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Journal

San Francisco Estuary and Watershed Science, 23(2)

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Foster-Martinez, Madeline
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Publication Date
2025

DOI
10.15447/sfews.2025v23iss2art6

SAN FRANCISCO
ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Stewardship Council and UC Davis Institute of the Environment

RESEARCH

Marsh Sediment in Translation: A Review of Sediment Transport Across a Natural Tidal Salt Marsh in Northern San Francisco Bay

Madeline R. Foster-Martinez*[1 ‡], Matthew C. Ferner[2‡], John C. Callaway[3‡], Brenda Goeden[4‡], Jessica R. Lacy[5‡]

ABSTRACT

Deposition of inorganic sediment is essential for the sustainability of tidal salt marshes. Understanding variability in sediment sources and the processes of sediment delivery to salt marshes are high priorities for decision-makers responsible for managing sediment and conserving and restoring marshes. Research on sediment transport to marshes is published in technical journals, but these scientific findings must be translated and communicated to inform critical decisions related to managing sediment in estuaries. We convened a diverse group of collaborators—including natural-resource managers, regulators, scientists, and restoration planners and practitioners—to review and interpret the results of previously published field investigations on and around the salt marsh at China Camp State Park in Marin County, California. We discussed and translated key results of those studies using new graphics and more accessible language. Here, we present a general introduction to the topic of sediment delivery to salt marshes, background descriptions of the China Camp marsh and the physical processes that we characterized there, key scientific conclusions, and proposed management implications. Key conclusions include (1) bay shallows are an important but variable source of marsh sediment, (2) flood tides and waves move sediment across the bay–marsh edge, (3) tidal creeks may not always import sediment to the marsh platform, and (4) protective effects of marsh vegetation depend on species and season. China Camp marsh is one of the last remaining pre-colonial salt marshes in the San Francisco Estuary and is unique in being relatively unmodified by humans and in retaining an unimpeded transition into natural uplands. Additional studies in a variety of marshes with different attributes and sediment regimes will

SFEWS Volume 23 | Issue 2 | Article 6
https://doi.org/10.15447/sfews.2025v23iss2art6

* Corresponding author: *mrfoster@uno.edu*

1 University of New Orleans
Pontchartrain Institute for Environmental Sciences
Geology–Psychology Building
New Orleans, LA 70148 USA

2 San Francisco Bay National Estuarine Research Reserve and San Francisco State University, Estuary and Ocean Science Center, CA 94920 USA

3 University of San Francisco
Department of Environmental Science
San Francisco, CA 94117 USA

4 San Francisco Bay Conservation and Development Commission
San Francisco, CA 94105 USA

5 US Geological Survey
Pacific Coastal and Marine Science Center
Santa Cruz, CA 95060 USA

‡ *Authors contributed equally to this work.*

broaden understanding of how best to conserve, manage, and restore tidal marshes that provide numerous ecosystem services to for humans and wildlife.

KEY WORDS

China Camp State Park, coastal resilience, erosion, hydrodynamics, inundation, marsh sustainability, sedimentation, tidal currents, wave attenuation, wetland restoration

INTRODUCTION

Sustainability of tidal salt marshes is a global priority because of the ecosystem services that salt marshes provide (Zedler and Kercher 2005; Barbier et al. 2011; Duarte et al. 2013), including protection from flooding and shoreline erosion (Narayan et al. 2016; FitzGerald and Hughes 2019), removal of excess nutrients and pollutants from coastal waters (Valiela and Cole 2002), sequestration of carbon (e.g., Mcleod et al. 2011), and habitat for valued fish and wildlife (Takekawa et al. 2011; Wood et al. 2012; Colombano et al. 2021). The accelerating rate of sea level rise (SLR) projected over the coming decades will significantly challenge the sustainability of both natural and restored salt marshes that can only survive within a relatively narrow range of intertidal elevation (Kirwan and Megonigal 2013; Schuerch et al. 2018). The zone where salt marshes thrive is periodically flooded by saltwater, precluding colonization by upland plants, but not submerging to the point of drowning the emergent vegetation that defines these ecosystems. The maintenance of salt marshes within this intertidal range depends on a dynamic balance between inundation and the gradual accumulation of mineral sediment and belowground organic matter (peat). Although the organic component contributes to salt marsh soil structure and stability, salt marshes require ongoing inputs of mineral sediment to maintain elevation and will require even more as rates of SLR accelerate (Morris et al. 2016; Ganju et al. 2017). Salt marsh soils have higher mineral content and are denser than the more peat-rich soils found in brackish and freshwater marshes (Nyman et al. 1990; Callaway et al. 2012), making the mineral component relatively more important.

In California, increasing sustainability of salt marshes is particularly urgent in the San Francisco Estuary (“the estuary”) where approximately 90% to 95% of historic marshes have been diked and developed, or converted to agriculture and salt ponds (Goals Project 2015). Salt marshes in the estuary are under threat not only from SLR but also from diminishing sediment supply and other factors (Wright and Schoellhamer 2004; Jaffe et al. 2007; Parker and Boyer 2019). Annually averaged suspended-sediment concentrations (SSCs) in the estuary decreased 36% from the 1990s to the 2000s (Schoellhamer 2011) and are expected to continue decreasing as a result of terrigenous sediment being trapping behind dams in the watershed and the erodible pool of sediment within the estuary being depleted. Furthermore, ecological forecasting models show that most tidal marshes in the estuary will be drowned by 2100, and drowning was most frequently the result of two factors: the rate of SLR and sediment availability (e.g., Schile et al. 2014; Swanson et al. 2014).

As a response to these challenges, salt marsh restoration projects have been undertaken in the estuary at a variety of scales and with mixed success (Williams and Faber 2001; Callaway and Parker 2012; Parker and Boyer 2019). The report *Sediment for Survival* (Dusterhoff et al. 2021) highlighted that under current management practices, there is not enough sediment in the estuary to maintain the elevation of existing and restored marshes, much less adapt to rising seas. As a result, the coastal-zone management community is motivated to better understand how and when sediment moves onto tidal marshes and the processes that enhance its retention. Improving our understanding of sediment delivery to salt marshes—how sediment reaches and is retained by marshes—will greatly improve our ability to design effective interventions (e.g., beneficial re-use of dredged material) and resource-management plans, leading to more efficient use of public funds. Long-term

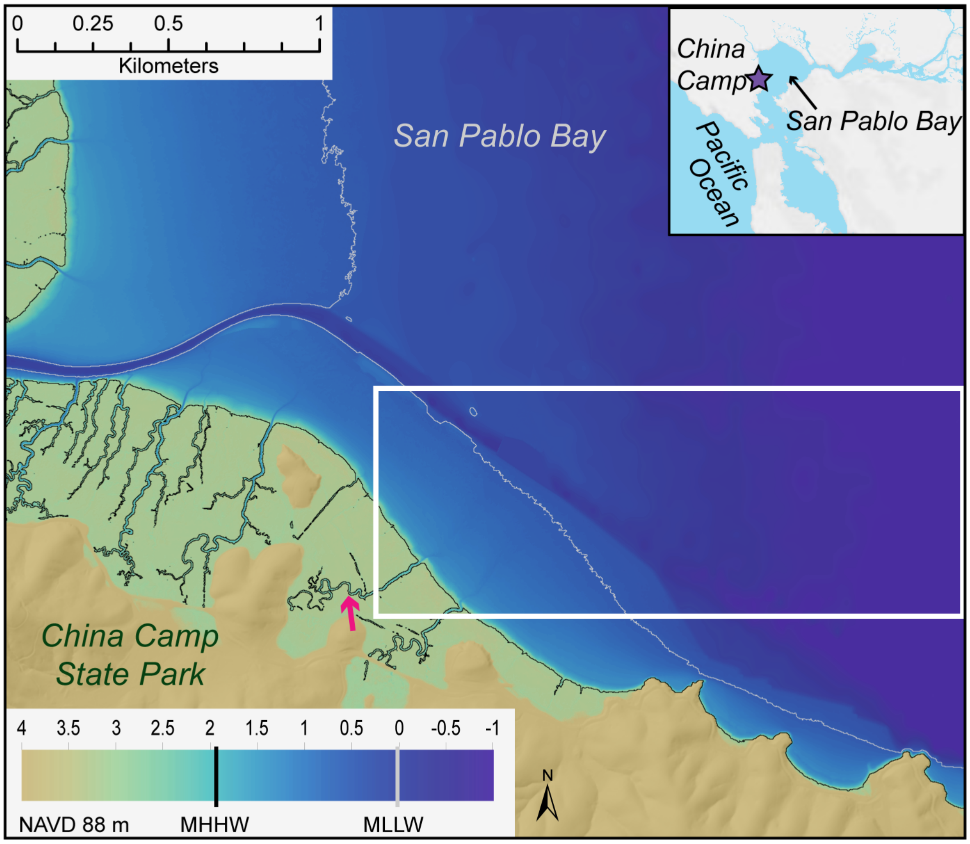


Figure 1 Map of study area: China Camp State Park and the adjacent shallows of San Pablo Bay. *Black* and *gray bathymetry lines* indicate the location of mean higher high water (MHHW) and mean lower low water (MLLW), respectively. Elevations in meters of those tidal datums are referenced to the North American Vertical Datum of 1988 (NAVD 88). The *white box* is the area shown in Figure 6, and the *red arrow* indicates the location and orientation of where we took the photograph shown in Figure 2. *Source:* US Geological Survey (2013).

monitoring of SSCs in the estuary has mostly been restricted to deeper waters (Schoellhamer 2011; but refer to Brand et al. 2010; Lacy et al. 2014; MacVean and Lacy 2014; Allen et al. 2019; Egan et al. 2020). To relate basin-scale SSCs to marsh sustainability, it is critical to consider how sediment moves from deeper waters to bay shallows, mudflats, tidal creeks, and eventually onto salt marshes.

The environmental conditions and physical processes that lead to sediment accretion on salt marshes can be site-specific even across a limited geographic area, and there are numerous uncertainties about how the relevant processes interact across scales (e.g., Cahoon and Reed 1995; Temmerman et al. 2003; FitzGerald et al. 2020). A multi-year collaborative field study conducted by scientists (including the authors) from the US Geological Survey, the San Francisco Bay National Estuarine Research Reserve (NERR), and the University of California–Berkeley investigated spatial and temporal variability in hydrodynamics and sediment transport between the shallows of San Pablo Bay and the marsh at China Camp State Park (Figure 1). This marsh is a part of the San Francisco Bay NERR and is referred to hereafter as the China Camp marsh. We collected data throughout the study area: in sub-tidal and intertidal shallows; in two tidal creeks; and within the marsh along transects that extend away from creeks as well as landward from the bay–marsh edge. We published detailed methods and the results of these field studies in peer-reviewed articles (Foster–Martinez et al. 2018; Lacy et al. 2018; Allen et al. 2019; Lacy et al. 2020), and published the associated datasets in Lacy et al. (2017). These studies led to novel understanding of sediment transport and delivery to salt marshes.

