ASSESSING SEDIMENT DYNAMICS AND SALT MARSH SUSTAINABILITY IN HUMBOLDT BAY: WHITE PAPER ON MANAGEMENT IMPLICATIONS OF PRELIMINARY RESEARCH FINDINGS

September 10, 2019

Executive Summary

Humboldt Bay marshes are threatened by sea level rise: Early short-term results suggest that Humboldt Bay marshes are not accreting sediment fast enough to keep up with Relative Sea Level Rise. Definitive results require longer-term data but it appears likely that over the next century, as sea level rise accelerates, Humboldt Bay marshes will convert to subtidal habitats. In order to maintain salt marshes around Humboldt Bay, managers should plan for some combination of upslope migration to allow for wetlands in new locations, and sediment augmentation to maintain wetlands for a longer period in their current locations.

Fine sediment supply for Humboldt Bay may be in deficit: A comparison of model sediment discharge and annual rates of historic maintenance dredging indicate a potential deficit of fine sediment in Humboldt Bay that may be filled by external or internal sediment sources. Definitive results require a comprehensive sediment budget, which remains a critical data gap.

Beneficially reuse sediment: Wetland managers should consider augmenting the supply of sediment to Humboldt Bay marshes, rather than disposing of it outside the littoral cell.

Plan for upslope wetland migration: In order to maximize the extent of wetlands around Humboldt Bay, it will be necessary to plan for upslope wetland migration. A planning effort should be undertaken to identify the most promising locations where upslope migration could occur and the feasibility of protecting them, and should consider the significant constraints to upslope migration.

Consider sediment supply implications of current wetland management: If a deficit of fine sediment exists in Humboldt Bay, restoring and enhancing specific marshes may impact the overall sediment supply in ways that could degrade other marshes. The potential for sediment supply impacts should not prevent marsh restoration and enhancement, but they should be considered in the design phase.

Improve understanding of sediment dynamics in Humboldt Bay: More information about accretion rates and elevation changes at specific marshes would aid in determining which marshes are most in need of intervention to increase resilience to sea level rise and where restored marshes could persist longest.

Introduction

Humboldt Bay's tidal wetlands are a key part of an important estuarine ecosystem, providing rearing habitat for threatened salmonids and nurseries for a diversity of fish and wildlife that feed the Bay with their high productivity. These wetlands also provide important ecosystem services for the Humboldt Bay community, including protection for infrastructure from storms, water quality improvement, and carbon sequestration. Management planning for existing tidal marshes and marsh restoration prioritization and design in Humboldt Bay are hampered because key information about sediment dynamics in the estuary is lacking. Sediment dynamics are critical to understanding the resiliency of existing wetlands and potential restored wetlands to sea level rise (SLR). Because certain sites in the

Bay are accreting while others are eroding, information on sediment dynamics is important to determine where sediment can be beneficially reused to enhance or restore wetlands.

A climate change workshop held by the US Geological Survey (USGS) in October 2014 for the Humboldt Bay estuary identified sediment information as a key science need for managers to plan and implement climate change adaptation measures. In response, sediment dynamics research and modelling was undertaken by USGS and University of California Los Angeles (UCLA) researchers. Funding for the research was provided by a Wetlands Program Development Grant from the US Environmental Protection Agency (EPA) to the State Coastal Conservancy (Conservancy). Conservancy staff and California Sea Grant staff assisted with scoping the project and with preparing this white paper.

Sediment Dynamics Research Summary

The sediment dynamics research conducted for this project had three components. Methodology and results for each of the three components are summarized below. Additional information on study methodology including contact information for the lead researchers who conducted this work is available in Appendix A. Additional information on analysis and results is available in forthcoming publications (Curtis et al, 2019; Curtis et al., in review, Brown et al., in prep).

1. *Measurement of historic accretion rates:* UCLA researchers, led by Professor Glen MacDonald and Lauren Brown, collected 24 sediment cores from five Humboldt Bay salt marshes, three in the Arcata Bay and two in the South Bay (Figure 1). High resolution age-dating and lab analyses of marsh sediment cores were used to estimate sediment accretion rates and carbon sequestration rates. Accretion rates were estimated using multiple chronological tools (^{137}Cs, ^{210}Pb and ^{14}C age-dating), and carbon sequestration was estimated using Loss on Ignition (LOI) analyses of percent carbon in subsamples of the soil cores to one-meter depth, combined with accretion rates. X-Ray Fluorescence (XRF) was used to analyze mineral content of core subsamples in order to assess sediment influx to marshes over time.

Results

<u>Accretion rates</u>: The three dating methods yielded different historic accretion rates, ranging from ~2.9 mm/yr for radiocarbon dating to 8.4 mm/yr for radiolead dating. These should be considered minimum rates because of sediment compaction during core collection. Carbon dating indicated that the various cores covered periods ranging from 100 to 5,760 years, with an average age of 408 years. The average accretion rate measured by coring is 2.86 mm/yr. Looking at carbon dating for only the past several hundred years yields a similar average accretion rate of 2.91 $\pm$ 0.46 mm/yr (n=19 cores). Comparing this measure of accretion to the long-term eustatic SLR trend over the past several thousand years of 1-2 mm/yr shows that Humboldt salt marsh accretion has exceeded rates of eustatic SLR in recent history. Accretion at Mad River and Jacoby was observed to be ~1 mm/yr higher than marshes at Eureka, Hookton, and White Sloughs. Assessment of salt marsh stability using this accretion rate would be inappropriate, however, due to the large timespan of the measurement as well as the results of sediment compaction.

Radiocesium (^{137}Cs, n=7 cores) gives an average accretion rate of 4.5 $\pm$ 0.4 mm/yr, with the salt marsh at White Slough accreting ~1-2 mm/yr slower than other sites.

Radiolead (^{210}Pb) dating is less certain due to disturbance of the lead profile from natural reworking of marsh sediments. Preliminary results (n=6 cores) give an average accretion rate of 8.4 $\pm$ 1.5 mm/yr. As with radiocesium dating, these results indicate that White Slough is accreting 1-2 mm/yr slower than Mad River and Hookton Slough.

Carbon sequestration: Average % carbon to one-meter depth for cores analyzed with LOI was 4.9 $\pm$ 3.1% (n=11 cores), with samples ranging up to 15% organic carbon. An estimation of carbon sequestration can be made using the average radiocesium-derived accretion rate of 3.1 mm/yr for all cores. Assuming this static accretion rate for all sites returns an average sequestration rate of 85.62 ±0.02 g C/m^2/yr, with a maximum sequestration rates of 240 g C/m^2/yr. The average rate calculated for Humboldt Bay is significantly lower than global average rates estimated by Chmura (2003) and Ouyang et al (2011) of 220 – 240 g C/m^2/yr.

Mineral content and sediment influx: XRF results consistently show an increase in mineral content at approximately 150-200 cm depth and estimated to be 500 years before present. This is likely a tectonic event which caused an influx of sediments to marshes in all parts of the bay.

2. *Measurement of current accretion rates:* Sediment accretion and changes in elevation were monitored quarterly for two years (November 2015 through December 2017) at five salt marsh sites in Humboldt Bay: three in North Bay (Mad River Slough, Manila, and Jacoby Creek) and two in South Bay (White Slough, Hookton Slough; MS Fig. 2). USGS researchers, led by Jenny Curtis, installed two deep rod surface elevation tables (SETs) and six feldspar marker horizon (MH) plots at each of the five study marshes (MS Figure 1). Data were collected from the SETs and MH plots to quantify overall elevation change and surface accretion rates.

