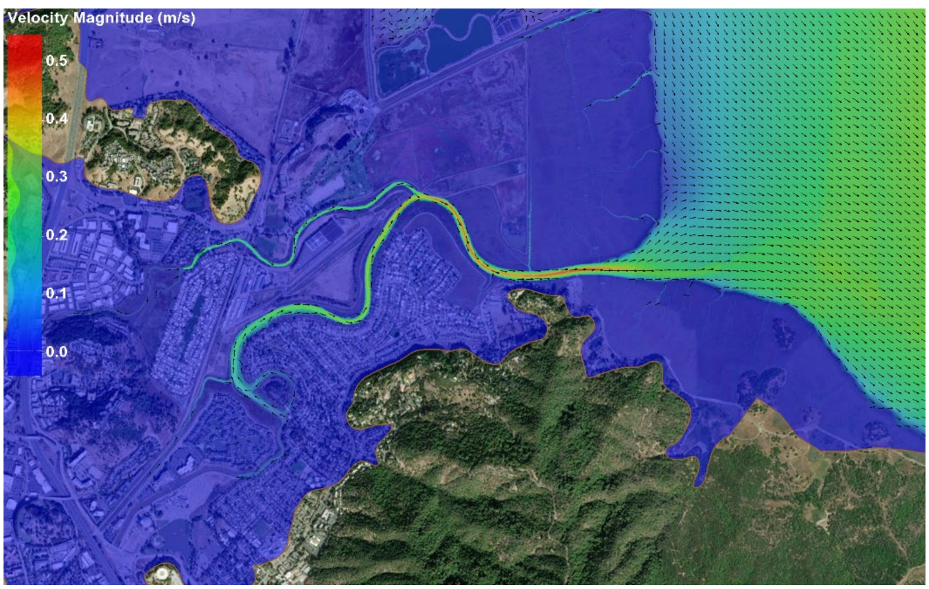

Figure 37 : Velocity magnitude on ebb tide June 22 during dredge event for steady inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

Figure 38 through Figure 40 show the total suspended sediment concentrations generated directly after the dredge event for all freshwater inflows during January. The 100-year inflow generates the largest pulse of sediment as expected, due to the higher velocities throughout Gallinas creek. The sediment pulse would persist for multiple hours after the event. It should be noted that if a wave model were coupled with the 2D model, these pulses of sediment would likely persist and propagate on longer time scales. Figure 41 displays the June event. The total suspended sediment plug is smaller and less concentrated due to less energy in the system from inflow and winds.

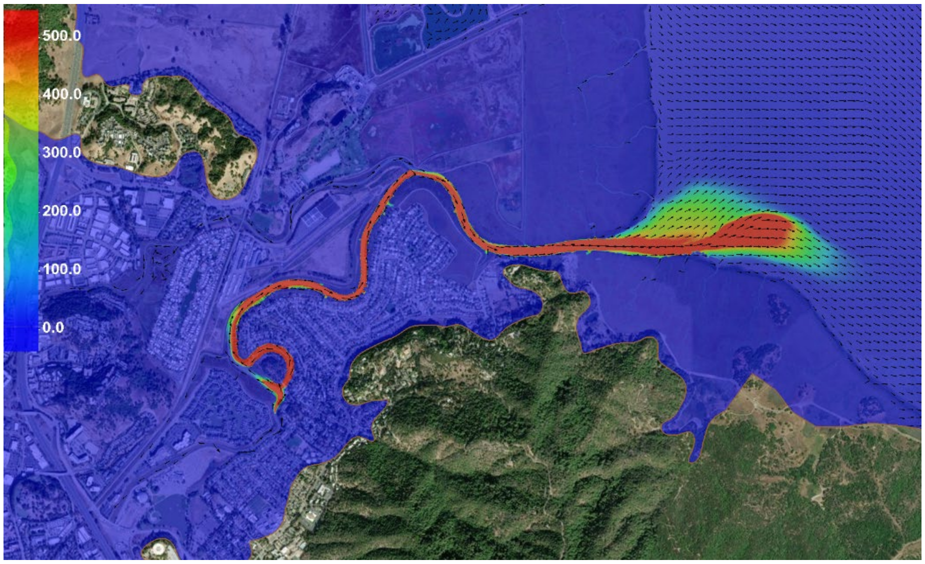

Figure 38 : SSC (mg/L) on ebb tide January 11 during dredge event for 2-year inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