Given the importance and urgency of sediment management and wetland restoration, and prompted by our regional collaborators, we concluded that the results should be translated into less technical terms and communicated

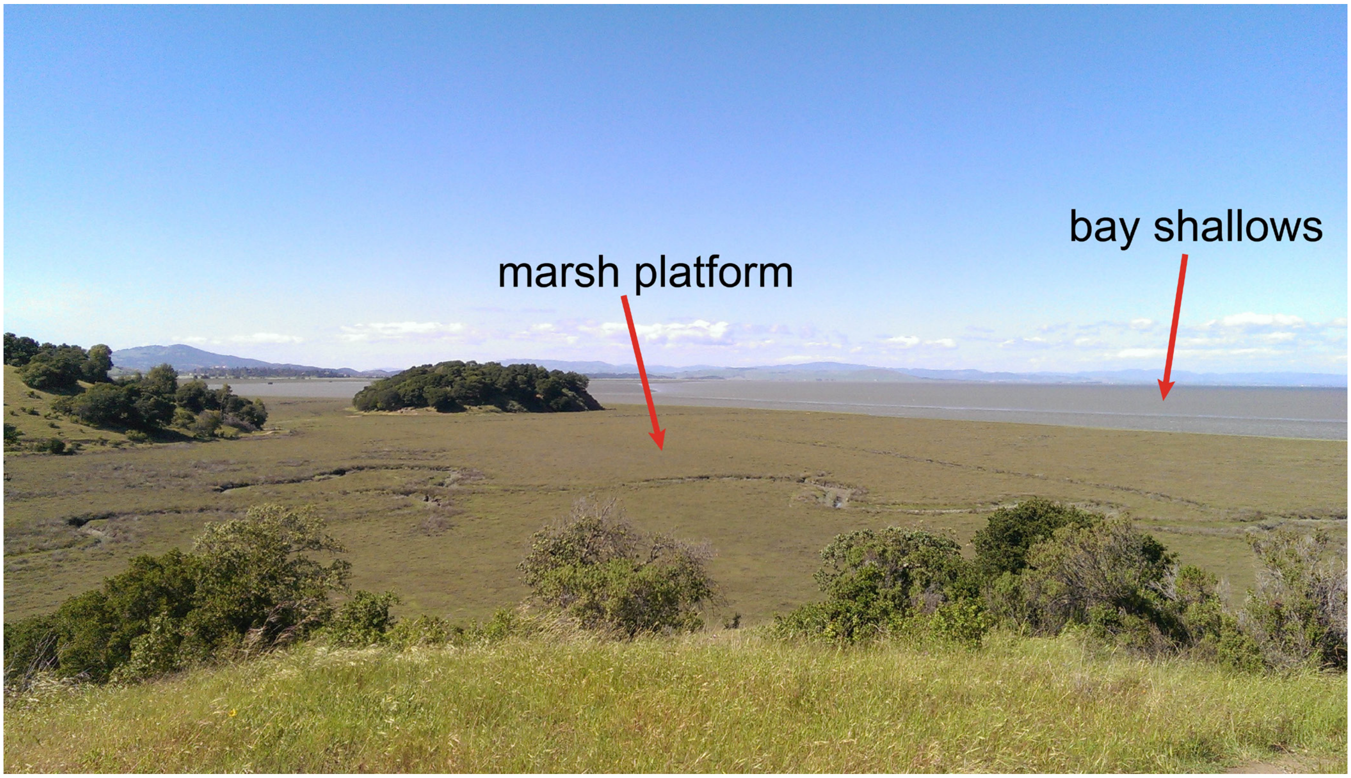


Figure 2 Photograph of the study area at China Camp marsh showing the marsh platform (dominated by pickleweed, *Salicornia pacifica*) and the bay shallows of San Pablo Bay. Marsh sustainability as mean sea level continues to rise will depend on sediment delivery from the bay shallows to the marsh platform through tidal creeks and/or across the bay–marsh edge. Note that the dominant plant species along the bay–marsh edge is California cordgrass (*Spartina foliosa*), not clearly visible in this picture. *Photo credit: San Francisco Bay NERR.*

more broadly. Our goal was to extract the most relevant results from the previously published research studies and communicate those findings so a variety of audiences can access and interpret them. To achieve this goal, we held structured workshops and reviewed documents iteratively with a broad group of collaborators, including natural-resource managers, regulators, and restoration planners and practitioners working in the estuary. This monograph—its organization, format, and figures—is the result of that collaborative process, which we describe in more detail on our project webpage (NERRS 2023).

We organized the remainder of this monograph into three sections:

1. The first is a background on marsh processes and the setting of China Camp marsh.
2. Next, we present our key scientific conclusions, each supported by an explanation of underlying mechanisms and accompanied by the associated implications for marsh management. These conclusions follow a question–answer format. Throughout, you will find blue boxes labeled “Sediment transport primer,” which explain concepts referenced in the main text.
3. We conclude with a short section discussing future opportunities.

BACKGROUND: CHINA CAMP MARSH AND RELATED PHYSICAL PROCESSES

Sitting on the southwestern shore of San Pablo Bay, China Camp marsh is an example of a healthy, relatively undisturbed, tidal, saline

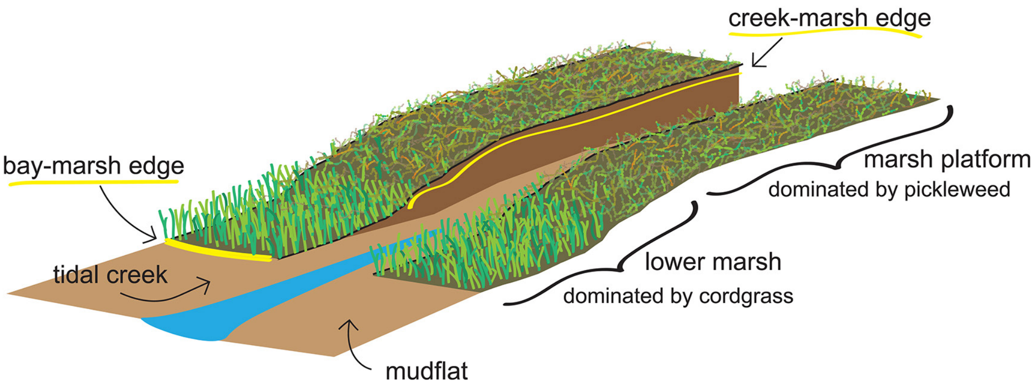


Figure 3 China Camp marsh consists of lower marsh, tidal creeks, and the marsh platform. It is bounded by uplands above and unvegetated mudflat and bay shallows below. Key boundaries or transition zones within the marsh include the bay–marsh edge and the creek–marsh edge. The vegetation begins in the lower marsh at about 0.77 m (2.5 ft), and the marsh platform begins at about 1.67 m (5.48 ft). Tidal datums at the nearby Richmond NOAA station (9414863) are: mean lower low water (MLLW) at 0.005 m (0.02 ft); mean sea level at 0.996 m (3.27 ft); and mean higher high water (MHHW) at 1.846 m (6.06 ft). All elevations are relative to NAVD88.

marsh (Figure 1, Figure 2) (Baye 2012). It is bordered by a large unvegetated intertidal mudflat that extends 400 m (1,312 ft) bayward from the marsh edge and is traversed by creeks that are inundated twice daily with the tide. The marsh edge slopes up gradually from the intertidal flats to the marsh platform (vertical increase of 1.4 m [4.6 ft] over about 60 m [197 ft]), which occupies an elevation around the mean higher high-water line. Most of the marsh platform extends about 0.5 km (0.31 mi) toward the uplands with only a minor change in elevation. The lowest marsh vegetation—a narrow band of California cordgrass (*Spartina foliosa* syn. *Sporobolus foliosus*)—begins at around mean sea level and transitions up to pickleweed (*Salicornia pacifica*) on the marsh platform (Figure 3). The site is not sheltered, and when the marsh is inundated, the lower edge is exposed to waves from the bay. This gradually sloped and vegetated marsh edge indicates a **prograding marsh**, and from 1855 to 1993, the marsh in this area expanded bayward at a rate between 1.1 to 4 m yr^{-1} (3.6 to 13 ft yr^{-1}) (Beagle et al. 2015).

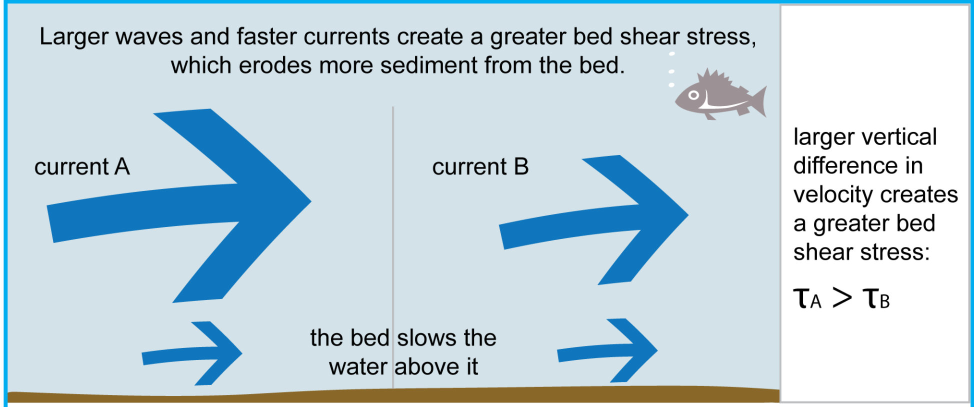
There are two main pathways for sediment to reach the China Camp marsh platform: across the bay–marsh edge and across the creek–marsh edge (Figure 3). In the following sections, we refer to these two types of edges. Not all marshes have these characteristics; **fringing marshes**—common along San Francisco Bay (hereafter, "the bay")—often lack the marsh platform, and **laterally eroding marshes** tend to have a scarped edge without the band of California cordgrass that borders the bay. The questions we address about sediment delivery at China Camp marsh are important for all marsh types, but the answers will likely differ, depending upon the setting (Beagle et al. 2015). We consider China Camp marsh to be "healthy" in large part because it is not losing elevation relative to mean water level in the bay (also referred to as mean sea level). Soil cores taken at the site show that it has been accreting about 4 mm yr^{-1} (0.16 in yr^{-1}), keeping pace with SLR over the last century (Callaway et al. 2012). This outcome is a result of adequate rates of sediment deposition over time.

Tidal processes strongly influence salt marsh sedimentation and erosion. The estuary experiences mixed semi-diurnal tides, meaning there are two unequal tidal cycles each day (Walters et al. 1985). The two daily high tides are referred to as higher-high tide and lower-high tide and are separated by unequal low tides; the average elevation of higher-high tides is known as mean higher high water (MHHW). We refer to the period when water level is rising as a flood tide and when water level is dropping as an ebb tide. At the times of high and low tides, currents are calmer, or "slack." Daily tidal range between low and high tide in the estuary varies spatially and temporally, with a greater range and stronger tidal currents during "spring tides" that coincide with the full and new moon, and a lesser range (and weaker currents) during "neap tides" that coincide with the first and third quarters of the moon. Daily (diurnal) inequality between the two high and/or low tides is greatest during spring tides and least during neap tides. Beyond astronomical effects, high tide elevation varies with barometric pressure and the amount of local rainfall and freshwater runoff from the watershed. In our study area, the range between mean lower low water (MLLW) and MHHW is 1.84 m (6.0 ft) (NOAA Station 9414863, Richmond, CA) (NOAA 2007).

The Mediterranean climate of the region means there are two seasons, a dry summer and a wet winter. In the summer, a daily sea breeze generates afternoon waves, and in the winter, intermittent storms (i.e., larger low-pressure systems) can generate the largest and longest-period waves (Walters et al. 1985). All waves are generated locally, as sea swell does not penetrate far into the estuary.