In order to understand the conditions determining accretion rates, water quality sondes were deployed at one site in North Bay and one site in South Bay to determine turbidity, which varies with suspended sediment concentration (SSC). At the same two sites, water samples were collected quarterly through a rising and falling tide to measure suspended sediment concentration directly. For each of these two sites, a statistical relation between directly measured SCC and turbidity was developed that allowed the conversion of continuous turbidity data into continuous estimates of SCC. Water level data were collected at the Mad River Slough and Hookton Slough tidal channels at six-minute intervals using Hobo® and Solinst® loggers. Water level data were used to determine local tidal datums. Elevation data from 2012-2013 RTK-GPS surveys were used to generate a Digital Elevation Model (DEM) for the study marshes, which was corrected for the effects of vegetation cover using Normalized Difference Vegetation Index data. The DEM and water level data were used to determine inundation extent and percent of time inundated at the study marshes.

Results

Elevation change as measured by the SETs averaged 2.28 mm/yr for the two South Bay marshes, and 0.89 mm/yr for the three North Bay marshes. Sediment accretion as measured by the MHs measured 4.41 mm/yr for the South Bay marshes and 0.71 mm/yr for the North Bay. Relative sea level rise (RSLR) rates estimated by Anderson (2015) are 3.11 mm/yr for the North Bay and 5.56 mm/yr for the South Bay. These rates indicate that the study marshes did not accrete sediment and gain elevation fast enough during the two-year study period to keep up with RSLR. It should be noted that accretion and elevation may vary significantly interannually, and it is therefore possible that these and/or other Humboldt Bay marshes are gaining elevation fast enough to keep up with RSLR. SSC varies significantly between the North Bay and South Bay, as indicated by the large differences in accretion rates. The mean SSC at Mad River Slough was 16.8 mg/L. The mean SSC at Hookton Slough was 41.1 mg/L, almost 2.5 times greater. There was also significant variation in the frequency of inundation between marshes.

Study marshes in the North Bay are inundated less frequently. Only 25% of high tides reach and flood the mean elevation of Jacoby Creek marsh, while 37% of high tides inundate Mad River Slough marsh, and Manila Marsh had 69% of high tides reaching its mean elevation. South Bay sites had the greatest number of high tides reach their respective mean elevations, with 70% at Hookton, and 71% at White Slough.

3. *Assess sediment supply from watershed sources under current and future climates:* An existing water balance model, the California Basin Characterization Model (BCM), was calibrated to represent local hydrologic conditions and a time series of daily streamflow was developed for all watersheds contributing suspended sediment to Humboldt Bay, including the Eel River. Suspended-sediment concentrations and streamflow data from gages within the Eel River watershed and within the Humboldt Bay watershed were used to calibrate the model. Sediment supply was estimated for current conditions. An ensemble of future climate projections and the calibrated BCM were used to estimate streamflow and sediment supply under future climate conditions. The modelling used ten downscaled climate change projections with two representative CO_2 concentration pathways (RCP 4.5 or mitigated emissions, and RCP 8.5 or business-as-usual emissions).

Results
Current fine sediment supply: The modeling indicated a potential fine sediment deficit in Humboldt Bay, due to the export of dredged fine sediment outside the littoral cell. Approximately 0.05 million metric tonnes per year (Mt/yr) of fine sediment is contributed to Humboldt Bay by its watershed, and approximately 0.08 Mt/yr is exported through annual maintenance dredging. External and internal sources of fine sediment available to balance the 0.03 Mt/yr deficit include plumes of fine sediment from the Eel River that enter the bay on flood tides and erosion of sediment from mudflats and marshes. However, the magnitude of the current fine sediment deficit, and even whether there is a deficit, is still unclear. The question depends largely on the amount of fine sediment from the Eel River that is currently depositing in Humboldt Bay, which is unknown. However, other studies have also identified indicators of fine sediment deficit in Humboldt Bay, such as tidal marsh erosion.

Future fine sediment supply: Modeling indicates that fine-sediment supply in Humboldt Bay is likely to increase significantly under all climate change scenarios by mid-century. The average increase in fine-sediment supply across all mid-century climate predictions for the Bay Basins was 17% for RCP 4.5 and 37% for RCP 8.5 with some climate models predicting increases of 60 – 100 %. The Eel River shows a greater percentage increase in predicted fine sediment supply. Modeling indicated an average increase for the Eel River in fine sediment supply for mid-century climate predictions of 41% for RCP 4.5 and 64% for RCP 8.5, with some climate models predicting increases of 105-129%. The increase in fine sediment supply will result from increases in peak streamflow, a function of the more intense storms that are expected with climate change. The average number of days exceeding peak streamflow per month during the rainy season increased by 14% for Humboldt Bay basins and by 23-29% for the Eel River.

Management Implications

Results from this research are preliminary, and data collection will continue for at least another two years. Nonetheless, these preliminary findings have implications for tidal marsh resiliency and regional sediment management.

Humboldt Bay marshes are threatened by Sea Level Rise

While results are short term and preliminary, it appears possible that some Humboldt Bay marshes are not accreting sediment and gaining elevation fast enough to keep up with RSLR. These preliminary, short term results indicate that relative sea level is currently rising between 1.5 and 3.4 mm/yr faster than the study marshes are gaining elevation through accretion and other processes. While the modeling conducted through this project indicates that fine sediment supply may increase significantly with climate change, RSLR rates are also expected to increase. These results are consistent with the findings of Thorne et al. (2015) that Humboldt Bay marshes are likely to convert to low elevation marshes and mudflats by the year 2110. Wetland managers should know that, if we do nothing, Humboldt Bay marshes will convert to subtidal habitats over the next century. In order to maintain tidal marshes around Humboldt Bay, managers should plan for some combination of upslope migration to allow for tidal marshes in new locations, and sediment augmentation to maintain marshes for a longer period of time in their current locations.

Fine sediment supply for Humboldt Bay may be in deficit

While the results are not conclusive, modeling suggests that there may be a significant deficit of fine sediment in Humboldt Bay, due partly to export of sediment dredged from marinas, docks, and other harbor facilities.

Beneficially reuse sediment

As noted above, wetland managers should explore ways to increase the resilience of Humboldt Bay marshes to SLR. Augmenting the supply of sediment is one promising approach to explore. Thin layer sediment augmentation has been used to enhance marshes in Seal Beach NWR (McAtee 2018), in coastal Louisiana (Hine 2015, Audubon Louisiana 2017), and in the northeastern US (Tyrrell 2017), and should be explored in Humboldt Bay. Keeping fine sediment within the littoral cell and within Humboldt Bay could balance a fine sediment deficit and enhance marsh resilience to SLR. Currently, both fine (diameter <63µm) and coarse sediment removed by dredging is taken to the Humboldt Offshore Ocean Disposal Site (HOODS) outside the littoral cell.

The Coastal Regional Sediment Management Plan for the Eureka Littoral Cell (CCSMW 2017) calls for beneficial reuse of dredged materials. The Humboldt Bay Harbor, Recreation, and Conservation District is currently developing a dredged materials management plan that will facilitate beneficial reuse of dredged materials. This plan will cover fine sediment dredged from marinas, docks, and similar facilities, totaling approximately 15,000 cubic yards annually. In addition, the US Army Corps of Engineers (Corps) is considering placing a fraction of the materials from the annual dredging of Humboldt Bay's navigation channels, which generates approximately 1,000,000 cubic yards annually, in a pilot disposal site adjacent to the North Spit within the littoral cell, instead of placing the material in the HOODS outside of the littoral cell. The material that the Corps proposed to place in the pilot disposal site would likely include both fine and coarse sediment.

Plan for upslope wetland migration

Sediment augmentation will not be possible for all tidal marshes and is likely to only be effective for a limited period. In order to maximize the extent of tidal marshes around Humboldt Bay, it will also be necessary to plan for upslope marsh migration. A planning effort should be undertaken to identify the most promising locations where upslope migration could occur and the feasibility of protecting them. The planning effort should consider the following constraints:

1. Multiple owners/managers within hydrologic subunits: If tidal influence is introduced to an area that is currently upslope of the tidal prism, the tidal marsh restoration area will be determined by topography and elevation, regardless of ownership and management goals. In other words, wetland conversion will occur based on future hydrologic subunits, not on ownership or land use boundaries. Multiple landowners may have to agree on allowing their property to convert to tidal marsh, or additional dikes/protective structures may need to be constructed to limit conversion areas.