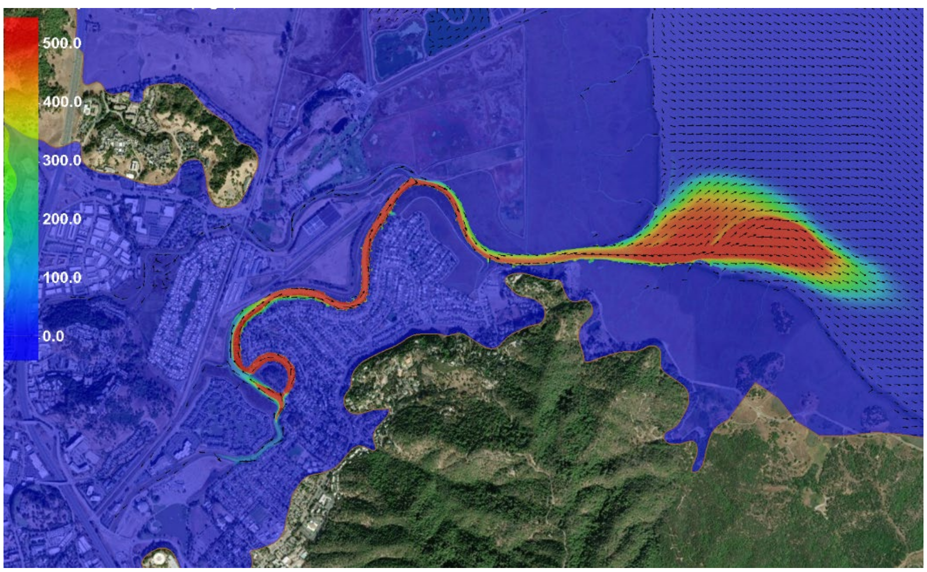

Figure 39 : SSC (mg/L) on ebb tide January 11 during dredge event for 10-year inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

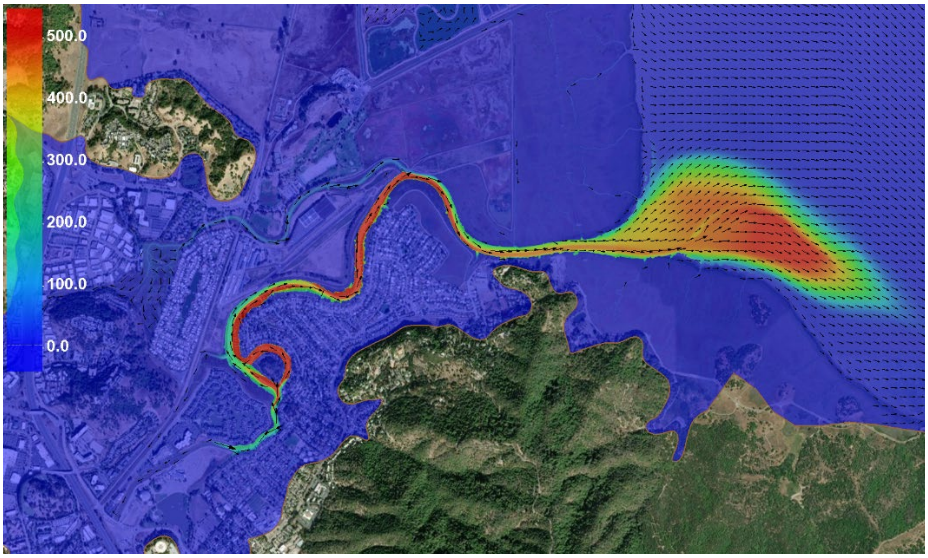

Figure 40 : SSC (mg/L) on ebb tide January 11 during dredge event for 100-year inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

