Using Process-Level Science on Peat Formation to Inform Wetland Restoration

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Wetland restoration in the Delta and Suisun Marsh is of key interest to increase and improve habitat for flora and fauna, particularly sensitive species. In these slightly brackish and freshwater parts of the San Francisco Estuary, both inorganic sedimentation and organic accumulation are important peat-forming processes required for marsh sustainability under sea-level rise. Several recent studies have shed light on marsh formation processes that could inform restoration decisions. In the Rates and Evolution of Peat through Time project (REPEAT), the peat column from four Delta marshes was analyzed for bulk density, organic carbon content, sediment content, and major/trace metals. Results showed that peat formation relied more on organic accumulation in marshes along low energy tributaries and more on inorganic sedimentation in marshes situated along the main channels. As part of the Computational Assessments of Scenarios of Change for the Delta Ecosystem project (CASCaDE II), modeling using the Wetland Accretion Model of Ecosystem Resilience (WARMER) showed that the rates of sea-level rise and inorganic sedimentation are key factors determining the future sustainability of marshes in the Delta. In the Waccamaw National Wildife Refuge (NWR) project, carbon sequestration rates were compared over a 40-year period in moist-soil managed (impounded) and naturally tidal marshes in South Carolina. The moist-soil managed marshes had ¼ the vertical accretion rate and less than half the carbon storage of the naturally tidal sites. A study similar to that carried out in the Waccamaw NWR is needed in Suisun Marsh to determine how naturally tidal vs. impounded marshes will fare under sea-level rise. All of these studies demonstrate that a strong understanding of soil formation processes is critical for choosing wetland restoration sites with a high likelihood of long-term sustainability.

Keywords: marsh, marsh sustainability, peat formation, sea-level rise, wetland restoration
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Evaluating the Influence of Suspended Sediment Concentrations on Marsh Resiliency for Three Marsh Accretion Models in San Francisco Bay

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Planning for effective conservation and management of tidal marshes necessitates the use of predictive models to evaluate the effects of increased sea-level rise rates, sediment availability, and plant productivity on marsh resiliency. A variety of marsh accretion models have been used to develop predictions of tidal marsh response to these factors; however, current management and planning options using these models remain restricted by uncertainty of model inputs, particularly for sediment concentrations. We evaluated the influence of suspended sediment concentrations on marsh resiliency at two tidal wetlands, China Camp and Rush Ranch, using three published accretion models calibrated for San Francisco Bay: Marsh98, Wetland Accretion Rate Model of Ecosystem Resilience (WARMER), and the Marsh Equilibrium Model (MEM). We aligned as many model inputs as possible and varied century sea-level rise rates, suspended sediment concentrations, and initial elevations to examine predicted changes in marsh elevation and habitat type. As sea-level rise rates increase and suspended sediment concentrations decrease, marsh resiliency decreased and elevations shifted to low marsh or mudflat habitat across all models. Elevation trajectories were comparable between WARMER and Marsh98, while MEM projected markedly slower rates of elevation loss over time. Our results highlight the importance of collecting field-based data (e.g., suspended sediment) to improve the calibration of marsh accretion models. Differences across models highlight the need to better understand the relative roles of mineral and organic matter accumulation for marsh resiliency and to identify the particular factors that are driving these processes within each model. However, the similarities in the general trends in predictions across models demonstrates the agreement from previous studies that tidal marshes are vulnerable to sea level rise and that current suspended sediment concentrations may not be sufficient to prevent future marsh drowning. .

Keywords: tidal wetlands, marsh accretion models, sea-level rise
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Sediment Flux between San Francisco Bay Shallows and Marshes

