

Conceptual Understanding of Fine Sediment Transport in San Francisco Bay

Final Report

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Table of Contents

Glossary	iv
Summary	vii
1. Introduction	1
2. Conceptual Understanding of Open-Bay Sediment Processes.....	7
2.1. Overview	7
2.1.1 Supply.....	10
2.1.2 Transport	11
2.1.3 Deposition/Erosion/Extraction	12
2.1.4 Key Processes that Drive Sediment Dynamics in the Bay.....	13
2.2 Subembayment Scale Sediment Dynamics.....	16
2.2.1 Current Conditions	16
2.2.1.1 Methods and Data Sources	16
2.2.1.2 Conceptual Understanding of Wet Season Sediment Dynamics by Subembayment (Wet year, Dry year)	17
2.2.1.3 Conceptual Understanding of Dry Season Sediment Dynamics by Subembayment (Wet year, Dry year)	21
2.2.2 Future Conditions.....	25
2.2.2.1 Methods and Data Sources.....	25
2.2.2.2 Wetter Future Supply.....	25
2.2.2.3 Drier Future Supply	26
3. Conceptual Understanding of Baylands Sediment Processes.....	29
3.1 Overview	29
3.2 Sediment Transport Pathways and Sediment Fate at the Baylands Scale	33
3.2.1 Current Conditions	33
3.2.1.1 Pathway 1 - Uplands to Tributaries	33
3.2.1.2 Pathway 2 - Tributaries to Marshes, Mudflats, and Erodible Sediment Pool.....	35
3.2.1.3 Pathway 3 – Erodible Sediment Pool to Mudflats and Deep Bay	40
3.2.1.4 Pathway 4 - Mudflats to Marshes	42
3.2.2 Future Conditions.....	47
3.2.2.1 Sea-level Rise	47
3.2.2.2 Air and Water Temperatures	47
3.2.2.3 Precipitation	48
3.2.2.4 Wildfires	48
3.2.2.5 Salinity	48
4. Summary of Key Knowledge Gaps and Uncertainties	51
5. References.....	54

Glossary

Baylands: The area between the maximum and minimum extent of the tides including tidal and diked habitats (i.e. areas that would be subject to tidal influence if not for unnatural obstructions like levees and berms). The focus of this report is on baylands that are fully or partially connected to the tides and sustained, in part, by fine-grained sediment (i.e. tidal marshes and mudflats). Common baylands habitats referenced in this report are defined below, based on definitions from the Goals Project (1999, 2015), SFEI and SPUR (2020), and WRMP (2022):

- **Tidal marsh:** Vegetated wetland subject to tidal action located at elevations where vascular vegetation grows within San Francisco Bay, typically ranging from Mean Low Water (MLW) to Mean Higher High Water (MHHW).
- **Mudflat:** Broadly used to encompass all tidal areas within San Francisco Bay that exist from below the local Mean Lower Low Water (MLLW) to Mean Tide Level (MTL), which may vary in dominant grain size and thus terminology (e.g., sandflat, shellflat).
- **Beach:** Coarse or composite features that can consist of a mixture of sand, shell, gravel, or cobble and are typically located at the mouths of creeks, along the bayward edge of marshes, or between headlands in San Francisco Bay. Estuarine beaches include a supratidal beach berm and a beach face, and the lowest portion is often characterized by a low tide terrace and transitions to tidal flat. While beaches are an integral part of baylands, this first version of a conceptualized understanding of sediment transport focuses on fine-grained sediment with the hopes of including coarse-grained sediment (e.g. beaches) in a next iteration.
- **Shallows:** Tidal areas within San Francisco Bay ranging from MLLW to 12 feet below MLLW.
- **Deep Bay/channels:** Tidal areas within San Francisco Bay exceeding 12 ft below MLLW.

Data richness: Qualitative indication of the amount of data available to estimate average sediment flux at key locations throughout the Bay under different hydrologic conditions.

Erodible sediment pool: Any intertidal or subtidal area within San Francisco Bay containing sediment that can be mobilized and transported, which includes marshes, mudflats, shallows, and deep Bay/channels. However, for the purposes of this report, we define the erodible sediment pool as only the shallows, and consider marshes, mudflats, and deep Bay/channels as separate from the larger erodible sediment pool in order to conceptualize how sediment moves between the baylands and the more subtidal areas within the Bay.

Flocculation: The process by which small particles in water clump together to form larger aggregates through an electrostatically charged attraction.

Operational Landscape Unit (OLU): Connected geographic areas sharing certain physical characteristics that would benefit from being managed as a unit to provide particular desired ecosystem functions and services. For more information, see SFEI and SPUR (2019).

Polders: Low-lying areas of land that would normally be inundated by regular tides if they were not protected by dikes. Polders are the diked, ditched, and drained historical marshes and mudflats that are locally known in San Francisco Bay as “diked baylands.”

Resilience: The ability of a system to maintain function after being perturbed by a disturbance: either a long-term trend (e.g., rising sea levels) or a specific event (e.g., storm)

San Francisco Bay (Bay): Includes the subembayments of Suisun Bay, San Pablo Bay, Central Bay, South Bay, Lower South Bay.

Sediment loading: The amount of sediment transported to San Francisco Bay.

Sediment pathway: The pathway along which sediment is transported from one location to another. The types of sediment transport pathways in San Francisco Bay include fluvial (e.g., Sacramento and San Joaquin Rivers, Bay-draining tributaries), intra-Bay (e.g., flux between subembayments), oceanic (i.e., exchange with the Pacific Ocean at the Golden Gate), mechanical/anthropogenic (e.g., sediment removal by dredging and mining activities, sediment deposition from municipal and industrial wastewater), and atmospheric.

Sediment sink: Sediment sinks are areas that store sediment temporarily or indefinitely, including mudflats, accretionary tidal marshes, deep channels, and the Pacific Ocean by way of the Golden Gate.

Sediment source: Areas that generate sediment flowing to San Francisco Bay, including all Bay-draining watersheds above head of the tide, as well as sediment inflow from the Delta and the Pacific Ocean.

Shoreline: Broadly used to encompass all elements of the “shore,” including natural features like marshes, beaches, and mudflats, as well as the “shoreline”, or the “line of defense” from coastal flooding.

Subembayment: Smaller, more distinct embayments within San Francisco Bay that include Suisun Bay, San Pablo Bay, Central San Francisco Bay (Central Bay), South San Francisco Bay (South Bay), and Lower South San Francisco Bay (Lower South Bay). Breaks between subembayments used in this study were delineated based on existing Baylands Operational Landscape Unit (OLU) boundaries (as described in SFEI and SPUR 2019) in addition to suspended sediment concentration monitoring site locations (as described in Schoellhamer et al. 2018). Subembayments boundaries are also consistent with those used in Dusterhoff et al. (2021). It is also worth noting that while this report uses the term “subembayment”, other efforts studying sediment transport in San Francisco Bay may refer to these units as “Bay segments” or “embayments”.

Supply-regulated: Areas or periods where there is sufficient energy and time to suspend sediment but the quantity of sediment transported is limited by the amount of erodible sediment.

Transport-regulated: Areas or periods where there is sufficient erodible sediment but the quantity of sediment transported is limited by the energy or time needed to suspend the sediment.



Photo by Shira Bezalel (SFEI)

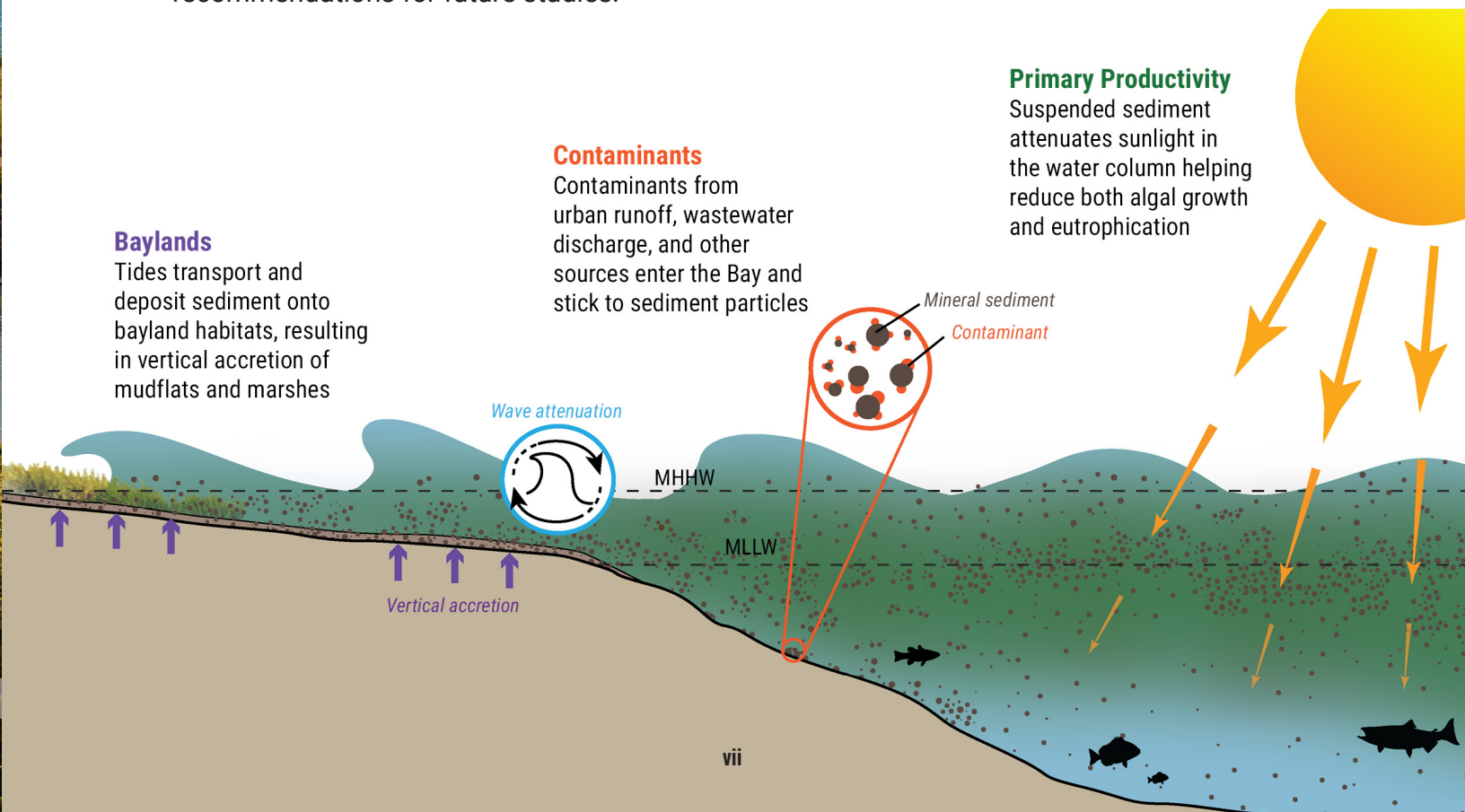
Summary

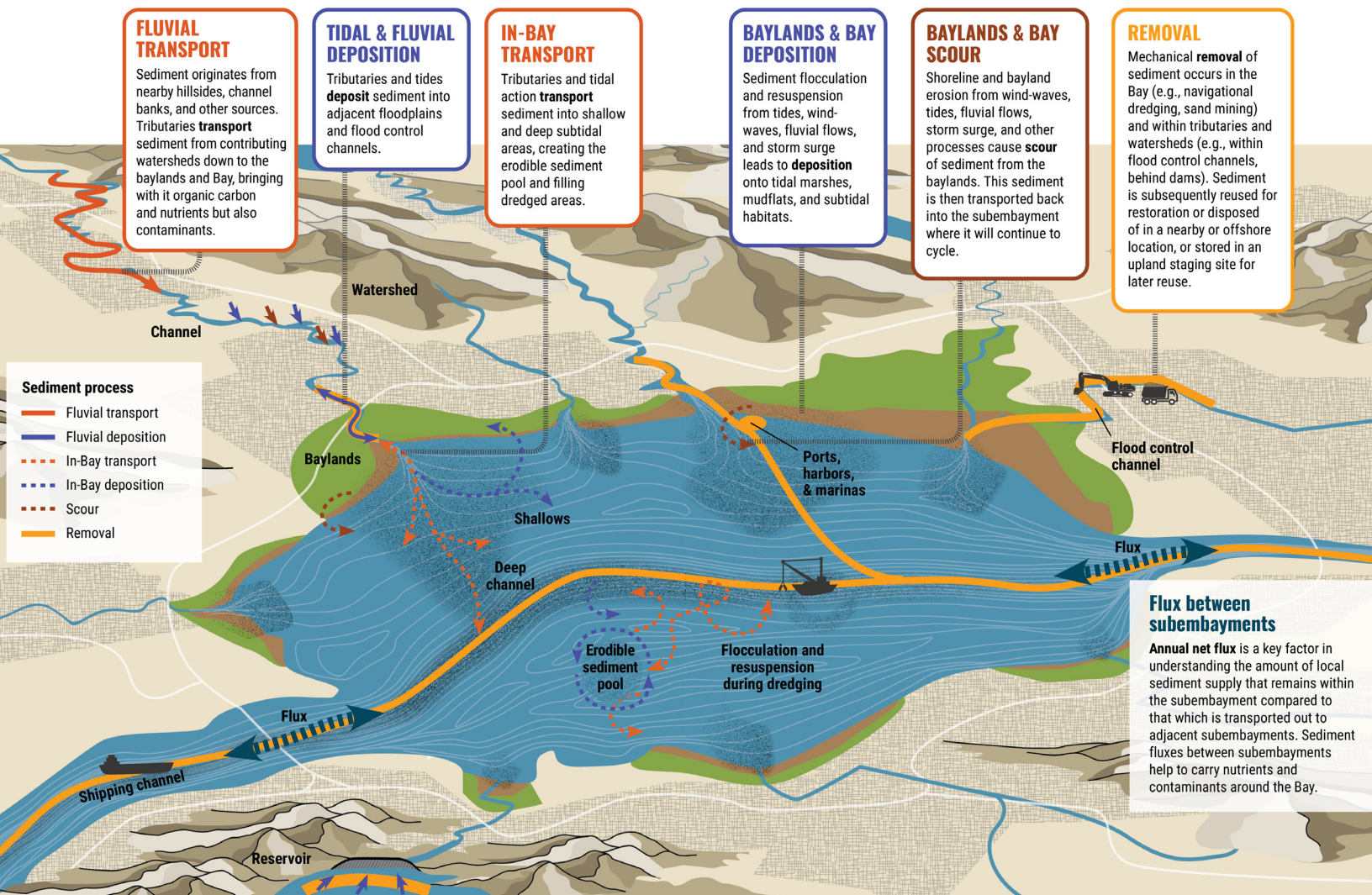
A Conceptual Understanding of Sediment Processes in San Francisco Bay

Sediment is a lifeblood of San Francisco Bay (Bay). It serves three key functions: (1) create and maintain tidal marshes and mudflats, (2) transport nutrients and contaminants, and (3) reduce impacts from excessive human-derived nutrients in the Bay. Because of these important roles, we need a detailed understanding of sediment processes in the Bay.

This report offers a conceptual understanding of how fine-grained sediment (i.e. silt and finer, henceforth called fine sediment) moves around at different scales within the Bay, now and into the future, to synthesize current knowledge and identify critical knowledge gaps. This information can be used to support Bay sediment management efforts and help prioritize funding for research and monitoring. In particular, this conceptual understanding is designed to inform future San Francisco Bay Regional Monitoring Program (RMP) work under the guidance of the Sediment Workgroup of the RMP for Water Quality in San Francisco Bay, which brings together experts who have worked on many different components of the landscape, including watersheds and tributaries, marshes and mudflats, beaches, and the open Bay. This report describes sediment at two scales: a conceptual understanding of open-Bay sediment processes at the Bay and subembayment scale (Chapter 2); and a conceptual understanding of sediment processes at the baylands scale (Chapter 3). Chapter 4 summarizes the key knowledge gaps and provides recommendations for future studies.

Sediment serves three key functions in the Bay: building and maintaining baylands, transporting contaminants, and attenuating sunlight in the water column which reduces the impacts of eutrophication.





Conceptual diagram of the primary processes governing Bay sediment supply, fate, and transport at the subembayment scale.

Open-Bay Sediment Processes

Supply

Sediment supply to the Bay, from both the Delta and local tributaries, is driven by runoff from the watersheds. Thus, sediment is transported to the Bay predominantly during the wet season and the amount varies considerably from year to year with precipitation.

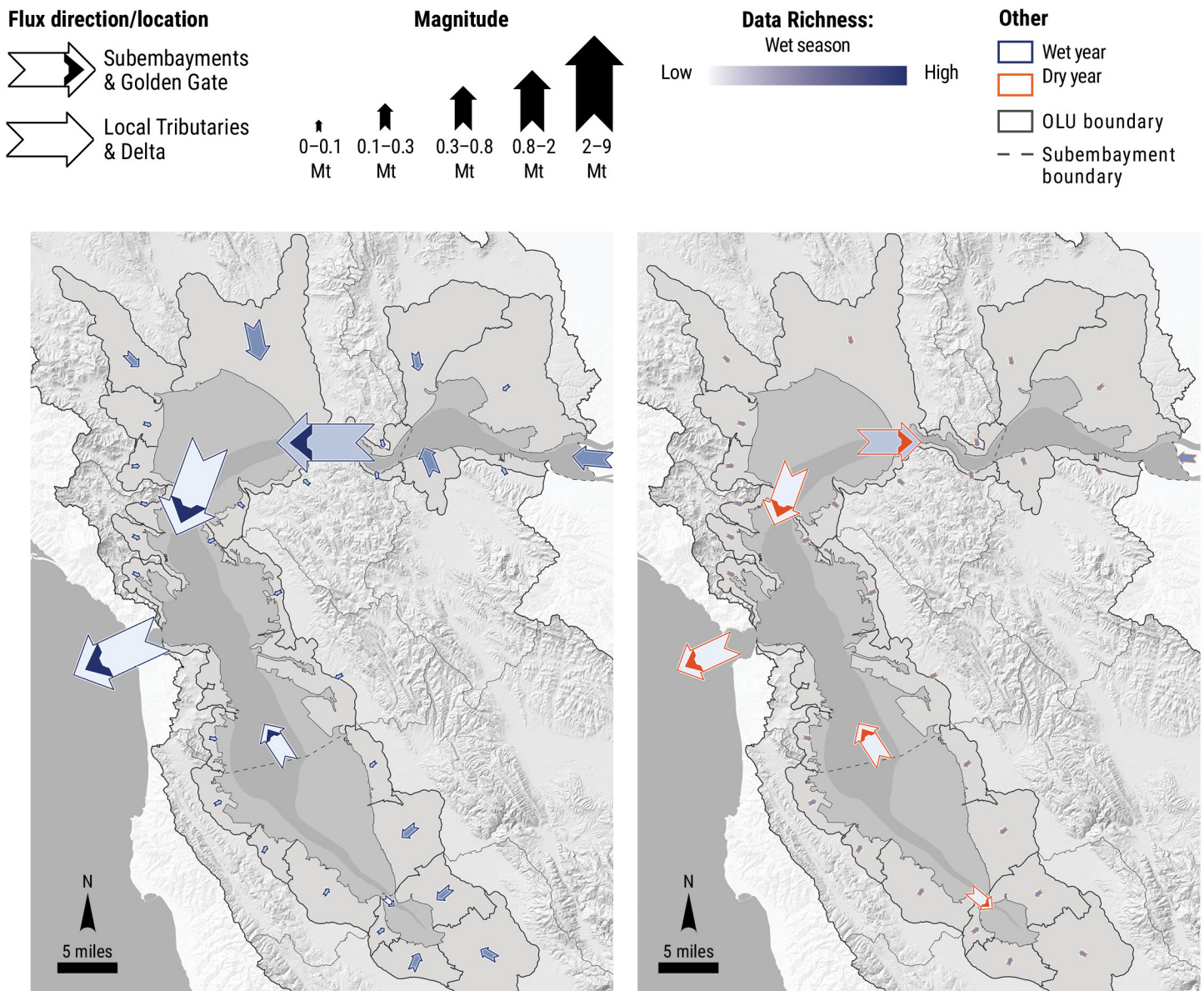
Transport

Within the Bay, sediment moves between subembayments and the Pacific Ocean, as well as depositing for long periods of time within the Bay and baylands. Central Bay has a consistent annual net sediment flux direction coming from San Pablo Bay and South Bay. Sediment fluxes to the other subembayments are more variable, but in most years the net flux is out of San Pablo Bay and South Bay, creating an influx of sediment into Central Bay, Suisun Bay, and Lower South Bay. However, strong Delta outflows cause a flushing mechanism to occur, resupplying sediment to San Pablo Bay and often resulting in strong gravitational circulation. The net flux to the ocean has a large amount of uncertainty in both magnitude and direction, despite being potentially one of the most significant drivers of the overall sediment budget of the Bay. The reason for this knowledge

gap is that the Golden Gate presents significant challenges for measuring sediment flux, given the depth, velocity, variability, and magnitude of water passing through the constriction.

Two modeled future conditions (slightly wetter and slightly drier climates) offer quite different pictures of sediment supply. For the wetter future considered, there is a considerable increase in sediment loading to the Bay, with the historically dominant sediment-supplying watersheds in the North Bay showing the greatest increase. In contrast, the drier future shows much less sediment delivery to the Bay, particularly south of the Golden Gate. Under a drier future, relatively wetter conditions north of the Golden Gate are projected to result in a late century sediment supply that is similar to current conditions, while generally drier conditions to the south result in a drastic decrease in sediment supply from creeks.

Conceptual diagram of the magnitude and direction of wet season sediment flux for Wet years (below left) and Dry years (below right) under current conditions, estimated in million metric tonnes (Mt).



Deposition/Erosion/Extraction

Some areas of the Bay are accreting, while others are eroding. A recent analysis of several decades of bathymetric data showed that the Bay overall and Suisun, San Pablo, and South Bay are net erosive, while Central Bay and Lower South Bay are accreting. Tidal marshes across the Bay are currently keeping up with sea-level rise by accreting, but are not projected to be able to continue to do so in the later decades of this century. Some marshes are eroding laterally (i.e. retreating landward) and others are prograding (i.e. expanding bayward) out into the Bay. The net effect on marsh extent has not been assessed.

On average, 3.6 million metric tonnes of sediment is dredged annually for navigation (which is equal to almost twice the average annual amount of sediment delivered to the Bay). About 40% of this sediment is relocated to marsh restoration projects, while 60% is dumped in regulated disposal sites inside the Bay and outside the Golden Gate. Also, an average of 1.2 million cubic yards of sand is mined annually from designated areas, mainly in Central Bay, and removed entirely from the Bay.