2. Subsidence of lands: Diked former tidelands constitute the majority of the lands adjacent to existing Humboldt Bay salt marshes. Most of these lands have subsided due to compaction and oxidative decomposition of soil organic matter and are currently ~1 m below sea level. If tidal influence is reintroduced to these lands, especially with added sea level rise, they will convert to mudflats rather than vegetated salt marshes. In addition, they would become sediment sinks and may further reduce accretion rates on other wetlands. Restoring wetlands on diked historic tidelands would require large sediment inputs.

3. Need to protect, relocate, or accommodate critical infrastructure: Highways, utility lines, wastewater treatment plants, the Humboldt Bay Power Plant, and other critical infrastructure are located adjacent to Humboldt Bay's wetlands. Upslope wetland migration plans will need to account for the presence of this infrastructure. It may be possible to relocate infrastructure. In other cases, infrastructure may be altered to accommodate sea level rise and allow upslope wetland migration. For example, some low-lying reaches of Highway 101 could be reconstructed as causeways. However, these approaches are likely to be very expensive, and the feasibility of securing adequate financing should be considered.

Consider Sediment Supply Implications of Current Wetland Management

If a deficit of fine sediment exists in Humboldt Bay, restoring and enhancing tidal marshes may impact the overall sediment supply in ways that could degrade existing marshes. For example, opening diked historic subsided tidelands to tidal influence restores tidal marsh on those tidelands, with multiple benefits, but also creates a sediment sink and increases sediment demand which may reduce the supply of sediment available for accretion or lead to erosion elsewhere. Invasive Spartina removal could have a similar but more minor effect by temporarily lowering marsh elevation in areas that undergo primary mechanical treatment. The significance of these impacts depends on the demand for sediment created by the project area. In many cases, the effect may be insignificant. The potential for sediment supply impacts should not prevent marsh restoration and enhancement, but they should be considered in the design phase. Where feasible and necessary, localized sediment augmentation with dredged materials could mitigate any impacts on overall sediment supply. For example, thin layer sediment augmentation on Spartina treatment areas may prevent potential marsh or mudflat erosion in the vicinity, while also increasing the resilience of the enhanced wetland.

Improve Understanding of Sediment Dynamics in Humboldt Bay

It is a truism that every research study includes a call for more research. In this instance, too, it would be helpful to have more information about accretion rates and elevation changes at specific marshes, in order to determine which marshes are most in need of intervention to increase resilience and where restored marshes could persist longest. This study has collected two years of data at five marshes, and will collect two more years of data. It would be helpful to continue data collection beyond that point, and to add SETs and MHs at additional Humboldt Bay marshes which are likely to have different sediment regimes, such as the Elk River Estuary. These preliminary data support concerns that many stakeholders already share about the threats facing Humboldt Bay's tidal marshes. Limited data and high interannual variability in accretion make it hard to determine whether some of Humboldt Bay's marshes are more resilient than others. South Bay marshes appear to have higher accretion rates but face higher rates of RSLR than the North Bay, indicating that there may not be a dramatic difference between the two regions in resiliency to SLR. However, our current knowledge is not adequate to determine which parts of Humboldt Bay would be most resilient to SLR.

References

Audubon Louisiana. 2017. Utilizing Small Dredge Technology for Restoration of Marsh on Private Properties. Available: https://la.audubon.org/sites/g/files/amh596/f/audubonla_dredgeguide_2017_.pdf

California Coastal Sediment Management Workgroup (CCSMW) 2017. Coastal Regional Sediment Management Plan: Eureka Littoral Cell, California. Available: http://humboldtbay.org/sites/humboldtbay2.org/files/documents/ELC%20CRSMP%20clean%20draft%2020170510_reduced.pdf

Curtis, J.A., Flint, L.E., Stern, M.A., Lewis, J. Klein, R.D. *In review.* Amplified impacts of climate change on fine-sediment supply and tidal marsh resiliency, Humboldt Bay, California.

Curtis, J.A., Freeman, C. and Thorne, K.M. 2019. Early results - salt marsh response to changing fine-sediment supply conditions, Humboldt Bay, CA. In SEDHYD 2019.

Hine, S.K. 2015. Adapting to Rising Sea Levels in San Francisco Bay: The Potential for Thin Layer Sediment Application to Enhance Tidal Marsh Resiliency through This Century.
Master's Projects and Capstones. 275. Available: https://repository.usfca.edu/capstone/275

McAtee, K. 2018. Impact of Sediment Augmentation on Plant and Invertebrate Communities in a Southern California Coastal Wetland. Master's thesis, CSU Long Beach. Available: https://pqdtopen.proquest.com/doc/2015122098.html?FMT=AI

Thorne, K.M., Takekawa, J.Y., Buffington, K.J., Freeman, C.M., and Janousek, C.N. 2015. Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge. Unpubl. Addendum - Data Summary Report. USGS Western Ecological Research Center, Vallejo, CA. 61pp.
Available: https://www.sciencebase.gov/catalog/item/54b017cee4b061c233108661

Tyrrell, M. 2017. Increasing Salt Marsh Resilience in the Face of Sea Level Rise – Investigating Thin Layer Deposition (Sediment Augmentation) as a New Management Technique. Presentation at Cape Coastal Conference, December 2017. Available: http://www.waquoitbayreserve.org/wp-content/uploads/Tyrrell_Sediment-Augmentation.pdf

Appendix A. Methodology for Humboldt Bay Sediment Dynamics Studies

Appendix A-1. Curtis, J.A., Freeman, C. and Thorne, K.M. 2019. Early results - salt marsh response to changing fine sediment supply conditions, Humboldt Bay, CA. In SEDHYD 2019.

Available:
https://www.sedhyd.org/2019/openconf/modules/request.php?module=oc_program&action=view.php&id=80&file=1/80.pdf

Early results - salt marsh response to changing fine-sediment supply conditions, Humboldt Bay, CA

Jennifer A. Curtis, Geologist, U.S. Geological Survey, Eureka, CA, jacurtis@usgs.gov
Chase Freeman, Biologist, U.S. Geological Survey, Davis, CA, cfreeman@usgs.gov
Karen Thorne, Research Ecologist, U.S. Geological Survey, Davis, CA, kthorne@usgs.gov

1.0 Introduction

The resiliency and vulnerability of natural and restored salt marshes is highly dependent upon the mineral sediment supply (Weston, 2014; Ganju et al.,2015) carried by the water that inundates the marsh surface. Marsh surface elevations are maintained through complex morpho-dynamics and marsh evolution models assume that sediment deposition, vertical accretion and elevation gain are directly proportional to suspended-sediment concentrations (Kirwan and Murray, 2007; Fagherazzi et al., 2012). In this study we use direct measurements of vertical accretion, marsh elevation change, and suspended-sediment concentrations (SSC) to investigate salt marsh response to changing fine-sediment (<63 µm) supply conditions in Humboldt Bay, CA.

Both mineral- and organic-sediment supply maintain marsh surface elevations (D'Alpaos et al., 2011; Thorne et al., 2016), which must keep pace with relative sea-level rise (RSLR) to avoid submergence and conversion to subtidal habitat if marsh transgression is not possible (Kirwan et al., 2010; Thorne et al., 2018). Modeling and field-based studies agree that sediment-rich marshes are less vulnerable to RSLR and sediment-limited marshes are more vulnerable to RSLR (Patrick and DeLaune, 1990; Thom, 1992; Stralberg et al., 2011; Thorne et al., 2016).

