Title

China Camp's race against the tides: Predicting tidal marsh survival through comparison of project sea level rise elevations and sediment accretion rates

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Final Draft

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Abstract

China Camp State Park salt marsh is an ancient, relatively unaltered tidal marsh system threatened by accelerating sea level rise. Marsh morphology is dependent on multiple dynamic variables, making the prediction of marsh morphologic evolution difficult, if not impossible. Within this set of variables, the relationship between the estimated sea level rise and sediment accretion rates is the principal determinant of saltwater tidal marsh form. Isolating these two primary controlling variables and using localized observed and projected data, we created scenarios to evaluate the China Camp State Park tidal marsh system within the context of imminent sea level rise. Evaluating the scenarios derived from these two variables, we recommend removal of barriers to estuarine transgression to aid in the continued evolution and survival of the China Camp tidal marsh.

Introduction

In the past century, mean sea level has risen approximately 8 inches along the California coast (Heberger 2009). Accelerating sea level rise due to global climate change is now projected to result in a rise of 40 to 55 inches by 2100 (CALFED 2007). In addition to higher water elevations, accelerating sea level rise will result in changes to wave action and sediment transport processes, such that entire coastlines could be eroded, expanded, or re-contoured (Williams 2009). Sea level rise will likely enact particularly devastating impacts on coastal tidal marsh systems, dynamic habitats defined and shaped by marine intertidal ranges. Tidal marshes are vertically compressed systems: several distinct zones exist within the elevation range of the diurnal tides (figure 1), which is typically about 6 feet of elevation difference in the San Francisco Bay Area. Due to this very small vertical zone of occupation, tidal marshes are in jeopardy if current sea level rise projections are accurate.

Tidal salt marshes tend to show high levels of flora complexity within their short vertical ranges. On the Pacific Coast of the United States, marsh zones are often defined in intervals of every 2 to 3 feet (or fewer) of elevation, as determined by both inundation periods and subsequently by plant communities at those elevations (figure 2). The lowest zone, the mudflat, is primarily unvegetated except for algal mats and is found at the level of constant cyclical inundation. Bands of Pacific cordgrass (*Spartina foliosa*) occupy the next elevational and vegetative zone. Pickleweed (*Salicornia pacifica*) dominates the marsh plain, found at approximately Mean Higher High Water, but sporadic patches of Pacific cordgrass are also present, and gumplant (*Grindelia stricta*) is found along tidal channel berms within the marsh plain. Above the marsh plain is an upper marsh zone populated by salt grass (*Distichilis spicata*) that is rarely inundated (Faber 1996). The complexity of salt marsh ecosystems is in part driven by the interplay between the distribution of marsh vegetation and the physical processes related to sediment transport. The role of vegetation in marsh plain sediment accumulation lies in its ability to slow water and trap sediment through surface roughness and through the organic inputs provided by its metabolic processes (Williams and Faber 2004).

The rate of sediment build-up in a tidal marsh plain depends on the concentration of suspended sediment brought in by the flood tide, the relative rate of change in sea level elevations, the amount of wind-created wave action, and the rate of organic sediment accreting from vegetative growth and decay (figure 3). In this way, tidal marsh form at any given time is “the expression of the interaction and evolution of hydrologic and geomorphic processes within the estuary” (Williams and Faber 2004). Suspended sediment itself can come from several sources including eroded materials draining to the bay, estuarine circulation causing turbidity, and re-suspension of intertidal mudflats. Each of the aforementioned accretion factors can vary with tidal cycles, storms, and seasonal and climatic effects (Williams and Faber 2004). Because of the number and variability of these defining factors, predicting tidal marsh form with any degree of precision is a nearly impossible task and will be made exponentially more difficult with anticipated global climate changes.

With rapid sea level rise, there are two possible mechanisms for tidal marsh survival; they are independent rather than exclusive and the greatest chance of marsh survival occurs when the two mechanisms proceed simultaneously. The first mechanism is sediment accretion in the marsh plain that occurs at a pace comparable to the rate of sea level rise. Erosion of coastal edges caused by wave action and higher tidal elevations will lead to re-suspension of sediments presently at the water’s edge, such as from existing mudflats, and those newly suspended sediments can then be re-deposited within the marsh plain, leading to higher marsh elevations. The second means of marsh endurance is inland transgression: the marsh moves inland as it occupies newly inundated land areas uphill of the existing marsh plain (figure 4).

Transgression to upland areas is only feasible where the marsh is not bordered by heavily urbanized or otherwise fixed edges and where the topography adjacent to the marsh is gently sloping.