Waves and currents generate **bed shear stress**, which re-suspends sediment in the bay shallows (Figure 4). Water inundates the marsh on sufficiently high tides, carrying with it suspended sediment. In the absence of wave energy, the movement of sediment particles across the marsh platform is governed by tidal currents and gravity (Figure 5). Tidal currents move sediment horizontally. Gravity causes

Sediment transport primer



Bed shear stress is what drives sediment resuspension from the bed[a] to the water column. Bed shear stress is typically represented with the Greek letter tau (τ). The units are the same as pressure, force applied to an area. You get a force any time you have changes in velocity (i.e. acceleration or deceleration). When a fluid moves past a stationary object (or anything moving slower than the fluid), the object slows down the moving fluid, and you get a change in the velocity. In the bay, while individual sediment particles move, the bed as a whole remains stationary and slows down the water above it. The water closest to the bed gets slowed down the most.

Because the water at the bed is moving slower than the water above, you get a force between them. The faster the water above, the greater the change in velocity, and the greater the force applied to the bed. That is why faster currents resuspend more sediment compared to slower currents and can cause scour. Waves also cause bed shear stress. When these motions die down or out (i.e., wave and current attenuation), the difference in velocity at the bed is small, and there is little to no bed shear stress. We can measure the bed shear stress from waves and currents individually and combined.

[a] When we say bed, we mean the bottom. That could be the bottom of the bay or the surface of the marsh or mudflat. All of these are considered the "bed."

Figure 4 Sediment transport primer on bed shear stress. Generic fish graphic from the Integration and Application Network. *Source: UMCES Integration and Application Network media library* https://ian.umces.edu/media-library.

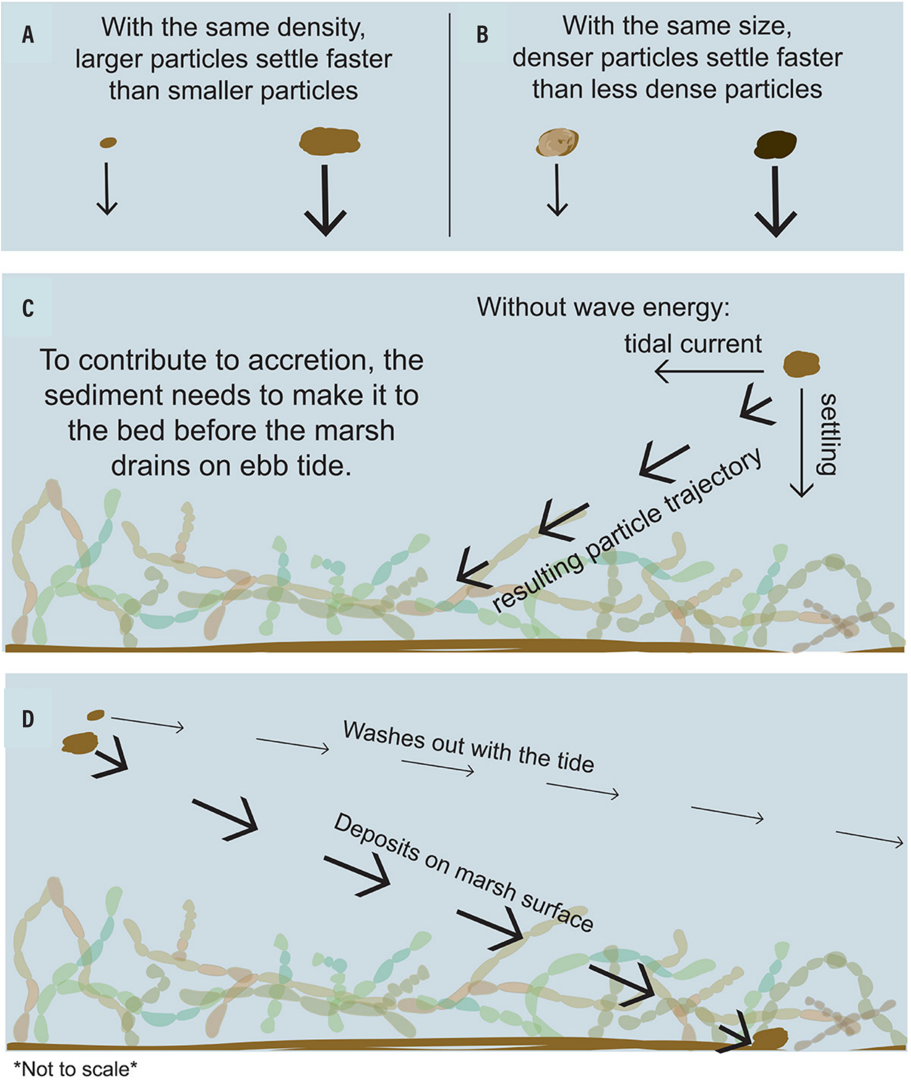


Figure 5 Depictions of particle settling dynamics. (**A**) Larger particles settle faster than smaller particles, if they have the same density. (**B**) Denser particles settle faster than less dense particles, if they have the same size. (**C**) Once wave energy dies out, gravity and horizontal tidal currents govern particle motion (causing settling), which results in a diagonal trajectory. (**D**) Trajectories of two sediment particles of similar density: a small particle that does not make it to the marsh surface and washes out with the tide, and a larger particle that deposits on the marsh surface.

sediment to settle downward at a speed called the **settling velocity**, which is primarily dictated by particle size and density. For material of the same density, large particles settle to the marsh surface (or bed) faster than smaller particles. Similarly, for particles of the same size, those of higher density settle faster than those of lower density. Sediment particles that reach the marsh bed before the tide drains water out of the marsh successfully contribute to deposition, thereby increasing the surface elevation of the marsh platform. Fine sediment with a slower settling velocity often remains in suspension and is carried off the marsh by the ebb tide, especially during more energetic conditions or when the period of high-tide inundation is short. Prolonged quiescent periods are required for fine sediment or particles with low density (e.g., fluffy organic material) to settle to the bed. Larger or denser particles can settle out more quickly over a tidal cycle. Of course, it is not quite as straightforward as it seems, because particle size can increase via **flocculation** (the process by which particles stick together). Likewise, flocs, or clumps of particles, can break apart. Vegetation also affects the deposition process on the marsh platform because it slows down tidal currents and decreases wave energy, allowing more sediment to be deposited before the water recedes.

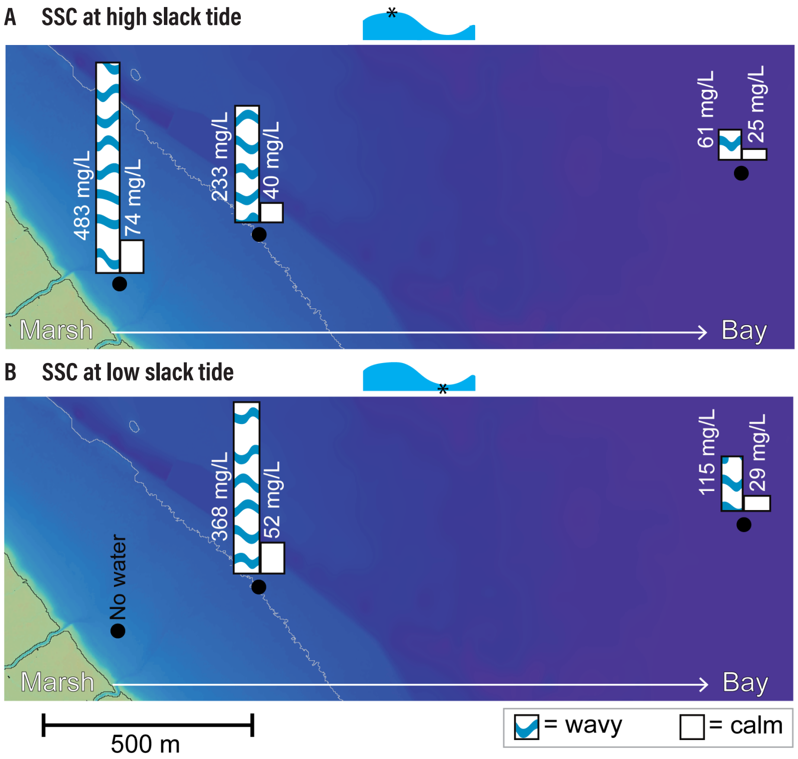


Figure 6 Discrete measurements of suspended-sediment concentration (SSC in mg L^{-1}) at three locations (*black dots*) in the bay shallows at (**A**) high tide and (**B**) low tide during both a wavy condition (30-cm wave height at the farthest offshore station) and a calm condition (6-cm wave height at the farthest offshore station). *Background color* shows bathymetry and follows the scale shown in Figure 1. *Black* and *gray bathymetry lines* indicate mean higher high water (MHHW) and mean lower low water (MLLW), respectively. Note that these wave-height conditions differ from thresholds used for waves crossing the bay–marsh edge, which were based on ranges of wave heights measured at the lower mudflat station (~MLLW).

SCIENTIFIC CONCLUSIONS

Conclusion 1. Bay Shallows are an Important but Variable Source of Marsh Sediment

Are suspended-sediment concentrations relatively constant in the bay shallows?

No, quite the opposite: SSCs vary with time and space. SSCs vary among the embayments of the estuary because of relative proximity to the Sacramento–San Joaquin Delta or to the Pacific Ocean and to the extent of shallows where sediment is easily re-suspended. SSCs also vary more locally within shallows. This variability is primarily driven by processes that change the water depth and/or energy above the bay floor. Shallower water closer to shore generally has a higher SSC than deeper water farther offshore, and more energetic water (i.e., faster currents, larger waves) has a greater SSC than calmer water (i.e., quiescent conditions). These drivers of variability are important to consider if measurements of SSC in the bay shallows are intended to help predict when and where sediment accretion occurs in nearby salt marshes.

Why does shallower water tend to have higher SSCs than deeper water?

There are two main reasons for this difference. The first is that waves interact with the bay floor (or bed) more in shallow water, resulting in greater bed shear stress (illustrated in Figure 4) and thus more sediment re-suspension from waves. In the deeper water of the shallows, the motion of the short-period (e.g., 2 seconds between passing wave crests) wind–waves typical in the estuary does not reach all the way to the bed, and therefore the currents play a relatively larger role in re-suspending sediment.

The second reason shallower water has higher SSCs is that the greater volume of water above the bed in deeper water dilutes the suspended sediment, reducing SSCs. To see this, consider the total mass of sediment in the water column (the product of SSC x depth x unit surface area) for two sites with similar bed shear stress but different water depths. Even if the mass of sediment in the water column is similar at the two sites, the SSCs will be different. This dilution effect also reverses tidally at each location; SSCs increase as the water level drops from high tide to low tide.

What is the magnitude of this variability in SSCs?