There is a dynamic balance that exists between the rates of RSLR, local morphology, sediment supply, hydrodynamics, plant productivity, and the ability of marsh vegetation to trap and stabilize available sediment (Thom, 1992; Callaway et al, 1996; Cahoon, 1997; Morris et al., 2002). To manage and restore salt marshes effectively and sustainably, we need to understand resiliency and how they respond to changing sediment supply conditions. In Humboldt Bay, where long-term RSLR ranges from 3.11 to 5.56 mm/yr (Anderson, 2015), which is greater than most west coast regions due to tectonic subsidence (Russell, 2012; Montillet et al., 2018), an adequate sediment supply is critical if existing and restored salt marshes are to persist into the future. This study was designed to inform management actions that may affect the trajectory of vertical marsh accretion and vulnerability to sea-level rise (SLR) such as regional sediment management, dredging, and tidal restoration to subsided former baylands.

2.0 Regional Setting

Humboldt Bay is located on the north coast of California (Figure 1). The bay is protected by coastal barriers and sand spits but is subject to energetic conditions driven by storms, waves, and wind events. Costa (1982) described the bay as a tide-driven coastal lagoon with limited freshwater contributions that occur primarily during large winter storms. There are three subembayments referred to as the Entrance Bay, North Bay and South Bay. The subembayments are connected by the entrance channel and a network of navigation channels that require periodic maintenance dredging (HBHRCD, 2007). Dredging began in 1881 and currently the average annual volume of dredged fine-sediment (<63 µm) is approximately 60,500 m3 (CCSMW, 2017), which equates to 0.10 Mt/yr using a conversion factor of 1.7 Mt/m3.

The sheltering effect of the barrier spits protects the interior of the bay from wave exposure and allowed expansive areas of salt marsh to form historically in low energy environments along the bay margins. In 1870 salt marshes occupied approximately 36 km2 (Figure 1) but the present distribution represents less than 10% of the former extent (Pickart, 2001). Currently, salt marshes exist as fragments along the bay's margins, at the mouths of local tributaries, or recessed upstream within tidal slough channels. Approximately 70, 25, and 5% of the remaining salt marshes (<3.6 km2) are found in the North Bay, Entrance Bay and South Bay, respectively (Schlosser and Eicher, 2012). These tidal marshes are important habitat for migratory and resident birds and juvenile coho salmon (Oncorhynchus kisutch).

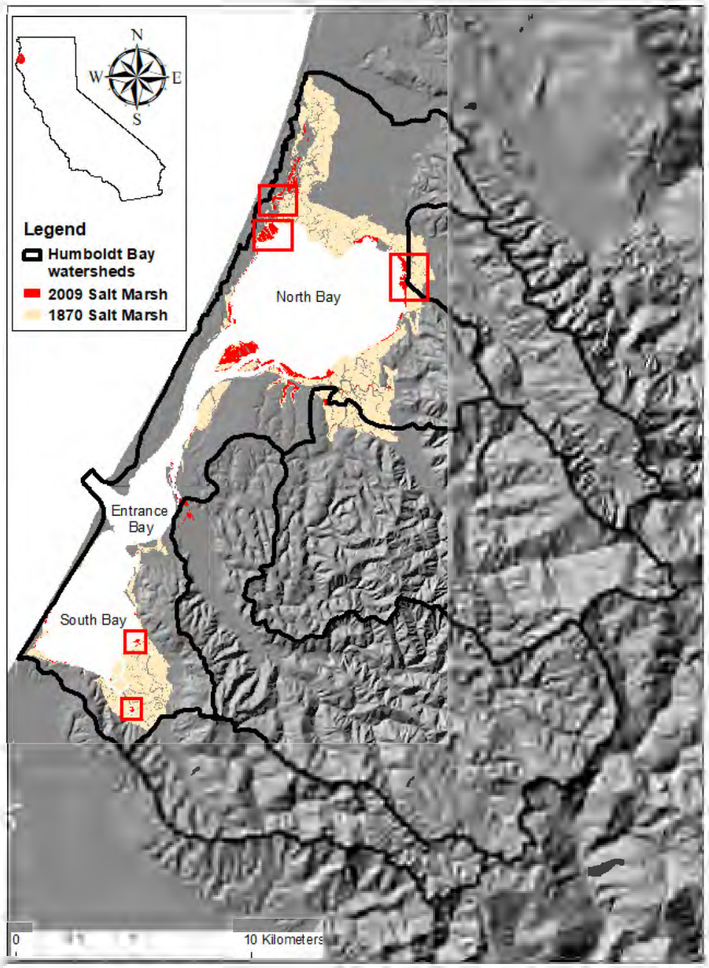

Figure 1. Humboldt Bay study area showing spatial extent of tidal salt marshes in 1870 (Laird, 2007) and 2009 (Schlosser and Eicher, 2012). Red bounding boxes delineate five salt marsh study sites (see Figure 2 for detailed study marsh maps).

2.1 Hydrodynamics

Humboldt Bay is relatively shallow with 39 km2 of mudflats exposed at mean lower low water (MLLW) and the mean daily tidal exchange volume is approximately 114 million m3/day (Anderson, 2015). The exchange volume, or tidal prism, is quite large in comparison to the freshwater discharge from the local watersheds. The mean annual freshwater discharge is approximately 0.6 million m3/yr (Curtis et al., in review). The relatively small freshwater inflow from the bay watersheds results in tidally-dominated circulation, with estuarine conditions existing only during the winter-runoff season at the tributary-bay interface.

The bay experiences mixed-semidiurnal tides with a mean diurnal range of 2.1 meters (estimated as the difference between MLLW and MHHW) and mean tide of 1.49 meters (National Oceanic and Atmospheric Agency Station, North Spit, 9418767; https://tidesandcurrents.noaa.gov/). The North Bay is deeper relative to South Bay and the contributions to the tidal prism are ~50% and ~25% respectively (Anderson, 2015).

Notably, the flushing rates of North Bay are lower than South Bay due to the bay's morphology (Costa, 1982) and this influences the amount of marine-derived sediment that can enter and the amount of freshwater-derived sediment that can exit. Because the volume of the three subembayments is large in comparison to the tidal channels, water that flows into the bay on a high tide cannot be completely replaced during a single tidal exchange. Approximately 41% of the water is replaced during each tide cycle and full tidal exchange can take 4 to 21 days (Schlosser and Eicher, 2012).

2.2 Climate, hydrology, and fine-sediment supply

Humboldt Bay is located at the transition between the Pacific Northwest and California climate regions, within the Coast Range geologic province, and has a Mediterranean climate with distinct cool-dry summers and mild-wet winters. The average annual precipitation is 1,585 mm/yr, of which only 3% falls between June and September (Curtis et al., in review). The orographic effect of the Coast Range creates a strong precipitation gradient and the hydrology is characterized by extremes. Winter discharge peaks are typically rainfall-driven, and snowmelt plays a less significant role. However heavy rain events, referred to as atmospheric rivers (Dettinger et al., 2011), can produce dramatic floods (Brown and Ritter, 1971; Waananen, 1971).

Watersheds that deliver sediment to the north coast of California are characterized by steep-forested uplands and low-lying areas near the mouth composed of floodplains, pastures and wetlands. These coastal watersheds have high rates of fine-sediment yield related to regional tectonics, erodible lithology, climate and land use history (Brown and Ritter, 1971; Kelsey, 1980; Milliman and Farnsworth. 2001; Warrick et al., 2013).

Humboldt Bay receives direct inputs of fine-sediment and freshwater from several small tributary watersheds with a combined contributing area of 442 km2 (Figure 1). Historically, the upland forests were extensively logged (Leithold et al., 2005; Klein et al., 2012) and low-lying areas have been diked and leveed (Schlosser and Eicher, 2012).

The coastal sediment budget is dominated by sediment discharged from the Eel River (9,415 km2) during winter runoff events (Wheatcroft et al., 1997; Wheatcroft and Borgeld, 2000; Farnsworth and Warrick, 2007, Warrick, 2014). Sediment discharge from the coastal rivers of northern California peaked in water year 1965 and have since declined (Warrick et al., 2013). The peak in sediment discharge was related to intense logging and a devastating flood in 1964 (Brown and Ritter, 1971; Waananen, 1971). Because the daily tidal exchange within Humboldt Bay is much larger than the annual freshwater input, the bay may be a sink for fine-sediment derived from oceanic sources but there are no direct measurements available to support this assertion.