North America's Pacific Coast topography tends to be more steeply sloped where it meets the water than the Atlantic Coast, resulting in coastal squeeze[1] such that the area available for marsh plain is limited by geomorphology (Haltiner 2011). Therefore coastal tidal marshes on the Pacific Coast tend to be fewer than those on North America's Atlantic Coast. Shoreline development has further reduced or eliminated Pacific Coast marshes, making the small number that remain even more rare and valuable.

Tidal marsh systems provide many essential infrastructural and ecological services including "flood protection, water purification, wildlife habitat, recreational opportunities, and carbon sequestration" (Heberger 2009). They are particularly valuable as buffer systems; for example, they protect inland landforms and developed areas from wave action caused by wind and storm events. Though coastal marshes can be readily overlooked in discussions of expected financial loss in conjunction with accelerating sea level rise, Costanza (1997) estimated wetland value at $5,700 per acre in year 2007 American dollars, and restoration of wetlands in the San Francisco Bay Area typically costs between $5,000 and $200,000 per acre (Heberger 2009). While monetary values and restoration efforts focus on individual salt marsh parcels and acreage counts, it is the global network of salt marshes and the potential impending loss of this network's intrinsic and performative value that concerns the scientific community in the context of expected sea level rise.

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[1] Coastal squeeze is the phenomenon where tidal marsh transgression upland is stopped by either human development or a sharp vertical rise in topography. The marsh is then literally "squeezed" between the rising tides and the impediment, whether natural or man-made, shrinking marsh area or eliminating it entirely.

China Camp State Park salt marsh is one example of a Pacific Coast salt marsh with established value, both ecological and scholarly. Located in the San Francisco Bay estuary, on the southwestern edge of San Pablo Bay, this tidal marsh occupies the Southern portion of the 5.6-square-mile Gallinas Creek watershed of Marin County and is threatened by rising tides due to global climate change (figure 5). Among Pacific Coast salt marshes, this one is particularly important because it is an ancient marsh, formed at the end of the last age when the rapid sea level rise of the Holocene era[2] slowed to its current rates of approximately 1 – 2 millimeters per year. Sediment accumulation rates in the vegetated marsh plain during that time were sufficient for the marsh plain elevation to keep pace with the rising Mean Higher High Water level (Williams and Faber 2004).

During the late 1800's and early 1900's, large sediment inputs to the San Francisco Bay from hydraulic mining activities in the Sierra Nevada provided enough material for the China Camp State Park marsh plain to expand bayward. The marsh is considered unaltered by human impact and urbanization except for the digging of minor mosquito mitigation ditches in the 1930's; this unaltered status is rare in the San Francisco Bay Area as well as along the U.S. Pacific Coast. Characteristics of an ancient tidal salt marsh, including "complex, meandering slough channels traversing the marsh plain" (figures 1, 6) are visible evidence of its mature status (Williams and Faber 2004). It is considered a closed system: its entire sub-watershed is enclosed within the State Park, the majority of which is undeveloped. The marsh has been used as a study

[2] Holocene era: a geologic epoch, dating to approximately 11,700 years ago to the present. It is part of the Quaternary period. The Holocene era corresponds with the recession of the glaciers and the rise of sea level to present day measurements.

site for salt marsh monitoring and as a paradigm for restoration projects around the San Francisco Bay Area.

As a landform, the China Camp State Park salt marsh is the result of an accumulation of organic and inorganic sediment in response to its tidal prism. Its physical position at the edge of land and water parallels its biological role as an ecotone, or transition zone, between terrestrial and marine systems. The vegetated marsh plain exists roughly at the elevation of Mean Higher High Water, such that inundation periods vary on daily and seasonal scales. This dynamic pulse system relies on hydrologic forces and sediment transport processes for its existence and ultimately its formation or deformation (Haltiner 2011).

Given these formative processes and the changes in sea level expected over the next century, the continued existence of China Camp's salt marsh currently remains uncertain. The primary determinant to understanding whether the China Camp salt marsh will endure is: Will the sediment deposition rate at the China Camp tidal marsh be sufficient to keep up with increasing water elevations due to accelerating sea level rise? To consider this question, we use sediment accretion rates measured at China Camp marsh and projected sea level rise and suspended sediment estimates to compare 2100 sea level and marsh plain elevations. From the results of these comparisons, we can make recommendations to ameliorate the risk of China Camp marsh devastation threatened by rising tides.

Methods

Following a literature search and interviews with marsh researchers, we used elevation and monitoring data collected at China Camp State Park salt marsh from 1990 to 2003 (Williams and Faber 2004) to understand sediment accretion rates at the marsh and assess recent trends in marsh evolution. After determining that the factors necessary to accurately predict China Camp marsh's future were too numerous, independently dynamic, and complex for us to accurately quantify or model within our means, we decided to isolate the two factors that we deemed most critical: tidal elevations and sediment accumulation rates. Because accurately predicting future sediment accumulation rates was not feasible within the scope of our study, we created simplified scenarios by projecting observed sediment accretion rates and using previously established estimates for suspended sediment concentrations in San Pablo Bay (Ganju 2004).