Variability in SSCs can be seen in field observations. Figure 6 shows three locations in the bay shallows at four snapshots in time: low and high slack tide with wavy and calm conditions. The trend of greater SSC with shallower water holds for all conditions. The bars that contain blue lines indicate the SSC with wavy conditions (the wave height at the farthest offshore station was 0.3 m (about 1 ft) during data collection), while the open bars indicate the SSC with calm conditions (wave height at the farthest offshore station was 0.06 m (about 2.4 in) during data collection). Waves increase the SSC at all stations, but the increase is larger in shallower water. During high slack tide, greater waviness increases the SSC by over 6-fold at the shallowest station, whereas at the deepest station the increase in SSC is slightly less than 2.5 times. During low slack tide when the water is shallower throughout the area, we see the other stations "act" like the shallow station, and waviness increases SSC more than during high tide.

For Figure 6, we selected high and low slack tides to minimize how tidal currents affected the comparisons; however, the greatest SSC occurs when the combined effect of waves and currents on the bay floor generates large bed shear stress (see Figure 4 for an explanation of shear stress). As the tide was flooding before the high slack tide shown under wavy conditions (see Figure 6), the SSC at the farthest offshore station was 125 mg L^{-1}, about double the concentration at high slack tide, and at the middle station the SSC was 352 mg L^{-1}, which is about 50% greater.

What about vertical variability of SSCs from the surface to the bed?

There is more suspended sediment near the bay floor than closer to the water surface because re-suspension from the bed is a dominant source, and because sediment, which is denser than water, is continually settling toward the bed. We measured SSCs at a single water depth at each station, but the values shown in Figure 6 are depth-averaged SSCs. We determined depth-averaged SSCs from measurements at a single elevation based on a well-established expression (the Rouse equation, see Rouse [1937]) for the vertical distribution of sediment as a function of settling velocity and measured near-bed turbulence.

Considerations for Managers

Data on SSC should inform site selection for future marsh restoration, because marshes with an ample supply of sediment will likely be able to accrete and gain elevation (i.e., achieve restoration success). If SSC is measured to inform plans that relate to tidal marshes, when and where you measure it matters. The concentration of suspended sediment in the water quickly responds to a range of factors that vary in both time and space.

- **Conclusion 1A – *WHEN you measure SSC matters.*** SSC varies at a range of time-scales. There is periodic variability in SSC seasonally as a result of wet and dry periods, on the order of weeks with the spring-neap tidal cycle, and on the order of hours with the daily tidal cycle. SSC is higher when tidal currents are fastest and when water levels are lowest. Episodic events, like storms that bring greater wave action, increase SSC over the duration of the event.

- **Conclusion 1B - *WHERE you measure SSC matters.*** SSC is lower in deeper water than shallower water, and lower near the water surface than near the bed. Measurements of SSC from deeper portions of the bay (i.e., shipping channels) are less relevant to sediment supply to salt marshes than measurements in the shallows. Water that flows onto the marsh (delivering sediment) comes from close to the water surface at high tide, which—based on the processes explained above—is not the most sediment-rich water. The increase in SSC throughout the water column from waves is therefore especially important for getting sediment-rich water to marshes, as explored further in Conclusion 2.

- **Conclusion 1C - *Continuous data is best, and discrete data in context is good.*** Given the natural variability in SSC, single measurements in time (even at multiple locations) do not provide enough information to improve decision-making. Rather, long-term records that encompass a range of seasons and tidal conditions could increase understanding of how SSC varies. If only discrete samples are possible, it is important to put them into context:

- *At what point in the tidal cycle was the measurement taken?*
- *What were the wave conditions at the time?*
- *How close to shore and to the bed was the measurement taken?*

Conclusion 2. Flood Tides and Waves Move Sediment across the Bay–Marsh Edge

What physical conditions allow for sediment delivery to the marsh platform?

Sediment deposition on the marsh occurs only when the marsh platform is inundated. Suspended sediment in bay shallows does not do marshes much good unless it can get to the marsh platform and settle out of suspension. Where (and whether) suspended sediment settles onto the marsh depends on the magnitude of incoming currents and wave energy, the damping forces at work, inundation time, and the settling velocity of the suspended sediment particles.

Do all high tides deposit sediment on the marsh?

Specific patterns of marsh inundation vary over the spring-neap cycle, but, in general, deposition occurs on some portion of the marsh whenever it is inundated. The marsh platform is only under water during higher-high tides, thereby limiting the time available for sediment deposition on most of the marsh. When water levels are very high and the lower marsh is deeply inundated, measurements at China Camp marsh showed net erosion of sediment from the lower marsh (specifically during summer, as detailed in the next question). However, during lower-high tides when inundation depth is reduced, sediment is typically deposited on the lower marsh, making more sediment available for re-suspension during the subsequent flood tide that inundates the marsh platform.

Does vegetation in the lower marsh affect sediment delivery to the marsh platform?

Yes, plants in the lower marsh strongly affect sediment transport at China Camp marsh. The band of California cordgrass (*Spartina foliosa*) at the bay edge is full and leafy in the summer (represented in Figure 3). Plant leaves and stems block the flow, slowing tidal currents, reducing the height of wind-driven waves,

Figure 7 Sediment on cordgrass stems is visible after a lower-high tide (Sept. 29, 2016). The larger stems shown here are about 1 cm wide. Eastern mud snails (*Tritia obsoleta*, aka *Ilyanassa obsoleta*) are scattered throughout the image. *Photo credit: M. Foster-Martinez.*

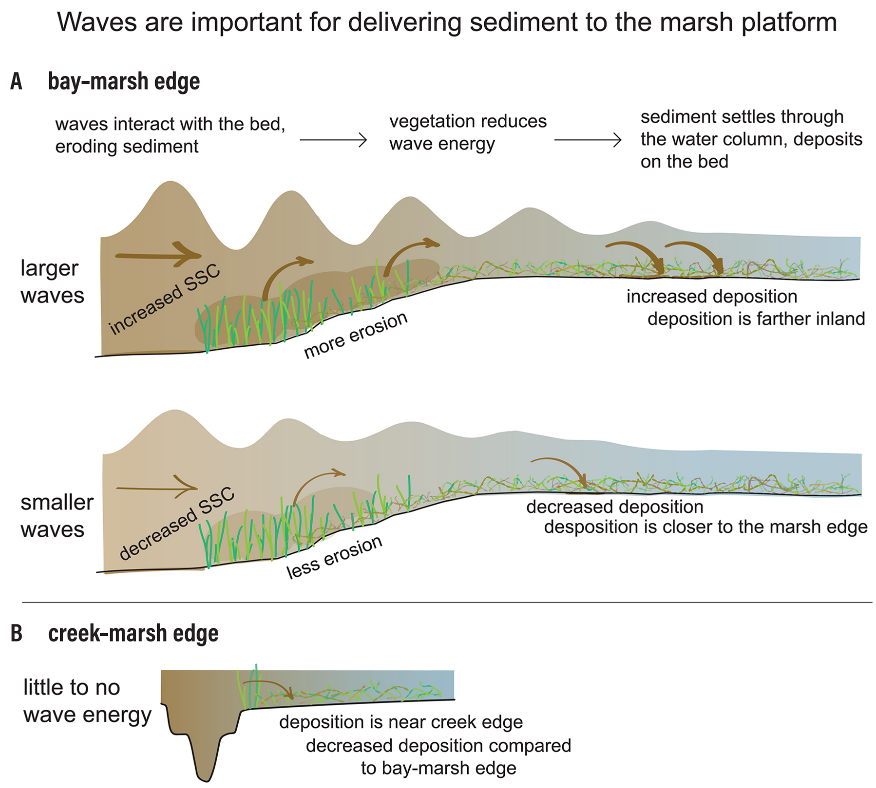


Figure 8 Processes responsible for moving sediment onto the marsh platform for conditions (**A**) across the bay–marsh edge with larger waves (*top*), across the bay–marsh edge with smaller waves (*bottom*), and (**B**) across the creek–marsh edge. Vegetation depictions represent conditions in the summer when stems and leaves are most robust.

and consequently capturing sediment through deposition to the marsh surface. When the tide drops, you can see residual sediment coating the plant stems (Figure 7). During the next flood tide, that fine-grained sediment in the lower marsh is easily re-suspended, increasing the amount of sediment available for transport to the marsh platform. Our *in situ* measurements during summer show that SSC is greater landward of this lower marsh vegetation, indicating that it is a source of sediment. In contrast, during winter the cordgrass in the lower marsh dies back, leaving only a sparse array of stems that does not trap as much sediment during lower-high tides and therefore cannot boost the delivery of sediment to the marsh platform on the following higher-high tide. Instead, during winter, the measured SSC decreases in the landward direction across the lower marsh during higher-high tides, indicating deposition in this zone rather than the erosion observed during summer.

How do waves and plants interact to affect sediment movement across the bay-marsh edge?

Waves are important for increasing the supply of sediment that reaches the marsh. As described in Conclusion 1, when waves approach the shore and reach shallower water, they interact with the bed, eroding sediment and increasing the SSC. During that process the waves are damped by **bottom friction**, also known as bottom (or bed) roughness. Plants in the lower marsh also damp the passing waves, particularly as water rises during the early stages of a flood tide. During the highest tides when the marsh platform is under water, vegetation in the lower marsh does little to reduce the wave energy because it is too deeply inundated; during those times, the lower marsh becomes a source of sediment for the higher marsh platform.

How do waves affect delivery of sediment onto the marsh platform?

Waves increase the sediment supply and carry sediment farther onto the marsh platform. On the marsh platform above the bay–marsh edge, pickleweed (*Salicornia pacifica*) occupies a large portion of the water above the marsh and effectively eliminates wave energy over relatively short distances (further discussed in Conclusion 4). Without wave energy, gravity and tidal currents are the main drivers of sediment movement, as shown in Figure 5. But with increased wave energy, the same basic processes that regulate how sediment is deposited are amplified and pushed further landward across the marsh platform (Figure 8A). Incoming SSC and erosion in the lower marsh also are increased, leading to more sediment being available to be deposited. In addition, larger waves penetrate farther into the marsh before dissipating, further increasing the sediment being deposited across the marsh platform.

The creek–marsh edge is protected from waves, and we see less deposition compared to the bay–marsh edge. Since there is little to no wave energy to carry sediment farther onto the marsh platform, more deposition occurs close to the creek edge in a narrower band than along the bay–marsh edge (Figure 8B). These dynamics lead to less accretion (millimeters per year) along the creek–marsh edge, and 4-year measurements showed the maximum accretion was about half as much along the creek–marsh edge as the bay–marsh edge.

Our field studies did not include the uppermost portions of the marsh platform, where wave energy is negligible and where only weak currents during flood tides can redistribute sediment through the pickleweed farther into the marsh. However, the periodic pulses of sediment delivery associated with waves in the lower marsh likely translate to gradual deposition across the high marsh platform, as subsequent higher-high tides flood the marsh to varying degrees, repeatedly re-suspending and re-distributing small amounts of sediment.

How does deposition of sediment on the marsh vary between wavy and calm conditions?

Deposition of sediment on the marsh platform near the bay–marsh edge was about 16 times greater during wavy conditions than calm conditions. Here, we define wave conditions by the wave height on the mudflat about 50 m (164 ft) from the marsh edge: “wavy” is greater than 0.06 m (2.4 in), and “calm” is less than 0.025 m (< 1 in). Although erosion in the lower marsh was also greater during wavy conditions, the re-suspension of that sediment did not account for all additional deposition on the marsh platform. At most, the bay–marsh edge supplies the marsh platform with about one-third of the sediment deposited there. The other two-thirds are supplied by suspended sediment in the shallows that is transported onto the marsh during flood tides, or from within marsh re-suspension as water flows across the marsh platform.