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As sea level rises, marshes accrete a combination of plant-derived material and mineral sediment imported from adjacent waters, and their ability to maintain elevation depends largely on the magnitude of sediment supply. We conducted a study for ten weeks in the winter of 2013/2014 spanning the large spring ('king') tides of December and January to investigate factors governing sediment delivery to the China Camp marsh in southwestern San Pablo Bay. We measured time series of suspended-sediment concentration (SSC), water level, and tidal currents in the subtidal shallows, on the intertidal mudflats, and in two channels within the marsh. Discrete samples for SSC were collected over the marsh plain during each king flood tide in transects perpendicular to the channels, and in cross-shore transects between channels extending landward from the Bay's edge. We observed significant sediment export during king tides in the marsh channels. Cumulative suspended sediment flux (SSF) over four days during the January king tides was approximately 10 tons/m of channel width, towards the bay. During neap tides SSF in the channels was directed landward, but was lower in magnitude. Elevated velocities in the channels during ebb king tides suggest that resuspension within the channels, rather than erosion of the marsh, accounts for much of the bayward SSF. On the marsh plain, SSC was highest at the bayward end of the cross-shore transects, indicating landward sediment flux. Taken together, our results suggest that sediment is primarily supplied to the marsh across the marsh-Bay interface, and exported from the marsh through tidal channels. These findings are relevant to the design and monitoring of restored marshes, which frequently rely on transport through breaches for sediment supply. They also indicate the importance of accounting for sediment export as well as import in modeling the response of marshes to sea level rise.

Keywords: marsh sustainability, sediment flux, suspended sediment concentration, marsh restoration
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Mitigating Wave-induced Erosion with Vegetation on Breached Delta Wetlands Levees

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The breaching of Delta levees to initiate tidal wetlands restoration may expose the remaining levees to wave-induced erosion. The levees surrounding the restored area can prevent wave impacts from the restored open water from negatively impacting levees on adjacent property. Hence, restoration designs often need to consider the levee vulnerability to erosion and management actions to protect against erosion.

Based on wave modeling and vegetation monitoring on breached Liberty Island, we assessed levee vulnerability to wind-wave erosion and the capacity of vegetation to mitigate this vulnerability. The two-dimensional SWAN wave model was used to hindcast six and half years of wave conditions at tidally-inundated Liberty Island. The resulting seasonal and extreme wave climate is compared with levee erosion rates and observations of vegetation evolution quantified from ground surveys and aerial photographs.

These results characterize the relative contribution of typical and extreme wind events to wave power. Fetch and water depth are both key factors in levee vulnerability, such that levees exposed to long fetches are less vulnerable if they are fronted by intertidal mudflats that dissipate wave energy. Even at Liberty Island, where breaching was unplanned and minimal management actions have been taken, vegetation has been able to colonize and expand in areas exposed to relatively high wave power. Other studies demonstrate that similar vegetation significantly attenuates wave power, and presumably, reduces levee erosion vulnerability.

Although more information is needed, these findings suggest that the design of Delta tidal wetlands restoration could be guided by assessing levee vulnerability. Where indicated, levee vulnerability can be mitigated by grading to create dissipative bed elevations and to provide improved conditions for vegetation. By using vegetation, rather than traditional rock armoring, wave-induced erosion can be managed to minimize impacts to neighboring properties while also providing tidal marsh vegetation habitat.

Keywords: levee vulnerability, wave modeling, vegetation
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Sea-Level Rise Impacts on Salt Marsh Vegetation in the San Francisco Bay Estuary

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Salt marsh plants mediate many important estuarine functions including food web support, sediment accretion and habitat provision for wildlife. While it is generally understood that species abundance, composition and productivity vary along tidal gradients, species and site-specific responses of vegetation to future sea-level rise must be quantified to assess future changes in wetland function and climate resilience. Since 2008 our team has investigated potential vegetation responses to sea-level rise (SLR) in San Francisco Bay using observational surveys, SLR modeling, and manipulative experimentation of flooding effects on plant growth. Vegetation and elevation surveys conducted at sites throughout San Francisco and San Pablo Bays showed that most marshes in the region are dominated by pickleweed (*Sarcocornia pacifica*), with additional areas dominated by *Spartina* spp. (low-elevation, high-salinity marshes) or sedges (low-elevation, low-salinity marshes). SLR modeling results using digital elevation models and estimates of long-term accretion rates from sediment cores suggests that many existing San Francisco Bay marshes will drown over the next century. Greater inundation may lead to shifts in vegetation composition or conversion to mudflat habitat. To test flooding effects on plant productivity, we are conducting an on-going manipulative SLR experiment in Petaluma marsh with *Sarcocornia*, *Spartina* and *Bolboschoenus*, three common species in the region. Preliminary results suggest that all three species show relatively high growth rates between mean high water (MHW) and mean tide level (MTL). *Sarcocornia* growth (the dominant marsh plain species throughout much of California) tended to have reduced growth at depths about 40 cm below MTL, but otherwise grew relatively well across a range of flooding levels. Our results provide species and site-specific information about coastal wetland vulnerability to SLR, information that resource managers can use to plan for restoration and management of coastal resources in changing landscapes.