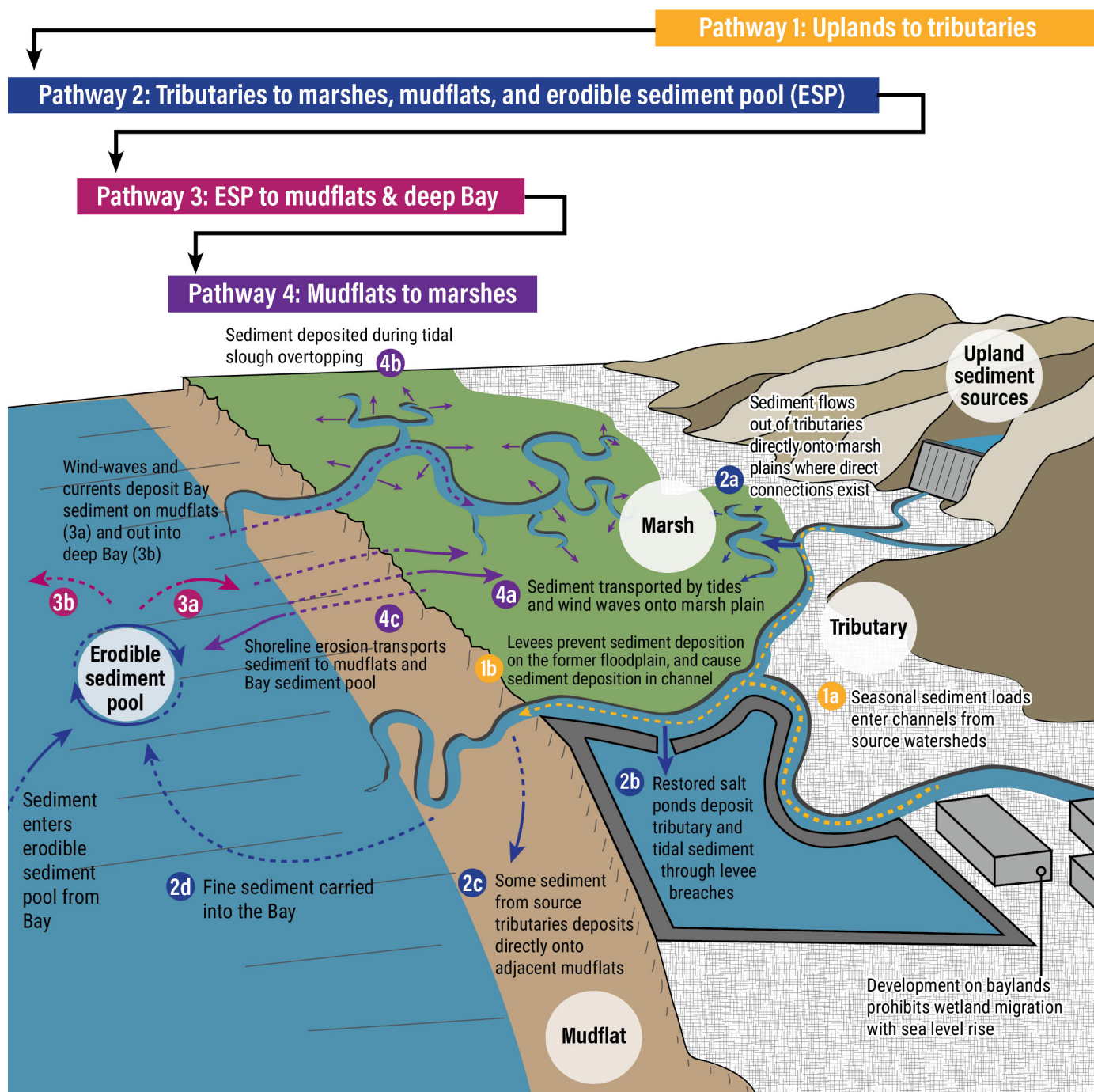


Photo by Shira Bezael (SFEI)

Baylands Sediment Processes

The conceptual understanding of sediment transport at the scale of upland sediment sources to baylands consists of several interacting transport pathways. These pathways lead from mineral sediment origins in the surrounding local watersheds and the Central Valley/Sierra Nevada rivers, to the erodible sediment pool, loss to the Pacific Ocean, and deposition in the Bay's tidal marshes, mudflats, and subtidal areas. The erodible sediment pool includes shallows and mudflats where sediment deposits and is then resuspended by wind-waves and tides to move elsewhere.

Conceptual diagram of the dynamic nature by which sediment moves from upland sediment sources to marshes, mudflats, and the larger erodible sediment pool.



The setting of a given marsh (morphology, history, and location) plays a large role in determining the most important processes and pathways that result in accretion of sediment. Important factors include local sediment supply from creeks and rivers, wind-wave exposure and mudflat characteristics, marsh elevation, vegetation type, channel network characteristics, and hardened shoreline infrastructure.

Less quantification of sediment traveling through these pathways is available for the Baylands processes relative to the open Bay (previous section). Thus, the following sections provide a general overview of what is known, and future research will be required to be able to compare quantities and develop numerical models.

Sediment Pathways

Wet-season sediment loads from watersheds flow into tributaries and comprise a significant source of fine mineral sediment that feeds the baylands (Pathway 1a). Levees and other flood infrastructure prevent sediment deposition onto marshes and mudflats, silting up the channels (Pathway 1b). Only around 55% of the sediment generated in Bay Area watersheds (approximately 3 MCY annually) is estimated to reach the Bay. Sediment flows out of tributaries directly onto marsh plains in the rare instances where direct creek-marsh connections have been maintained (Pathway 2a).

As sediment flows down tributary channels to the baylands, some sediment deposits in restoration projects (Pathway 2b), while some deposits onto mudflats (Pathway 2c) or replenishes the erodible sediment pool more broadly (Pathway 2d). Local geography around tributary mouths greatly influences the capacity for sediment storage and delivery to marshes and mudflats. Notably, the presence of levees and other flood infrastructure around channels can restrict sediment deposition to channels, preventing accretion on adjacent marshes and other baylands.

Sediment accumulates in the erodible sediment pool, moving into, out of, and between the mudflats and shallows over variable timeframes and spatial scales. Bay sediment deposits onto mudflats (Pathway 3a) and some flows out into the deep Bay (Pathway 3b). The amount of sediment available in the erodible sediment pool may vary widely based on local conditions and is key for projecting future marsh resilience to sea-level rise.

Sediment is resuspended from mudflats and other parts of the erodible sediment pool onto the marsh plain during times of high water, either directly over the bayward marsh edge (Pathway 4a), or through tidal channel networks (Pathway 4b). Mudflats play a crucial role in determining sediment delivery to marsh plains: mudflats temporarily store sediment that is then resuspended via wind-waves and the tides to nourish nearby marshes. The shape of a mudflat's profile helps explain the dominant processes at work. A convex

profile generally acts as a sediment sink and promotes marsh formation, whereas a concave profile is generally more vulnerable to erosion.

On the marsh plain, the water is slowed by vegetation and reaches zero velocity during high slack tide, allowing sediment to fall out of the water column and deposit on the marsh surface. Tidal channel density within a marsh network affects the distribution of sediment-laden water across the marsh plain and thus, resilience of that marsh.

Sediment can also leave the marsh. Marsh edge erosion and channel bank collapse lead to sediment remobilization and transport from marshes back onto mudflats and out into the larger erodible sediment pool or to be redeposited onto the marsh plain (Pathway 4c). The morphology of the marsh edge can indicate whether that marsh is growing laterally into the Bay (prograding and gaining sediment) or eroding laterally back toward the upland and losing edge sediment.

Future Conditions

Major uncertainties exist regarding how the sediment pathways described above will evolve in the future as the climate changes. Changes in sea level, precipitation, and wind are likely to be critical drivers, with changes in nutrients, wildfires, and salinity potentially playing major roles as well. A more quantitative understanding of current conditions is needed before detailed models of future outcomes will be viable.



Photo by Shira Bezalel (SFEI)

Key Knowledge Gaps

Of the many knowledge gaps and uncertainties in our understanding of Bay sediment processes discussed in this report, the following table describes the gaps that we consider most pressing to address in the near future, with an emphasis on fine-sediment supply for baylands habitat support.

Priority actions for addressing key knowledge gaps and uncertainties in Bay sediment processes.

Category	Priority actions for addressing key knowledge gaps and uncertainties
<i>Flux</i>	Update and refine estimates of flux from the Delta by improving estimates of suspended and bedload sediment at Mallard Island.
	Update and refine current and future flux estimates through the Golden Gate and between subembayments.
	Refine modeling of suspended sediment concentrations in Bay subembayments to account for more dynamic processes, such as mixing, flocculation, bioturbation, and variation over time.
<i>Uplands to tributaries pathway</i>	Model effects of shifting rainfall patterns (e.g., atmospheric river events, prolonged droughts) and land use/land cover changes on watershed flow-sediment load relationships for all Bay and Delta tributaries.
<i>Tributaries to marshes, mudflats, and erodible sediment pool pathway</i>	Estimate the proportion of tributary sediment versus sediment from the erodible sediment pool that deposits onto mudflats and marshes within each Bay subembayment, and the key drivers determining location and timescale.
<i>Erodible sediment pool to mudflats and deep Bay pathway</i>	Estimate the size, location, and rate of depletion of current erodible sediment pools at the Bay subembayment and local scales.
<i>Mudflats to marshes pathway</i>	Develop strategies and create pilot projects in collaboration with marsh restoration engineers to increase sediment resuspension near marshes and maximize sediment deposition onto marshes using restoration design features and techniques (e.g., warping techniques, strategic sediment placement, subsidence reversal/building peat using municipal wastewater effluent).
<i>Additional future conditions</i>	Model the effect of sea-level rise on sediment transport and deposition to the baylands to determine if a transition of mudflats to shallows and the loss of sediment to expanding deeper areas of the Bay will result in less resuspension of sediment by wind-waves and currents and, thus, less transport and deposition onto marshes and mudflats.
	Assess the projected impact of changing climatic conditions, Bay sediment supply, and increasing water depth on shoreline erosion rates around the Bay, and develop a method to systematically measure and monitor regional marsh and mudflat erosion rates.

1. Introduction

San Francisco Bay-Delta Estuary (Estuary) is the downstream end of an extensive fluvial and tidal system, where salt water from the Pacific mixes with freshwater flowing from major rivers draining the Central Valley and from hundreds of local tributaries that ring the edge of the Bay. The Estuary is of great importance for both people and wildlife. Approximately 14 million people live in the Estuary's watershed (SCDF 2020) and a large extent of California's tidal wetlands are located there (Goals Project 2015, SFC 2021). In all, approximately 40% of California's landmass drains to the Estuary (USEPA 2022). These freshwater flows drive important physical, chemical, and biological processes that shape the health of the downstream baylands—the continuum of habitats subject to tidal action which include tidal marshes, mudflats, beaches, and shallows. The Estuary is a biological resource of great national, regional, and local importance, providing a productive nursery for many species of juvenile fish and shellfish, essential winter foraging grounds for over a million migratory birds, and a home for a wide variety of flora and fauna (SFEP 2022). The baylands provide numerous ecological services such as shoreline protection through buffering wave energy, water filtration through the uptake of contaminants and nutrients by marshes, and recreational and aesthetic value to residents and visitors (Goals Project 2015). While the baylands remain a protected and cherished resource in the Estuary, the increasing impacts from sea-level rise threatens their long term persistence. While many elements like temperature, salinity, turbidity, depth, freshwater, and tidal flows have a role in shaping the baylands, there is one element in particular that their survival hinges upon. That element is sediment.

Sediment is the lifeblood to the habitats of the Estuary, bringing nutrients that nourish wetland vegetation; providing materials for spawning grounds for fish; increasing elevations for habitats to keep pace with sea-level rise; and supplying the basic building blocks of marshes, mudflats, subtidal habitats, and beaches. Without adequate sediment supply as sea-level rises, marshes will transition into mudflats or subtidal habitats, resulting in major losses in primary productivity and habitat availability due to loss of vegetation that would negatively impact the health of the Estuary and its resident wildlife. If there is insufficient open space at elevations suitable for marshes to migrate up slope, which is often the case in the highly urbanized Estuary, marshes could become squeezed and disappear entirely.

In San Francisco Bay (Bay), three key considerations exist when managing sediment: (1) sediment creates and maintains baylands landforms, (2) sediment transport nutrients and contaminants, and (3) sediment in suspension can reduce impacts from eutrophication (Figure 1.1). When adequate suspended sediment is available in the water column, wind-waves and tides are able to deposit sediment onto baylands, allowing them to accrete vertically and keep pace with sea-level rise. In turn, the baylands act as a buffer by absorbing wave energy and flood waters which reduces wave action on critical shoreline infrastructure like roads, railways, and levees (Goals Project 2015). For this reason, the baylands and the sediment that sustains them serve as important natural defenses to our critical infrastructure and the low-lying communities that they protect (SFEI and SPUR 2020). Secondly, fine sediment has a role in transporting contaminants into and around the Bay that can negatively impact both people and wildlife. As contaminants from

urban runoff, wastewater discharge, agricultural activities, and other sources enter the Bay, some contaminants adhere to fine sediment particles. A wide range of legacy and emerging contaminants—including mercury, pesticides, pharmaceuticals, heavy metals, polychlorinated biphenyls (PCBs), and per- and polyfluoroalkyl substances (PFAS)—threaten the health and survival of wildlife at all levels of the Bay’s food web, and they are physically coupled with the Bay’s sediment (SFBRWQCB et al. 2017). Such sediment-bound contaminants remain bioavailable until they are deeply buried, posing management challenges to safeguard wildlife. Sediment also carries with it organic carbon and organic bound nitrogen, organic and inorganic phosphorus and trace nutrients that help to support primary and secondary productivity. Thirdly, suspended sediment in the water column helps attenuate sunlight, which in turn limits phytoplankton and algal growth (Cloern 1987, Cloern et al. 2020). In this way, high suspended sediment concentrations within the Bay can help reduce the impacts of eutrophication (Schoellhamer 2011). This report focuses on the first consideration: sediment making its way onto marshes, mudflats, and other baylands habitats to build vertical elevation.

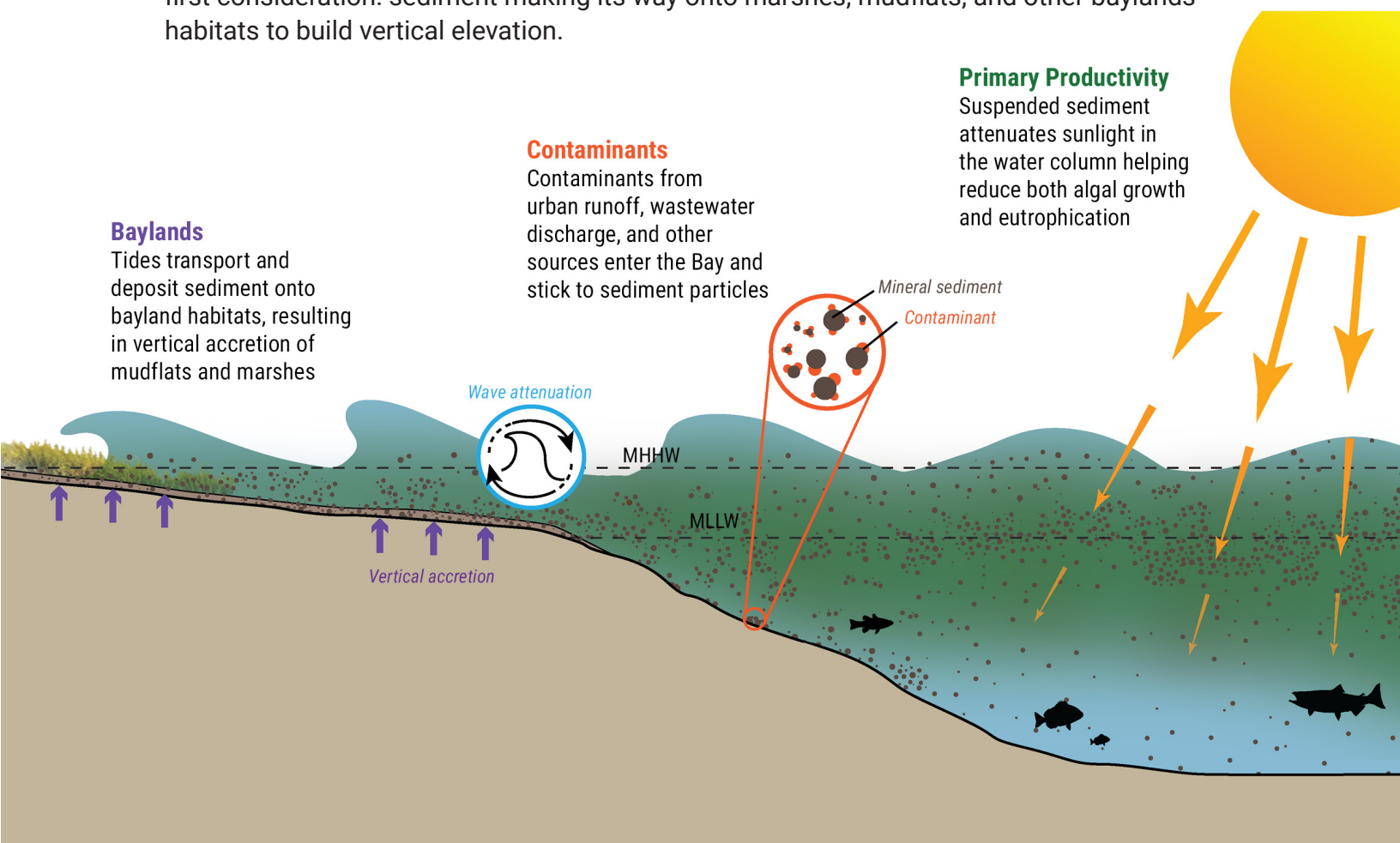


Figure 1.1. Three key considerations of sediment in the Bay include: (1) sediment builds and maintains habitat; (2) sediment transports nutrients and contaminants; (3) sediment in suspension attenuates sunlight in the water column which reduces the impacts of eutrophication.

As sea level rises, the Bay's need for sediment to adapt existing habitats increases. To plan for the baylands' changing sediment needs and provide science to better understand the three key sediment functions described above, the Bay's sediment management community seeks to understand how much sediment is passively reaching baylands and restoration projects and the extent to which management actions could increase the amount of sediment reaching these habitats. There are currently several efforts in the Bay that will help with developing this understanding, including those funded by the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP), United States Army Corp of Engineers (USACE), the United States Geological Survey (USGS), the United States Environmental Protection Agency (EPA), the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB), the San Francisco Bay Conservation and Development Commission (BCDC), the San Francisco Bay Restoration Authority, and other institutions. However, there are still considerable gaps in our understanding of how sediment moves within the Bay at different spatial and temporal scales.

Numerous studies over the past several decades have resulted in a wealth of information around sediment processes and conceptual understandings of the Bay. In 2020, the Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) created the Sediment Monitoring and Modeling Strategy (SMMS), which provides an overview of key sediment management questions, a basic understanding of Bay sediment processes and available data, and high-priority monitoring and modeling recommendations needed to fill critical data gaps (McKee et al. 2020). The SMMS provides the foundation and starting point for the graphics and narratives on sediment processes described in this report. This report also builds on earlier efforts, including the 2015 workshop conducted by BCDC to identify regional sediment science priorities (BCDC 2016a), and the 2016 Central San Francisco Bay Regional Sediment Management Plan (RSM) by BCDC which recommends ways to maximize sediment reuse, align management efforts, and help address impacts from climate change and other stressors (BCDC 2016b). This report has benefited from the work by the Wetland Regional Monitoring Program (WRMP) which is in the process of creating a regional plan to assess and track the health of the Bay's wetland habitats, as well as the work by the RMP Sediment Working Group, which conducts key studies and gap analyses focused on the future of sediment in the Bay. Numerous other research has been key in informing this effort, spanning sediment supply to the Bay (e.g., Perry et al. 2015, Dusterhoff et al. 2021), sediment transport pathways (e.g., MacWilliams et al. 2012, Barnard et al. 2013, Bever et al. 2014), and suspended sediment concentration trends (e.g., Schoellhamer 2005, 2011; Schoellhamer et al. 2018).

While much of the information described above helps to understand how sediment moves from tributaries to the open Bay, research is limited in understanding the ways in which sediment deposits on and moves around the baylands. A likely reason that Bay-focused research often stops at water depths that exclude marshes and mudflats is due to the increasing challenges of numerical modeling and collecting field data in these shallow locations (i.e., difficulty in accessing shallow areas by boat/research vessel). Several papers have made important headway in understanding sediment processes within the baylands. Krone (1979) created a detailed conceptual model of how sediment moves from the Delta and local tributaries during large, winter storms to replenish the erodible pool of

sediment that flows through Bay channels and shallows. Collins et al. (1986) found that suspended sediment is conveyed to a marsh within tidal channels on tides that inundate the marsh plain, with a higher distribution of sediment settling immediately at the channel margins, partly due to vegetation trapping. Swanson et al. (2014) found that the rate of mineral accretion on a marsh is determined by a combination of suspended sediment concentration, water depth over the marsh, and period of slack water. These conceptual models and understanding of sediment movement have been further explored by Lacy et al. through measurement of suspended sediment flux in two tidal creeks during spring and neap tides and wind-wave events (2015), and through sampling over a multi-year period to understand how mineral accretion rates vary across the marsh plain and with distance to a tidal creek (2020). While these studies and other efforts are critical to understand general sediment deposition and transport dynamics within the baylands, more research is needed to measure and monitor sediment in the baylands to refine our understanding and account for the wide variability of sediment movement over time and by location. To this end, the Wetland Regional Monitoring Program (WRMP), established in 2017, is developing a pilot program to monitor mature and restored tidal marsh habitats at key locations throughout the Bay (WRMP 2020). The WRMP's efforts combined with those funded by the RMP Sediment Workgroup and the U.S. Army Corps of Engineers' Regional Dredge Material Management Plan (RDMMP) are leading the way to monitor and model the Bay's sediment to inform more holistic management, by uniting the sediment needs of the Bay and its baylands as one.