3.0 Salt Marsh Descriptions

We selected five study marshes (Table 1) distributed throughout Humboldt Bay (Figure 2) for monitoring salt marsh accretion and elevation change. Two of the sites (Mad River and Manila) were established in 2013. Baseline measurements for this study began in November of 2015. Mad River marsh and Manila marsh are in the western region of North Bay. Mad River marsh is a high elevation island marsh located upstream within Mad River Slough; while Manila marsh is a low elevation fringe marsh located at the bay margin. Sediment is supplied from the tidal channels; however, there is freshwater drainage from the dunes to the west and a perennial stream that emerges at the base of the moving dunes that discharges to Mad River Slough. Jacoby marsh, located on the eastern edge of North Bay at the mouth of Jacoby Creek, is a high elevation deltaic marsh with direct inputs of freshwater and sediment. White marsh and Hookton marsh are in the eastern region of South Bay. White marsh is a low elevation island marsh located at the bay margin; while Hookton marsh is a low elevation island marsh located upstream within Hookton Slough. Salmon Creek flows into Hookton Slough downstream from Hookton marsh and supplies direct inputs of freshwater and sediment.

Four of the study marshes (Mad River, Manila, White and Hookton) are within the USFWS Humboldt Bay National Wildlife Refuge and are part of a regional Spartina densiflora eradication program. *S.densiflora* is an invasive cordgrass that has infested approximately 90% of the salt marshes within Humboldt Bay (Pickart, 2001). Manila marsh, managed by the California Department of Fish and Wildlife, is not part of the eradication program. In 2006, pilot studies for mechanical treatments to remove *S.densiflora* began in Mad River Slough and in 2010 a regional eradication effort began (Pickart, 2012). During mechanical treatments low elevation zones and microtopography are created that could contribute to incremental lowering of marsh surface elevations. Pickart (2013) conducted repeat laser level surveys at Jacoby marsh to measure changes in mean marsh elevations related to various *S.densiflora* treatments. After 1.5 years marsh elevations had recovered and were within +/-1.3 cm of the baseline elevations; but this may have been accelerated due to the site being located at the mouth of Jacoby Creek, which is one of the primary tributaries that contributes sediment to the bay (Curtis et al., in review).

Table 1. Descriptions and attribute information for five salt marshes located in Humboldt Bay, CA. Relative sea-level rise (RSLR) estimates are from Anderson, 2015.

Site Name	Geomorphic Setting	Area (km^2)	RTK-GPS (Number of points)	Elevation (NAVD88) Mean (m)	Elevation (NAVD88) Range (m)	Spartina Treatment	Base Line Date	RSLR (mm/yr)
North Bay Marshes								
Mad River	Island	0.06	852	2.05	1.20-2.29	2006, 2008, 2013 + maintenance	11/19/15	3.11
Manila	Fringe	0.13	732	1.72	0.79-2.53	none	11/19/15	3.11
Jacoby	Deltaic	0.12	558	2.02	1.03-2.43	2010, 2011 + maintenance	11/20/15	3.11
South Bay Marshes								
White	Island	0.03	109	1.79	1.00-1.99	2010, 2011+ maintenance	11/22/15	5.56
Hookton	Island	0.02	83	1.83	1.12-2.17	2010, 2011+ maintenance	11/22/15	5.56

4.0 Methods

4.1 Marsh Elevation and Vertical Accretion Monitoring

We installed deep rod Surface Elevation Table (SET) and feldspar marker horizon (MH) plots (Figure 3) to quantify the relative contributions of surface and subsurface processes to vertical accretion and elevation change in each of the five study marshes. The SET-MHs were installed in Mad River and Manila marshes in 2013. The SET-MHs were installed in Jacoby, White and Hookton marshes in 2015. A summary of the SET-MH protocol was published by Lynch et al. (2015).

Vertical changes in the marsh surface are the result of accretion, erosion, decomposition, compaction, shrink-swell caused by groundwater flux, swell caused by root growth, and deeper processes such as regional subsidence or uplift. The SET measurements quantify surface elevation change and the MH measurements quantify vertical accretion above a feldspar layer applied on the marsh surface. Vertical accretion is defined as the buildup of mineral and organic sediment on the marsh surface, and elevation change is defined as a change in the height of the wetland surface relative to a local benchmark.

At each study marsh two representative sites were selected after considering surface elevations, vegetation composition and distance from tidal sources (Figure 2). One SET and three MHs were deployed at each site (a total of two SETs and six MHs per marsh) following standardized methods (Cahoon et al., 2002; Webb at al., 2013). SET-MHs were measured during quarterly site visits. Measurement of the MH entails removing a small plug of soil using a soil knife, measuring the depth of surface accretion above the feldspar layer, and replacing the plug. Elevation change is measured by attaching the SET instrument to a collar installed at the top of the local benchmark, in this case the top of the deep rod. The SET instrument provides a constant reference plane in space from which the distance to the marsh surface can be measured. Nine pins are lowered to the surface in four ninety-degree cardinal directions yielding 36 observations. Repeat measurements can resolve millimeter-scale change (Cahoon et al, 2002) because the orientation of the table in space remains fixed in time.

4.2 Bias-Corrected Digital Elevation Model Generation

Baseline elevation RTK-GPS surveys, completed in 2012 and 2013 at the five study marshes (Takekawa et al., 2013), were used to correct the vegetation bias in an available bare-earth high resolution (1 meter) digital elevation model (DEM; CA-SCC, 2012). The bias-corrected DEM was used to estimate the marsh elevations presented in Table 1. Elevations were surveyed using a Leica survey-grade GNSS rover (Viva GS15 and RX1250X models). GPS real-time kinematic (RTK) corrections were streamed to the rover from a Leica base station (Leica GNSS Receiver GS10 with Leica AS10 antenna) during the surveys. The mean vertical error was ±2 cm (Thorne et al. 2015, Thorne et al., 2016) and the ellipsoid heights of the marsh surface were post-processed to determine orthometric heights referenced to NAVD88 and the geoid 12A model.

The RTK-GPS elevations and a Normalized Difference Vegetation Index (NDVI) were used to correct a positive bias in the marsh DEMs related vegetation cover using the LEAN method (Buffington et al., 2016). We obtained LiDAR-derived DEMs from the Digital Coastal Data Access Viewer (https://coast.noaa.gov/dataviewer/) and 2016 multispectral airborne imagery data from the National Agriculture Imagery Program (NAIP; https://catalog.data.gov/dataset/naip-public-image-services). From the NAIP imagery we calculated an NDVI:

$$NDVI = ([NIR-Red]/[NIR+Red])$$

where “Red” included wavelengths of 608-662 nm and “NIR” included wavelengths of 833-887 nm. Using the LEAN method, the positive bias in the LiDAR -DEM was calculated by determining elevations difference between the LiDAR -DEM and the RTK-GPS elevations. We then used a multivariate linear regression model to define a statistical relationship between LiDAR error, NDVI, and LiDAR elevation. The regression model was used to develop bias-corrected mean elevations estimates for each study marsh (Table 1).

4.3 Water Quality and Suspended-Sediment Monitoring

Water quality stations (Table 2) were established in Mad River Slough (USGS 405219124085601 MAD R SLOUGH NR ARCATA CA) and Hookton Slough (USGS 404038124131801 HOOKTON SLOUGH NR LOLETA C) in the primary tide tidal channels that supply sediment to the adjacent study marshes (Figure 2). Water quality sondes (YSI-EXO2), equipped with a turbidity sensor and a combined temperature and specific conductance sensor, were deployed in March of 2016 at a fixed water depth of 1.0 meter. The sondes and sensors were cleaned monthly and calibrations checked during quarterly site visits. Specific conductance was converted to salinity using a temperature (25^{o} C) compensated method (*Wagner et al., 2006*). Continuous 15-minute records of turbidity, temperature, specific conductance, and salinity are available for each station at https://waterdata.usgs.gov/nwis/qw .