Using the values for projected sea level rise, recently observed sediment accretion rates at China Camp tidal marsh (Williams and Faber 2004), and hypothetical sedimentation rates based on projected values of sediment suspension (Ganju 2004) and sea level rise (DRMS/CALFED 2007), we constructed six scenarios for the morphologic evolution of China Camp tidal marsh.

1	Observed sediment accretion rate: 0.2"/yr	Projected high sea level rise: 55"
2	Observed sediment accretion rate: 0.2"/yr	Projected low sea level rise: 40"
3	Decreased sediment accretion rate: 0.1"/yr	Projected high sea level rise: 55"
4	Decreased sediment accretion rate: 0.1"/yr	Projected low sea level rise: 40"
5	Increased sediment accretion rate: 1.0"/yr	Projected high sea level rise: 55"
6	Increased sediment accretion rate: 1.0"/yr	Projected low sea level rise: 40"

With these conjectures we determined areas available for marsh transgression, evaluated the feasibility of marsh transgression, and recommended adaptation strategies to facilitate marsh survival.

Results

Sedimentation rates at 11 points along a land-to-bay transect at China Camp State Park salt marsh for 1991 to 1999 ranged from 0.1 to 0.4 inches per year and averaged 0.2 inches per year. If these rates of sedimentation continue through 2100, we expect the China Camp marsh plain to occur at elevations on average 20 inches higher than their 1999 elevations. Sea levels in 2100, on the other hand, are expected to occur at 40 to 55 inches higher than contemporary levels, resulting in permanent inundation for our anticipated marsh plain elevation (figure 7). Permanent inundation, in turn, negates its marsh plain zone classification, since this zone is defined by both elevation and vegetation. Vegetation monitoring data along the same transect for 1990 to 2003 suggest an expansion of the marsh plain bayward: cordgrass occurred as far as 1,950 feet from the land edge in 2003, compared to its farthest occurrence in 1990 at 1,750 feet from land.

Potential increases or decreases in marsh sediment accretion rates proposed in our marsh evolution scenarios are strongly dependent on suspended sediment concentrations in San Francisco Bay waters, and suspended sediment concentrations in turn vary with water turbidity. Ganju (2004) measured suspended sediment near the mouth of the Petaluma River, a high turbidity estuarine zone, at a range of <100 mg/L to 2500 mg/L, with average suspended sediment around 500 mg/L. These concentrations can result in accretion rates of 6 to 16 inches per year in local sediment sinks (Ganju 2004). Based on sedimentation rates observed at China Camp marsh in 1991 – 1999 and China Camp's location south of the high turbidity Petaluma River mouth, we estimate a sediment accretion rate of 1 inch per year within the marsh if suspended sediment concentrations in the bay increase with rising sea levels. In this scenario, with sediment accretion rates five times as much as the average observed from 1991 to 1999 (0.2 inches per year), the China Camp marsh plain will outpace the projected 40 to 55 inches of sea level rise by accumulating 100 inches of sediment. By definition the marsh plain cannot accumulate so much sediment that it is above the daily tidal range, but these estimates nonetheless indicate that sediment accretion rates may be sufficient for marsh survival and suggest that bayward expansion of the marsh plain could also be possible under rising sea level conditions.

Conversely, if the San Francisco Bay sediment budget continues to decline due to dredge removal, increased wave action, and larger tidal ranges, sediment accretion rates at China Camp marsh may similarly decline. For such a scenario, we estimate a low sediment accretion rate of 0.1 inches per year, the minimum accretion rate observed along the study transect for 1991 – 1999 (Williams and Faber 2004). With an assumed declining bay sediment budget and low accretion rate, survival chances for China Camp salt marsh appear poor. In this scenario, 40 inches or more of sea level rise may consistently inundate the small fragmented inlets currently available for marsh transgression.

Regardless of exact sedimentation rates, the China Camp tidal marsh is presently constrained from its full transgression potential by San Pedro Dam Road and the culverts that run beneath it (figure 8). This road cuts through the marsh plain and, if left in place, will block the marsh from transgressing to upland elevations with rising sea levels. Based on marsh plain and road elevations, we expect that the tidal marsh will succumb to coastal squeeze and ultimately disappear against the road's edge unless the State Park intervenes.

Discussion

The bayward expansion of China Camp salt marsh's cordgrass band from 1990 to 2003 contradicts expected erosion due to bay-wide suspended sediment decline caused by upriver dams and the end of 19th century hydraulic mining sediment inputs.