Photo by Shira Bezalel (SFEI)

No effort to date has woven together the information described above into one narrative that examines sediment at multiple scales in a way that is easy to understand for a broad audience. Synthesizing this information into a narrative account will provide more clarity on which Bay sediment dynamics are well researched and which have not been thoroughly studied and would benefit from more data. It will also enable better communication and collaboration between restoration practitioners, regulators, policymakers and other key stakeholders to help identify and drive forward necessary sediment management actions given the pressures of climate change.

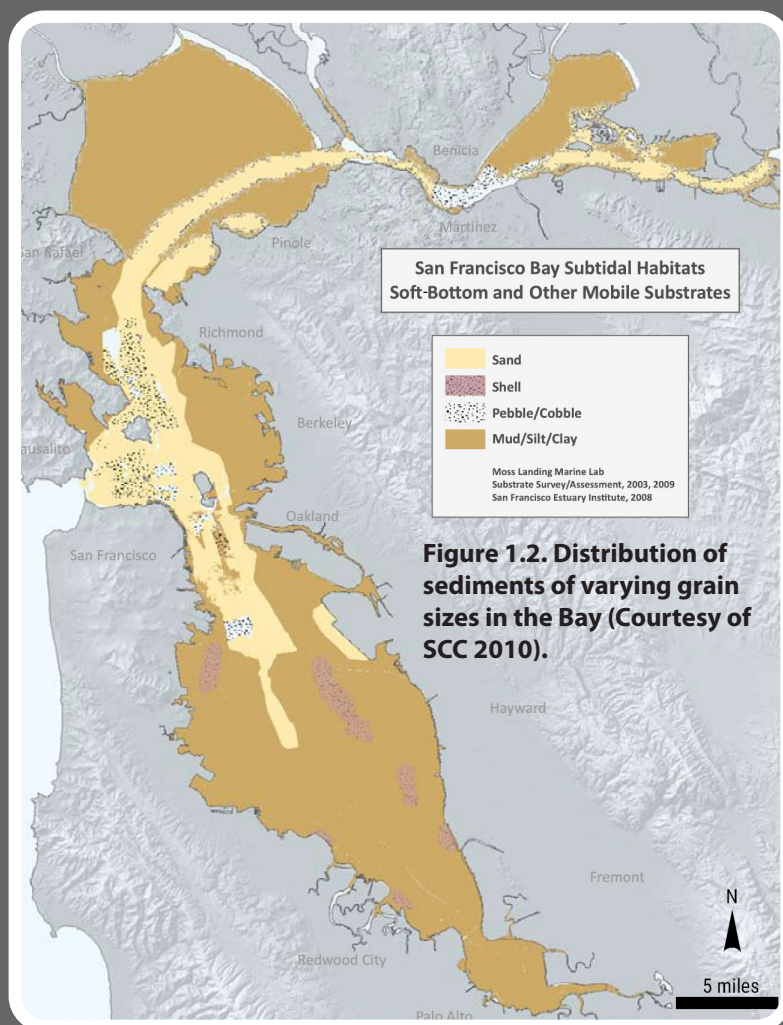
This report provides a conceptual-level, common understanding of how fine-grained sediment (i.e. silt and finer, henceforth called fine sediment) moves around at different scales within the Bay to synthesize the current state of information while also identifying the key data gaps in need of more research. To do this, this report first considers overarching sediment pathways that supply sediment to the entire Estuary and then identifies more specific pathways for the baylands in the Bay, a subwatershed of the larger Estuary, between the Golden Gate and the western boundary of the Sacramento-San Joaquin Delta at Broad Slough. The visuals and narratives put forth in this report can be used as a tool to improve current and future Bay sediment management efforts to plan for the likely effects of ongoing climate change. Content from this report can also be used to aid in communication on the state of regional sediment knowledge to help prioritize limited resources to address questions regarding sediment loading to the Bay and sediment delivery to marshes. Additionally, findings can support statewide efforts, such as those underway through the California Sediment Management Workgroup (CSMW) to evaluate the state's coastal sediment management needs and promote regional, system-wide solutions.

The chapters that follow describe sediment at three scales: a conceptual understanding of open-Bay sediment processes at the Bay and subembayment scales (Chapter 2); and a conceptual understanding of sediment processes at the baylands scale (Chapter 3). Chapter 4 summarizes the key data gaps described throughout Chapters 2 and 3 and offers recommendations for next steps.

THE NEED TO EXPAND OUR CONCEPTUAL UNDERSTANDING TO INCLUDE COARSE-GRAINED SEDIMENT

While this conceptual understanding of sediment transport offers a useful starting place to understand how fine-grained sediment moves around at the Bay/subembayment and baylands scales, a next iteration needs to integrate coarse-grained sediment. Coarse and fine-grained sediments behave differently in terms of transport and deposition processes due to their difference in size and weight and are found throughout the Bay (Figure 1.2). This report focuses on fine-grained sediment, with an emphasis on sustaining marsh and mudflat habitats, but this is only one aspect of sediment management at the baylands scale. There is a pressing need to integrate coarse-grained sediment into this conceptual understanding to anticipate whether estuarine beaches and sandflats will have the coarse sediment supply necessary to adapt to sea-level rise.

Estuarine beaches hold high potential to be used as a multi-benefit, soft-shoreline stabilization tool while providing a range of wildlife benefits for specific species, including shorebirds, small mammals, invertebrates, and native plants. While coarse sediment inputs to the Bay and outer-coast ocean beaches historically were transported from the Sierra Nevada (Barnard et al. 2013), sediment sources for estuarine beaches and other Bay-margin habitats were mainly from local bluff erosion and local tributary watersheds (Schoellhamer et al. 2018). Both sources have greatly reduced in volume over the course of the 20th century, partly due to sand and gravel mining (Barnard et al. 2013), rip rap, and shoreline development. This report does not detail the magnitudes, timing, variability, or other important considerations of coarse sediment in the Bay. However, there is a recent effort that describes the annual bayscale coarse sediment budget that addresses these considerations (SFEI-ASC 2023). By considering both fine and coarse sediment, a more accurate representation of sediment transport can be developed, which can be used to inform management actions to support the full spectrum of baylands habitats. For more information on estuarine beaches in the Bay, see SFEI and Baye (2020).



2. Conceptual Understanding of Open-Bay Sediment Processes

2.1. Overview

The Bay is a highly urbanized estuarine system with a complex set of sediment processes that are driven by both natural and anthropogenic factors (Figure 2.1). Sediment is supplied to the Bay from the Sierra Nevada Mountains through the Sacramento-San Joaquin Delta (hereafter called the Delta) and from local Bay tributaries. Once in the Bay, sediment is transported between subembayments, deposited within intertidal locations (tidal marshes, mudflats, flood control channels) and subtidal locations (open Bay, shipping channels, ports, harbors, marinas, and petroleum refinery wharfs), and transported out the Golden Gate. Deposited sediment is removed from managed channels and maritime infrastructure to ensure proper functioning. In addition, sand is extracted from subtidal areas in the Bay for use in the construction industry. The magnitude of sediment supply to Bay subembayments is a key component for understanding local hydrophobic contaminant loads (i.e., loads of harmful contaminants that bond to fine-grained sediments), suspended sediment concentrations and associated eutrophication and harmful algae bloom risk, and sediment availability for maintaining intertidal habitat elevations over time. Sediment supply, transport, deposition, and extraction vary seasonally and annually, and depend on weather conditions (e.g., wintertime storm events, summertime wind events) as well as financial and permitting considerations that ultimately drive sediment removal.

This chapter provides a detailed description of the state of knowledge of Bay sediment dynamics. It begins with an overview of bayscale sediment supply, transport, deposition/erosion, and extraction, and how these processes have changed over the past 200 years. A conceptual understanding of subembayment scale sediment supply and transport is then presented for both current and future conditions under varying hydrologic conditions. The conceptual understanding is used to highlight key knowledge gaps that need to be addressed to improve the overall understanding of the magnitude and direction of sediment flux within each subembayment now and in the future under a changed climate.

FLUVIAL TRANSPORT

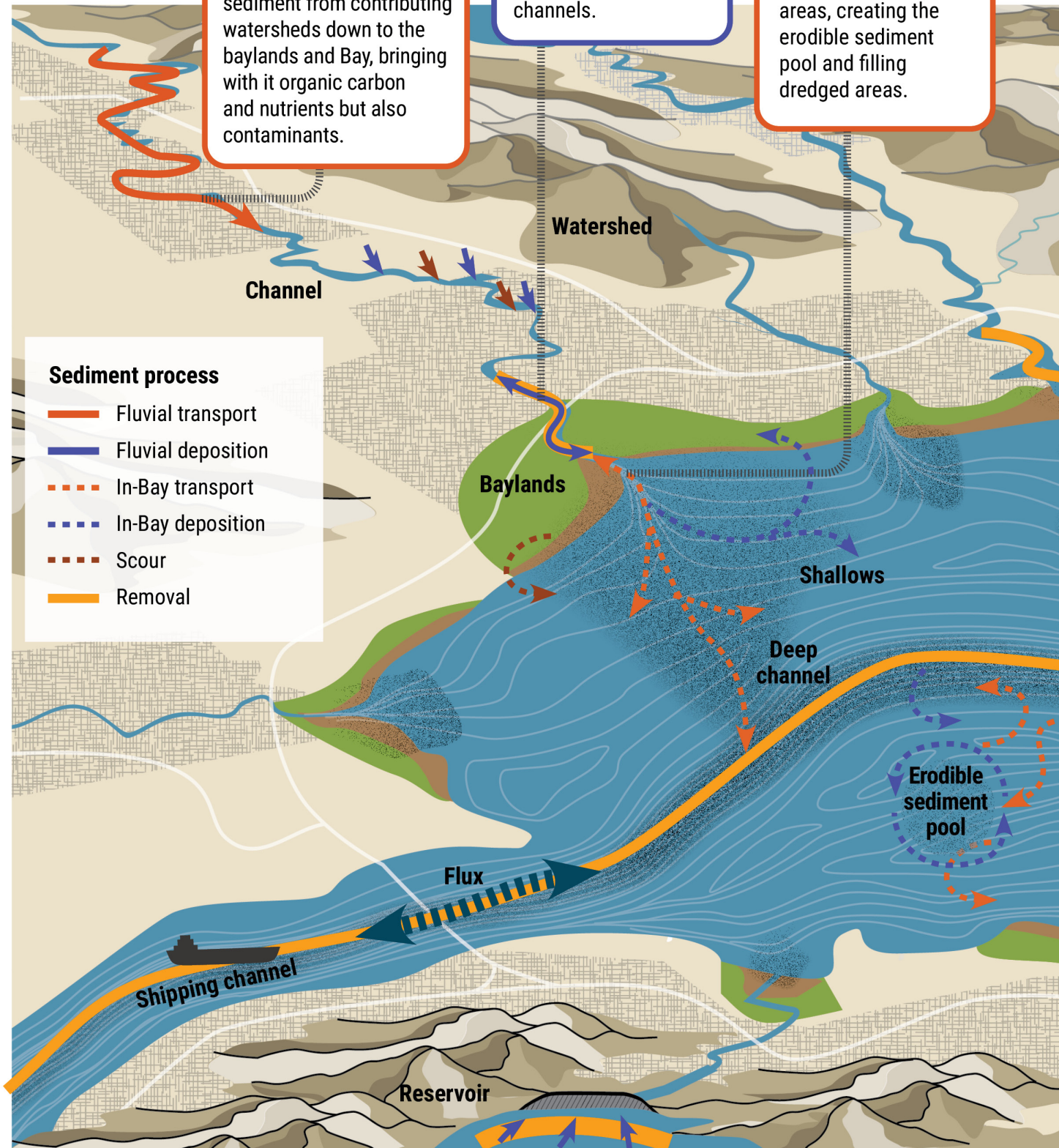
Sediment originates from nearby hillsides, channel banks, and other sources. Tributaries **transport** sediment from contributing watersheds down to the baylands and Bay, bringing with it organic carbon and nutrients but also contaminants.

TIDAL & FLUVIAL DEPOSITION

Tributaries and tides **deposit** sediment into adjacent floodplains and flood control channels.

IN-BAY TRANSPORT

Tributaries and tidal action **transport** sediment into shallow and deep subtidal areas, creating the erodible sediment pool and filling dredged areas.



BAYLANDS & BAY DEPOSITION

Sediment flocculation and resuspension from tides, wind-waves, fluvial flows, and storm surge leads to **deposition** onto tidal marshes, mudflats, and subtidal habitats.

BAYLANDS & BAY SCOUR

Shoreline and bayland erosion from wind-waves, tides, fluvial flows, storm surge, and other processes cause **scour** of sediment from the baylands. This sediment is then transported back into the subembayment where it will continue to cycle.

REMOVAL

Mechanical **removal** of sediment occurs in the Bay (e.g., navigational dredging, sand mining) and within tributaries and watersheds (e.g., within flood control channels, behind dams). Sediment is subsequently reused for restoration or disposed of in a nearby or offshore location, or stored in an upland staging site for later reuse.

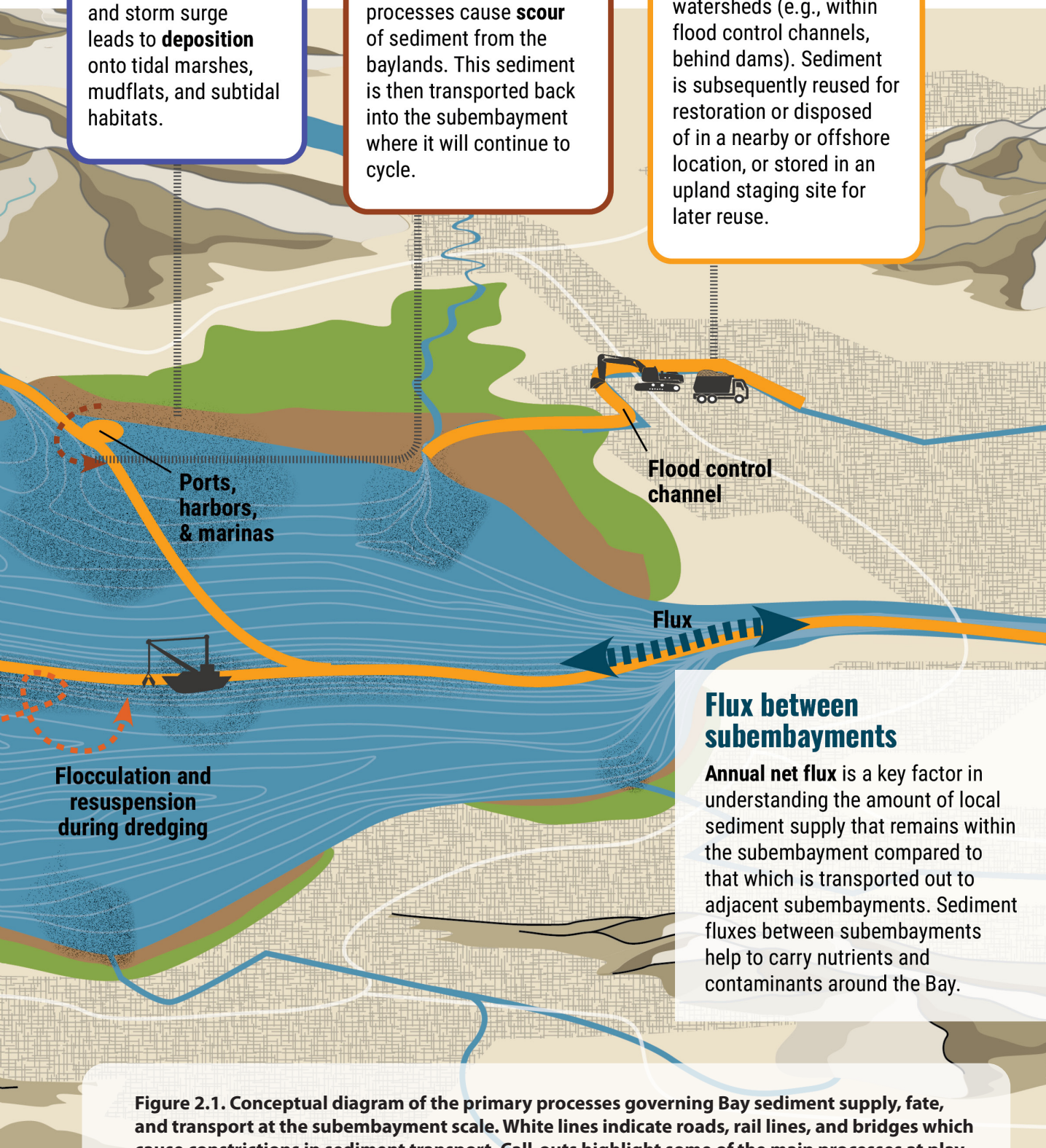


Figure 2.1. Conceptual diagram of the primary processes governing Bay sediment supply, fate, and transport at the subembayment scale. White lines indicate roads, rail lines, and bridges which cause constrictions in sediment transport. Call-outs highlight some of the main processes at play but are not exhaustive descriptions.

2.1.1 Supply

Sediment is supplied to the Bay predominantly during the wet season and the quantity of supply can vary considerably from year to year. Approximately 90% of the Bay Area precipitation and >95% of sediment transport to the Bay occurs during the wet season between October and April (McKee et al. 2006, McKee et al. 2013). Between water year (WY) 1995 and 2016, the annual Delta supply ranged from 0.1 million metric tonnes (Mt) in WY 2014 to 2.38 Mt in WY 1998 (Schoellhamer et al. 2018). The Bay tributaries showed even greater variability during this time, with the largest watersheds showing annual loads that varied by a factor of 100 to 300. Combining the annual Bay tributary loads over the 22-year time period shows that approximately 60% of the total tributary sediment supply was delivered in just four of the wettest years (WYs 1995, 1997, 1998, 2006) (Schoellhamer et al. 2018).

Over the past 200 years, anthropogenic activities have had a profound influence on the amount of sediment supplied to the Bay. In particular, mining activities during the Gold Rush era through the second half of the nineteenth century drastically impacted the sediment supply from the Delta. Prior to the Gold Rush, sediment supplied from the Central Valley was estimated to be about 0.8 Mt per year (Gilbert 1917). At the peak of the Gold Rush, sediment supplied to the Bay from the Sacramento and San Joaquin rivers was estimated to be 7.3 Mt per year (Gilbert 1917). This is in large part due to the practices of hydraulic mining used in the pursuit of gold in the Sierra Nevada foothills, but significant timber harvest practices throughout the region also played a factor (Burns 1972, Laudenslayer and Darr 1990). Despite the end of widespread hydraulic mining practices and the Gold Rush in the 1880s, this pulse of sediment generated from mining activities continued to gradually make its way across the Central Valley during the twentieth century. Little change was identified in the Bay sediment bed volume between 1892-1925, but an increase of 160 million cubic meters illustrates a second pulse of sediment from 1926-1949 as urbanization and increased agricultural land use took over the Central Valley. It is thought that the Delta continued to supply roughly 85-90% of the overall sediment load into the Bay for the first half of the century (Smith, 1965, Porterfield, 1980, Ogden Beeman and Associates 1992, Moftakhari et al. 2015), and gradually decreased to approximately 75% by 1960 (Krone 1979).

At the beginning of the twenty-first century, there was a dramatic shift in Bay sediment supply. There was a 36% step-decrease in suspended sediment concentration from 1991-1998 to 1999-2007 (Schoellhamer 2011), which is attributed to the depletion of Gold Rush era sediment as well as extensive modifications to the drainages of the Central Valley and Delta that trap sediment behind dams and in flood bypasses. Today, the major source of sediment has flipped, with the local Bay tributaries contributing roughly 60% (1.4 Mt) of the annual suspended sediment load to the Bay (McKee et al. 2013). Within the nine-county Bay Area, the largest contributions of sediment supply are the Napa River, Sonoma Creek, Walnut Creek, and Alameda Creek, accounting for about 40% of the local supply (Schoellhamer et al. 2018). The current average annual Delta sediment supply to the Bay is 0.6 Mt (Schoellhamer et al. 2018), which is considerably lower than the peak sediment load during the Gold Rush era of 7-8 Mt. In addition, the contribution of bedload and coarse-grained material, like sand, from the local tributaries and the Delta has been hypothesized to be practically negligible when considering the amount removed by dredging or mining

practices (Schoellhamer et al. 2018, SFEI-ASC 2021). Work presently underway will provide accurate estimates and better context for sand supply to and removal from the Bay.

2.1.2 Transport

The Bay is a series of connected subembayments that differ in terms of terrestrial sediment supply, freshwater inflow, salinity, bathymetry, and ocean connectivity.

Central Bay has a consistent supply of sediment coming from San Pablo Bay and South Bay. Delta Modeling Associates (2015) showed through a modeling exercise that annual net sediment flux near the Richmond Bridge was towards Central Bay for WY1998, 2002, 2006, and 2012, with the annual flux estimated to be between 1.2 and 3.6 Mt and the fluxes being highest for the wettest water years (WY1998 and 2006). Based on these modeled values, the average Wet year transports ~3 Mt into Central Bay while a Dry year transports ~2 Mt. Sediment flux modeling near the Bay Bridge also showed a consistent annual net sediment flux direction towards Central Bay. The annual fluxes varied between 0.8 and 1.8 Mt. Based on estimates from WY1998 and 2006, an average wet year contributes 0.9 Mt of sediment from South Bay to Central Bay, while a single Dry year (2012) showed transport of 1.3 Mt (Delta Modeling Associates 2015).

In Suisun Bay and Lower South Bay, both the direction and magnitude of the annual net sediment flux between subembayments is driven by freshwater inflow, particularly from the Delta. Sediment flux measurements at Benicia Bridge, near the eastern end of Carquinez Strait, between Suisun Bay and San Pablo Bay, indicate that tidal forcing drove an annual net suspended sediment flux of 3 Mt into Suisun Bay during a dry year (WY 2014), but high freshwater flows resulted in a net flux of 21 Mt towards San Pablo Bay during a particularly wet year (WY 1998) (Ganju and Schoellhamer 2006, Schoellhamer et al. 2018). Similarly, flux measurements at the Dumbarton Bridge showed a net export of 0.15 Mt of sediment from Lower South Bay into South Bay during a high Delta outflow year (WY 2011) (Livsey et al. 2021). During Dry years, the net flux direction is typically towards Lower South Bay, with 0.6 Mt transported in WY 2014 and WY 2015 (Livsey et al. 2021). In general, previous studies have shown that the annual sediment flux is out of San Pablo Bay and South Bay, creating influx into Central Bay, Suisun Bay, and Lower South Bay. However, strong Delta outflows create a flushing mechanism, resupplying sediment to San Pablo Bay.