Keywords: climate change, primary productivity, *Sarcocornia*, sea-level rise, *Spartina*
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Estuarine Tidal Flat Evolution at Decadal and Seasonal Time Scales

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Estuarine tidal flats are rich habitats that change at seasonal and decadal time scales. Their shape and width is determined by the interplay of wind waves, tides and sediment availability. To explore the processes governing tidal flat evolution, we use a combination of observations and 1D process based modeling (Delft3D) of the tidal flat-channel system at Dumbarton Bridge in South San Francisco Bay. At the seasonal time scale, 8 interferometric sidescan sonar swath bathymetry surveys collected from December 2008 to January 2011 reveal subtle changes in tidal flat morphology. Tidal flats tended to accrete during the winter and early spring when sediment supply from tributaries is high and erode during the late spring, summer, and fall when stronger winds generate larger waves. At the decadal time scale, a series of bathymetric surveys collected approximately every 30 years from 1858 to 2005 shows that tidal flat width varied from 550 to 900 m. Width is correlated with net deposition/erosion of the entire South Bay. Tidal flats widen during periods of net sediment import and narrow during net sediment export from South Bay. Model runs with constant sediment supply and wave and tide forcing show bayward progradation of the channel margin and slow development from a flat bed towards a concave-up equilibrium within 5 years. Equilibrium consists of similar erosion and deposition rates, maintaining locally high sediment concentrations above the tidal flat. Sensitivity analysis is carried out with respect to forcing conditions and sediment characteristics. Important research questions are to what extent rare, extreme events (large wave heights) determine the bathymetric profile compared to typical conditions and whether forcing and sediment availability change to rapidly for the system to ever reach equilibrium. This study will improve assessment of possible impacts of restoration and sea level rise on tidal flats and their ecosystems.

Keywords: intertidal flats tidal modeling sediment supply equilibrium
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Hydraulic and Geomorphic Processes in an Overbank Flood Along a Gravel-Bed, Meandering, River: Implications for Chute Formation

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The hydraulic interactions between meandering rivers and floodplains produce off-channel chutes, whose presence can increase the ecological value of the valley floor. Detailed studies of the hydrologic exchanges between channels and floodplains are usually conducted in laboratory facilities, and studies documenting chute development are generally limited to qualitative observations. Here we use a reconstructed, meandering reach of the Merced River as a field laboratory for studying these ecologically significant mechanisms at a realistic scale. Using an integrated field and modeling approach, we quantified the flow exchanges between the river channel and its floodplain during an overbank flood, and identified locations where flow had the capacity to erode floodplain chutes. Hydraulic measurements and modeling indicated high rates of flow exchange between the channel and floodplain, with flow rapidly decelerating as water was decanted from the channel onto the floodplain due to the frictional drag provided by substrate and vegetation. Peak shear stresses were greatest downstream of the maxima in bend curvature, along the concave bank, where terrestrial LiDAR scans indicate initial floodplain chute formation. A second chute is developing across the convex bank of a meander bend, in a location where sediment accretion, point bar development and plant colonization have created divergent flow paths between the main channel and floodplain. In both cases, the off-channel chutes are evolving slowly during infrequent floods due to the coarse nature of the floodplain, though rapid chute formation would be more likely in finer-grained floodplains. The controls on chute formation at these locations include the river curvature, cross-stream position of the high velocity core, floodplain gradient and the density of riparian vegetation. This study illuminates the mechanisms that promote chute formation in a meandering river, with a thinly vegetated floodplain, and provides a predictive modeling framework that can be transferred to other Central Valley rivers.

Keywords: meandering, river, floodplain, chute cutoff, vegetation, modeling, restoration
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Subsurface Flow through a Gravel River Bar: Physical Controls to Suitable Spawning Habitat for Chinook Salmon (*O. tshawytscha*) in the San Joaquin River Basin