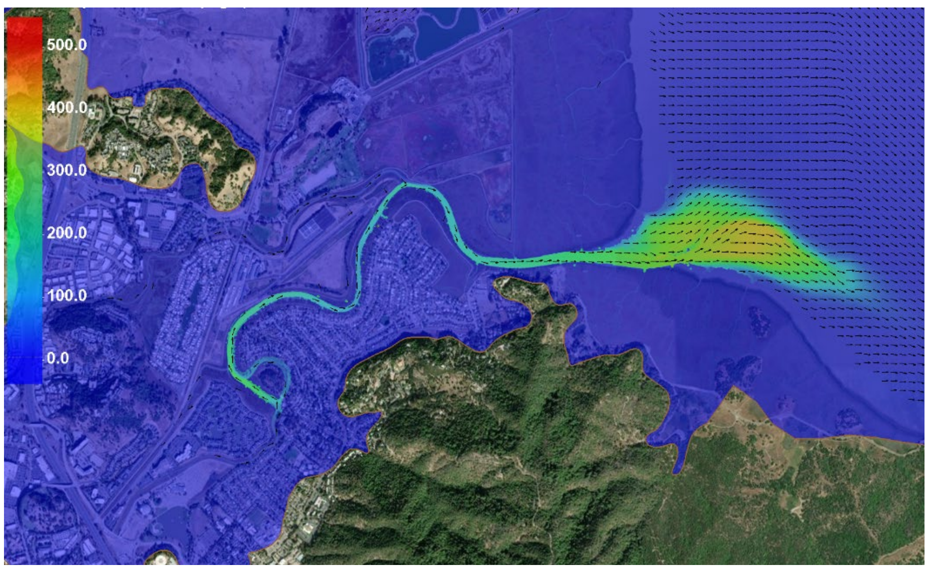

Figure 41 : SSC (mg/L) on ebb tide June 22 during dredge event for steady inflow (Image reproduced with permission from Esri 2024. Powered by Esri.)

Figure 42 illustrates the flux line used to calculate sediment flux out of Gallinas Creek for the modeled events. These fluxes are plotted below in Figure 42 and Figure 44 for January and June, respectively. The fluxes are much higher (6-10X) for the January scenario due to larger freshwater inflows as well as stronger winds. This reflects what was shown above in the suspended sediment plots.

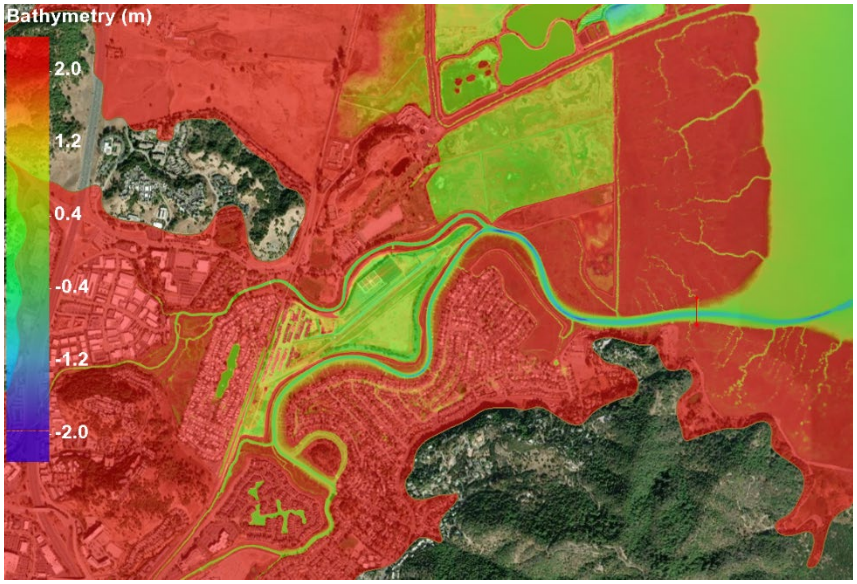

Figure 42 : Gallinas flux line (Image reproduced with permission from Esri 2024. Powered by Esri.)