Despite being potentially one of the most significant drivers of the overall sediment budget of the Bay, the net flux through the Golden Gate has a large amount of uncertainty in both magnitude and direction. Previous estimates have suggested the annual net flux to be an export of 4-5 Mt (Erikson et al. 2013, Schoellhamer et al. 2005). However, fieldwork by the USGS in 2017 and modeling by Anchor QEA has shown the wet season net sediment flux at the Golden Gate to be quite larger, with 8.8 Mt moving from the Bay to the Pacific Ocean (Downing-Kunz et al. 2021, Anchor QEA LLC. 2021). These efforts have provided further evidence that sediment flux at the Golden Gate is heavily influenced by tidal asymmetry and that the correlation between water flow and sediment flux is extremely variable. Work is ongoing on a sediment budget for the Bay (SFEI-ASC 2023, in preparation) that will offer some new insights into annual average fluxes between sub-embayments and the flux and the Golden Gate and quantify some of the qualitative findings described in this section. Fluxes during storms and individual years will continue to be informed by modeling.

2.1.3 Deposition/Erosion/Extraction

A large portion of sediment supplied to the Bay deposits in low energy areas, such as ports and harbors; in the tidal portions of flood control channels at the mouths of local tributaries; or in shallows and tidal marshes. This sediment may be stored for long periods of time or be stored only temporarily as large winter storm waves and summertime wind-waves scour and redistribute the sediment. An examination of recent bathymetric surveys captured between the 1980s and the 2010s shows that, overall, the Bay lost an estimated 34 million cubic meters of material over the past several decades (Fregoso et al. 2023). At the subembayment scale, Suisun, San Pablo, and South Bay are all documented to be net erosive, ranging from a mean erosion rate of 0.1 cm/yr (South Bay) to 2.1 cm/yr (Suisun Bay). In contrast, Central Bay is experiencing a mean bed increase of 0.1 cm/yr, and the highest rates of accretion are occurring in Lower South Bay, averaging in some locations a net gain of 1-2 cm/yr. This accretion balances out some of the loss occurring in South Bay, which has areas losing 2-3 cm/yr. Fregoso et al. (2023) concluded that the net sediment loss from the Bay can be attributed to changes in sediment supply to the Bay as well as the impacts of human activities such as channel dredging and sediment mining.

In addition to bathymetric surveys, several research efforts have evaluated the lateral and vertical changes occurring in tidal marshes, particularly in relation to their resilience to sea-level rise. While a baywide assessment of foreshore marsh erosion has not been pursued, various lateral shoreline change analyses around the Bay have shown that many marshes are eroding (Fischel and Robilliard 1991, Beagle et al. 2015, SFEI and Peter Baye 2020). However, in some places, marshes are prograding, or growing laterally out into the Bay, such as the northern shore of San Pablo Bay. In terms of vertical accretion, recent research has shown that Bay marshes are gaining elevation at a rate of 2-8 mm/yr, roughly in keeping with sea-level rise (Thorne et al. 2018, Lacy et al. 2020). Modeling results concur with this empirical research: current organic and mineral sediment supply is enough to sustain marshes at current rates of sea-level rise (Schile et al. 2014, Buffington et al. 2021). With the anticipated future acceleration of sea-level rise, models predict that even marshes high in the tidal frame will experience increased inundation over time leading to elevation loss of low marshes and mudflats by 2100 (Parker and Boyer 2019, Buffington et al. 2021). However, many marshes around the region are adjacent to low elevation land and could therefore migrate inland with changes to current landscape features and land management approaches.

Extraction of deposited sediment occurs around the Bay to support navigation, commercial sand supplies, and flood management. On average, 3.6 Mt of sediment is dredged annually from shipping channels, refinery wharfs, harbors, small marinas, and other maritime features (Moffatt and Nichol 1997, Foley et al. 2019, LTMS 2019). About 40% of this sediment is relocated to marsh restoration projects, while 60% (2.1 Mt) is dumped in regulated disposal sites (SFEI-ASC 2017). This includes a site outside the Golden Gate, in which the sediment is permanently lost from the Bay, as well as several high-energy dispersive in-Bay sites in which sediment fate is difficult to discern. An additional average of 1.4 million cubic yards of sand is mined annually from designated areas in the Bay, with roughly 80% occurring in Central Bay and 20% in Suisun Bay (BCDC 2021). At the margins of the Bay, 4.9 Mt of sediment have been removed over a 40-year span (1973-2013) from 33

of the largest flood control channels (SFEI-ASC 2017). This equates to about 0.12 Mt each year, with Alameda Creek being the largest, accounting for almost 50% of overall sediment removed. While some sediment is used for tidal marsh restoration projects, over 60% ends up either in landfills or disposed of as a waste product (SFEI-ASC 2017).

2.1.4 Key Processes that Drive Sediment Dynamics in the Bay

The state of the Bay ecosystem is event-driven; storm events cause large influxes of water and sediment over short periods of time, changing salinity and with it sediment transport. In between these events, tides are the major driver of sediment dynamics. Since the sediment in the Bay is predominantly composed of silt and clay, wind waves, flocculation, and gravitational circulation also dictate the resuspension, transport, and deposition of sediment. Apart from areas in Central Bay that are exposed to ocean swell propagating through the Golden Gate, waves in the Bay are mainly generated by local winds. These wind waves result in resuspension of fine sediment in shallow parts of the Bay. Once suspended, these cohesive sediment particles are susceptible to flocculation. Flocculation is the process by which small particles in water clump together to form larger aggregates through an electrostatically charged attraction. In terms of sediment transport, flocculation has a significant influence on the settling velocity of suspended particles (Figure 2.2) and without consideration, can bias sediment flux estimates (Livsey et al. 2020). Flocculation in the Bay varies longitudinally due to gradients in physical, chemical, and biological processes (Manning and Schoellhamer 2013). Gravitational circulation drives sediment transport in parts of the Bay during high runoff events when strong density gradients lead to up-estuary flow near the bed and down-estuary flow near the surface. Gravitational circulation

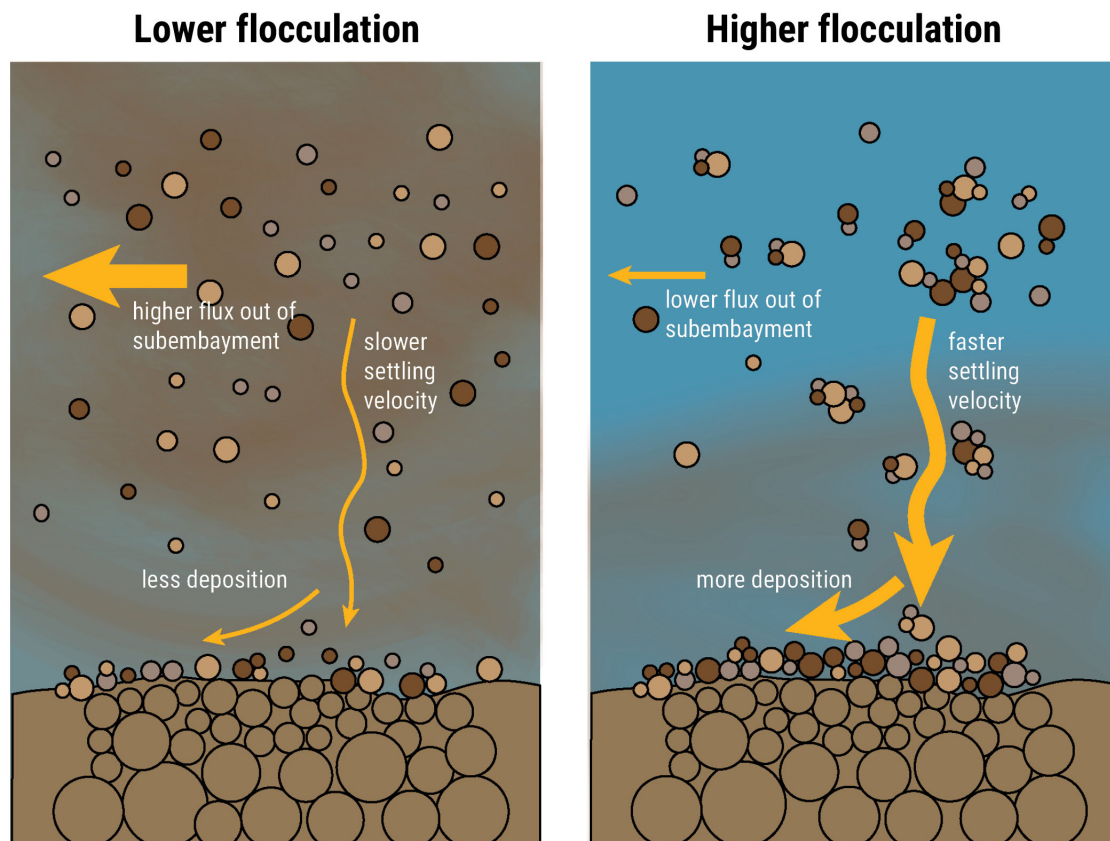


Figure 2.2.
Conceptual
understanding
of the effect
of flocculation
on suspended
sediment flux
and deposition

occurs throughout the northern portion of the Bay (Peterson et al. 1975, Smith et al. 1995, Monismith et al. 2002, Barnard 2013, Schoellhamer 2018) and has been observed in the Central Bay (McCulloch et al. 1970, Conomos 1979, Petzrick et al. 1996).

Sediment deposition and erosion are constantly changing with season and location in the Bay. Tidal channels, tidal marshes, mudflats, subtidal shoals, and deep channels can all undergo cycles of erosion and deposition. The erodible sediment pool is both a source and sink of sediment, and can be found wherever erosive conditions exist in the Bay (see pages iv and 15 for erodible sediment pool definition). Changes to the erodible sediment pool occur over long time periods as a result of large pulses of sediment deposition and periods of erosion that bring sediment into and out of the pool (Geyer and Ralston 2017). Vertically, the erodible sediment pool refers to the upper layer of more recently deposited fine sediment that is unconsolidated and able to be resuspended by wind waves, tides, and currents (Krone 1979, SFEI 2022). In contrast, underlying the active layer are older sediment deposits that are consolidated and more resistant to remobilization and may not be considered part of the erodible sediment pool (SFEI 2022). Sediment that enters the deep channels of the Bay stays within the deep channel system and is unlikely to provide significant amounts of sediment to mudflats and marshes (SFEI 2022); thus, the deep Bay is less likely to contribute to the erodible sediment pool compared to shallows and mudflats.



Photo by Scott Dusterhoff (SFEI)

WHAT IS THE ERODIBLE SEDIMENT POOL?



Photo by Micha Salomon (SFEI)

A large portion of the sediment that flows into the Bay from the Delta and local tributaries during wet winter months is thought to deposit into the Bay's erodible sediment pool. The availability of sediment for resuspension onto bayland habitats from the erodible sediment pool depends on whether an area is supply- or transport-regulated. Areas are considered transport-regulated when there is more sediment in the erodible sediment pool than is resuspended and transported by the local hydrodynamic energy. Conversely, areas are considered supply-regulated when the amount of sediment in the erodible sediment pool is less than could be resuspended with the available hydrodynamic energy (Schoellhamer 2011, SFEI 2022). At the most simplified level, sediment transported to mudflats and shallow margin areas from local tributaries, the Delta, and the Pacific Ocean increase the volume of the erodible sediment pool. In contrast, sediment flowing to the Pacific Ocean, depositing onto tidal marshes, or removed during dredging reduces the volume of the erodible sediment pool (Schoellhamer 2011).

In the Bay, suspended sediment concentrations (SSC) have been correlated to the presence of the erodible sediment pool, as opposed to solely tributary sediment supply for the recent past (i.e., ca 1850-1999; Schoellhamer 2011). This suggests that in the dry season, even when tributary loads to the Bay were small, there was adequate sediment in the erodible sediment pool to maintain relatively high SSC for deposition onto mudflats and marshes. However, San Francisco Bay experienced a sharp decrease in SSC (approximately 36%) in the period from WY 1999-2007 compared to the period from WY 1991-1998. Modeling studies suggest that this downshift in SSC was due to the Bay transitioning from a transport-regulated to supply-regulated system due to depletion of the erodible sediment pool (Schoellhamer 2011). Hydraulic mining and high rates of land development in the mid- and late-19th century led to large pulses of sediment entering the Bay, building up the erodible sediment pool. As population growth and agricultural developments slowed by the mid-20th century and flood-risk management practices like dams increased the trapping of sediment, sediment inflows substantially declined. As the erodible sediment pool continues to decline, SSC will become more dependent upon local sediment sources than prior to 2000 (Stantec and SFEI 2017).

2.2 Subembayment scale sediment dynamics

2.2.1 Current Conditions

2.2.1.1 Methods and Data Sources

A conceptual understanding of current sediment transport dynamics at the subembayment scale for a range of hydrologic conditions was developed using Baywide sediment flux data for WY1995-2016. To capture hydrologic variability, transport dynamics were assessed for typical wet season (October 1 to April 30) and dry season (May 1 to September 30) conditions for both Wet years and Dry years. Water year type (i.e., Wet or Dry) was determined based on the annual Delta outflow at Mallard Island (Ganju and Schoellhamer 2006, Schoellhamer et al. 2018) and outflow from the largest Bay tributaries (McKee et al. 2013, Schoellhamer et al. 2018). Five Wet years (WY 1997, 1998, 2005, 2006, 2011) and five Dry years (WY 2007, 2009, 2012, 2014, 2015) were selected for use in the analysis. Wet year Delta outflows ranged from 19,046 million cubic meters in WY 2005 to 53,600 million cubic meters in WY 1998, while dry year Delta outflows ranged from 5,290 million cubic meters in WY 2014 to 9,940 million cubic meters in WY 2012. Although outside the time range under consideration, modeled Golden Gate flux from WY 2017 (a year with high Delta and Bay tributary outflow) was included in the Wet year assessment as it is the only Wet year data for that location that exists.

A variety of data sources were used to estimate the seasonal average net fluxes used to build the conceptual understanding presented here. Ganju and Schoellhamer (2006) and Schoellhamer et al. (2018) provided calculated values for Delta flux and flux between Suisun Bay and San Pablo Bay at Benicia Bridge for each Wet and Dry year considered. Schoellhamer et al. (2018) provided calculated Bay tributary load values for each Wet and Dry year considered, and these values were combined to determine total tributary sediment load for each Bay Operational Landscape Unit (OLU, see SFEI and SPUR 2019). Estimates of sediment flux between San Pablo Bay and Central Bay at the Richmond-San Rafael Bridge and between Central Bay and South Bay at the Bay Bridge were derived from modeling efforts by Delta Modeling Associates (2015). Modeled flux estimates were available at both locations for two of the Wet years considered (WY 1998 and 2006) and one of the Dry years (WY 2012). Livsey et al. (2021) provided modeled estimates of sediment flux between South Bay and Lower South Bay at Dumbarton Bridge for one of the Wet years considered (WY 2011) and three of the Dry years (WY 2009, 2014, 2015). Lastly, Anchor QEA (2021) provided modeled estimates of sediment flux at the Golden Gate for WY 2017. To build a conceptual understanding of general conditions, average seasonal flux rates for Bay tributaries, the Delta, and in-Bay locations were classified into 5 categories, with the lowest rate being >0.1 Mt and the highest rate being 2-9 Mt.

Within the conceptual understanding of Bay-scale sediment flux presented below, there are important caveats that need to be considered when viewing the findings. There was not the same amount of data available for each element of the model and many of the estimates shown are derived from monitoring data for a short period of time or unvalidated model results. The degree of data richness (the measure of how much data were available) for each estimate is therefore shown as an indication of overall confidence. In addition, this

conceptual understanding combines sediment supply and flux estimates from several years to determine average conditions for Wet years and Dry years. In reality, flux values at subembayment boundaries and at the Golden Gate for any given year are highly dependent on the amount of sediment supplied to the Bay during that year and in previous years. However, as there is limited flux data throughout the Bay, the conceptual understanding presented here reflects the best possible estimates with the available data.

2.2.1.2 Conceptual Understanding of Wet Season Sediment Dynamics by Subembayment (Wet year, Dry year)

In Suisun Bay and San Pablo Bay, wet season sediment dynamics vary considerably between Wet Years and Dry years. In general, sediment supply from the Delta and the largest Bay tributaries with highest sediment supplies (e.g., Napa River, Sonoma Creek, Walnut Creek, and Petaluma River) is much higher in the wet season of Wet years compared to the wet season of Dry years (Figure 2.3). For example, the average sediment load from the Napa River is approximately 0.34 Mt for the Wet years considered and approximately 0.02 Mt for the Dry years considered. During Wet years, there is a large net flux of sediment from Suisun Bay towards San Pablo Bay and from San Pablo Bay towards Central Bay due to the high inflow from the Delta and the large tributaries pushing water and sediment bayward. The magnitude of sediment flux from Suisun Bay to San Pablo Bay can be greater than sediment input from the Delta and local tributaries, suggesting Suisun Bay is losing sediment on average during these conditions. San Pablo Bay, however, shows greater sediment input from local tributaries than output to Central Bay during Wet years and therefore is predominantly accumulating sediment (which stays in suspension and deposits). During wet seasons in Dry years, conditions in these two subembayments appear to switch. Smaller Delta and Suisun Bay tributary outflows result in a stronger influence of flood tidal forcing on sediment transport dynamics and a net eastward (or landward) flux of sediment from San Pablo Bay to Suisun Bay, suggesting Suisun Bay accumulates sediment. Conversely, flux out of San Pablo Bay to Suisun Bay and Central Bay during Dry years is estimated to be greater on average than local tributary input, suggesting San Pablo Bay is losing sediment under those conditions.

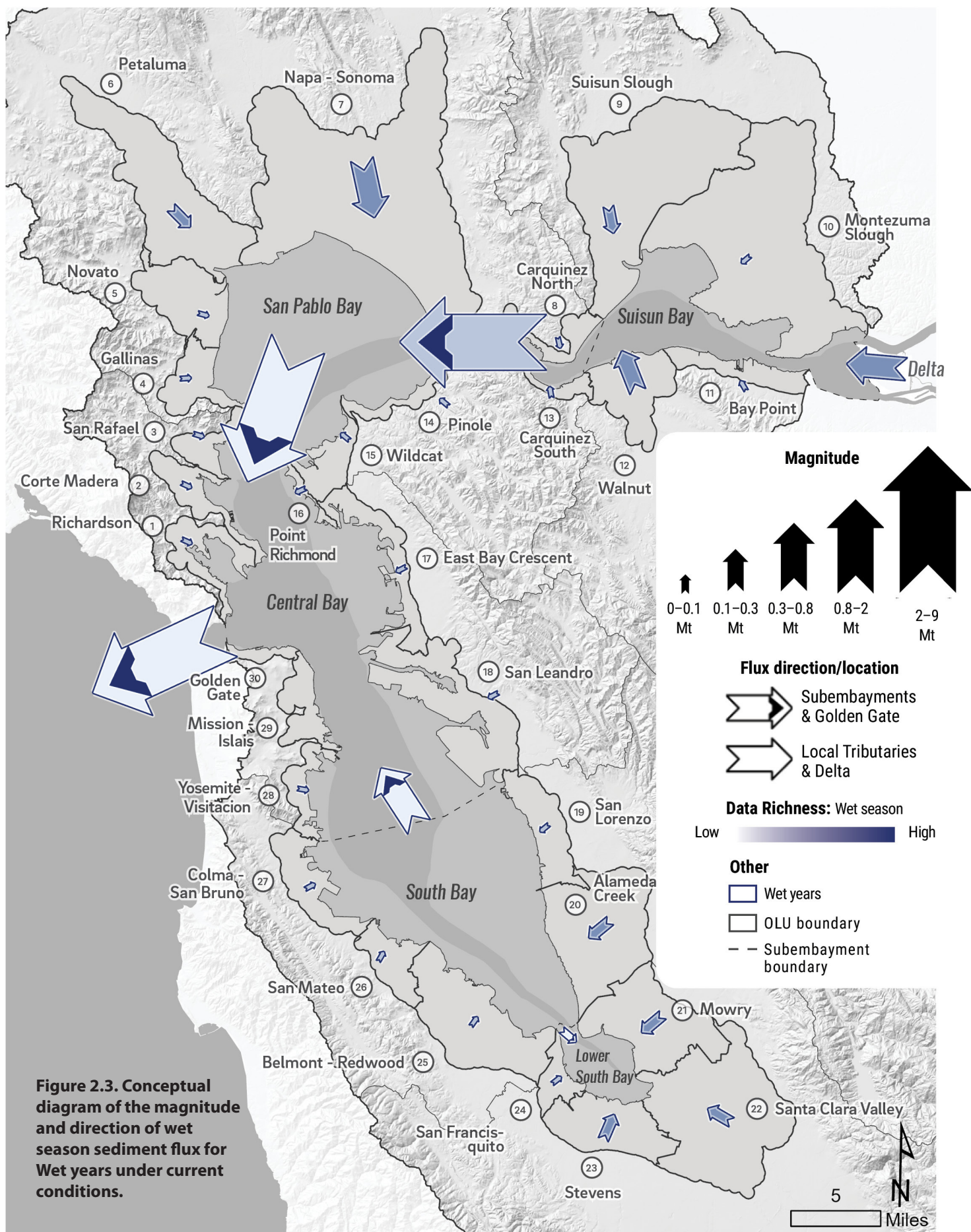
In Central Bay, differences in the wet season flux between adjacent subembayments and at the Golden Gate drives differences in Wet year and Dry year sediment dynamics.