On the other hand, vegetative expansion does not contradict the positive sedimentation rates seen along the entire transect; as previously mentioned, vegetation both traps suspended sediment and adds organic sediment to its substrate, so a vegetated marsh will logically expand bayward if permitted by a relative lack of erosive forces. High levels of suspended sediment measured just north of China Camp at the Petaluma River mouth (Ganju 2004) suggest an increasing sediment budget for the China Camp salt marsh that may provide an additional explanation for the expanding cordgrass band.

Due to the high number of variables involved in tidal marsh formation and the inherent complexity to their relationships, it is nearly impossible to predict the future morphology of an individual salt marsh such as the one at China Camp State Park. Because the individual marsh is subject to forces acting on the entire estuary, future marsh morphology can only be understood by projecting changes in estuary-wide processes including sediment transport and availability. At the San Francisco Bay estuary scale, sediment delivery is on a declining trend because of upriver dams and the end of 19th century hydraulic mining. Potential sediment sinks in the Delta may further compound the sediment deficit: if subsided leveed lands in the Bay Delta are abandoned following levee failure, these areas will become sediment traps, reducing the amount of suspended sediment entering the San Francisco Bay from upstream (Williams 2001). The probability of these sediment sinks greatly increases with rising tides and aging, costly levees.

At the same time, a greater total bay water volume could result in greater total suspended sediment due to recirculation capture in deeper waters as well as erosion, wave action, and re-suspension of existing tidal mudflat sediment (Williams 2001). The possibility that suspended sediment will increase with rising sea levels is supported by Ganju's (2004) data from the Petaluma River mouth showing high levels of suspended sediment due to high turbidity. With increased wave action across deeper water conditions, we expect increases in San Francisco Bay sediment supply and therefore suspended sediment concentrations.

On a watershed scale, it is not unreasonable to expect changes in sediment inputs to the China Camp marsh caused by changes in climatic conditions and precipitation. The mouth of Gallinas Creek lies just north of the China Camp salt marsh, and changes in the creek's sediment load could impact marsh deposition or erosion, alone or in conjunction with other variables. Inputs of freshwater and sediment from precipitation across the watershed, from Gallinas Creek, and from watershed runoff are important factors for the tidal marsh system, impacting erosion, deposition, salinity, and vegetation distribution.

Examining the six scenarios based on observed and projected data for sea level and sediment accretion rates at China Camp tidal marsh, we find that the existing marsh plain will be lost to sea level rise unless there is a dramatic increase in sediment accretion rates. The four scenarios that include observed and decreased sediment accretion result in significant loss of marsh area as well as fragmentation into isolated marsh patches vulnerable to coastal squeeze (figure 9). The two scenarios showing increased sediment accretion rates for the tidal marsh suggest that the marsh may be able to advance if it receives adequate sediment supply.

Careful sediment budget management within the San Pablo Bay and the greater San Francisco Bay estuary system is likely required in order to provide the necessary sediment supply for marsh advancement through accretion. The Bay Conservation and Development Commission currently performs regular dredging activities to maintain commercial shipways but deposits removed dredge material outside of the San Francisco Bay. Examining and altering current dredging practices could offer an opportunity to positively impact sediment budgets within the Bay. Similarly, activities related to shoreline development, dams, levees, and upstream river management practices all impact the sediment budget and provide opportunity for sediment budget modification.

Conclusions

China Camp salt marsh's physical footprint, at approximately 100 acres, is small in comparison to large tidal marsh restoration projects currently being planned in the San Francisco Bay Area. While vast wildlife habitat areas often support proportionally greater species richness compared to small parcels, scale is not the only measure of wetland value. Perhaps due to the dynamic and multi-functional nature of wetlands, small wetlands can serve critical functions and should not be valued purely by acreage (Heberger 2009). Furthermore, China Camp State Park salt marsh's rare status as an ancient, nearly unaltered marsh and its history as a study site increase its overall value and present credible impetus for facilitating marsh transgression. The marsh is ideal for targeted sustainable adaptation strategies and continued study: its location within China Camp State Park provides personnel capable of overseeing and facilitating landscape changes within the park and affords it few infrastructural surroundings that would require flood mitigation strategies.

We do not recommend radical adaptive strategies for China Camp tidal marsh. Our primary and only adaptive recommendation is the removal or elevation of San Pablo Dam Road where it presently borders the China Camp State Park salt marsh, to allow inland marsh transgression in conjunction with accelerating sea level rise (figure 8). With the removal of the road and associated culverts as barriers to transgression, the tidal marsh will have a chance to transgress inland and uphill. The result will probably be a series of pocket marshes, isolated from each other by the governing topography (figure 10).