Water samples were collected, and water depths measured, during quarterly site visits. A Van-Dorn sampler was used to collect 1-liter water samples throughout a rising and falling tide at 1.5-hour intervals. During each visit one replicate sample was collected to address variability and field blanks were collected periodically to verify adequate cleaning procedures. Water samples were stored in brown HDPE bottles, kept cool and shipped to the USGS Cascade Volcanic Observatory sediment laboratory (Vancouver, WA) for analysis. Suspended-sediment concentrations (SSC) were determined by filtration methods for all the samples. Due to funding limitations percent organic material was determined by loss on ignition (LOI) for a subset of samples, typically two samples per site per visit. The water sample data are also available for each station at https://waterdata.usgs.gov/nwis/qw.

Turbidity can be used as a surrogate for SSC (*Rasmussen et al., 2009*) and we used ordinary least-squares regression to convert the turbidity time series to SSC. The time and date stamp for each of the water samples was synced with the turbidity time series to determine associated turbidity values. A least-squares linear regression equation was determined using the lab-derived SSC and associated turbidity values. The regression model was used to convert turbidity values to SSC and derive a continuous 15-minute SSC time series. The converted SSC time series was used to assess variations in SSC and to investigate correlations with marsh accretion measurements.

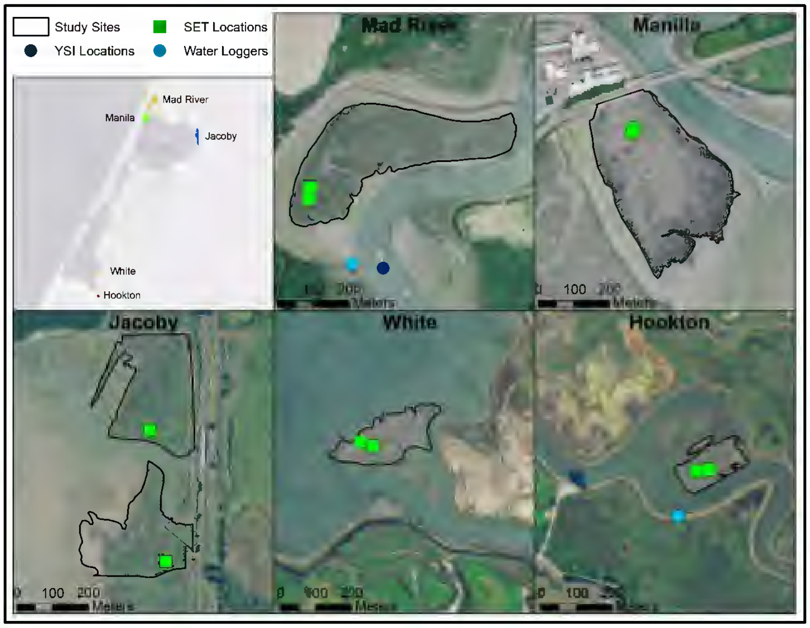

Figure 2. Five study marsh monitoring sites in Humboldt Bay, CA. Map shows the location of study marshes, Sediment Elevation Tables (SET), Marker Horizons (MH), water quality sondes (YSI), and water level loggers.

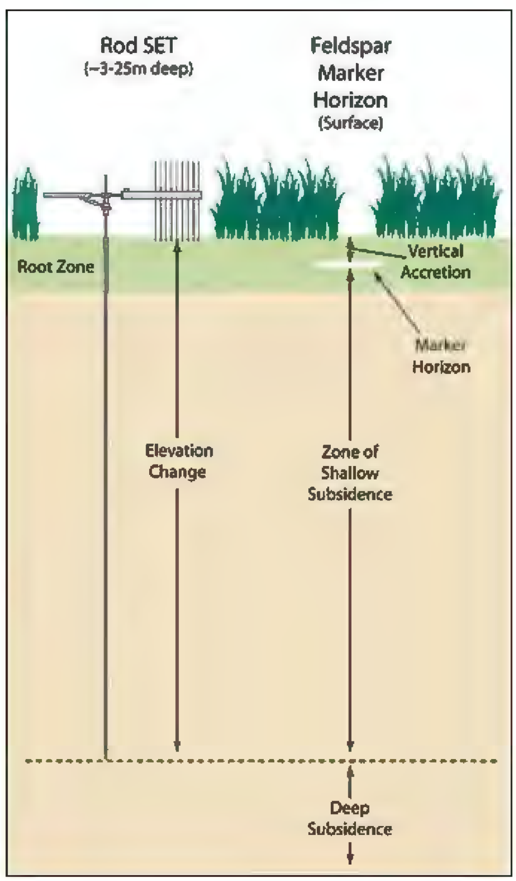

Figure 3. Conceptual diagram showing how the soil profile is measured to assess marsh surface and subsurface processes by Surface Elevation Table (SET) and Marker Horizon (MH) techniques (Cahoon et al, 2002).

Table 2. Descriptions of two water quality monitoring stations located in Humboldt Bay, CA.

Water Quality Station	Instruments	Parameters	Easting	Northing	Deployment Date
USGS 405219124085601 MAD R SLOUGH NR ARCATA CA	YSI-EXO2	Turbidity (FNU) Specific conductance (µs/cm @25°C) Temperature (°C)	403198	4525162	3/5/2016 - present
	Hobo U20	Water level (m)	403133	4525173	3/17/2016 – 12/8/16
	LT Edge (2...)	Water level (m)	403133	4525173	12/8/16 - present
USGS 404038124131801 HOOKTON SLOUGH NR LOLETA C	YSI-EXO2	Turbidity (FNU) Specific conductance (µs/cm @25°C) Temperature (°C)	396746	4503666	3/5/2016 - present
	Hobo U20	Water level (m)	397033	4503557	3/17/2016 – 12/8/16
	LT Edge (2...)	Water level (m)	397033	4503557	12/8/16 - present

5.0 Results

5.1 Marsh Elevation and Accretion Measurements

There were nine SET-MH measurements collected during the 2-year study period between November 22nd, 2015 and December 3rd, 2017. Again, SET measurements quantify elevation change and feldspar MH measurements quantify vertical accretion (Cahoon et al., 2002; Lynch et al., 2015). If vertical accretion is greater than elevation change, shallow subsidence (accretion minus elevation change) related to decomposition or compaction may be occurring. If accretion is equal to elevation change we can infer that surface accretion is driving elevation change and subsurface processes are negligible. If accretion is less than elevation change we can infer that shallow expansion related to swelling of soils by water storage or an increase in root volume may be occurring.

Over the 2-year study period elevation changes and accretion was spatially and temporally variable (Table 3). At the South Bay sites (Hookton and White) accretion rates were about 1.5 times greater than elevation changes; but changes in elevation and accretion were about equal at the North Bay sites (Mad River, Manila, and Jacoby). Across all the sites elevation change and accretion were lower during 2016 (-0.26mm ±0.64; 1.56mm ±1.66) and higher in 2017 (3.15mm ±0.30; 2.82mm ±1.04).

We also compared the annual rates of elevation change and accretion to estimates of long-term trends in RLSR (Figure 4) estimated for the Humboldt Bay region (Anderson, 2015). RSLR estimates for North Bay and South Bay are 3.11 mm/yr and 5.56 mm/yr respectively (Table 1). During the 2-year study period the rates of annual elevation gain did not outpace long-term trends in RSLR; however, these short-term results represent initial baseline measurements and should be interpreted with caution within the framework of the longer-term trends in RSLR. Continued monitoring, over decadal or longer periods, is required to detect trends in elevation gain and vertical accretion.

Table 3. Summary of elevation change and accretion measurements and the associated standard errors over a 2-year period for five study marshes located in Humboldt Bay, CA.