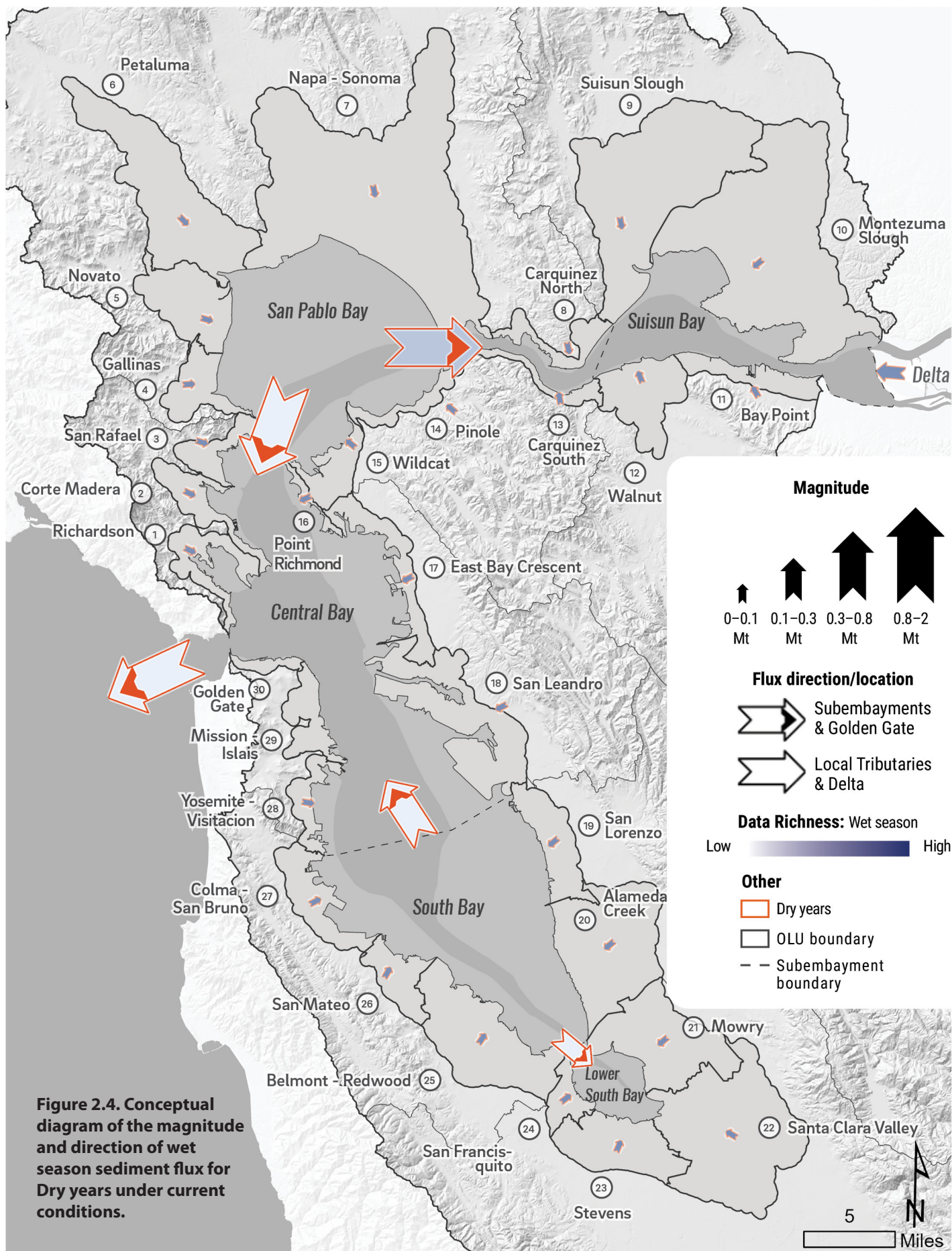
In general, the surrounding tributaries have small watersheds and small sediment loads compared to subembayments to the north and south, resulting in relatively little difference in wet season sediment loads in Wet years and Dry years (Figure 2.3). For both Wet and Dry years, wet season net flux direction is towards Central Bay from both the north and south. In Wet years, the wet season flux from San Pablo Bay to Central Bay can be much larger than the flux from South Bay and there can be a net flux out the Golden Gate of similar magnitude to the net influx from San Pablo Bay, suggesting that Central Bay could be accumulating sediment on average. The conditions are similar during the wet season in Dry years, with the overall magnitude of net sediment accumulation likely being less on average than during Wet years.

Similar to Central Bay, the difference in wet season flux between adjacent subembayments drives differences in Wet year and Dry year sediment dynamics in South Bay, but the overall story is different. The relatively small size of most South Bay tributaries and associated small sediment loads results in similar sediment loads for wet seasons in both Wet years and Dry years (Figures 2.3 and 2.4). The exception is Alameda Creek, which has the largest watershed in the nine county Bay Area region and a considerably higher sediment load during wet seasons in Wet years when there is widespread hillslope and channel erosion. In both Wet years and Dry years, wet season flux out of South Bay into Central Bay to the north and Lower South Bay to the south can be much greater than local tributary supply, suggesting overall sediment loss in South Bay for most years.

For Lower South Bay, the net wet season influx during both Wet and Dry years indicates it is consistently accumulating sediment, but there are key differences between water year types. Similar to Suisun Bay and San Pablo Bay, wet season sediment supply from most local tributaries during Wet years can be an order of magnitude higher than during Dry years (the exception being San Francisquito Creek, which has similar Wet Year and Dry Year sediment loads). The wet season net flux from South Bay into Lower South Bay, however, is shown to be of relatively small magnitude on average (Figure 2.3). Livsey (2021) discussed this phenomenon, hypothesizing that during periods of low freshwater flow, corresponding to Dry years, a reduction in saline density gradients leads to more sediment in the main channel of the South Bay, allowing for more tidal dispersion into Lower South Bay on the flood tide. The available data therefore suggest that Lower South Bay accumulates more sediment on average in Wet years than in Dry years due to higher tributary sediment supply even though there is greater influx from South Bay.







2.2.1.3 Conceptual Understanding of Dry Season Sediment Dynamics by Subembayment (Wet year, Dry year)

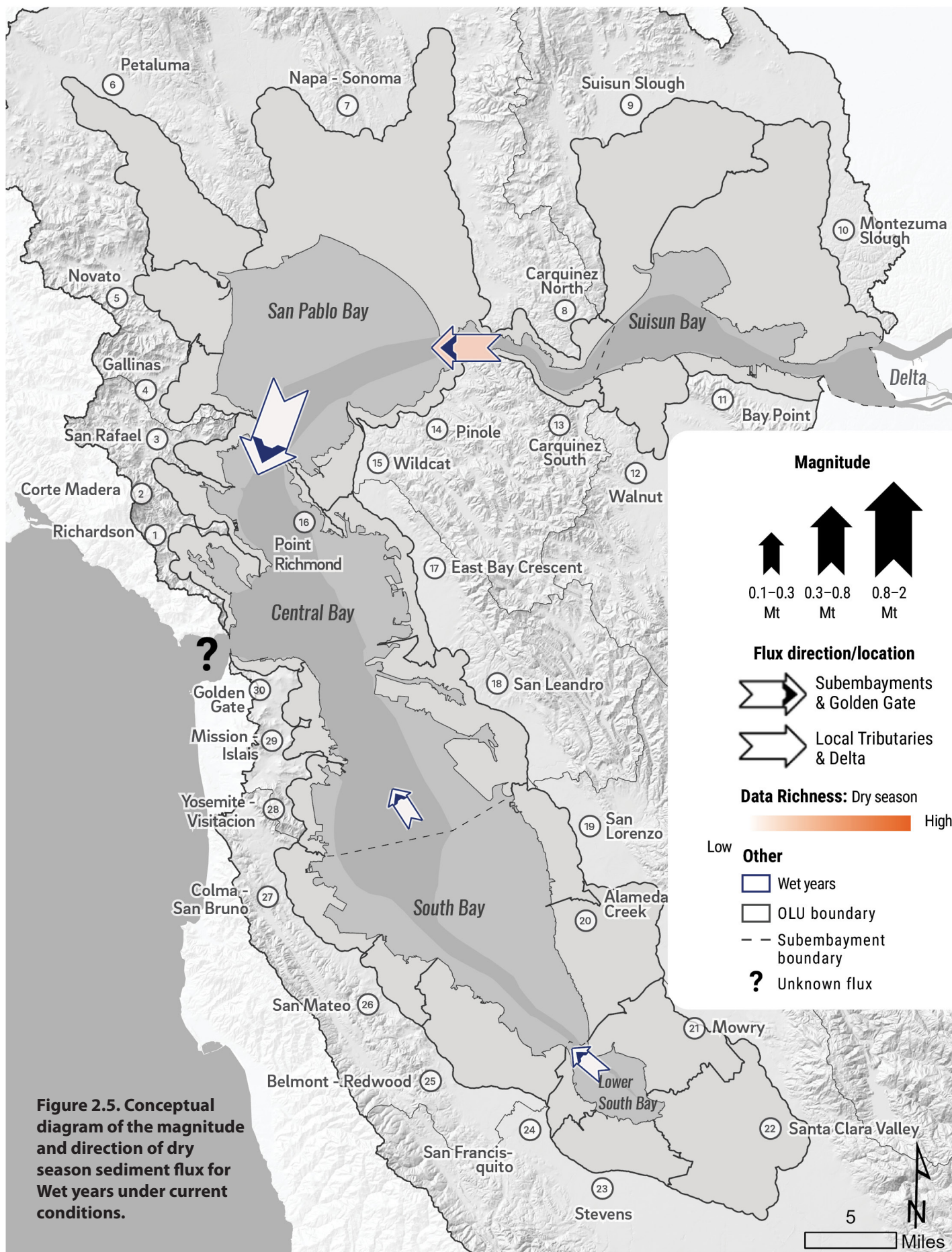
The overall patterns of sediment transport in the Bay during the dry season is similar to wet season conditions, but there are some differences in net seasonal sediment accumulation and loss at the subembayments scale (Table 1, Figures 2.5 and 2.6). The general assumption is that sediment supply to the Bay from the Delta and local tributaries during the dry season of most years is essentially negligible. During Wet years, flows coming into the Bay during the dry season are generally high enough to flush water towards Central Bay and out the Golden Gate, which results in a net flux of sediment from Suisun Bay to San Pablo to Central Bay, and from Lower South Bay to South Bay to Central Bay. This suggests there is generally net sediment loss during the dry season in Wet years from Suisun Bay, San Pablo Bay, and Lower South Bay, but gravitational circulation can occur in high flow years and result in sediment trapping in San Pablo Bay (see Downing-Kunz et al. 2017). The available data suggest that South Bay neither accumulates nor loses sediment during these conditions, and the lack of Golden Gate flux information for these conditions prohibits an understanding of sediment accumulation or loss within Central Bay. During Dry years when dry season flows into the Bay are typically very low, sediment flux is landward towards Suisun Bay and Lower South Bay, resulting in net sediment accumulation in both subembayments, and towards Central Bay, resulting in net sediment loss in San Pablo Bay and South Bay. The flux out the Golden Gate during these conditions can be somewhat less than the influx from San Pablo Bay and South Bay, suggesting Central Bay could be generally accumulating sediment.

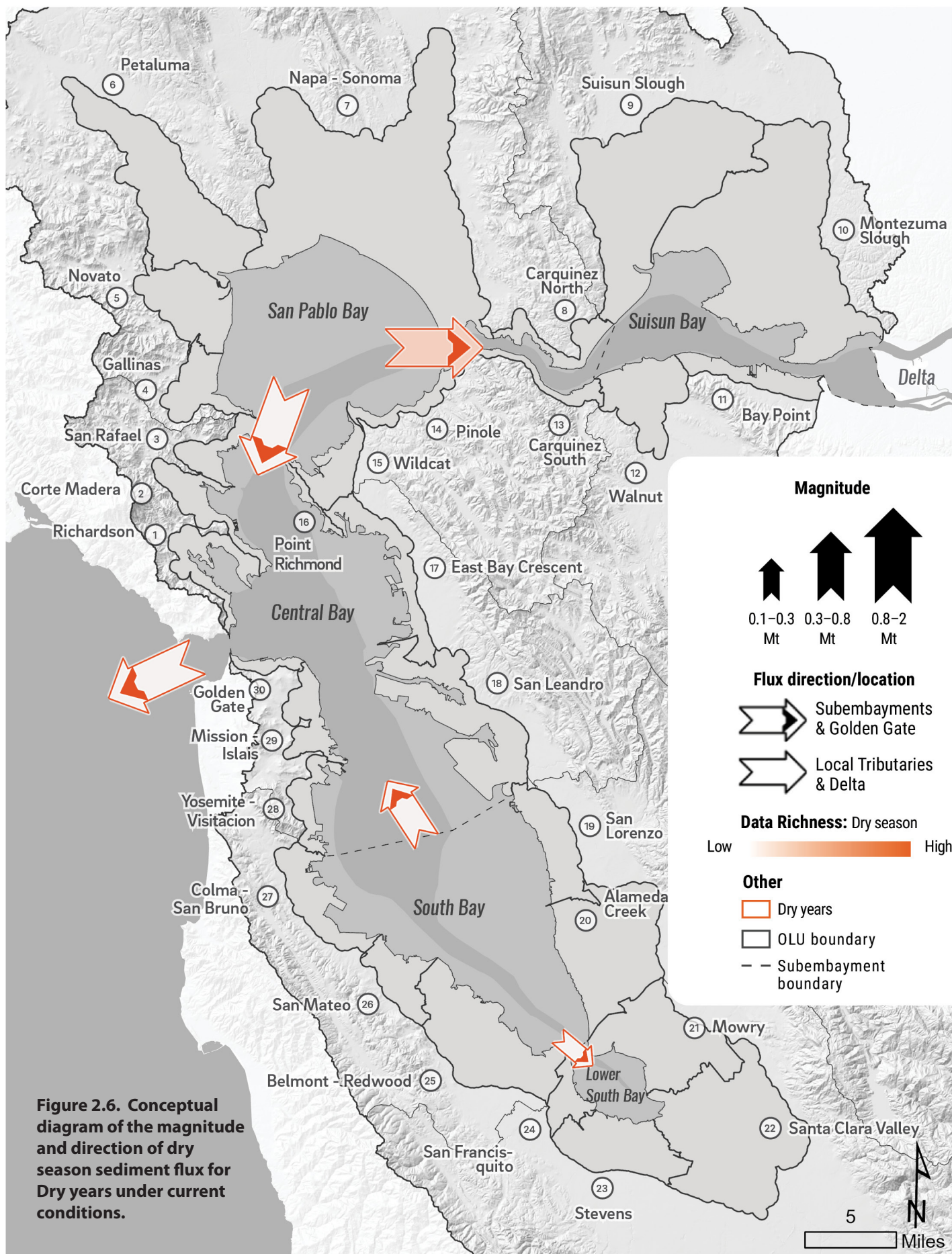
Table 1. Summary of estimated average subembayment sediment budgets under different hydrologic conditions.

Subembayment	Wet season (Oct-Mar)		Dry season (April-Sept)	
	Wet year	Dry year	Wet year	Dry year
Suisun Bay	—	+	—	+
San Pablo Bay	+	—	—	—
Central Bay	+	+	?	+
South Bay	—	—	0	—
Lower South Bay	+	+	—	+

— Net loss
0 Neutral
+ Net accumulation
? Unknown

Note: Net accumulation and loss estimates are based in part on results from unvalidated modeling exercises and short-duration monitoring efforts. There is therefore a varying degree of uncertainty associated with each estimate.





Priority actions for addressing key knowledge gaps and uncertainties:

- Develop estimates for daily suspended load and bedload for the Bay tributaries that are known to be significant sources of sediment (McKee et al. 2020).
- Develop estimates for Delta suspended load and bedload (current estimates at Mallard Island are developed from an analytical approach that is likely outdated) (McKee et al. 2020).
- Develop hypotheses of the dominant process controlling sediment supply within each subembayment and identify critical data needed to validate hypotheses.
- Model and monitor flux at the subembayment boundaries (particularly at the Suisun Bay-San Pablo Bay, San Pablo Bay-Central Bay, and Central Bay-South Bay boundaries) and at the Golden Gate for a range of conditions (Wet year, Dry year, wet season, dry season). Develop validated models capable of addressing specific sediment flux questions at spatial and temporal scales of interest (McKee et al. 2020).
- Determine the impacts of vertical turbulent mixing and flocculation on Bay-scale sediment flux estimates (magnitude and direction) (McKee et al. 2020).



Photo by Shira Bezalel (SFEI)

2.2.2 Future Conditions

2.2.2.1 Methods and Data Sources

Developing a conceptual understanding of future sediment dynamics at the subembayment scale involved compiling calculated annual sediment load data throughout the Bay for mid- and late 21st century. Some climate models predict a wetter future in the Bay watershed and some predict a drier future. Estimates of future sediment loads from the Delta were derived from modeled future sediment loads at Sacramento River at Freeport for a wetter future (CESM1-BGC RCP 8.5) and a drier future (HadGEM2-CC RCP 8.5) (USGS CASCaDE Project, Stern et al. 2020). These loads were converted to loads to the Bay using a regression equation relating historical Sacramento River at Freeport loads (from Stern et al. 2020) and calculated historical loads coming into the Bay at Mallard Island (from Schoellhamer et al. 2018). The resulting loads were then used to determine average annual mid- and late century Delta loads for the wetter and drier futures. Estimates of mid- and late century Bay tributary sediment loads came directly from the analyses conducted for the Sediment for Survival report (see Dusterhoff et al. 2021 for more detail). Tributary load values were combined to determine total mid- and late century average annual tributary sediment load for each Bay Operational Landscape Unit (OLU) for the wetter and drier futures considered. As there are no available estimates for future sediment flux between subembayments and the Golden Gate, the analysis focused solely on the future sediment supply to the Bay. Similar to the current conditions analysis above, average annual flux rates for the Bay tributaries and Delta were classified into 5 categories. It is important to note that these future sediment load estimates represent average annual conditions with a high degree of uncertainty and include all types of water years, while the estimates for current conditions shown in Section 2.2.1 are seasonal and averaged across significant Wet and Dry years.

2.2.2.2 Wetter Future Supply

For the wetter future considered, there is a considerable increase in sediment loading to the Bay, with the historically dominant sediment-supplying watersheds in North Bay showing the greatest increase (Figure 2.5). At mid-century, average annual sediment load is similar to current conditions for the Delta and for tributaries throughout the Bay, with the Delta load being approximately 1 Mt and total tributary load being approximately 1.4 Mt. South Bay, however, shows a modest decrease in tributary sediment load at mid-century driven in large part by the decrease in Alameda Creek load (which accounts for 60% of the South Bay tributary supply). By late century, average annual precipitation increases within the wetter future considered, resulting in the sediment loads from the Delta and major Suisun Bay and San Pablo Bay tributaries being a factor of two or more higher than current conditions. At this time, the Delta load is estimated to be approximately 1.8 Mt/yr, the Walnut Creek load (which accounts for approximately half of the Suisun Bay tributary supply) is estimated to be approximately 0.3 Mt/yr, and the Napa River load (which accounts for approximately 40% of the San Pablo Bay tributary supply) is estimated to be approximately 0.6 Mt/y. Major tributaries in South Bay and Lower South Bay also show loads that are higher than current conditions, but the amount of increase is generally more

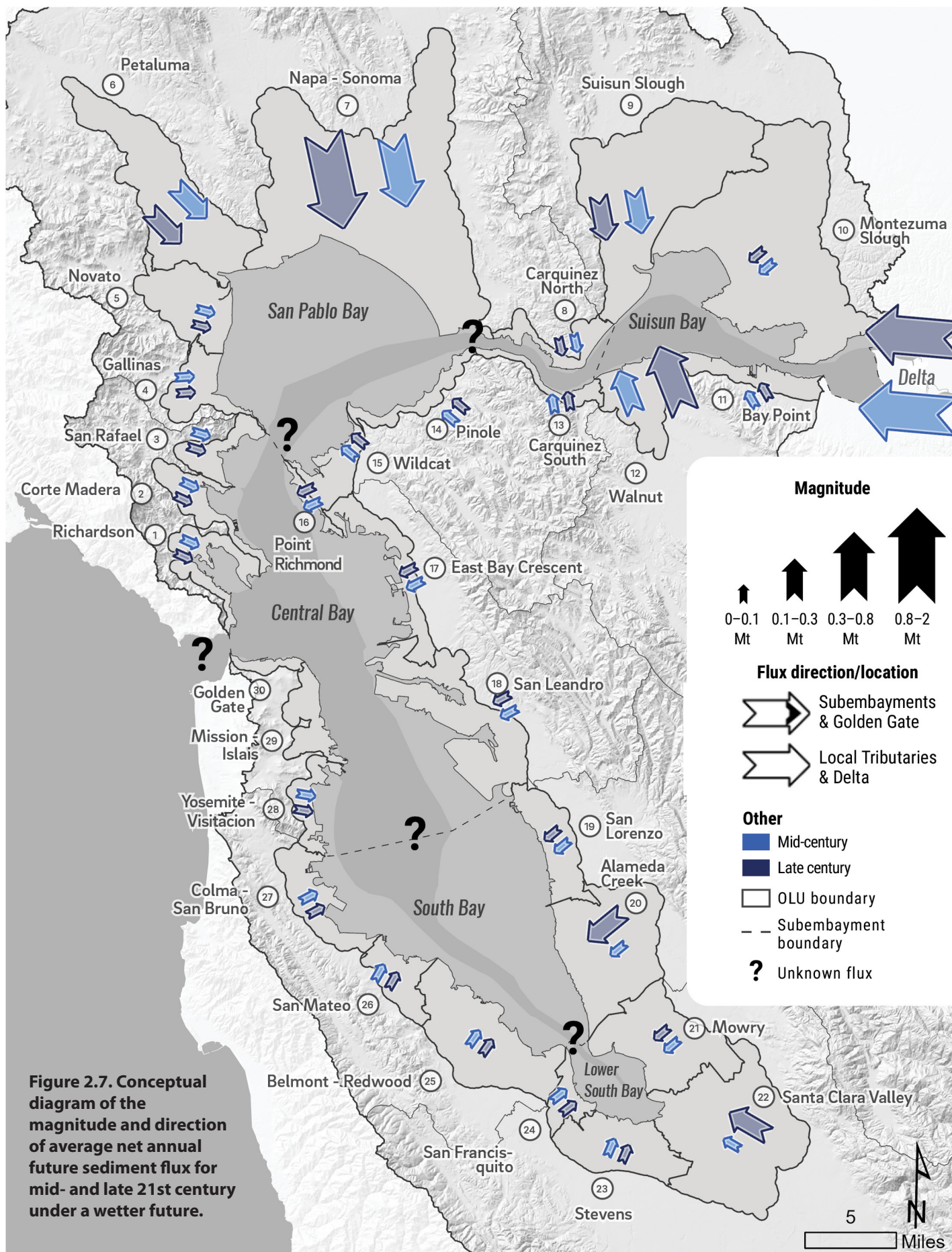
modest (between a factor of 1.2 and 1.4). Therefore, under a wetter future, Suisun Bay and San Pablo Bay could have a relatively high sediment supply by the later part of the century driven primarily by large supply increases from the Delta and a few key watersheds.