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Shallow alluvial aquifers beneath river channels have distinct hydrologic and geomorphic characteristics whose variability determines the extent of suitable spawning habitat for Chinook salmon (*O. tshawytscha*). We investigate how bedform morphology and heterogeneity of hydraulic conductivity affect patterns of subsurface flow through gravel bars, the magnitude and extent of infiltration and seepage, and the residence time distribution when surface water stage varies with flow releases in select gravel bed reaches of the San Joaquin River Basin, CA. We measured *in situ* hydraulic conductivity, interstitial pore water temperature in Artificial Redds, and near-bed temperature. We then quantify bedform-flux interactions using high-resolution derived terrain, discharge information measured at multiple gauging sites, and climate information in distinct bar-bend reaches to inform and evaluate a two-dimensional subsurface hydrologic model in channel bedforms where the spatial distribution of hydraulic conductivity is measured *in situ*. Field and modeling results show that (1) riffle-pool asymmetry is a key control to the extent and magnitude of infiltration, (2) riffle-pool channels may be recharge-limited, constituting as little as 15-20 percent of the length of the riffle during low flows, and (3) the magnitude of infiltration fluxes is greatest during low flows rather than high flows. The areas of most active recharge exhibit the lowest hydraulic conductivities, impregnated with sand after a flood. Intragravel temperature patterns are controlled by infiltrating surface water temperatures where streambed water fluxes are high. Where recharge is limited, the role of bed conduction may be significant. These results suggest that management through flow modification can alter flow and thermal conditions in the hyporheic zone, however, streambed morphology, the presence of sand, and the systematic downstream coarsening of the surface layer due to the genesis of gravel bars are primary controls to the variability of intragravel flow and temperature critical to *O. tshawytscha* early life stages.

Keywords: subsurface flow, river, gravel bars, physical, habitat, hyporheic flow, salmon
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Effects of Human Alterations on the Hydrodynamics and Sediment Transport in the Sacramento-San Joaquin Delta, California

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The Sacramento-San Joaquin Delta, California, (Delta) has been significantly altered since the mid-nineteenth century. Many existing channels have been widened or deepened and new channels have been created for navigation and water conveyance. Tidal marshes have been drained and leveed to form islands that have subsided. All of these islands have flooded temporarily due to levee breeches; however, the levees of a few islands have never been repaired and are considered to be permanently flooded. To understand how these alterations have affected hydrodynamics and sediment transport in the Delta, we analyzed measurements from 27 sites, along with other spatial data, and previous literature. Results show that (a) the permanent flooding of islands results in an increase in the shear velocity in channels downstream, (b) artificial widening and deepening of channels generally results in a decrease in shear velocity except when the channel is also located downstream of a flooded island, (c) 1.5 Mt/yr of sediment was deposited in the Delta (1997-2010), and of this deposited sediment, 0.31 Mt/yr (20%) was removed through dredging.

Keywords: sediment transport, dredging, tidal prism, sediment budget, shear velocity
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Exploring the Complex Couplings between Environmental Drivers and Greenhouse Gas Exchange in Restored Delta Wetlands

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Restoring agricultural areas to wetlands in the Sacramento-San Joaquin River Delta of California can help reverse subsidence and reduce greenhouse gas (GHG) emissions. Some or all of the costs of wetland restoration can be recouped by selling the generated carbon credits on emerging markets. Determining financial feasibility and developing best management practices of wetland restoration in this regard therefore requires a robust understanding of the sensitivity of GHG exchange in these ecosystems to factors such as management and meteorology. However, developing this understanding is no small feat. Wetlands can exhibit complex, overlapping, and asynchronous couplings between site characteristics, environmental drivers and GHG exchange. Sophisticated tools are needed to disentangle and characterize these couplings so that they can be effectively modeled. In this research we use the combination of wavelets and information theory to explore interactions between environmental drivers and GHG exchange (CO_2 and CH_4 exchange measured by eddy covariance) from hourly to monthly time scales in two restored Delta wetlands. Despite differences in age and architecture, CO_2 exchange at both wetlands was similarly sensitive to meteorological conditions up to a time scale of several days. At the monthly timescale, however, the effects of a more variable water table management at one wetland became apparent. Relatively large and prolonged drops in water table resulted in a reduction in net CO_2 uptake. The same analysis applied to CH_4 exchange revealed a more sensitive and complex coupling with water table management. CH_4 exchange was sensitive to even small, multi-day shifts in water table and displayed a lagged response to larger shifts. With these methods we were able to disentangle the effects of management from meteorology, and better understand how site age and architecture influence the sensitivities of GHG exchange. Our results provide important insights for modeling efforts and management practices.

Keywords: carbon sequestration, wetland management, gas flux, restoration, methane, carbon dioxide
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