During what seasons does China Camp marsh experience wavy vs. calm conditions?

In summer, consistent afternoon winds in the bay generate wavy conditions in the shallows. The winter does not have this daily pattern; rather, occasional storms (lasting 1 to 4 days) generate the largest waves of the year, separated by calm periods. Our results suggest that the moderately-windy summer conditions are the largest overall contributor to sediment being deposited on the marsh platform, responsible for about one-half of the annual total. Winter storms were the second-largest contributor, responsible for about one-third of the annual total. However, it is important to note that our field studies occurred during a relatively dry winter (2014–2015). In stormier winters, the relative importance of deposition during winter storms is likely greater. In addition, an increase in sediment deposition on salt marshes during the months that follow wet winters has been observed in the estuary (Thorne et al. 2022).

Are there other sources of sediment entering China Camp marsh?

Our field studies were focused on mineral sediment from the bay reaching the marsh platform, but there are other processes important for marsh accretion. In addition to belowground peat accumulation and sediment transport into marshes through tidal creeks (discussed in Conclusion 3), local upland watersheds can supply sediment. The importance of local upland sources of sediment around the estuary varies considerably, but channelization and diking have disconnected many marshes from local watersheds. At China Camp marsh, very little sediment enters the marsh from the adjacent uplands, and no overground flows enter the marsh except during extreme rainfall events. These processes are beyond the scope of this review but are likely important to other marshes in the estuary (Dusterhoff et al. 2021).

Considerations for Managers

Conserving sloped bay–marsh edges can help facilitate sediment delivery and thus salt marsh sustainability. This benefit should be balanced against the benefits of creating areas that are not often or deeply inundated as high-tide refugia for wildlife and accommodation space as sea level continues to rise. Waves in the bay shallows are important for re-suspending sediment, which increases the supply of sediment available to the marsh, and for delivering sediment across the bay–marsh edge to the marsh platform. While waves can be erosive, they can also contribute to maintaining a healthy salt marsh.

- **Conclusion 2A – *Consider local wave conditions.*** When selecting a site for marsh restoration or when designing an intervention to increase marsh sustainability, it is important to consider wave conditions. High wave energy can lead to marsh loss through edge erosion. Features or management actions that reduce wave energy are often seen as positive, because they can lead to less erosion, but because waves can be important for delivering sediment, the greater context of the physical processes at work within a given salt marsh should also be examined. Fringing marshes with little or no marsh platform between the bay shallows and uplands may not reduce waves enough to protect adjacent uplands (refer to Conclusion 4), so trade-offs between the various effects of waves could be different for those marshes.

- **Conclusion 2B – *Maintain or increase vegetation in the lower marsh where possible.*** Vegetation in the lower marsh and potentially also in bay shallows (e.g., seagrass) can be an important feature to trap suspended sediment and subsequently deliver that sediment to the marsh platform, as well as providing other ecosystem benefits such as wave attenuation and food-web support. However, too much wave attenuation (e.g., from breakwaters or the like) in bay shallows adjacent to the marsh could limit the effectiveness of wave re-suspension of sediment in the lower marsh; ultimately, reducing the delivery of sediment to the marsh platform during higher-high tides would be counter-productive to the goal of marsh sustainability.

- **Conclusion 2C – *Characterize a broad range of physical conditions and processes.*** Physical attributes that affect the transport and deposition of sediment on salt marshes include marsh width, elevation profile of the marsh, temporal and spatial variability of incoming wave energy, and wave attenuation and amplification mechanisms. When assessing the importance of waves and low marsh vegetation in site-level sediment dynamics, consider the following questions:

  - *Is there sufficient wave energy to increase the SSC in flood-tide water (i.e., in surface waters during high tide)?*

  - *Would the proposed project reduce wave energy and thereby the SSC in flood-tide water (i.e., adding wave barriers, large stones, etc.)?*

  - *To what extent is wave energy reduced across the bay–marsh edge? How does that energy reduction change over the course of a tidal cycle?*

  - *What are the typical water levels when waves are the largest (i.e., which part of the marsh do waves influence)?*

  - *Is marsh inundation conducive to suspended sediment settling on the marsh platform (e.g., is there sufficient time, considering particle-settling velocities)?*

- *With increased inundation from SLR, how might the previous responses change?*

Conclusion 3. Tidal Creeks May Not Always Import Sediment to the Marsh Platform

What makes a creek a tidal creek, and why are tidal creeks important for transport of sediment?

If the flow direction within a creek changes with the reversing tide, it is considered a tidal creek. The tidal creeks at China Camp marsh contain little to no water at low tide and can overflow their banks during large high tides. Tidal creeks are important for transporting sediment because they provide a connection between the bay and the marsh platform (extending as far as the uplands), that conveys sediment and water, and allows for drainage.

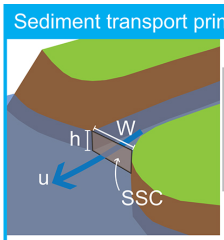
Do tidal creeks import sediment to marshes?

Sometimes yes, but not always. **Net sediment exchange** is gauged by measuring the suspended sediment flux at the creek mouth (Figure 9). If more sediment is imported through a tidal creek during flood tides than is exported during ebb tides, that creek provides a net import of sediment for that tidal cycle. At China Camp marsh, we observed both net import and net export events. During extreme (spring) tides and storm events, tidal creeks exported large quantities of sediment. Sediment import was observed during small (neap) tides and during moderate tides if conditions were wavy (wave heights >0.10 m [0.33 ft] offshore), but overall, this import of sediment was less than the export during the larger spring tides that we measured.

Does net sediment export from creeks indicate the marsh platform is eroding?

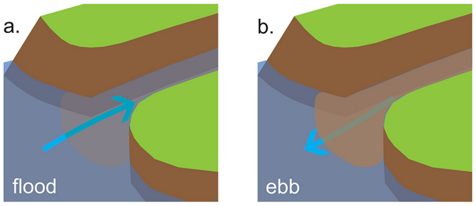
No, creek export does not necessarily constitute erosion of the marsh platform. The fast velocities at the times of maximum export indicate that the source of sediment was likely the creek bed and not the marsh platform. The same high tides that export large quantities of sediment may also generate the most deposition on the marsh platform as a result of the extended inundation. With our data from China Camp marsh, we could not determine whether this was the case.

Sediment transport primer



suspended sediment flux at the creek mouth is a product of the water depth (h), creek width (W), flow velocity (u), and suspended sediment concentration (SSC)

Suspended sediment flux (SSF) is the rate of sediment mass entering (positive flux) or exiting (negative flux) at a given cross-section in the creek. Flux is a measure of the movement of anything through a defined area per unit time (i.e., a rate). Flux is used in a wide range of applications, and here, we calculate sediment flux, particularly suspended sediment flux (SSF) in tidal creeks. Adding up the product SSF and the sampling interval (Δt) over a longer time yields cumulative, or net, SSF. If we gather data over multiple tidal cycles, we can determine the tidally averaged SSF.



Two primary processes driving SSF are advection and dispersion. Advection is transport by the mean or tidally averaged flow. In **a**. and **b**. above, the same amount of water moves landward on flood as bayward on ebb, but more sediment is transported out on ebb than in on flood. Therefore, advective SSF is zero, but the dispersive SSF is bayward. Dispersion is responsible for the tidally-averaged sediment transport. In tidal systems, where tidal currents are much greater than the tidal average, dispersive transport can be very important.

Figure 9 Sediment transport primer on suspended-sediment flux

However, a conceptual model that supports this idea is that creek beds may serve as a temporary reservoir for sediment carried in during small or moderate tides. This sediment is then mobilized during extreme tides, with some of the mobilized sediment carried onto the marsh platform, and some exported to the bay. As noted, the marsh at China Camp is accreting over time, implying: (1) there are other pathways besides creeks for sediment import (i.e., bay–marsh edge); (2) there are enough moderate tides with wavy conditions during other times of the year; (3) sediment flux in the creek cannot be equated with delivery to the marsh platform in this system; or (4) some combination of these factors. Additional instrumentation on the marsh platform could further quantify these pathways.

Do waves influence how much sediment tidal creeks deliver to the marsh?

Yes, even though the creek–marsh edge is not exposed to waves except at the lowest point where creeks cross the bay–marsh edge (Figure 3), waves increase SSC in bay shallows, which are source waters for tidal creeks during flood tides. If a tide is large enough to overflow the creek's banks, then greater SSC during flood tide means more sediment that can be deposited on the marsh platform.

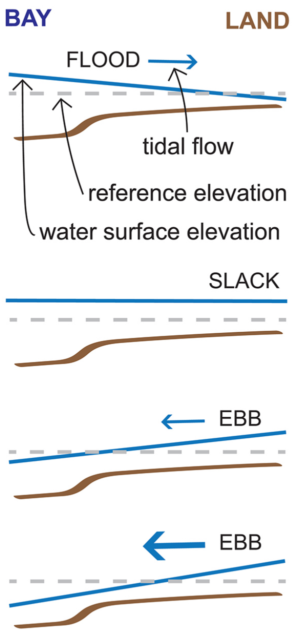
There is less opportunity to erode sediment across the marsh–creek edge because there is little to no wave action and since the transition from creek to marsh platform is abrupt, rather than the gradual slope found along the bay–marsh edge. Erosion of the creek bed certainly occurs during periods of fast flow, and periodic slumping of creek banks could also exacerbate erosion within creeks throughout the marsh platform, but waves have little to no effect on those processes.

Why does the size of the tide affect transport of sediment in tidal creeks?

Large tides (i.e., spring tides and some higher-high tides) and small tides (i.e., neap tides and lower-high tides) have contrasting sediment outcomes because they interact with the marsh platform differently. Small tides stay confined to the creek banks, and the velocity stays relatively constant as the water level increases (Figure 11A). For moderate and extreme tides, the creeks overtop their banks as the tide rises, and things get much more interesting (Figures 12 and 13). When the creek banks overtop, the velocity suddenly increases as the water is not confined by the banks and spills over on to the marsh platform (Figure 12B and Figure 13B). The velocity continues to increase until the water level reaches its peak at high tide, at which point the velocity slows before reversing direction.

For small tides, the process during ebb tide is the same as during flood tide with a near constant velocity as the water drains back into the bay (Figure 11B). For moderate and extreme tides, velocity continuously increases as the marsh and creek drain (Figure 12D and 13D). The creek

Sediment transport primer



Water surface elevation (WSE) is the elevation of the water surface, typically referenced to NAVD88. If the surface elevation changes over space, then there is a slope, or gradient, in the WSE. The WSE gradient drives flow downslope.

On flood tide, the WSE gradient drives water inland, as the tide rises more quickly in the deeper water of the bay.

At high slack, there is no gradient, and the water surface is flat. The flow stops as the tide changes direction.

On ebb tide, the WSE gradient drives water bayward, as the bayward end is lower than the landward end. A steeper WSE gradient drives faster flow (higher current speed).

The WSE gradients in the estuary can't be seen by eye (unlike in rivers) and are exaggerated in the diagrams shown here. A vertical change of 0.01 mm for every horizontal meter (or 0.0001 in per ft) typically drives maximum tidal currents in the bay. During extreme tides, the ebb WSE gradient reached 1.3 mm per meter between the creek and the bay (130 times greater!).