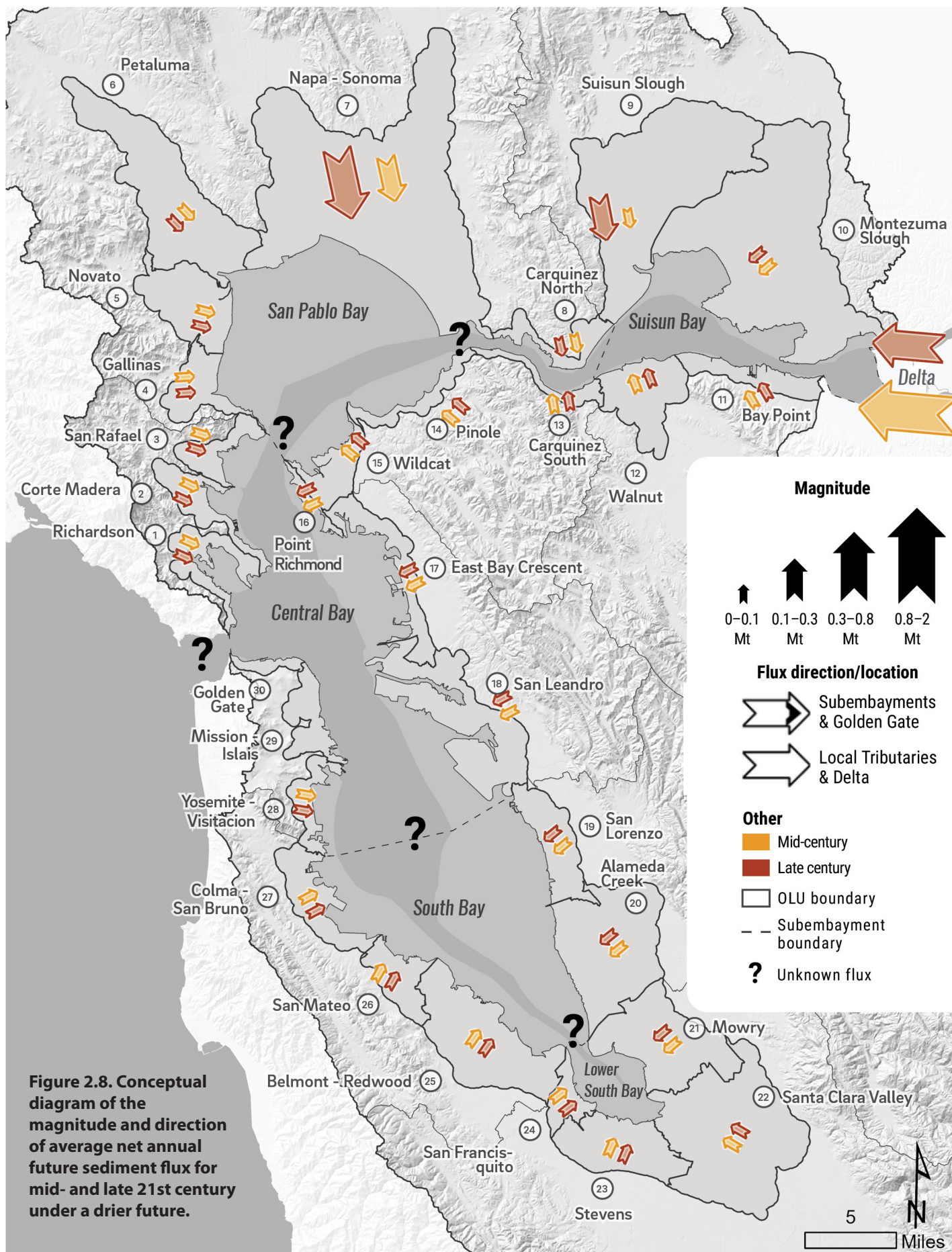
2.2.2.3 Drier Future Supply

Compared to the wetter future, the drier future shows much less sediment delivery to the Bay, particularly south of the Bay Bridge (Figures 2.7 and 2.8). At mid-century, total average annual baywide tributary sediment load is estimated at 0.9 t/yr (60% of current load). Total tributary load to Suisun Bay, San Pablo Bay, and Central Bay is predicted to be approximately 70% of current conditions, while South Bay load is predicted to be approximately 40% of current conditions and Lower South Bay is predicted to be approximately 50% of current conditions. Surprisingly, the Delta load at mid-century is predicted to be somewhat higher than current conditions, which is likely associated with decreased snow pack and increased days with high streamflows (see Stern et al. 2020). By late century, the Delta sediment supply is predicted to be similar to current conditions (1.1 Mt) and the total average annual baywide tributary sediment load is predicted to be 1.1 Mt. At this time, Suisun Bay, San Pablo Bay, and Central Bay total tributary loads are predicted to be similar to current conditions, but South Bay tributary load is 40% and Lower South Bay load is 60% of current conditions. For South Bay, the relatively large decrease in tributary load at mid-century and late century compared to current conditions is driven in large part by the large decrease in the Alameda Creek load (0.12 t/yr to 0.04 t/yr at mid century and 0.03 t/yr by late century). For Lower South Bay, there is a widespread decrease in sediment supply from all tributary watersheds. Therefore, under a drier future, relatively wetter conditions north of the Bay Bridge could result in a late century sediment supply that is similar to current conditions, whereas generally drier conditions to the south result in a drastic decrease in tributary sediment supply.

Priority actions for addressing key knowledge gaps and uncertainties:

- Develop an estimate of the magnitude of future monthly or annual Bay Area tributaries and Delta sediment supply for a range of likely climate, land use, and land cover scenarios (Dusterhoff et al. 2021).
- Develop an estimate of the magnitude and direction of future daily or monthly flux between subembayments and at the Golden Gate for a range of likely climate and sediment supply scenarios (Dusterhoff et al. 2021).





3. Conceptual Understanding of Baylands Sediment Processes

3.1 Overview

An understanding of the overarching pathways that supply sediment to the entire Bay, as discussed in Chapter 2, is important for regional sediment management: management decisions made at the Bay and subembayment scale or in the Delta will affect flux into neighboring subembayments, which in turn impacts the sediment supply available for baylands in specific subembayments to accrete in vertical elevation and keep pace with sea-level rise, at the most general level. Filling the knowledge gaps described in Chapter 2 will help create a more accurate understanding of current and future sediment supply trends as it relates to regional restoration goals and underscores the interdependencies of managing sediment across watershed and jurisdictional divides. While critical, this bird's eye view of sediment at the Bay and subembayment scale is not enough on its own to answer important management questions such as, "how are baylands habitats likely to evolve over the next century" or "what management actions can we take to guide the evolution of baylands habitats in the short- and long-term, and where are such actions appropriate" (Goals Project 2015)? Understanding sediment availability within local erodible sediment pools and adjacent mudflats for deposition onto specific marshes, for example, will help adaptively manage our baylands so they continue to buffer storms, provide wildlife habitat, and carry out the numerous other benefits to people and wildlife in the face of accelerating sea-level rise. As a first step to answering such management questions, we need to understand sediment processes at a more granular scale: how fine-grained sediment moves on and within the baylands, with an emphasis on marshes and mudflats, the typical target of sediment management practices.

The heterogeneity in shoreline types and conditions around the Bay impact where, when, and how much sediment reaches the baylands. Factors like channel alignment, stream power, the quality of the creek-to-bayland connection, local erodible sediment pool, and many other considerations are important to consider when evaluating sediment movement at the baylands scale. Moreover, the setting of a given marsh in the Bay greatly influences vertical sediment accretion, in particular sediment supply, marsh characteristics, and the barriers or conduits of sediment and water. In addition, interactions between a variety of processes and factors determine the amount of sediment transported in each pathway, its variability, timescale, mechanisms at play, and, ultimately, where that sediment ends up, whether temporarily or long term. Table 2 provides an overview of important local factors affecting sediment accretion in tidal marshes in the Bay and provides important context to accompany the more simplified representation of sediment movement at the baylands scale in the conceptual understanding that follows.

Table 2. Important local factors affecting sediment accretion in tidal marshes in the Bay.

Category	Important local factors affecting sediment accretion	Priority actions for addressing key knowledge gaps and uncertainties
Local sediment supply	Local fluvial sediment supply and local erodible sediment pool	The magnitude, duration, and frequency of sediment transported from upland watersheds into creeks and flood control or stormwater channels, primarily during periods of high runoff, is a main factor in the magnitude of sediment available for baylands to accrete vertically. In addition, the magnitude and timing of suspended sediment in the local erodible sediment pool also plays a role in how much and when sediment is available for deposition on the baylands.
	Wind-wave exposure and mudflat width, elevation, and proximity	The Golden Gate restricts large swells from the Pacific Ocean, limiting most wave activity acting on marshes and mudflats to locally-generated wind waves. The height of a wind wave is dependent on the fetch length, depth of water, wind speed, and duration. The direction varies by location based on prevailing winds (SFEI and SPUR 2019). Wind waves resuspend sediment in the erodible sediment pool, they can also cause marsh edge erosion. Mudflat width, elevation, concavity, and proximity can also play an important role in reducing wave energy before waves reach a marsh (Beagle et al. 2015).
Marsh characteristics	Marsh elevation	Elevation of a marsh relative to tides, wind waves, and storm surges plays a critical role in the depth, duration, and frequency of sediment-laden water making its way onto a marsh. Water depth and duration of inundation of the marsh plain during high water events are positively correlated with inorganic sediment accretion.
	Marsh vegetation density and sediment trapping efficiency	Marsh vegetation slows down incoming water and damps waves, which causes sediment to drop out of suspension and settle onto the marsh plain. The trapping efficiency of sediment depends on the marsh vegetation type and density.
Barriers or conduits of sediment and water to marsh	Tidal marsh channel network density and complexity	Tidal marsh channel network density and sinuosity impacts energy dissipation, exchange, and residence time of the tides in the marsh. Channel density within a marsh network impacts distribution of sediment and water across the marsh plain (SFEI 2023).
	Presence and degree of hardened shoreline infrastructure	Levees and other infrastructure along the shoreline, like berms and flood walls, can restrict the flow of sediment from both channels and the erodible sediment pool onto adjacent marshes and mudflats. In some cases, though, remnant berms or other structures can reduce wind wave fetch and create calm areas where sediment can drop out onto marshes and promote sediment accretion.

A useful starting point in understanding sediment movement at the baylands scale is a conceptual model described by Ganju et al. (2013) that looks at the role of sediment fluxes as an indicator of tidal marsh stability. Ganju et al. (2013) presents four main considerations to assess tidal marsh stability: (1) dominant sediment source location (e.g., fluvial, Bay shallows, oceanic); (2) tidal marsh location relative to the dominant sediment source; (3) the mobilization mechanism (e.g., wind-waves, tidal currents, fluvial flows) and timing of sediment source delivery; and (4) the transfer mechanism (e.g., wind-waves, tidal currents, fluvial flows) and timing of mobilized sediment delivery. In an ideal situation, several continuous external sediment sources would feed sediment into a tidal marsh complex, and mobilization and transfer of sediment onto the marsh would occur regularly. The tidal marsh would be close to the sediment sources, less than a tidal excursion length (i.e., the distance the suspended sediment travels in one tide) (Ganju et al. 2013).

This chapter identifies and describes important considerations, similar to those outlined by Ganju et al. (2013) and other described above, for each of the four sediment transport pathways that occur at the baylands scale, beginning with upland sediment sources and ending on the baylands. This chapter also highlights key knowledge gaps within each pathway that need filling in order to arrive at a more comprehensive understanding of sediment transport at the baylands scale in the Bay.

The four sediment transport pathways described in this chapter are as follows (Figure 3.1):

- ▶ **Pathway 1: Uplands to tributaries:** Wet-season sediment loads from watersheds flow into tributaries and comprise a significant source of fine mineral sediment that feeds the baylands.
- ▶ **Pathway 2: Tributaries to marshes, mudflats, and erodible sediment pool (ESP):** Sediment flows out of creeks and stormwater channels to deposit onto current tidal marshes, evolving restored baylands adjacent to the channels, mudflats, and the rest of the larger erodible sediment pool, including shallows and deeper areas of the Bay.
- ▶ **Pathway 3: ESP to mudflats and deep Bay:** Sediment is stored in the erodible sediment pool, moving between different components (mudflats, shallows, deep Bay) over variable timeframes and spatial scales. During this mixing, Bay sediment deposits onto mudflats and some flows out into the deep Bay.
- ▶ **Pathway 4: Mudflats to marshes:** Suspended sediment is transported from mudflats onto the marsh plain in one of two ways during times of high water: directly over the bayward marsh edge or through tidal channel networks. Tidal marsh erosion and channel bank collapse leads to sediment remobilization and transport from marshes back onto mudflats and out into the larger erodible sediment pool or to be redeposited onto the marsh plain

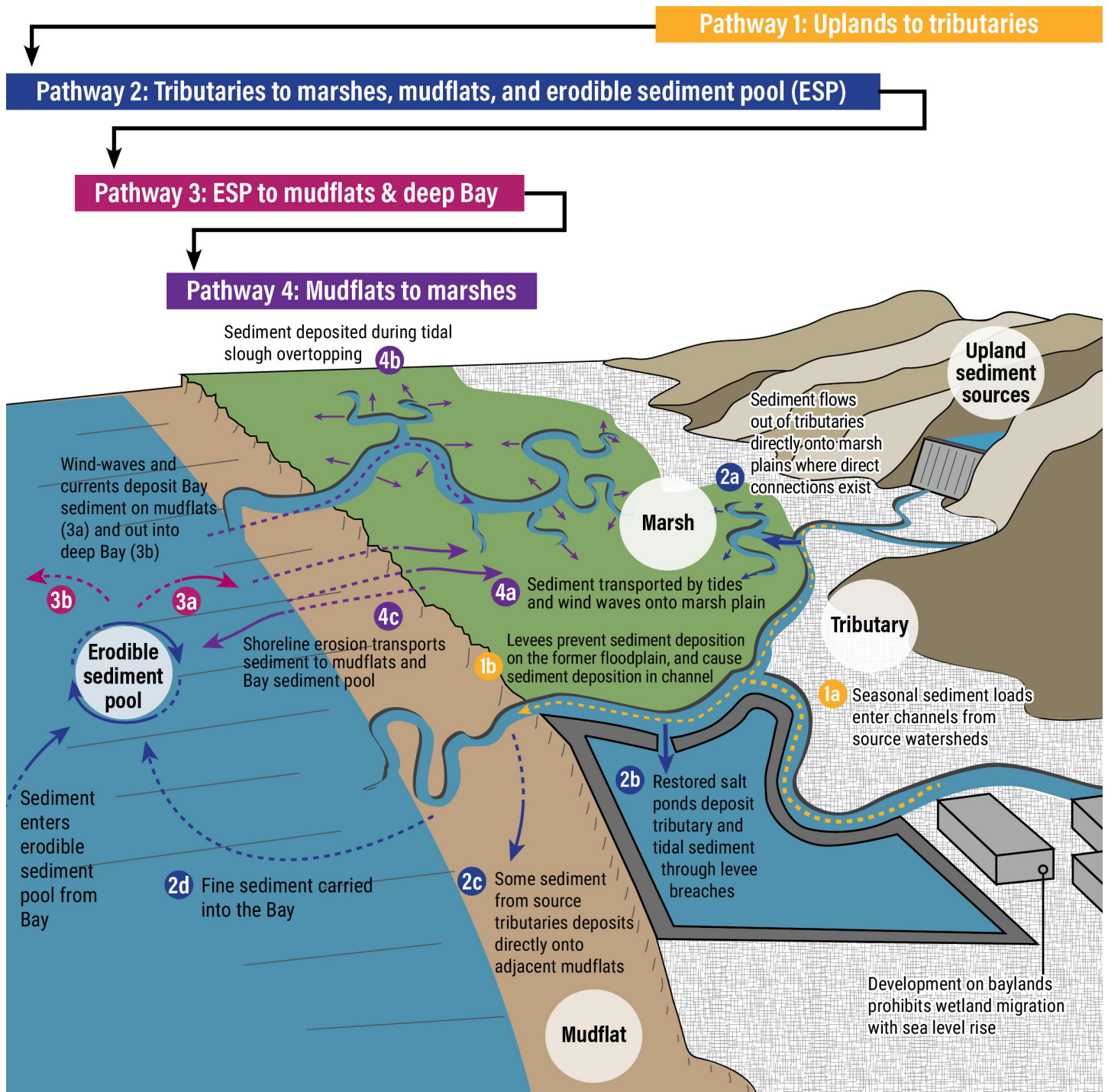


Figure 3.1. Conceptual diagram of the dynamic nature by which sediment moves from upland sediment sources to marshes, mudflats, shallows, deep Bay, and the larger erodible sediment pool.

3.2 Sediment Transport Pathways and Sediment Fate at the Baylands Scale

The baylands-scale conceptual understanding, described below, offers a more localized understanding of the sediment transport pathways and fate described at the Bay and subembayment scale in the previous chapter. While some overlap exists between the information provided by these two scales, in particular within the uplands to tributaries pathway, this chapter aims to provide more details and perspective on how the concepts described in Chapter 2 translate to a simplified representation of sediment movement at the smaller, more localized baylands scale. At the end of each pathway description, we highlight priority actions for addressing key knowledge gaps and uncertainties to improve our understanding of sediment transport at the baylands scale.

3.2.1 Current Conditions

3.2.1.1 Pathway 1 - Uplands to Tributaries

This pathway describes the movement of sediment from upper watersheds into local tributaries and includes considerations of sediment transport above and below head of tide.

Wet-season sediment loads from watersheds flow into tributaries and comprise a significant source of fine mineral sediment that feeds the baylands (1a). Nearly all mineral sediment in the Bay ultimately originates from upland sources, which consist of local watersheds that comprise Bay Area hillslopes; and Sierra Nevada mountain and foothill sediment that passes through the Central Valley and Sacramento-San Joaquin River Delta to arrive in the Bay (Barnard et al. 2013). The relative abundance of each source within the erodible sediment pool varies by location, timing, and intensity of wet and dry periods, and is influenced by the degree of channel and floodplain modifications (e.g., bridges, culverts, dams) that inadvertently trap sediment within a watershed.

Tributary and Delta sediment delivery into the Bay mostly occurs in the wet season months from October-April, mainly isolated to event-based sediment “pulses.” These event-based sediment pulses are dictated by the frequency and intensity of rainfall events and their timing relative to prolonged dry periods (especially the “first flush” of sediment after a prolonged dry period). Snowmelt is also a significant source of runoff to the the Bay via the Delta, making up an average of approximately 40% of annual flow (Cloern et al. 2011). Regional precipitation patterns are projected to shift over the next century, with both storms and droughts becoming more extreme, and a lower contribution of snow to annual precipitation (Cloern et al. 2011, Ackerly et al. 2018). In terms of overall precipitation quantity, the climate may become somewhat wetter or drier depending on the rate of global climate emissions in the coming decades (Dusterhoff et al. 2021). The overall result will likely be extended dry periods punctuated by more extreme storm events delivering large pulses of sediment to the Bay.

Watershed slope, geology, and land cover are also important factors in determining sediment supply to this pathway. The ability of a tributary to transport sediment depends on its stream power, a measure of slope, river discharge, and weight of water (Bagnold 1966). The geology of the source watershed determines the texture and grain size of the

sediment that flows downstream. Generally, coarser sediment (e.g., sand, gravel, cobble) will be deposited in upper reaches of the watershed while finer sediment (e.g., clay, mud, silt) will be transported to lower reaches and ultimately into the Bay (SFEI-ASC 2017, Pearce et al. 2021). Additionally, the land cover within the watershed, which could shift under a changing climate, could impact soil permeability and therefore the magnitude and timing of downstream runoff.

Levees and other flood risk infrastructure downstream of head of tide prevent sediment deposition onto marshes and mudflats (1b). It is estimated that, at present, only 55% of the sediment naturally generated in Bay Area watersheds (approximately 3 MCY annually) reaches the Bay (Pearce et al. 2021). Many of the tributaries that drain the Bay and Delta have undergone significant modifications due to urban development, agriculture, and flood risk management that have altered how sediment flows through tributaries and into their adjacent and downstream landscapes. In the upper watersheds, dams and stormwater infrastructure have dramatically disrupted the flow of coarse sediment downstream (Roni and Beechie 2013). Since the 1850s, over 150 dams have been constructed in the watersheds that drain to the Bay for flood risk management and water supply, with the majority built around the middle of the 20th century (DSOD 2020). In the lower watersheds, the creation of levees and berms to control flooding along creek channels have disrupted the flow of fine sediment to downstream baylands. Levees and berms are linked to a decrease in tidal prism and subsequent increase in tidal sediment accumulation (SFEI-ASC 2017).

Sedimentation issues in modern channels are likely due in part to the natural reduction in channel slope and associated stream power as the channels flow from higher elevations to flatter terrain and due to unnatural 90-degree bends to convey flows around development. For example, several of the creeks that once spread out onto alluvial fans and lost definition well before reaching the Bay (e.g., Upper Penitencia, Calabazas, San Tomas Aquino) now maintain a direct, year-round connection to the Bay. This connection requires costly repeat dredging to periodically clear sediment that has deposited into the channel (SFEI-ASC 2018). In other instances, levees and berms were constructed to disconnect marshes to the tides and, in many places, these areas were subsequently drained for development or agriculture (SFEI-ASC 2017). Flood control channels were routed around these reclaimed areas, causing unnatural bends and channel alignments that also cause water to slow and in-channel sediment to accumulate.

Priority actions for addressing key knowledge gaps and uncertainties:

- Assess the magnitude of future monthly or annual Bay and Delta sediment supply for a range of likely climate and land use scenarios (Dusterhoff et al. 2021).
- Model effects of shifting rainfall patterns (e.g., atmospheric river events, prolonged droughts) and land use/land cover changes on watershed flow-sediment load relationships for all Bay and Delta tributaries (Dusterhoff et al. 2021).