Regardless of morphology and connectivity, allowing marsh transgression that results in isolated fragments in response to higher water levels is the most sustainable and appropriate strategy to maintain the undisturbed, unmanaged status of this marsh. If aggressive adaptive strategies are implemented for preservation purposes, the China Camp marsh will no longer exemplify a pristine, continuously undisturbed system. Instigating a management regime for China Camp marsh will eliminate its value as a paradigm ancient tidal marsh and likely necessitate continued long-term intervention.

As a sustainable management strategy for China Camp State Park tidal marsh, we support the continued observation of the marsh and its response to global climatic and local and regional estuarine changes. We recommend the implementation or continuation of comprehensive study on China Camp marsh transgression in relation to sediment dynamics within the San Pablo Bay, with the goal of applying these findings to marsh restoration projects. In addition to providing valuable data on the evolution of an ancient, established marsh system in response to rapid sea level rise, China Camp salt marsh provides the opportunity to compare ecological and morphological responses to environmental changes between ancient and constructed marsh habitats.

Based on potential sediment deficit effects and changes in sediment transport processes in the San Francisco Bay over the next century, we recommend that the Bay Conservation and Development Commission re-evaluate their policies on use and disposal of dredge material. Deposition of dredge material in strategic areas of the Bay could reduce marsh erosion and facilitate higher sediment accumulation rates, allowing marsh transgression and the preservation of marsh habitats and infrastructural functions.

A 1990 report for the Pacific Institute by Gleick and Maurer indicated that coastal wetlands “could not be protected and would likely be damaged or lost” to rising sea levels. The financial costs of mitigating accelerating sea level rise will be immense around the world, particularly to protect extensive infrastructure investments (Heberger

2009). Relative to what will be required for developed and constructed areas, the return on investment for road removal or elevation at China Camp in exchange for ecological value and study opportunity is very high. Furthermore, while salt marshes are not a high financial priority for sea level rise interventions (Heberger 2009), we recommend further study to evaluate the feasibility of protecting vulnerable urban edges through the creation of tidal marshes as flood protection infrastructure in place of or in conjunction with coastal armoring strategies.

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Figures

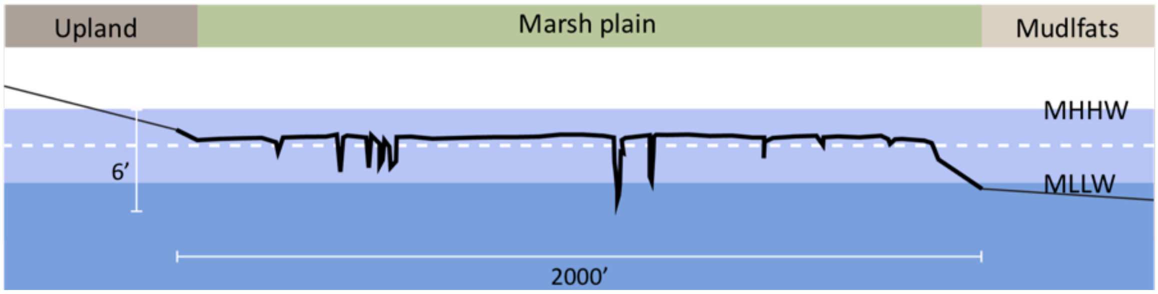


Figure 1. China Camp study transect (Williams and Faber 2004) showing marsh zones, vertically compressed system, and marsh plain channels in relation to present Mean Higher High Water and Mean Lower Low Water tidal elevations.

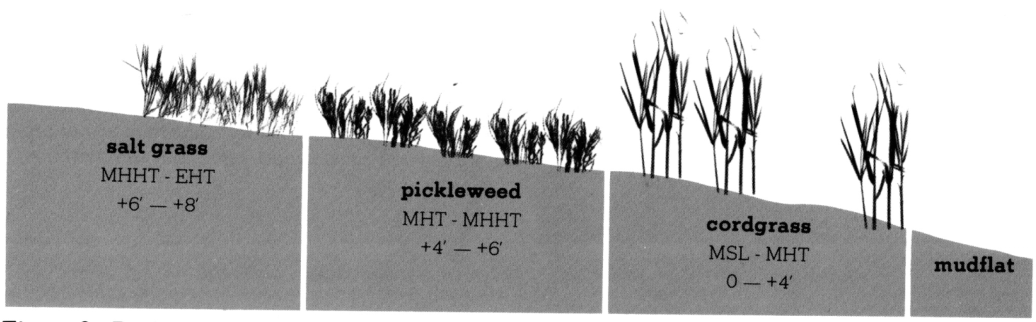


Figure 2. Profile of a typical west coast salt marsh

MSL = mean sea level, MHT = mean high tide. MHHT = mean higher high tide, EHT = extreme high tide

(diagram from Faber 1996)
Figure 2. Elevational zones and their corresponding dominant vegetation in Pacific Coast tidal salt marshes.