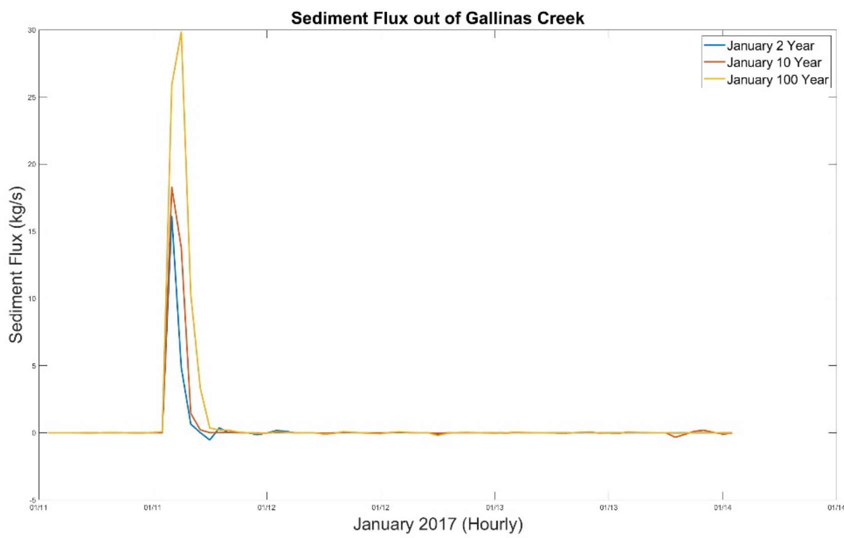

Figure 43 : Sediment flux for all January freshwater inflows out of Gallinas Creek during dredge event