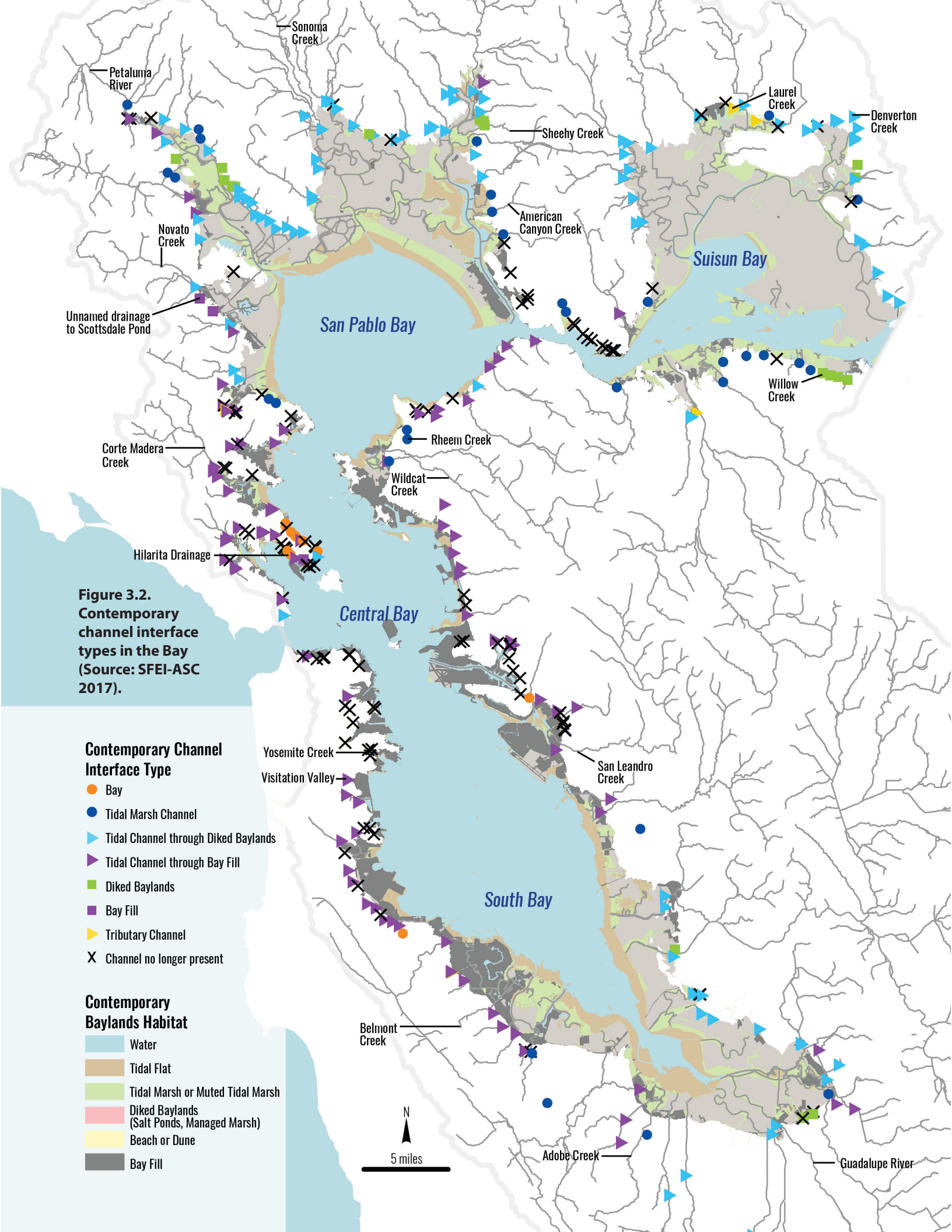
3.2.1.2 Pathway 2 - Tributaries to Marshes, Mudflats, and Erodible Sediment Pool

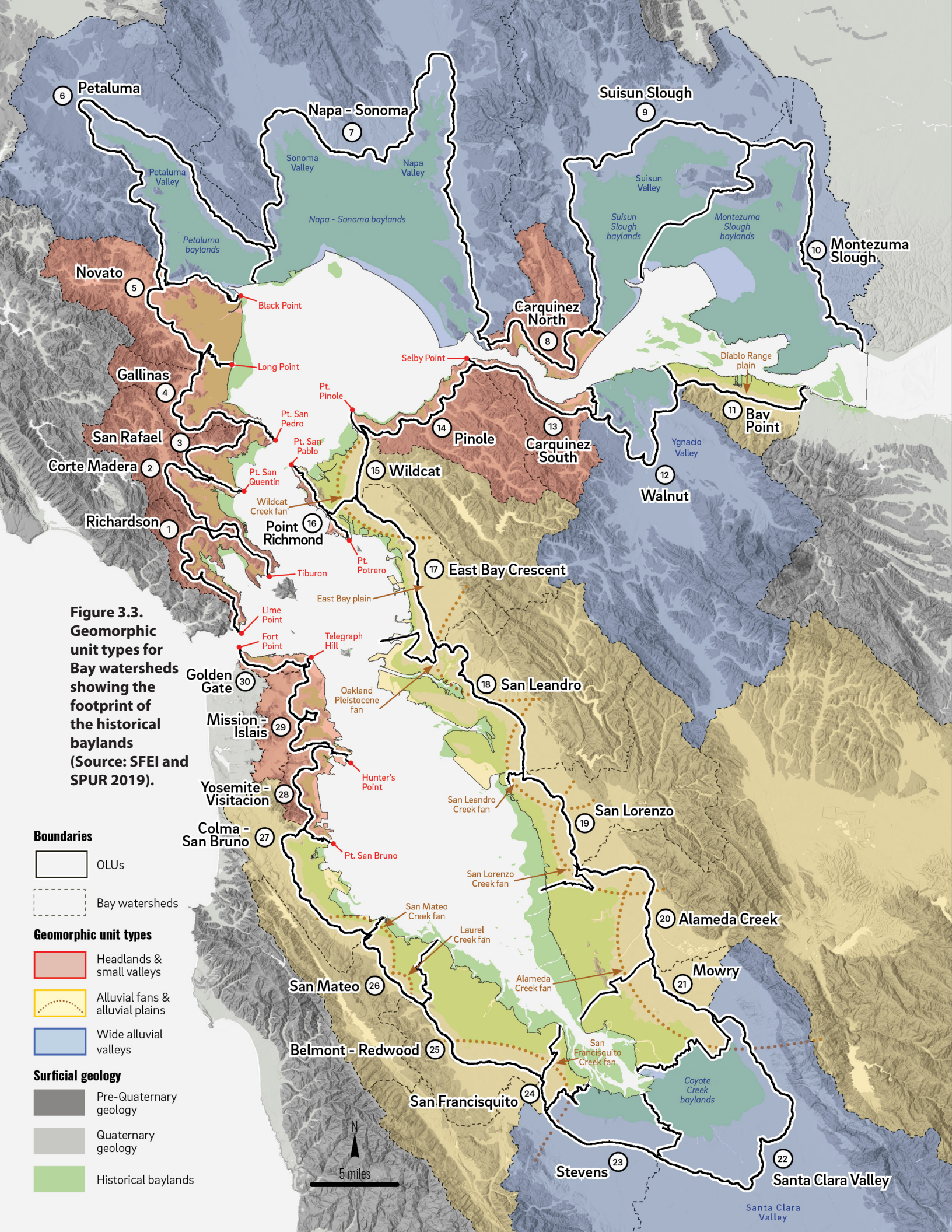
This pathway focuses on the movement of sediment below head of tide out of tributaries and onto the baylands and into the larger erodible sediment pool. For a detailed description of the erodible sediment pool, refer back to Chapter 2 (page 15).

Runoff from storms in the Bay Area has increased in peak discharge (and related sediment transport capacity) over the past 100 years, due to land use changes increasing impervious cover and reducing soil infiltration and evapotranspiration. The result has been a combination of more in-channel siltation due to increased sedimentation from land development patterns, as well as in-channel erosion during high-magnitude storm events. Atmospheric rivers—storms by which the amount of rain generally delivered in a year occurs in just a few days—already occur in the Bay Area. With a warming climate, rain events (and droughts) are expected to increase in intensity in coming decades. While these intense precipitation events can lead to an influx of sediment to the Bay/baylands, the amount of sediment delivered to marshes to build elevations may depend on how close a marsh is to the mouth of a tributary (Thorne et al. 2022). **[Note:** In this discussion, we consider sediment inflow from the Delta as an input to the erodible sediment pool. For more information on the Delta inflow at the Bay and subembayment scales, see Chapter 2].

Sediment flows out of tributaries directly onto marsh plains where direct creek-marsh connections have been maintained (2a). Although only a small number of the channels that drain to the Bay (approximately 9%) flow directly onto tidal marshes and mudflats (SFEI-ASC 2017) (Figure 3.2), local tributaries are an important sediment source for marshes located near tributary mouths. Stormwater flows transport a large proportion of the sediment deposited in the erodible sediment pool, which resides for varying amounts of time, some of which ultimately moves onto baylands. When a creek that flows adjacent to a tidal marsh overtops its banks during a large storm event, sediment-laden water flows over the adjacent marsh and, as it slows, drops coarser-grained sediment near the edge of the channel or tidal slough while finer-grained sediment is deposited farther out onto the marsh plain (Mitsch and Gosselink 1993). This direct connectivity between creeks and marshes delivers nutrients and sediment across the marsh plain as well as to adjacent mudflats and the Bay, which replenishes the erodible sediment pool. While creek-marsh connections are the most direct way to get sediment onto marshes, it is worth noting that the amount of sediment being delivered is often reduced compared to historical conditions due to channel modifications where the lower watersheds meet the baylands and from intensive development of impermeable surfaces higher in the watershed (as described in Pathway 1b).

As sediment flows down tributary channels to the baylands, some sediment deposits in restoration projects (e.g., breached former salt ponds) (2b) while some continues on to deposit onto mudflats (2c) or replenish the erodible sediment pool more broadly (2d). The majority of implemented and planned tidal marsh restoration projects are located in the tidal reaches of the Bay's wide alluvial valleys that flank the northern and southern axes of the Bay (i.e., San Pablo Bay, Suisun Bay, and South Bay; Figure 3.3), where the largest historical losses of tidal habitats occurred. Many marsh restoration projects are located in former salt ponds and former agricultural fields and are often deeply subsided due to





oxidation of the soils after diking and draining (Dusterhoff et al. 2021). When these areas are breached to restore full tidal action, tributaries can directly deposit sediment through breaches into these low-lying restoration areas. The act of breaching increases the tidal prism within the channel and may remobilize previously deposited sediment, making more sediment available for transport. Some of the sediment coming from the channel will deposit into the restoration area while some will continue downstream and deposit onto mudflats or other parts of the erodible sediment pool. These restoration sites are also a sink for sediment flowing in from the Bay via the tides. The length of time it takes for breached restoration sites to accrete to tidal marsh elevations depends on many factors, including a site's starting elevation relative to the tides, proportion of vegetation cover, local sediment supply, and suspended sediment concentrations (SFEI 2022). The rate at which breached restoration sites trap mineral sediment will decrease over time as the site approaches mature tidal marsh elevations. For deeply subsided sites, however, natural accretion alone could result in restoration sites acting as significant sediment sinks for very long periods. For example, it is estimated that Cullinan Ranch East, which is subsided by approximately 5 to 6 feet below MHHW, would take around 60 years of natural sedimentation to support tidal marsh vegetation in the areas where sediment is not placed before breaching (SFEI 2022).

CURRENT SEDIMENT ACCRETION RATES IN TIDAL MARSHES

Presently, existing tidal wetlands within the Bay Area appear to be accumulating enough sediment to keep pace with today's sea-level rise (~2 mm/yr: Flick et al. 1999). Accretion rates in mid- and high-marsh are close to 3-5 mm/yr, with slightly higher rates in low marshes and marshes close to the Bay (Callaway et al. 2012). Rates of sediment accretion at newly restored sites are often substantially greater immediately following tidal reconnection, especially at sites that are subsided. For example, in South Bay, the formerly diked Island Ponds and Pond A6 have accreted at rates greater than 100 mm/yr. The actual accretion rate for a specific project, though, will vary by site based on several localized factors.

Tidal wetlands maintain their elevation with respect to sea level through a combination of organic (vegetation-generated) sediment and inorganic (mineral-generated) sediment accretion. Inorganic sedimentation dominates in the Bay, with a maximum rate of inorganic sedimentation 15 and 60 times greater than the maximum rate of organic accumulation (Goals Project 2015, Swanson et al 2014). The rate of accretion of inorganic sediment is dependent on ambient suspended sediment concentration (SSC), the existing elevation of the marsh, and the timing and mechanisms of sediment delivery to the marshes. Fortunately, inorganic sedimentation increases with decreasing elevation and rising sea levels. As marshes are flooded more, there will likely be some positive feedback to maintain elevation, as lower elevations will lead to greater rates of mineral sediment inputs. However, this feedback depends greatly on the concentration of available suspended sediment. As the rate of sea-level rise increases, the maximum rates of sediment deposition and accretion may eventually be unable to maintain marsh plain elevation.

Local geography around tributary mouths greatly influences the capacity for sediment storage and delivery to marshes and mudflats. Notably, the presence of levees around channels can restrict sediment deposition to channels, preventing accretion on adjacent marshes and other baylands. Similarly, levees at the bay front limit sediment from sheet flow onto marshes. Storage of creek sediment in ebb deltas at the mouths of creeks is also of note, such as at San Lorenzo Creek. Ebb deltas can also affect shoreline evolution by trapping longshore movement of sediment and altering wave refraction patterns. Limited studies have indicated that local tributary sediment is deposited in marsh areas closest to tributary mouths (e.g., Thorne et al. 2022), and mineral accretion is otherwise dominated by sediment from the erodible sediment pool (Takesue and Jaffe 2013).

Priority actions for addressing key knowledge gaps and uncertainties:

- Estimate the proportion of tributary sediment versus sediment from the erodible sediment pool that deposits onto mudflats and marshes, and the key drivers determining location and timescale.
- Update topo-bathymetric data for polders (subsided baylands) slated to be breached and restored to tidal marsh (Dusterhoff et al. 2021) and at risk of levee/berm failure with sea-level rise to improve the estimate of elevation capital, sediment needed, and potential tidal prism.
- Assess the change in future sediment supply from the Delta to the Bay that results from increased Delta restoration. Increasing amounts of restoration will create more sediment sinks in the Delta to potentially reduce sediment supply to Bay marshes and mudflats (Dusterhoff et al. 2021).
- Assemble a regional dataset of all sediment dredging and mining events in flood control channels to better understand the magnitude, frequency, and timing of sediment deposition within flood control channels (SFEI-ASC 2017).

3.2.1.3 Pathway 3 – Erodible Sediment Pool to Mudflats and Deep Bay

Sediment mixes in the erodible sediment pool, moving between different components (mudflats, shallows, deep Bay) over variable timeframes and spatial scales. During this mixing, Bay sediment deposits onto mudflats (3a) and some flows out into the deep Bay (3b). The location and spatial distribution of the erodible sediment pool are related to sediment erodibility, including grain size, flocculation, benthic macrofauna activity, variations in bed structure, and the presence of submerged aquatic vegetation (Joensuu et al. 2018, SFEI 2022). The availability of sediment for resuspension from the erodible sediment pool depends on whether an area is supply- or transport-regulated. As described in Chapter 2 (see page 15), in supply-regulated areas, waves and currents are sufficient to resuspend and transport more sediment than is available in the erodible sediment pool. In transport-regulated areas, sediment transport is limited by the amount of sediment, and wind waves and tidal currents are able to resuspend from the erodible sediment pool (Schoellhamer 2011, SFEI 2022). Persistent onshore winds that generate wind waves are the strongest in spring and summer in the Bay and rework newer sediment deposits (Schoellhamer 2011, SFEI 2022). Daily tidal currents generated by flood and ebb flows of diurnal tides also fuel cyclical resuspension and transport between different components of the erodible sediment pool. In addition, the spring neap tidal cycle is also an important factor to consider (Schoellhamer 1996, Brand et al. 2010, MacVean and Lacy 2014). Sediment that deposits in the deep channels of the Bay is unlikely to provide significant amounts of sediment to mudflats and marshes due to their depths and the higher amount of energy needed to transport it up onto marshes and mudflats (SFEI 2022).

The volume of sediment stored in the erodible sediment pool and how it changes over time and by location is only beginning to be understood. Past modeling efforts did not account for all of the spatial and temporal variability affecting suspended sediment concentrations, thus the amount of sediment available in the erodible sediment pool pathway may vary widely based on local conditions (Schoellhamer 2011). Additionally, modeling studies of sediment transport within the Bay's shallows have been conducted for limited areas, with the primary goal of informing beneficial use of dredged sediment. San Pablo Bay (Allen et al. 2021), Corte Madera Bay (MacWilliams et al. 2012), South San Francisco Bay (Chou et al. 2018), and Lower South San Francisco Bay (Bever et al. 2014, Chou et al. 2018) are some examples of modeling studies that exist to date, but modeled findings need to be validated and these types of studies need to be expanded to more areas of the Bay to understand how bathymetry, wind waves, tidal currents, and other local drivers influence sediment transport. Sediment transport studies that take into account rising sea level are also lacking.

Priority actions for addressing key knowledge gaps and uncertainties:

- Estimate the size, location, and rate of depletion of the current erodible sediment pool at the regional and local scales (Stantec and SFEI 2017).
- Update bathymetric surveys and sediment budgets to track periods of erosion or aggregation in the Bay, and future modeling with sea-level rise.
- Collect data to better understand which areas of the Bay are transport- versus supply-regulated with regards to suspended sediment concentrations and the erodible sediment pool (Schoellhamer 2011).
- Assess the variability of suspended sediment regulation seasonally, and the effect of neap and spring tides on transport and supply regulation (Schoellhamer 2011).
- Evaluate the spatial extent of benthic invertebrates and microalgae and their quantitative effects on sediment erodibility and resuspension in the Bay shallows and mudflats (Stantec and SFEI 2017).



Photo by Pete Kauhanen, SFEI

3.2.1.4 Pathway 4 - Mudflats to Marshes

Suspended sediment is transported from mudflats onto the marsh plain in one of two ways during times of high water: (4a) directly over the bayward marsh edge, or (4b) through tidal channel networks. Mudflats play a crucial role in determining sediment delivery to marsh plains. Mudflats temporarily store sediment that becomes resuspended via wind waves and the tides to nourish nearby marshes. After tidal and fluvial processes have deposited fine sediment onto mudflats, wind-driven waves and tidal currents then resuspend that sediment and, when they coincide with high tides, transport sediment-laden water over the marsh edge on the marsh plain (Pathway 4a) or into marsh channel networks and then over the channel banks onto the marsh plain (Pathway 4b). On the marsh plain, the water is slowed by vegetation and reaches zero velocity during high slack tide, allowing the sediment to fall out of the water column and deposit on the marsh surface. The magnitude and frequency of sediment transport events from mudflats to marshes depend on the erodibility, width, grain size, and shape of the mudflat; frequency and height of wind waves; duration and depth of inundation of the marsh plain; and density of marsh vegetation. Tidal marsh channel complexity is another important factor to consider, as it impacts energy dissipation and exchange and residence time of the tides. As mentioned earlier, tidal channel density within a marsh network affects the distribution of sediment-laden water across the marsh plain (SFEI 2023). Mature marshes and centennial marshes typically feature more complex tidal sloughs and higher channel densities compared to younger tidal marsh restoration sites, which supports greater distribution of sediment-laden water to the marsh plain.

Tidal processes and wave action are the main drivers of mudflat shape and evolution over time (Bearman et al. 2010, Mariotti and Fagherazzi 2013, Hunt et al. 2015, Van der Wegen et al. 2019). It is thought that the shape of the mudflat profile indicates the dominant processes at work. A mudflat with a convex profile typically indicates a tidally-dominant, depositional environment with landward sediment transport, decreased grain size, and bayward progradation/expansion (Bearman et al. 2010, Friedrichs 2011). In contrast, a concave profile typically indicates a wave-dominated erosional environment, bayward sediment transport, increased grain size, and retreat landward (Bearman et al. 2010, Friedrichs 2011). A convex profile generally acts as a sediment sink and promotes marsh formation, whereas a concave profile is generally more vulnerable to erosion (Zhou et al. 2022). Mudflats are dynamic—their shape and size vary over different time scales, from hourly storms to twice-daily semidiurnal tides to multidecadal shifts in sediment supply and beyond (Friedrichs 2011, Van der Wegen et al. 2019). Mudflats are generally stable features on a yearly basis but their profiles may vary seasonally with changes in tides and wind-waves (Van der Wegen et al. 2019). Thus, mudflats are a relatively stable feature on the annual scale, typically evolving over decades. The overall volume and rate of change of mudflats, though, varies with geographic location and timescale, and may be influenced by human factors and may change more rapidly with sea-level rise.

For marshes connected to wide mudflats where levees do not inhibit flow to the marsh, exposure to regular and high-magnitude wind-waves may be an important mechanism to increase sediment deposition when incoming wind-waves overtop the marsh edge (Beagle et al. 2015). In addition to temporarily storing sediment, mudflats also attenuate wave energy (Lacy et al. 2016) which reduces marsh edge erosion (Beagle et al. 2015). In

areas with wide mudflats, marshes exposed to long, landward wind fetch could experience increases in sediment supply during late spring and summer, when wind speeds are highest and most consistent (Lacy et al. 2020). Lacy et al. (2020) found that wind waves in summer contributed to higher overall marsh accretion near the Bay margin and attributed the seasonal effect to increased vegetation-driven sediment trapping. Additional studies are underway to determine if the timing and trend of this process applies to marshes throughout the Bay more broadly. It is also unclear to what extent this sediment pathway nourishes the more interior parts of the marsh complex and is affected by wave energy. Suspended sediment flux through tidal creeks has been observed to increase with wave energy at China Camp State Park (Lacy et al. 2018), for example, but more studies are needed at additional locations to better understand how local factors influence sediment movement from mudflats onto marshes. Storm surges—associated with wind-waves, which typically occur during the winter season—can also transport significant amounts of sediment from mudflats onto marshes due to an increase in inundation depth, extent, and duration over the marsh (Stantec and SFEI 2017), or can result in a net export of sediment from marshes due to rapid draining following storm surge (Fagherazzi and Priestas 2010, Lacy et al 2018).

The processes conveying sediment from mudflats to marshes via tidal channel networks and wind-wave transport from overtopping and during storm surges likely overlap in complex ways. More research is needed to understand which source dominates at different times of the year for specific marshes in the Bay in order to create a more detailed and place-based understanding of this pathway.