Figure 10 Sediment transport primer on water surface elevation gradient

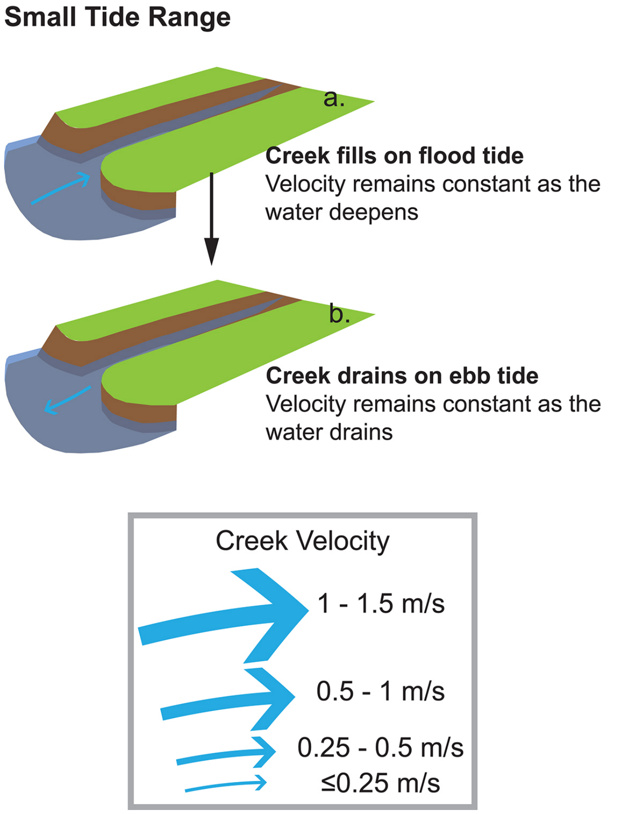


Figure 11 Water flux through a tidal creek with a small tide range during (**A**) a flood tide and (**B**) an ebb tide. Creek velocity legend also applies to Figures 12 and 13.

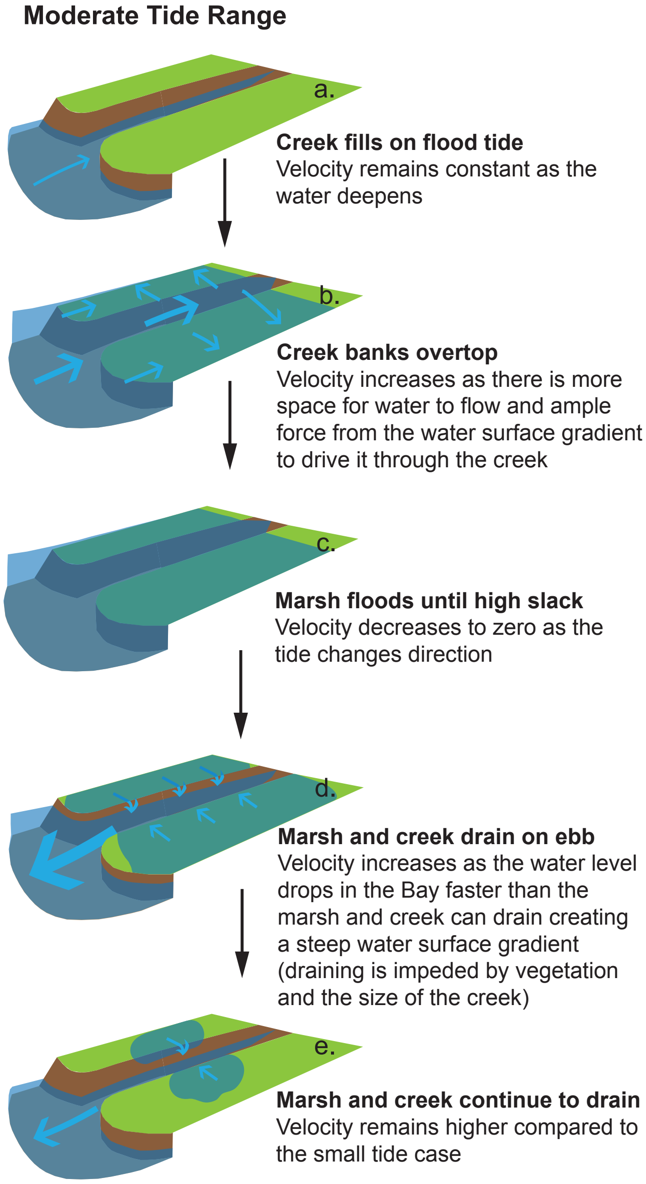


Figure 12 Water flux through a tidal creek with a moderate tide range and creek overtopping. *Velocity arrows* in the creek correspond to the legend in Figure 11.

velocity during ebb tides is much faster than during flood tides because the water surface elevation gradient is steeper (Figure 10). At China Camp marsh, we also find that some of the water that enters the marsh over the bay–marsh edge exits via the creek. We do not see this imbalance for small tides, when creek banks do not overtop.

Why is the water surface elevation gradient steeper during ebb tides after the creek banks overtop?

The water surface elevation gradient is steeper for two reasons. First, the vegetation on the marsh platform causes drag on the water that flows off the marsh. This drag keeps the landward water surface somewhat steady while the bayward end continues to drop with the ebbing tide, increasing the gradient between them. Second, the creek banks restrict the water flow. This process is the reverse of what happens when the creek banks overtop. As ebb tide begins, the water cannot drain fast enough and piles up in the creek, again causing the landward surface to be somewhat steady while the bayward end continues to drop. The peak velocity is reached when the water surface elevation gradient is the steepest, which is when the water surface is below the creek banks, but water is still draining off the marsh platform. For extreme tides, the ebb-tide water surface elevation gradient is even steeper because in the bay the higher high-tide always occurs before

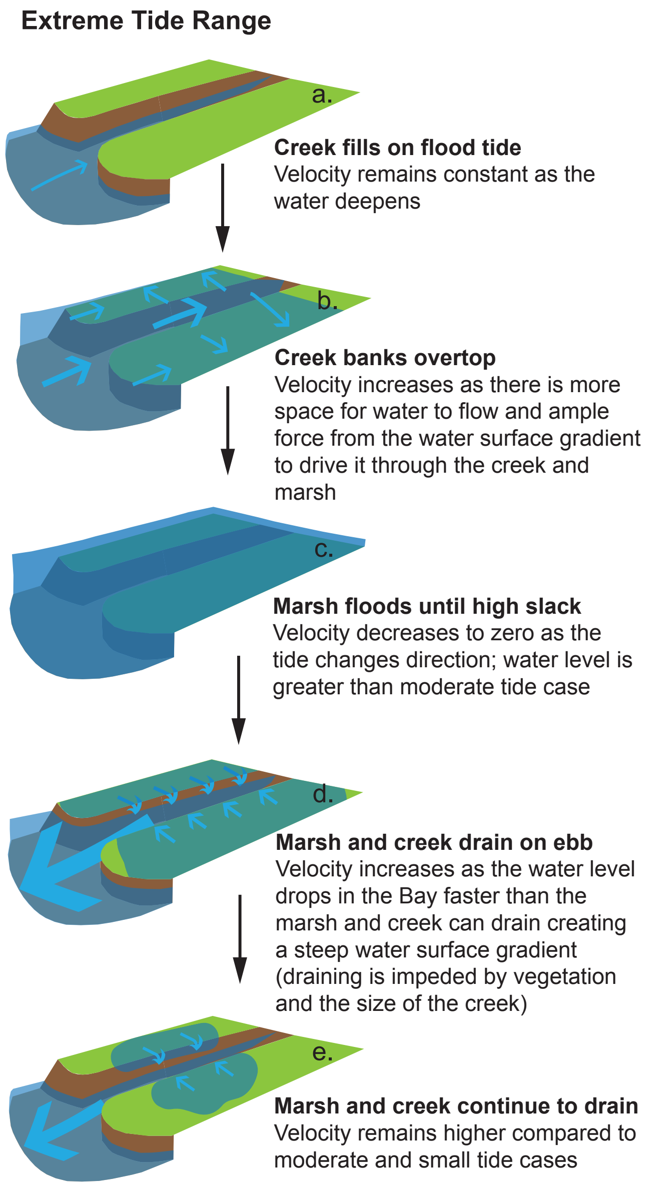


Figure 13 Water flux through a tidal creek with an extreme tide range and creek overtopping. *Velocity arrows* in the creek correspond to the legend in Figure 11.

lower low-water; the water surface gradient is enhanced by the bayward end changing faster than it does during more moderate tides.

How much faster are creek velocities during ebb tides than during flood tides?

For extreme tides, peak ebb velocity is about three times as fast as flood velocity (Figure 13D), and for moderate tides, it is about twice as fast (Figure 12D); these velocities are called "**ebb-dominant**." During small tides without creek overtopping, there is little to no ebb-dominance, and velocities are about the same during flood and ebb tides.

What Does the Ebb-Dominance Mean for Tidally Averaged Sediment Export from Creeks?

For extreme tides, faster ebb velocities move much more water and sediment out of creek mouths than is brought in by the slower flood velocities, leading to net export. Recall that velocity sets the sediment flux direction, and the SSC, velocity, and water level determine the flux magnitude in the creek (Figure 9). Fast ebb velocities increase both the **advective** and **dispersive flux**: the tidally averaged current is negative (advective) and the SSC is greater during ebb than flood (dispersive) because increased bed shear stress erodes sediment from the creek (Figure 9).

Doesn't more inundation lead to more sedimentation?

In general, yes, but additional factors influence sedimentation. As the tide changes, the water in the creek slows to a stop and reverses direction. This period of slow currents when sedimentation is maximized lasts longer if the tides are smaller than extreme tides. For example, the creek velocity is slower than 0.1 m s^{-}1 (in either direction) for about 2.5 hours on a small high slack tide, compared to only 20 minutes on an extreme high slack tide. Even though these measurements are in the creek, they indicate movement throughout the marsh–creek system. The shorter duration at low velocities means less time with conditions favorable for sedimentation.

When do tidal creeks import sediment?

We measured net sediment import during moderate tides and small tides with wavy conditions (Figure 14). Moderate tides on wavy days are the "Goldilocks" combination: the waves on the mudflat increase the SSC imported on the flood; the tide is large enough to get water to the marsh platform, but the water level is low enough that ebb velocities are not extremely high. This combination—high SSC during flood tides and moderate velocities during ebb tides—leads to net sediment import via creeks.