Site	2016		2017		Cumulative		Average Annual	
	Elevation change (mm)	Accretion (mm)	Elevation change (mm)	Accretion (mm)	Elevation change (mm)	Accretion (mm)	Elevation change (mm/yr)	Accretion (mm/yr)
North Bay Marshes								
Mad River	-0.89 ± 0.37	-4.29 ± 0.21	0.52 ± 0.18	5.33 ± 0.46	-0.38 ± 0.55	1.04 ± 0.67	-0.19 ± 0.28	0.52 ± 0.34
Manila	-3.04 ± 1.54	-0.3 ± 4.67	5.54 ± 0.44	0.67 ± 2.08	2.50 ± 1.98	0.36 ± 6.75	1.25 ± 0.99	0.19 ± 3.38
Jacoby	0.71 ± 0.40	2.13 ± 0.88	2.49 ± 0.18	0.75 ± 0.04	3.19 ± 0.58	2.88 ± 0.92	1.60 ± 0.29	1.44 ± 0.46
South Bay Marshes								
Hookton	1.09 ± 0.52	7.90 ± 2.23	3.25 ± 0.60	1.60 ± 2.08	4.34 ± 1.12	9.50 ±4.31	2.17 ± 0.56	4.75 ± 2.16
White	0.81 ± 0.37	2.38 ± 0.38	3.95 ± 0.11	5.75 ± 0.54	4.76 ± 0.48	8.13 ± 0.92	2.38 ± 0.24	4.07 ± 0.46
North Bay	-1.07 ± 0.77	-0.82 ± 1.89	2.85 ± 0.27	2.25 ± 0.86	1.77 ± 1.04	1.43 ± 2.78	0.89 ± 0.52	0.71 ± 1.39
South Bay	0.95 ± 0.45	5.14 ± 1.31	3.60 ± 0.36	3.68 ± 1.31	4.55 ± 0.80	8.82 ± 2.62	2.28 ± 0.40	4.41 ± 1.31
All sites	-0.26 ± 0.64	1.56 ± 1.66	3.15 ± 0.30	2.82 ± 1.04	2.88 ± 0.94	4.38 ± 2.71	1.44 ± 0.47	2.19 ± 1.36

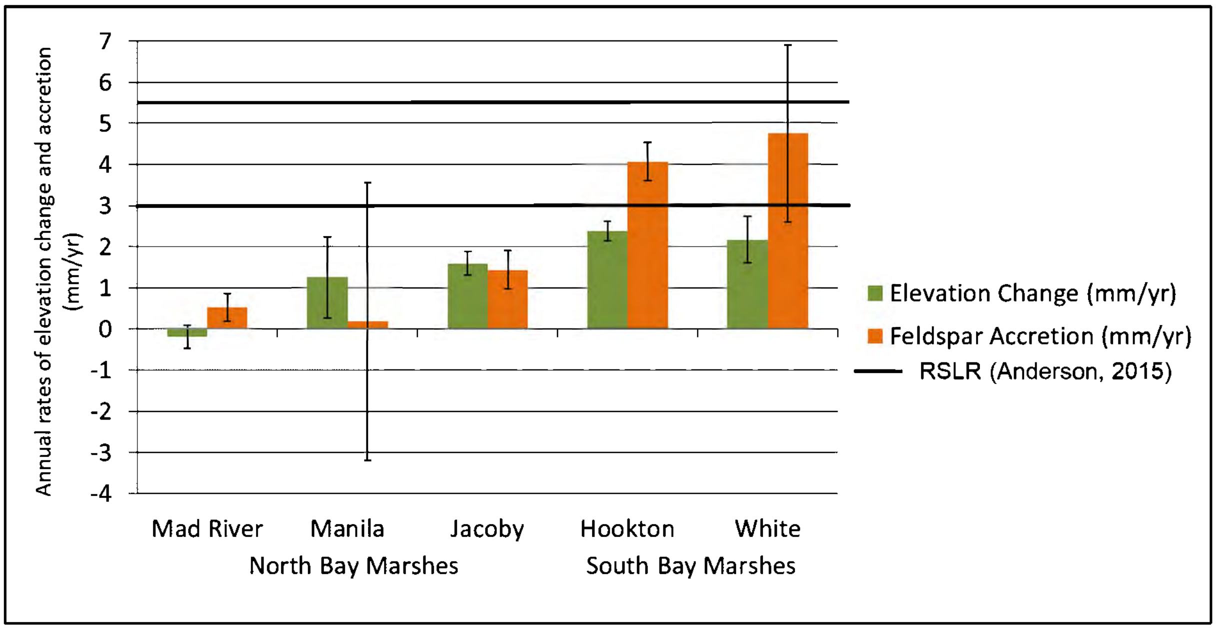

Figure 4. Summary of mean annual rates of elevation change and accretion for five study marshes located in Humboldt Bay, CA. When accretion is greater than elevation change this indicates shallow subsidence that can be caused by decomposition and compaction. When elevation change is greater than accretion this indicates accumulation of below-ground biomass or swelling of soils by water storage. The range of relative sea level rise (RSLR; Anderson, 2015) for Humboldt Bay (3.11 to 5.56 mm/yr) is shown with horizontal black lines. Uncertainty in the elevation change and accretion measurements is captured by the standard error shown as vertical error bars.

5.2 Water Quality and Suspended-Sediment Supply

We converted the turbidity records into a SSC time series using eq.1 and eq.2 and computed summary statistics for each monitoring station (Table 4). The mean SSC measured at Hookton slough (41.1 mg/L) was 2.5 times greater than the mean SSC measured at Mad River slough (16.8 mg/L). The median SSC values for the two sites were similar indicating that the bay is well-mixed and tidally-dominated for most of the year. The standard deviation (SD), coefficient of variation (CV) and range in SSC values are measures of statistical variance, which were much greater at Hookton indicating more variability in the sediment supply due to large episodic freshwater inputs.

$$\text{Hookton SSC} = 1.274 + 1.95 * \text{Turbidity} \quad r^2 = 0.928 \quad p < 0.0001, N=46 \qquad \text{eq.1}$$
$$\text{Mad River SSC} = 4.14 + 1.26 * \text{Turbidity} \quad r^2 = 0.396 \quad p < 0.0001, N=45 \qquad \text{eq.2}$$

The lack of variance in SSC measurements at Mad River Slough heavily influenced the regression model used to convert the turbidity signal to SSC values. Although the p-values indicate the Mad River and Hookton regression models are statistically significant, the lack of variance in the SSC values for the Mad River model resulted in a much lower slope and r^2 value.

Table 4. Statistical metrics for suspended-sediment concentrations (SSC) derived from continuous turbidity records collected over a 2-year study period at two water quality monitoring stations in Humboldt Bay, CA. Note: SD is the standard deviation and CV is the percent coefficient of variation.

Monitoring Station Location	USGS Water Quality Station Number	Mean SSC (mg/L)	SD SSC (mg/L)	CV SSC (%)	Min SSC (mg/L)	Max SSC (mg/L)	Median SSC (mg/L)
Mad River Slough	405219124085601	16.8	7.1	42	4.9	414.0	15.7
Hookton Slough	404038124131801	41.1	81.5	198	8.0	1598.0	19.7

6.0 Discussion

6.1 Geomorphic stability and vulnerability to SLR

Sediment supply is a primary variable for determining geomorphic stability and salt marsh vulnerability to RSLR (*Callaway, 1996; Pethick and Crooks 2000; Weston, 2014; Ganju et al., 2015 Thorne al., 2016*). Sufficient sediment supply must be available for salt marshes to gain elevation and persist in place. This study focused on direct measurements of three variables that control salt marsh resiliency and vulnerability to SLR in Humboldt Bay: fine-sediment supply, marsh elevation, and marsh accretion.