Photo by Shira Bezalel (SFEI)

Tidal marsh erosion and channel bank collapse leads to sediment remobilization and transport from marshes back onto mudflats and out into the larger erodible sediment pool or to be redeposited onto the marsh plain (4c). Marshes, like mudflats, are dynamic features that are constantly evolving. Consequently, when sediment becomes deposited on a marsh, that sediment does not necessarily stay on the marsh indefinitely. The morphology of the marsh edge can indicate whether that marsh is growing laterally into the bay (prograding and gaining sediment) or eroding laterally back toward the upland and losing edge sediment that may be transported back to the mudflats and erodible sediment pool. The main drivers sculpting the morphology of the marsh edge include sediment supply, wind wave heights, mudflat shape and size, marsh vegetation patterns, and orientation of the shoreline to incident waves (Allen 1989, Schwimmer 2001, Möller and Spencer 2002, Pedersen and Bartholdy 2007, Beagle et al. 2015). Beagle et al. (2015) outlines a conceptual model of marsh edge typology for San Pablo Bay that could explain the cyclical nature of a marsh edge transitioning from erosional to progradational states over time (Figure 3.4; adapted from Allen 1989). Wind waves and tidal action undercut the edge of the marsh which leads to block failure and sediment deposition in front of the scarp onto the adjacent mudflat (Figure 3.4a). The failed block breaks up wave energy until the deposit is scoured away and redistributed on the mudflat or marsh plain (Figure 3.4b). Depending on the failed block size and how long it persists, it could trap additional sediment between the old scarp and the failed block (Figure 3.4c). The marsh edge begins to form a ramped profile as sediment fills in behind the failed block, building elevation and creating new low marsh (Figure 3.4d). As the ramped profile continues to form, wave energy is broken up such that the low marsh vegetation traps sediment, building up mid-marsh habitat (Figure 3.4e). When the new mid-marsh levels off, the steepness of the ramped profile increases and wind-wave energy starts to erode the new mid-marsh vegetation, creating a new scarp, continuing the cycle (Figure 3.4f).

Sediment is also reworked in marsh channels on a continual basis. High flows, a reduction in sediment, or removal of sediment from the tidal marsh system can lead to flow-induced bank erosion or gravity-induced bank collapse (Zhao et al. 2019). Dredging a tidal marsh channel beyond its equilibrium condition, for example, will lead to oversteepening and slumping of the marsh channel's banks (Ganju 2019). When marsh channel banks slump, their sediment is available for resuspension and may help to protect further erosion by collapsing and depositing next to the channel (similar to the bank protection illustrated in Figure 3.4b–f; Zhao et al. 2019). Marsh channels can also migrate laterally over long time scales (Gabet 1998, Ganju 2019), further mobilizing sediment to be redistributed within the marsh, adjacent mudflat, or back into the larger erodible sediment pool.

As described above, several factors affect which processes and timescales are most relevant in considering transport from mudflats onto adjacent marshes, but more research is needed to understand how these considerations translate to specific marshes in the Bay. One consideration is the nature of the shore edge between the marsh and Bay. Marshes surrounded by levees and connected by relatively narrow breaches, have limited capacity for accreting sediment transported directly from mudflats by landward wind waves onto the marsh plain. However, marshes can still accrete through levee breaches during tides and storm events. For marshes fronted by levees, wind waves can still be a significant, yet indirect, source of sediment: resuspended sediment will be transported onto marshes via tidal channel networks.

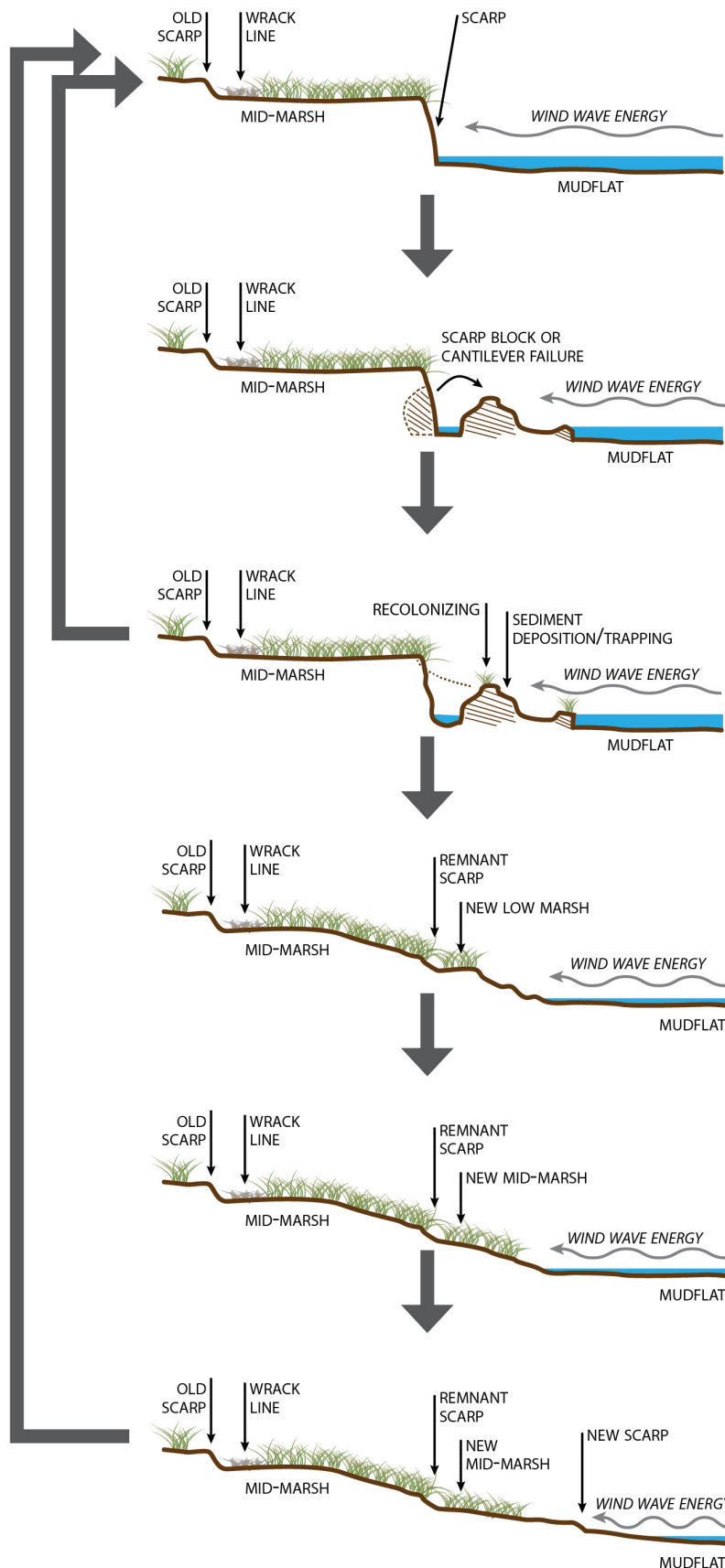


Figure 3.4. Conceptual model of marsh-edge evolution from concave erosional scarp to convex progradational ramp and back again (Source: Beagle et al. 2015; originally adapted from Allen 1989).

Priority actions for addressing key knowledge gaps and uncertainties:

- Evaluate ways to increase sediment resuspension near marshes and maximize sediment deposition onto marshes using restoration design features and techniques (e.g., warping techniques, strategic sediment placement, subsidence reversal/building peat using municipal wastewater effluent).
- Gather more site-specific knowledge of the variations and controls on marsh edge dynamics at specific marshes in the Bay.
- Estimate the volume and location of the local (marsh-scale) erodible sediment pool needed to support marshes and mudflats of a given area, and how the size, location, and transport mechanisms vary by season (Stantec and SFEI 2017).
- Assess the role of mudflat grain size on erodibility and resuspension and how that varies with location (Dusterhoff et al. 2021).
- Evaluate the impact of marsh and mudflat morphology and longitudinal profile (convex versus concave) on bayland vulnerability.

3.2.2 Future Conditions

While our understanding of the current state of how sediment moves to, on, around, and out of the baylands is still evolving and in need of further research, climate change adds another layer of complexity. Major uncertainties exist in how the sediment pathways described above will evolve in the future as the sea level rises and climate changes. Here, we present several factors and processes that are expected to change in the coming decades and some of the possible implications for the future of sediment in the San Francisco baylands.

3.2.2.1 Sea-level Rise

One of the biggest threats of climate change to Bay Area wildlife is the impact of sea-level rise on tidal marshes. These marshes may drown with accelerating sea-level rise due to insufficient sediment to maintain elevation capital and because of extremely limited opportunities to migrate inland due to development (Ackerly et al. 2018). At present, most of the marshes in the Bay have sufficient elevation capital and delivery of sediment to keep pace with the current rate of sea-level rise (~2 mm/yr) (Flick et al., 1999; Callaway et al. 2012), but this trend may not continue over time in some and possibly many marshes without interventions to increase sediment supply (Dusterhoff et al. 2021). Anticipated acceleration of sea-level rise in combination with insufficient sediment supply present major vulnerabilities to marsh and mudflat survival (Dusterhoff et al. 2021). There is general agreement that if the rate of sea-level rise exceeds 6-10 mm/yr with the current sediment supply, many marshes will not be able to keep pace (Orr et al. 2003, Stralberg et al. 2011, Takekawa et al. 2012, Schile et al. 2014, Swanson et al. 2014, Thorne et al. 2018). When considering the amount of sediment needed to support marsh restoration projects in addition to the marshes and mudflats that already exist, the projected deficit in mineral sediment supply is large. Dusterhoff et al. (2021) examined this potential future imbalance and found that in a wetter future scenario, natural supply could be approximately 50% of total bayland demand, and in the drier future, natural supply could be approximately 30% of total bayland demand. These estimates, though, do not reflect the proportion of sediment—a lower value than the 50% and 30% mention respectively—that will actually be deposited on the baylands, for reasons explained in Chapter 3 (e.g., in-channel sedimentation, deposition into the erodible sediment pool).

3.2.2.2 Air and Water Temperatures

Climate change goes beyond rising sea levels. Significant increases in temperature are likely to occur in the Bay Area by mid-century (Ackerly et al. 2018), including water temperatures throughout the Bay. Significant uncertainties exist in how changing ocean temperature will impact upwelling patterns, which could result in changes to seasonal thermal gradients between the Golden Gate and the Delta (Goals Project 2015). Additionally, extreme temperature events like heat waves are projected to become more frequent and severe in duration, while frost events are anticipated to be scarce locally (Goals Project 2015). A significant unknown of changing air and water temperature is the impact on prevailing wind conditions and wind wave formation throughout the Bay. Changes to the magnitude, duration, and frequency of wind waves acting on marshes and mudflats can

affect turbidity levels which, in turn, may impact the amount of sediment in suspension available for deposition on the baylands. A study by Bever et al. (2018) found a statistically significant decline of 13 to 48% in hourly wind speeds throughout the Estuary between 1995 to 2015. Additional modeling by Bever et al. (2018) suggests that declining wind speeds may have contributed to a reduction in turbulence and mixing throughout the Estuary, which in turn may be linked to the decrease in suspended sediment concentration observed over the last twenty years. More research is needed to predict how changes to air and water temperatures will impact future turbidity levels.

3.2.2.3 Precipitation

Rainfall in the Bay Area will continue to be highly variable from year to year, with anticipated swings between very dry and very wet years (Ackerly et al. 2018). Some of these impacts are already being felt in the Bay Area: an extreme period of drought in California between 2012-2016 led to a 1-in-500 year low in Sierra snowpack. This was followed by several atmospheric river events in WY 2017 that resulted in a mix of heavy winds, intense rainfall, regional flooding, and mudslides (NOAA 2017). A similar trend was observed between WYs 2020 and 2021, when California experienced some of the driest years on record, and WY 2023, when California's snowpack exceeded its highest level on record (CDWR et al. 2021, CDWR 2023). An anticipated rise in temperature will likely lead to longer and more intense periods of drought while, in wet years, winter storms will likely become more intense and potentially more damaging in the future (Ackerly et al. 2018). These periods of "booms and busts" in precipitation (or "whiplash", Swain et al. 2018) will likely lead to similar "booms and busts" in sediment transport along tributaries to the Bay. Additional modeling is needed to understand these trends under different greenhouse gas emission scenarios and how that affects the amount of sediment transported to downstream baylands.

3.2.2.4 Wildfires

Hotter temperatures and more intensive droughts make ideal conditions for wildfires, with several notable wildfire outbreaks in the Bay Area in the last few years (e.g., SCU Lightning Complex and LNU Lightning Complex in 2020; CalFire 2022). These fires can burn hundreds of thousands of acres and result in increases in postfire runoff, which can be accompanied by large sediment loads, widespread tree mortalities, debris, contaminant mobilization, and other adverse watershed impacts (Ackerly et al. 2018, Williams et al. 2022). While more research is needed to predict future changes in wildfire and runoff with accuracy and regional specificity, initial research by Williams et al. (2022) suggests that forest fire activity in the western United States is increasingly affecting creeks in more variable ways. How wildfires will indirectly impact sediment deposition and sediment quality on San Francisco's baylands remains largely unknown.

3.2.2.5 Salinity

Sea-level rise is anticipated to push higher-salinity water from the Pacific Ocean further inland in the Bay, resulting in low-salinity and freshwater areas becoming saltier (Ghalambor et al. 2021). Some changes in climate could compound these effects, such as droughts and heatwaves, while other changes may intermittently counteract them, such as periods

of intense rainfall and increased freshwater flows. In addition, salinity levels influence gravitational circulation which impacts water mixing and sediment resuspension and transport. Gravitational circulation is partially driven by a difference in density between heavier saltwater and lighter freshwater. In the upper reaches of the Bay, where there is greater freshwater inflow from the Delta, salinity levels tend to be lower and gravitational circulation is more active due to a fluctuating density gradient in the water column as freshwater meets saltier water. In the lower reaches of the Bay, where saltwater from the ocean is more dominant, salinity levels are generally higher and less prone to mixing. Changes to salinity levels with climate change may result in changes in gravitational circulation and could lead to changes in flux between subembayments and sediment deposition onto baylands.

Another key consideration of changing salinity levels is changes in organic matter accumulation rates. In addition to mineral sediment supply, organic matter can also play a key role in helping tidal marsh and mudflat accretion rates keep pace with sea-level rise (Stantec and SFEI 2017). Brackish and freshwater marshes are dominated by highly productive vegetation that typically accumulates organic matter (which builds peat) at higher rates compared to salt marsh vegetation (Stralberg et al 2011). Future salinity levels will be important to understand future marsh vegetation types and thus organic matter accretion rates.

A NOTE ABOUT NUTRIENTS

While nutrients alone do not present direct implications for the future of sediment in the Bay, knock-on effects such as eutrophication could occur, in part, from low suspended sediment concentration levels. Sediment plays an important role in regulating algal blooms: suspended sediment reduces the amount of sunlight—a factor that supports algal growth—that penetrates the water column (Cloern and Jassby 2012, Wang et al. 2021). Continued high nutrient loadings to the Bay along with rising temperatures, more intense droughts, and decreased sediment delivery could increase the magnitude and frequency of algal blooms in the Bay (Cloern 2020). Algal blooms can have wide ranging repercussions including fish kills, economic losses, and risks to human and wildlife health (Cloern 2020). These impacts were acutely felt in the Bay Area in summer 2022 when a several weeks-long harmful algal bloom occurred—the first major bloom in approximately 18 years (SFC 2022)—which led to a die-off of thousands of fish (OPC 2022), low oxygen levels in large swaths of the Bay, and lost harvesting and recreational opportunities for people (SFBRWQCB 2022). If future suspended sediment concentrations continue to decrease in the Bay as they are projected, light conditions could be ripe for the development of algal blooms when combined with high nutrient loads from wastewater treatment plants and a stratified water column caused by increased water temperature. Future modeling should consider the risk of large-scale algal blooms developing frequently in the Bay due to increased water temperature and decreased sediment supply combined with existing high nutrient loads.

Priority actions for addressing key knowledge gaps and uncertainties:

- Model the effect of sea-level rise on sediment transport and deposition to the baylands to determine if a transition of mudflats to shallows and the loss of sediment to expanding deeper areas of the Bay will result in less resuspension of sediment by wind-waves and currents and, thus, less transport and deposition onto marshes and mudflats.
- Model the effects of a changing climate, specifically atmospheric river events (e.g., unplanned levee and berm failures), heavy rains following wildfires (e.g., mudslides), intense droughts, and other disturbances on local sedimentation dynamics.
- Assess the impact of sea-level rise and changing runoff patterns on marsh salinity and organic matter accumulation rates (Dusterhoff et al. 2021).
- Assess the projected impact of changing climatic conditions, Bay sediment supply, and increasing water depth on shoreline erosion rates around the Bay, and develop a method to systematically measure and monitor regional marsh and mudflat erosion rates (Dusterhoff et al. 2021).



Photo by Shira Bezael (SFEI)

4. Summary of Key Knowledge Gaps and Uncertainties

Table 3 highlights pressing knowledge gaps and uncertainties of those discussed throughout this report in our understanding of open bay sediment flux and bayland sediment pathways for conditions now and in the future. Refined and updated flux estimates at Mallard Island, the Golden Gate, and between subembayments are all identified to improve the understanding of Bay-scale sediment dynamics. Refined watershed models that include future rainfall and land use projections coupled with scenarios of vegetation change and wildfire prevalence would also improve our understanding of tributary sediment supply. These will help to determine where sediment is delivered to the Bay, how it varies over time, and where marshes may be more at risk from limited sediment supply. In addition, a number of special studies on mixing, flocculation, and bioturbation will assist in the refinement of numerical models examining sediment resuspension dynamics.

Knowledge gaps related to current bayland sediment processes are of great importance to the management of marshes as these directly influence sediment accretion and are more influenced by management decisions. Determining how much and where sediment from tributaries enters the Bay and the size, location, and rate of depletion of erodible sediment pools will inform choices on the location and size of future marsh restorations and sediment placement. The design of future restorations to increase accretion rates will be guided in part by a better understanding of the pathways from the shallows and mudflats on to the marshes.

Understanding the range of variability and uncertainties related to future bayland sediment processes is also important for guiding management priorities on the location and design of future baylands restoration projects. Both vertical accretion and shoreline erosion will be affected by sea-level rise, necessitating an improved understanding of how a deeper Bay will change sediment resuspension, transport, and deposition.

Table 3. Priority actions for addressing key knowledge gaps and uncertainties in Bay sediment processes.

Category	Priority actions for addressing key knowledge gaps and uncertainties	What would knowledge in this area be used for or work to improve?	Existing efforts prioritizing this gap ¹
<i>Flux</i>	Update and refine estimates of flux from the Delta by improving estimates of suspended and bedload sediment at Mallard Island.	<ul style="list-style-type: none"> Update regional and subembayment-scale sediment budgets 	SMMS Q3, BCDC S2
	Update and refine current and future flux estimates through the Golden Gate and between subembayments.	<ul style="list-style-type: none"> Update regional and subembayment-scale sediment budgets Determine whether marshes in some subembayments are more at risk due to sediment due to net sediment export from that subembayment 	SMMS Q3, BCDC S2
	Refine modeling of suspended sediment concentrations in Bay subembayments to account for more dynamic processes, such as mixing, flocculation, bioturbation, and variation over time.	<ul style="list-style-type: none"> Improve support for permitting decisions (e.g., dredging, contaminants) by the SFBRWQCB Compare previous flux measurements to understand movement and settlement of sediments Potentially provide better sediment supply information for subembayments Inform estimates of available sediment for marsh resilience and restoration projects 	SMMS Q3 and Q5
<i>Uplands to tributaries pathway</i>	Model effects of shifting rainfall patterns (e.g., atmospheric river events, prolonged droughts) and land use/land cover changes on watershed flow-sediment load relationships for all Bay and Delta tributaries.	<ul style="list-style-type: none"> Update regional and subembayment-scale sediment budgets 	SMMS Q3, BCDC W2
<i>Tributaries to marshes, mudflats, and erodible sediment pool pathway</i>	Estimate the proportion of tributary sediment versus sediment from the erodible sediment pool that deposits onto mudflats and marshes within each Bay subembayment, and the key drivers determining location and timescale.	<ul style="list-style-type: none"> Develop marsh-scale sediment budgets to help inform management decisions Inform marsh restoration design such as the grading plan, amount of fill, source of fill, etc. Inform management of the shoreline to reduce the need for sediment rather than try to increase supply Help move from regional sediment deficit to local and subembayment scale understanding that can lead to more targeted actions 	SMMS Q3, SMMS Q4, BCDC M1

(Table 3 continued)

<i>Erodible sediment pool to mudflats and deep Bay pathway</i>	Estimate the size, location, and rate of depletion of current erodible sediment pools at the Bay subembayment and local scales.	<ul style="list-style-type: none">• Develop subembayment and marsh-scale sediment budgets for baylands resilience• Inform marsh restoration design such as grading plan, amount of fill, source of fill, etc.• Help move from regional sediment deficit to local and subembayment scale understanding that can lead to more targeted actions	WRMP Q13, SMMS Q3 and Q5, BCDC M3
<i>Mudflats to marshes pathway</i>	Develop strategies and create pilot projects in collaboration with marsh restoration engineers to increase sediment resuspension near marshes and maximize sediment deposition onto marshes using restoration design features and techniques (e.g., warping techniques, strategic sediment placement, subsidence reversal/ building peat using municipal wastewater effluent).	<ul style="list-style-type: none">• Improve sediment accretion rates and overall marsh resilience of restored marshes over time• Develop targeted local actions for baylands resilience	SMMS Q4, SMMS Q5, BCDC M2 and M4
<i>Additional future conditions</i>	Model the effect of sea-level rise on sediment transport and deposition to the baylands to determine if a transition of mudflats to shallows and the loss of sediment to expanding deeper areas of the Bay will result in less resuspension of sediment by wind-waves and currents and, thus, less transport and deposition onto marshes and mudflats.	<ul style="list-style-type: none">• Increased understanding of how management guidance and marsh restoration design need to account for sea-level rise• Increased understanding of future sedimentation dynamics for baylands resilience as well as water clarity (i.e., from nutrients) and contaminants	WRMP Q13, SMMS Q3 and Q4, BCDC S4
	Assess the projected impact of changing climatic conditions, Bay sediment supply, and increasing water depth on shoreline erosion rates around the Bay, and develop a method to systematically measure and monitor regional marsh and mudflat erosion rates.	<ul style="list-style-type: none">• Improved marsh management and restoration decision-making• Increased understanding of potential impacts of shoreline erosion, which could be as significant or more significant than marsh loss due to marsh drowning• Inform the need for nature-based solutions or mudflat nourishment to protect marsh edges	WRMP Q6, BCDC B1

¹Key knowledge gaps and uncertainties overlap with existing planning documents, including: the Sediment Monitoring and Modeling Strategy (SMMS) (McKee et al. 2020), which is crosswalked to the management questions (Q) it overlaps with in the SMMS; the Science of Sediment Workshop Summary Report prepared by BCDC (2016a), which is crosswalked to the management question ID in the BCDC report; and the San Francisco Bay Wetland Regional Monitoring Program (WRMP 2020), which is crosswalked to the monitoring questions (Q) it overlaps with in the matrix for monitoring sites spreadsheet for various indicator categories in the WRMP Program Plan.

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