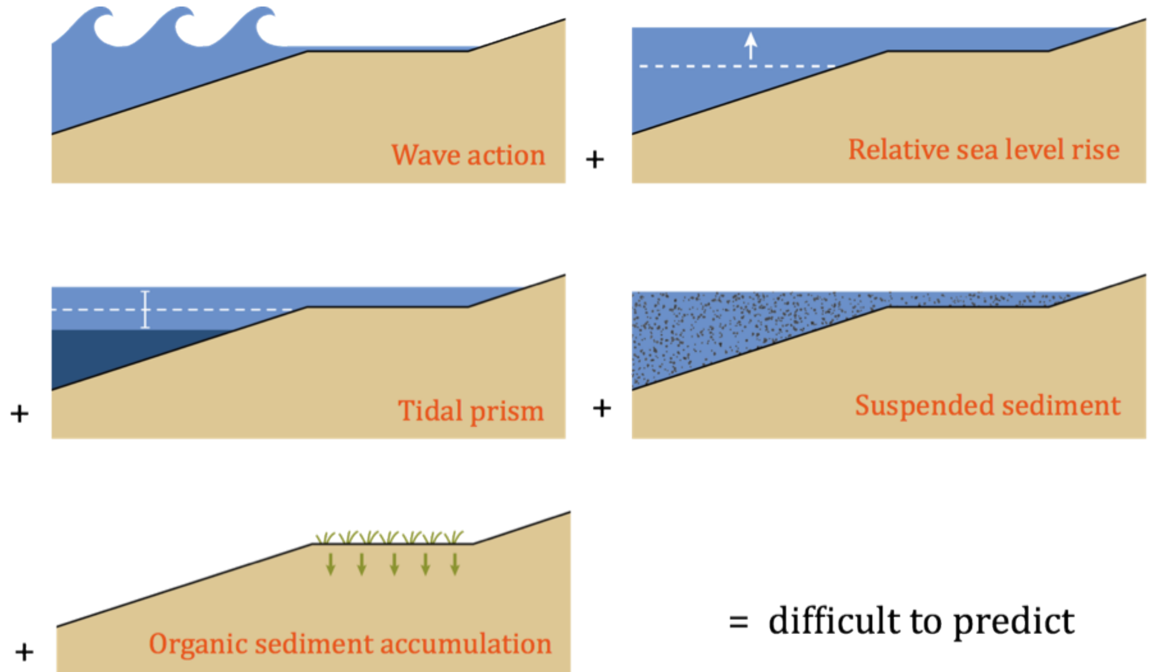
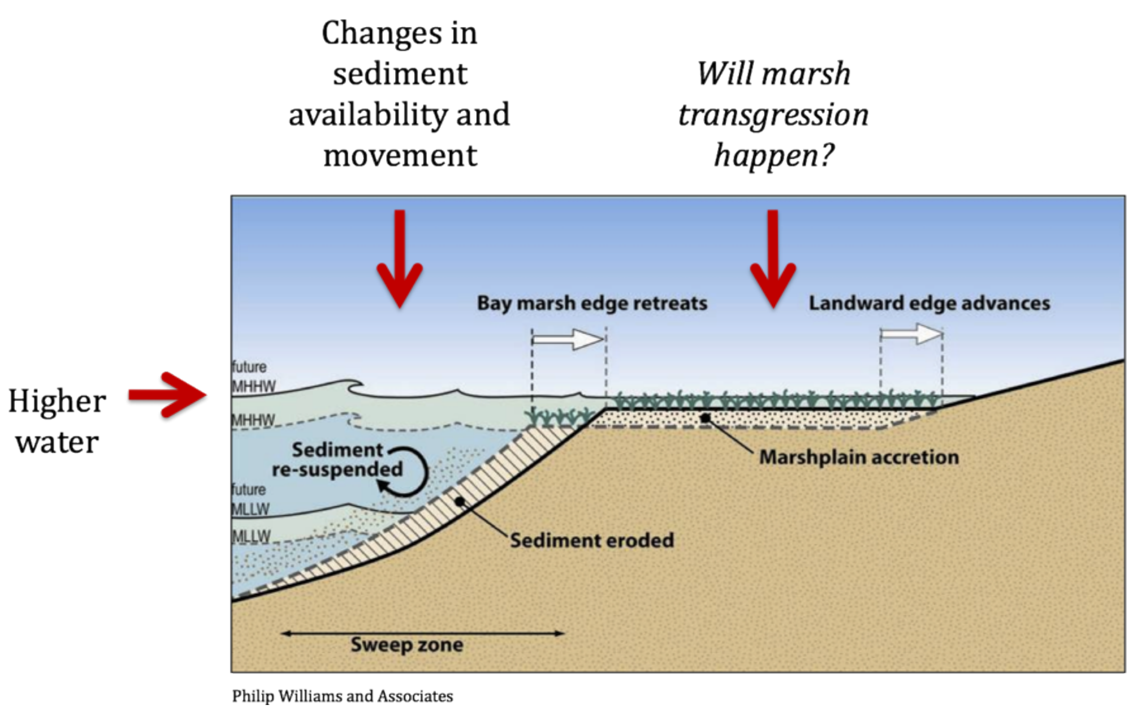