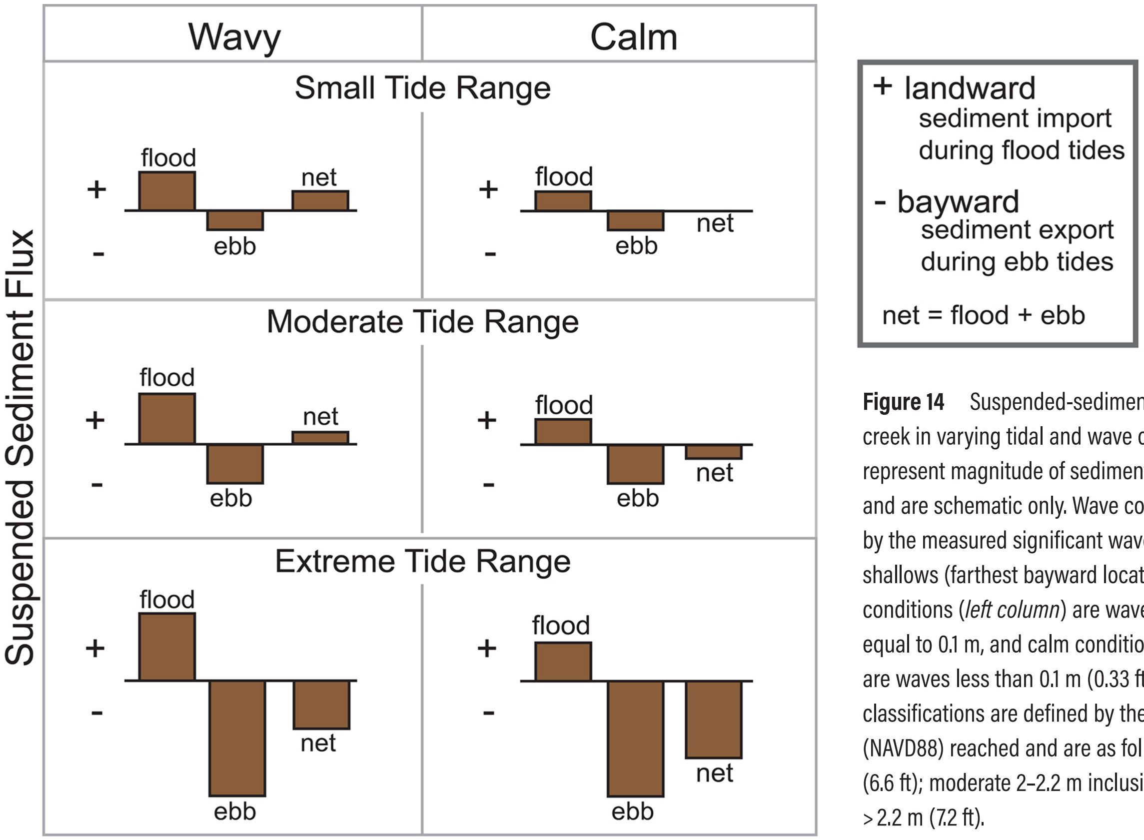


Figure 14 Suspended-sediment flux through a tidal creek in varying tidal and wave conditions. *Brown bars* represent magnitude of sediment flux to the marsh and are schematic only. Wave conditions are defined by the measured significant wave height in the bay shallows (farthest bayward location in Figure 6). Wavy conditions (*left column*) are waves greater than or equal to 0.1 m, and calm conditions (*right column*) are waves less than 0.1 m (0.33 ft). The tide range classifications are defined by the maximum elevation (NAVD88) reached and are as follows: small < 2 m (6.6 ft); moderate 2–2.2 m inclusive; and extreme > 2.2 m (7.2 ft).

of the creek over the full measurement period was greater than the import. This outcome was true for all four datasets used here, suggesting that sediment import across the bay–marsh edge likely provides a critical contribution to overall deposition and accretion across the marsh platform. However, our data-collection periods were chosen to coincide with the largest tides of the year, which the data show are the times of greatest creek export. Import during periods of weaker tides may compensate for some of the export.

How might delivery of sediment through creeks change with storm conditions or accelerated SLR?
The storm events during our study indicated that storm surge acts similarly to large tides, increasing tidally averaged export from the creek. SLR will affect multiple elements of the system, including vegetation patterns, making it difficult to isolate and predict effects to one process. However, increased water levels likely will lead to additional creek bank overtopping, which would increase the ebb-dominance and conditions for increased sediment export.

How can we increase the import of sediment via creeks?
The SSC in the flood water depends on the conditions on the mudflat. For example, if there are waves, the SSC that enters the creek is higher than with calm conditions. Sediment import should increase with higher amounts of sediment in the water during flood tides, arguing against the addition of structures that reduce wave action over the mudflat.

Does the ebb-dominance in creeks change with season?
No, not appreciably. While there is some cordgrass on the creek bank fringes that dies back in the winter, pickleweed is the vegetation that plays a dominant role in this process on the marsh platform. Pickleweed retains biomass year-round, removing seasonal influence from this process.

Considerations for Managers

Tidal creeks both import and export sediment. Measuring SSC or SSC flux in a tidal creek may not give an accurate picture of the sediment supply to the marsh platform, and sediment may be delivered through other pathways. Understanding these delivery dynamics at the site level is needed to guide approaches to augmenting sediment.

- **Conclusion 3A – Consider all possible sediment pathways to the marsh platform.** Concentrations of suspended sediment in tidal creeks are not always accurate proxies for understanding sedimentation on the marsh platform, particularly when that platform is broad and adjacent to open water such as at the China Camp marsh. Tidally averaged suspended sediment flux through creeks is more informative, but all pathways to the marsh should be considered when sediment budgets are assessed.

- **Conclusion 3B – Repeated observations and long-term monitoring are key.** Creek suspended sediment flux varies seasonally (i.e., summer and winter) and over the spring-neap tidal cycle and is affected by episodic events. Short-term measurements can lead to inaccurate conclusions on amounts of sediment being imported or exported through tidal creeks and misinform strategies to augment sediment. At China Camp marsh, large spring tides generate high creek velocities during ebb, causing a net export of sediment.

- **Conclusion 3C – Sediment-augmentation strategies should leverage times of creek import.** With the goal of making marshes more resilient to SLR, augmenting sediment is one intervention under consideration. Multiple options have been considered: depositing sediment on the marsh (thin or thick layer placement), in adjacent shallows, or near tidal creeks, and the optimal approach will vary depending on marsh conditions and context. Increasing the sediment supply in source waters is key, and, to maximize the likelihood that augmented sediment will be transported to and remain in the marsh, sediment-augmentation plans can take advantage of the times (i.e., season and spring-neap tidal cycle) when sediment import currently occurs. At China Camp marsh, moderate tides would be best, when the marsh is inundated but creek ebb velocities are lower. Augmenting sediment during periods of extreme tides could be ineffective, because tidal creeks export sediment at these times.

Conclusion 4. Protective Effects of Marsh Vegetation Depend on Species and Season

Why are marshes considered a natural form of coastal protection?

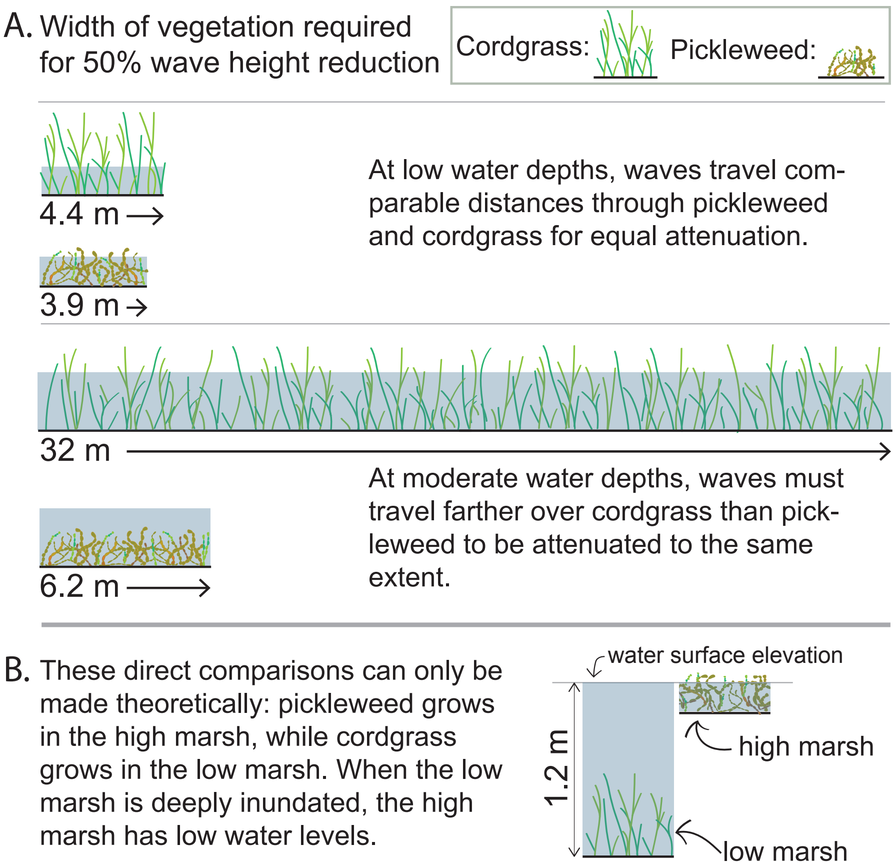
When waves and tidal currents travel over or through marsh vegetation, they lose energy. Compared to shorelines with no buffering marsh, areas upslope of marshes are exposed to smaller, less damaging waves and are inundated for shorter periods as a result of decreased wave run-up and the permeability of marsh soils. Reducing wave energy also creates conditions conducive to sediment deposition, as described in Conclusion 2.

Is wave attenuation an important consideration in bay marshes?

Yes, salt marshes along the bay's margins are exposed to waves—some more than others—and attenuate wave energy over relatively short distances (i.e., tens of meters). The typical species that interact with waves are cordgrass (*Spartina foliosa*) in the low marsh and pickleweed (*Salicornia pacifica*) in the high marsh (marsh platform).

Do all marshes provide the same wave attenuation?

No, the amount of energy reduction—or wave attenuation—within marshes is far from constant. The same marsh can attenuate waves to a different degree depending on vegetation, environmental, and hydrodynamic factors. Wave reduction has been measured directly in the field, in laboratory studies by vegetation (real or fake) being put in flumes, and via hydrodynamic numerical modeling. Broadly speaking, wave attenuation increases with the portion of the water depth occupied by vegetation (i.e., the


A. Width of vegetation required for 50% wave height reduction

At low water depths, waves travel comparable distances through pickleweed and cordgrass for equal attenuation.

At moderate water depths, waves must travel farther over cordgrass than pickleweed to be attenuated to the same extent.

B. These direct comparisons can only be made theoretically: pickleweed grows in the high marsh, while cordgrass grows in the low marsh. When the low marsh is deeply inundated, the high marsh has low water levels.

Figure 15 (**A**) Comparisons of distance to complete wave attenuation for waves moving over pickleweed and cordgrass at low and moderate water levels. (**B**) Illustration of inundation levels that occur simultaneously at China Camp marsh. Values and depictions reflect summer conditions.

fake) being put in flumes, and via hydrodynamic numerical modeling. Broadly speaking, wave attenuation increases with the portion of the water depth occupied by vegetation (i.e., the more vegetation in the water, the more waves are attenuated). Vegetation factors include species traits, such as stiffness and the stem width, height, density (number of stems per area), and branching pattern. For example, the amount of attenuation is different if the stems are concentrated on one part of the plant or evenly distributed. Environmental factors could be anything that affects the health and growth of the vegetation, such as the season, excessive water logging, or grazing, with less biomass leading to less attenuation. Hydrodynamic factors include the water depth relative to vegetation height as well as wave characteristics, including height and period. The same patch of vegetation attenuates wave energy to a different degree depending on inundation depth, which varies almost continuously with the tidal cycle. Deeply submerged vegetation will affect waves less than emergent vegetation.

Which species is more effective in attenuating wave energy: cordgrass or pickleweed?