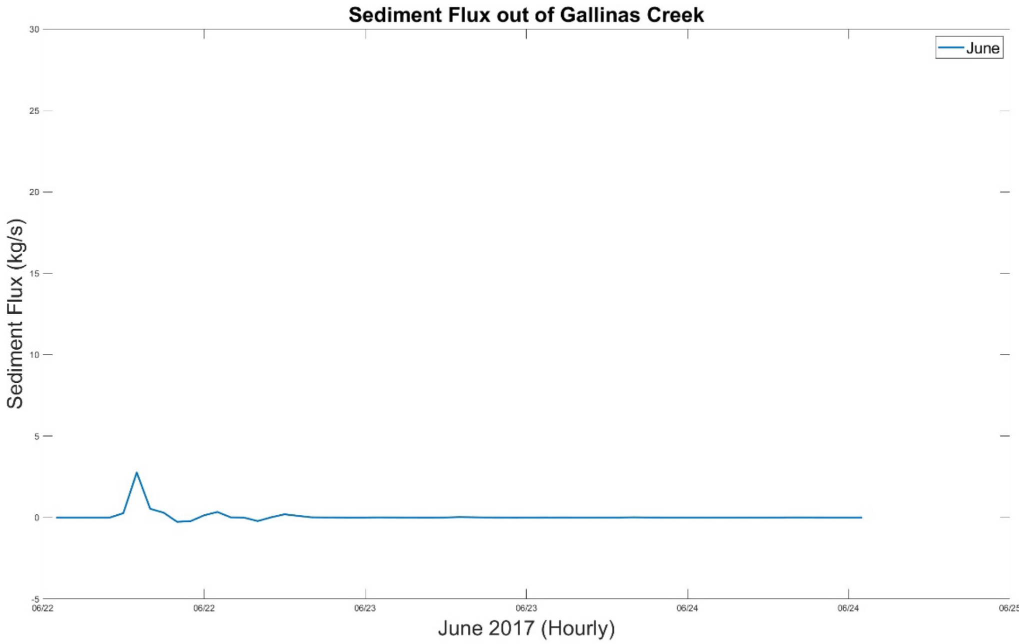

Figure 44 : Sediment flux for June out of Gallinas Creek during dredge event

Figure 45 and Figure 46 are polygons delineated in SMS where the total Gallinas Creek sediment masses were summed. The 2-year freshwater flow simulation was used for this to demonstrate that these values were reasonable. A total of 15,809 kg of Gallinas sediments were deposited in the China Camp polygon, while 3,209 kg were deposited in the northern marsh polygon These values are reasonable and are within known normal margins for sediments delivered for storm events. However, it should be noted that these values are most likely unrealistic as waves in the bay are important to sediment transport and resuspension, so if coupled with a wave model the sediments could stay is suspension longer and travel further. It is likely these values would then change.

Figure 45 : China Camp polygon used to calculate total deposited Gallinas sediments

Figure 46 : Marsh polygon north of Gallinas used to calculate total deposited Gallinas sediments

7. Summary, Recommendations, and Next Steps

SSPD presents an opportunity to address the tandem goals of flood risk resilience and marsh/mudflat resilience to SLR. This feasibility evaluation is a first step in characterizing the feasibility of such an approach in the San Francisco Bay Area at a Marin County tidal creek, with the goal of building towards an in-water pilot. The SSPD is intended to address a specific issue of maintenance dredging of (shallow, limited, or low-draft) tidal flood control projects that are silted in and out of compliance due to the prohibitive costs for dredging and disposal. Pending compliance, SSPD dredge technology can also address the practical logistical issues for dredging narrow, shallow-draft tidal channels that cannot be dredged using conventional cutterhead hydraulic approaches or are too shallow for cost-effective movement by scows and tugs.

The results of this study show that the proposed SSPD represents an innovative dredging approach that can accomplish dredging and provide both flood protection and navigation benefits to tidal flood control channels that are currently not being dredged due to costs, assuming environmental permits can be obtained. The SSPD utilizes proven dredging technology combined with an EWN approach of timing dredging with periods when the Bay tides and waves are more naturally elevated and thus able to move and deposit the sediments where they naturally provide the most benefit. A permitting approach that includes all impacts such as air, including the downstream mudflats, marshes and GHG emissions and not just aquatic impacts as currently evaluated would favor the proposed approach studied in this analysis.

The main goal of the hydrodynamic and sediment transport modeling conducted in this pilot study was to compare the effects of the sediment pulse dredge activity at the site against a no-action scenario. A suggested improvement to the existing model set up for subsequent phases would include incorporating wave processes, which would better predict ultimate sediment fate in San Pablo Bay after material is transported out of Gallinas Creek. A major topic of discussion amongst the project team and TWG also included the relative benefits of additional, refined modeling versus an in-the-ground pilot with physical monitoring to better capture what happens. Models are a representation of reality and not all the relevant physical processes that happen in real life can be realistically captured or represented explicitly in the model (e.g., bed surface physics). The best next step would be to conduct a field pilot study and collect actual data which can also be used to calibrate future modeling.

Based on project discussions and work conducted through 2024, the project team recommends the following next steps to further evaluate feasibility and establish the groundwork for a pilot project, pending funding:

- Incorporate wave processes into the hydrodynamic and sediment transport modeling
- Model dredge events in a scheduled sequence to quantify flood mitigation potential and suspended sediment to Bay
- Interview dredgers around the Bay Area/West Coast to ascertain the potential for industry to develop a shallow-draft hydrodynamic dredge vessel
- Engage environmental resource agencies on the SSPD approach and better understand the expected environmental compliance needs, and further development potential monitoring plans

- Continue coordination with potential regional project partners such as the USGS, and the Wetland Regional Monitoring Program (WRMP) on development of a monitoring program

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