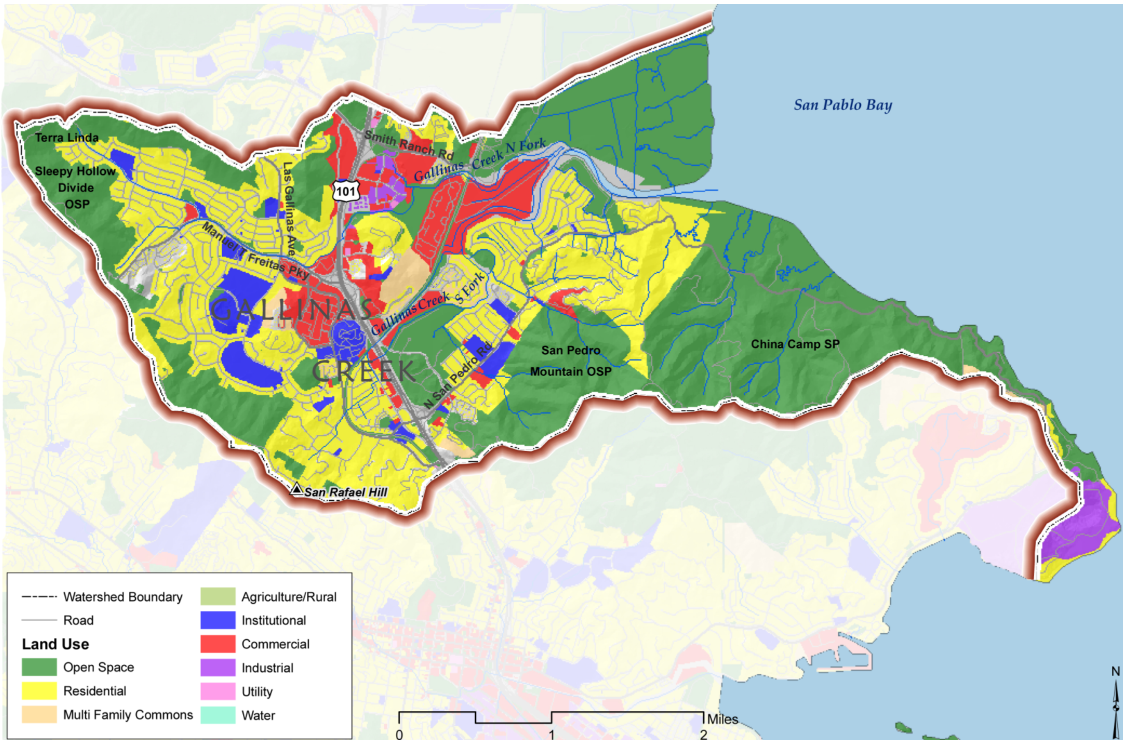