During high tide conditions in the bay, pickleweed is highly effective in attenuating waves, much more so than cordgrass. The differences between them largely depend on the season and the level of inundation. The season matters because the species have different seasonal signals: cordgrass dies back in the winter, with a corresponding decrease in the wave reduction; pickleweed retains the majority of its biomass year-round. The level of inundation matters for two reasons: the species have different vertical structures, and they occupy different elevations of the marsh (discussed further below). Measurements were taken at China Camp marsh to examine how wave heights changed as waves passed through cordgrass and pickleweed in the summer and the winter. Example results from the summer measurements are shown in Figure 15.

inundation levels. Cordgrass has a vertical stem (typically about 0.5 m [1.6 ft] tall) with highly flexible leaves that reach up to 0.75 m (2.5 ft). Pickleweed is highly branched and has a dense mat of stems closer to the bed (height typically 0.25 m [0.8 ft], up to 0.5 m [1.6 ft]). For low-inundation conditions (water depth of 0.2 m [0.65 ft]), the wave height reduction in cordgrass and pickleweed are comparable, and a wave would need to travel over about 4 m (13 ft) of either species for the wave height to be reduced by 50% (Figure 15). At this low depth, the bottom friction—or bottom roughness—that the bed provides also plays a role in reducing wave energy. With about 0.4 m (1.3 ft) of inundation, there is a difference between the species, and pickleweed reduces wave height more effectively. Much of the cordgrass is still emergent (sticking out of the water) at this inundation level, but since pickleweed is more densely packed over a shorter height, it occupies more of the water above the marsh surface compared to cordgrass. A wave would need to travel about 5 times as far over cordgrass as pickleweed for a 50% wave-height reduction.

Why is there no example given for a high-inundation scenario?

Our measurements do not allow us to compare the species for deeper inundation scenarios beyond a water depth of 0.4 m (1.3 ft). The field measurements took place during the largest tides of the year when water levels were at their highest, but since pickleweed grows higher in the tidal frame, it always spanned at least half of the water depth above the marsh. The bottom panel (Figure 15) shows the inundation levels that occur simultaneously, emphasizing the different conditions vegetation experiences in the low and high marsh.

We can see from the measurements in cordgrass that as the inundation exceeds the vegetation's height, the attenuation capacity quickly decreases. For example, if the water was about 2.5 times deeper than the cordgrass height, up to about 2 km (1.2 mile) would be required to reach the same 50% reduction in wave height. Based on equations for wave attenuation through vegetation, attenuation in pickleweed would also decrease significantly if inundated to that extent.

The other diagrams depict the lower marsh as sloped and the marsh platform as flat. How does that affect the results?

The cordgrass zone at China Camp marsh is sloped, meaning the bayward end is more inundated and the landward end is less inundated. The values discussed above are the results for the average depth across the zone. A sloped bed attenuates waves even without vegetation; a more steeply sloped bed attenuates waves faster. The elevation of the marsh platform is about flat, so the inundation conditions represent the entire pickleweed zone. This difference is site-specific, but it is important to consider when examining the variability in measurements around the bay or when selecting a location for future studies.

Why is a 50% wave-height reduction shown, rather than a wave height?

A range of wave heights was measured during the two study periods. The largest waves at the offshore station (Figure 1) were 30 cm (0.65 ft). Presenting the results as a percent reduction allows for the range of wave data collected to be presented together.

The measured waves seem small. Are marshes effective with larger, more destructive waves?

While we do not have direct measurements of larger waves, the data from China Camp marsh were used to calibrate a numerical model of wave processes (Taylor–Burns et al. 2023). With this calibrated model, researchers were able to explore the effect of marsh vegetation under a range of future conditions, including extremes. These modeling results show that marsh vegetation can meaningfully reduce wave heights and wave run-up (i.e., the sum of **swash** and wave set-up). For example, they studied conditions for a 100-yr storm in the bay with wave heights of 1.5 m (4.9 ft) and inundation of 1.15 m (3.8 ft) above the average MHHW. Having a marsh 50 m (55 yd) wide reduced the run-up by about 65%.

https://doi.org/10.15447/sfews.2025v23iss2art6

What changes can we expect with future SLR?

As the rate of SLR increases and exceeds the rate of vertical marsh accretion, marshes will be inundated more deeply and more often, requiring wider marshes (distance between upland and marsh edge) to achieve current levels of wave-height reduction. Waterlogged conditions can adversely affect the health of the vegetation, reducing the biomass, which will further diminish the capacity to reduce wave height. Sustained deeper inundation from SLR also will lead to shifts in vegetation; areas now covered in pickleweed will likely be converted to cordgrass, and cordgrass will be converted to unvegetated mudflats. If vegetation dies, less sediment will be trapped, and the marsh may begin to erode.

Considerations for Managers

Marshes protect upland areas by attenuating wave energy. While the level of attenuation is not constant, general principles apply: there is a greater reduction in wave height when more of the water depth is occupied by vegetation. Although wide expanses of marsh (tens to hundreds of meters or yards) provide higher likelihood that waves will completely die out, our results show that relatively narrow expanses of pickleweed are effective, reducing wave height by 50% over less than 10 m under current inundation levels. Marshes can be effective components in nature-based coastal protection strategies.

- **Conclusion 4A – Target native species that thrive at planted elevations.** When restoring or creating a marsh, vegetation should be planted at the elevations at which it naturally occurs. For example, planting pickleweed in the low marsh because it is effective in reducing wave energy is misguided, because the pickleweed will not be able to produce as much biomass under low marsh conditions. Greater biomass, occupying a larger portion of the water on the marsh, is more effective at reducing the energy of passing waves. While habitat typically dictates the type and density of vegetation, observations of the vertical structure and which parts interact with incoming waves are helpful to understanding how effectively the vegetation will attenuate waves under varying inundation conditions.

- **Conclusion 4B – Consider that waves also deliver sediment to the marsh platform.** As discussed in Conclusion 2, waves are important for increasing the amount of sediment available to the marsh and delivering it to the marsh platform. Deposition occurs once the wave energy dissipates, as greater sedimentation was observed in areas that coincided with complete wave attenuation. When designing with the aim of coastal protection, prioritizing immediate and complete attenuation of wave energy to the exclusion of sedimentation could negatively affect marshes. A balance between allowing waves to deliver sediment to larger expanses of marsh, and reducing their energy to allow sediment to be deposited and the coast to be protected, could help maintain healthy coastal marshes

- **Conclusion 4C – Marsh design should consider how SLR affects wave attenuation.** With greater daily inundation from SLR and the possibility of storm surge, wider expanses of marsh will be needed to achieve the desired reduction in wave energy. Marshes are key components of horizontal levees and other nature-based solutions to coastal protection, and current measurements may over-predict the amount of wave attenuation these projects will provide in the future, given rising seas. Modeling future conditions is key to properly sizing the width and elevation needed.

NEXT STEPS

We undertook this science translation project at the encouragement of the management community that is committed to conserving and restoring tidal salt marshes at a time when those marshes are dually challenged by rising sea levels and the decreasing availability of sediment (Dusterhoff et al. 2021). Published studies of physical processes at China Camp marsh reveal the importance of sediment derived from bay shallows, transport across the bay–marsh edge, bi-directional transport within tidal creeks, and variable influences of marsh vegetation on marsh sedimentation. Monitoring physical conditions and processes at China Camp marsh will continue, because that work supports efforts by California State Parks to adaptively manage the site under future hydrodynamic and sediment regimes.

While the physical processes discussed here are relevant to other salt marshes around the estuary, the details of how a particular site receives and responds to inputs of inorganic sediment will vary. Sediment management and marsh sustainability actions should be informed by a combination of empirical science and collaborative stake-holder engagement at both regional and local (site) scales. Not all marshes in the estuary exhibit the key features of China Camp marsh— such as the extensive high-elevation marsh platform and the broad transition zone along the bay–marsh edge—and all sites are best understood in the context of their own geographic setting and the local processes that drive deposition and erosion. New research that builds on the studies summarized in this paper is currently underway at other locations around the estuary, and as additional challenges and management priorities arise, more studies will be needed to guide appropriate conservation, restoration, and enhancement actions.

Collaboration between coastal decision-makers responsible for tidal salt marsh conservation and/or sediment management and stake-holders will strengthen the development of place-based sediment-management strategies as described in the *Sediment for Survival* report (Dusterhoff et al. 2021). That type of deliberate approach could facilitate understanding of sediment supply and demand within the context of appropriate scales of watershed and estuarine dynamics, increase public support, and enable timely and effective action by regulators, funders, land-owners, and others. Such an approach would also benefit future sediment-management decisions at China Camp marsh, for example incorporating information and input from agencies and stake-holders throughout the Gallinas Creek "**operational landscape unit**" (SFEI and SPUR 2019).

Long-term environmental monitoring is a critical component of informed and effective natural-resource management, especially in highly dynamic systems such as tidal salt marshes, which can only survive within a narrow elevation range relative to mean sea level. Both subtle and sudden changes in the interplay between marsh flooding, draining, subsidence, and sediment accretion can determine whether a marsh will, over time, survive or drown. The San Francisco Estuary Wetland Regional Monitoring Program (WRMP) is poised to fill this need in the lower estuary with its focus on evaluating tidal marsh-restoration projects in comparison with nearby reference sites and regional benchmark sites (WRMP Steering Committee 2020). Data collection at these saline and brackish sites will include long-term measurements of water levels, rates of sediment erosion and deposition, and changes in marsh elevation. Additional special studies and research projects will leverage these data to address a variety of prioritized questions and regional challenges (McKee et al. 2020; Dusterhoff et al. 2021). Long-term monitoring of SSCs at key locations in bay shallows could also help gauge the availability of sediment for marsh restoration and conservation as land use, sea level, and climate continue to change. The community's collective commitment to supporting management-relevant science through initiatives such as the WRMP will strengthen our ability to manage estuarine resources in the face of numerous stressors and during this period of unprecedented rates of environmental change.

ACKNOWLEDGMENTS

This project and resulting monograph would not have been possible without the experienced perspectives of Aimee Good and Rosa Schneider, as well as the dedicated group of project collaborators and volunteers including G. Archbald, J. Beagle, M. Busnardo, J. Collins, M. Downing–Kunz, S. Dusterhoff, A. Farres, X. Fernandez, D. Halsing, J. Kelly, J. Krause, D. Kunz, R. Leventhal, J. Lowe, A. Lydon, F. Malamud–

Roam, S. McGill, J. Meisler, S. Olsson, M. Orr, J. Siu, E. Sloane, P. Soumoy, R. Spenst, C. Thow, C. Toms, D. Trivedi, K. Ward, and A. Weber–Stover. We thank R. Allen, E. Variano, J. Ferreira, and A. O'Neill for critical contributions to the original research publications, and we thank L. Beers, K. Buffington, D. Ceppos, J. Cherry, T. Doherty, A. Engelstad, J. Morris, H. Nutters, C. Sloop, E. Smith, G. Taylor, K. Thorne, M. Vasey, S. Veloz, and M. Woodrey for their insights and involvement in the precursor project that expanded into these studies. We also thank S. Richmond for her original suggestion that we collaborate on this research endeavor at China Camp State Park. This monograph greatly benefitted from the review and comments from R. Allen and two anonymous reviewers. The NOAA/NERRS Science Collaborative provided funding for the collaborative production of this publication (NA19NOS4190058 SUBK00014140). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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