Figure 3. Factors that affect tidal salt marsh morphology. The complexity of relationships between factors makes it nearly impossible to predict future marsh morphology.



(diagram courtesy of PWA)
Figure 4. Tidal marsh accretion and transgression.



(map from Marin County DPW)
Figure 5. China Camp Salt Marsh is located at the base of the Gallinas Creek Watershed in Marin County, California.

(photograph from Google Earth)
Figure 6. The mature marsh plain of China Camp State Park tidal marsh.

Figure 7. Current 100-year flood levels at China Camp State Park salt marsh (light blue) and 100-year flood levels projected for 2100 assuming a 55-inch rise in sea levels (dark blue).

Figure 8. Inland transgression of China Camp tidal marsh is currently constrained by San Pedro Dam Road.

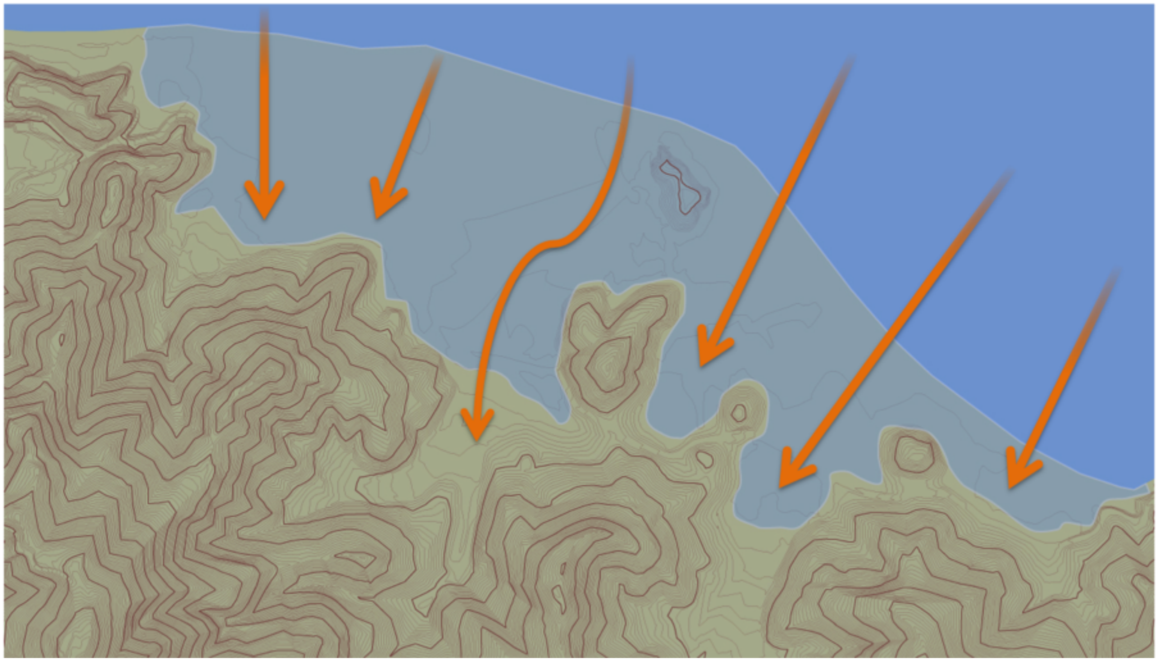


Figure 9. Based on surrounding topography, the China Camp State Park tidal marsh can be expected to transgress uphill in certain gently sloping areas if given the opportunity.

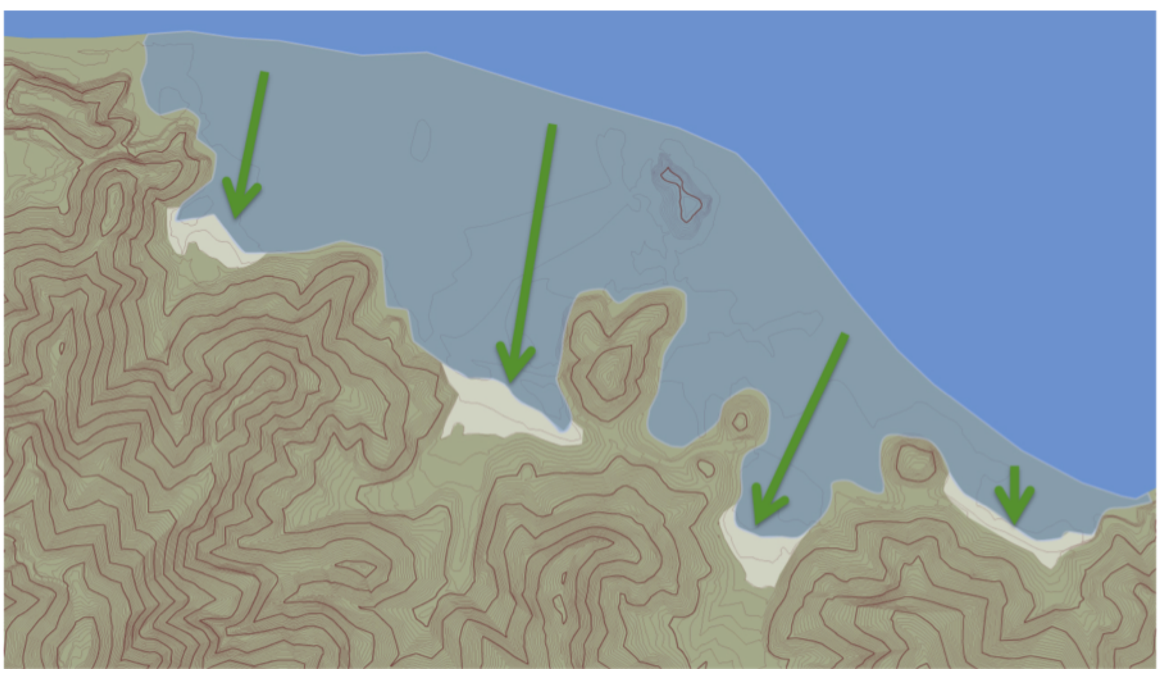


Figure 10: If barriers to marsh transgression are removed, fragments of the China Camp tidal marsh could remain intact with 55 inches of sea level rise and continued average marsh plain sediment accretion at 0.2 inches per year.