Salt marshes respond dynamically to accommodate change and have been referred to as "ephemeral landforms" (*Orr et al., 2003*). In general, wave and tidal energy is attenuated through the transfer of sediment from high-energy source areas, where transport and erosion occur, to low-energy sinks where sediment deposition and accumulation occurs. This transfer of sediment and the associated energy attenuation creates a strong morpho-dynamic response with wave and tidal energy creating morphologic change, which creates feedback that alters the local energy environment (*Pethick 1996; D'Alpaos et al., 2011; Fagherazzi et al., 2012*). The form and function of salt marshes therefore depends upon a dynamic balance between the energy regime and the transport and deposition of fine-sediment.

During periods of increased coastal energy, the natural marsh response is landward transgression to lower energy environments while the seaward edge of the marsh experiences erosion and is replaced by mudflat and subtidal habitat. Approximately 75% of the bay's shoreline is composed of artificial hard structures, including Highway 101 and a former railroad grade (*Laird, 2013*). Under current conditions much of the space to accommodate dynamic marsh transgression has been lost.

Recent studies indicate that sediment transport-based metrics are good indicators of vulnerability and wetland stability (*Ganju et al., 2013; Ganju et al., 2015*). In this study, we assumed that SSC is representative of the fine-sediment supply available for accretion. The SSC-metrics in Table 4 indicate Hookton slough (South Bay) is sediment-rich. In comparison, Mad River slough (North Bay) is sediment-limited with less fine-sediment available for accretion.

We further investigated our results to assess the correlation between accretion and SSC in Hookton and Mad River marsh using quarterly measurements of accretion and the average SSC estimated during eight quarterly intervals over the 2-year study period. There was a positive correlation between accretion and SSC for Hookton marsh where sediment-rich conditions exist, but the correlation was not statistically significant (r^2=0.16, p=0.3270). There was no correlation for Mad River marsh, where sediment-limited conditions exist ($r^2$0.00, p=0.9025) (Figure 5). Additional data collected in 2018 and 2019 may improve the correlations

In summary, the North Bay is sediment-limited and is experiencing lower long-term rates of RSLR (3.11 mm/yr). Our early results show that the North Bay marshes (Mad River, Manila, and Jacoby) are experiencing lower rates of vertical accretion (0.71±1.39 mm/yr) and elevation change (0.89±0.52 mm/yr) but there is high uncertainty associated with these measurements. In comparison, South Bay is sediment-rich and is experiencing higher long-term rates of RSLR (5.56 mm/yr) due to tectonic subsidence, which is mitigated somewhat by higher rates of accretion (4.41±1.31mm/yr) and elevation change (2.28±0.40 mm/yr). The South Bay accretion rates were greater than elevation changes, which may indicate that shallow subsidence, related to decomposition or compaction, could be a limiting factor influencing elevation gains.

The sediment-limited conditions in North Bay make Mad River and Manila marshes more vulnerable to accelerated RSLR, however, Jacoby marsh is a deltaic marsh located in the eastern region of North Bay with higher fetch and wind-wave exposure. Generally, deltaic marshes tend to have higher accretion rates (*Cahoon et al., 2006*) and the direct input of fine-sediment at Jacoby marsh may mitigate vulnerability, in this higher energy but more sediment-rich region of North Bay. South Bay marshes are more vulnerable than North Bay marshes to submergence due to higher rates of RLSR, but this is mitigated somewhat by greater sediment supply.

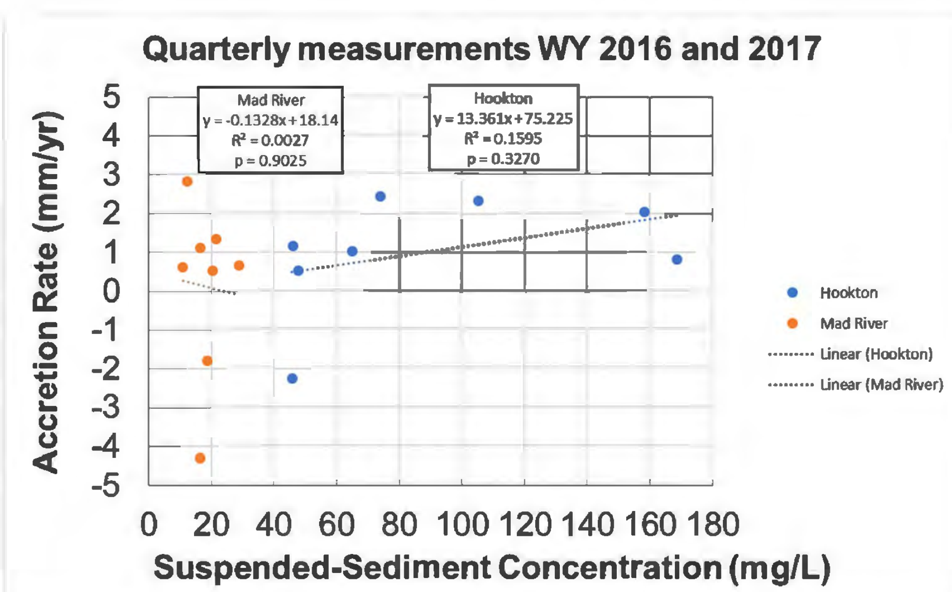

Figure 5. Correlation graph showing the relation between suspended-sediment concentration (SSC) and vertical accretion rates for two study marshes in Humboldt Bay, CA.

6.2 Fine-Sediment Budget and Management Implications

There are ongoing management and restoration activities that impact the fine-sediment budget of Humboldt Bay, which may alter the availability of sediment for marsh accretion and elevation gain. We assessed the potential impacts on the fine-sediment budget related to the regional *S.densiflora* eradication program, maintenance dredging of harbors and channels, and tidal restoration in subsided former baylands. All of these management activities alter local topography and create low elevation zones in the tidal prism. These low elevation zones impact the fine-sediment budget by increasing “sediment demand”, which may reduce the “sediment supply” available for marsh accretion and elevation gain.

The regional *S.densiflora* eradication program in Humboldt Bay uses mechanical treatments that create low-elevation microtopography. The impact of the *S.densiflora* treatments on marsh elevations was assessed at the Jacoby marsh (*Pickart, 2013*). Repeat laser level measurements indicated that after 1.5 years the surface elevations were within ± 1.3 cm of the original elevation. However, Jacoby marsh is a deltaic marsh with direct inputs of sediment and relatively high rates of accretion and elevation change and may not be representative of other North Bay marshes located in sediment-limited regions.

In a companion study Curtis et al. *(in review)* estimated the fine-sediment supply to Humboldt Bay from local watersheds (0.05 Mt/yr) and defined an imbalance created by maintenance dredging (0.10 Mt/yr). This fine-sediment deficit may be filled by natural deposition of sediment supplied from terrestrial or marine sources or by local recruitment of sediment within the bay through erosion of existing mudflats and marshes

Tidal restoration to subsided former baylands also impacts the fine-sediment budget by creating large “sediment sinks” and increasing “sediment demand”. There are several completed and planned tidal restoration projects within Humboldt Bay that involve strategically breaching dikes and levees to allow natural deposition and filling of subsided lands. A recently completed beneficial reuse study (*HBHRCD, 2015*) estimated the “sediment demand” associated with two projects in South Bay equates to 0.31 Mt, which is three times the annual maintenance dredging and 6 times the annual supply from the local watersheds.

Incorporating fine-sediment augmentation by direct placement into tidal restoration projects could ameliorate “sediment demand” and accelerate the rate of recovery to achieve adequate elevations to support salt marsh vegetation. A recent modeling study concluded that although RSLR is the primary controlling factor for marsh accretion and elevation gain, the starting surface elevation had the second greatest impact on elevation gain followed by the mineral-sediment supply (*Thorne et al., 2016*). Thus, initial elevation and sediment accretion rates, which are dependent on sediment supply, determine the effectiveness and success of salt marsh restoration.

Tidal restoration in subsided former baylands in sediment-rich areas of the bay may quickly fill and achieve the necessary elevations for the colonization of marsh vegetation. Conversely, projects located in sediment-limited areas may require augmentation to achieve desired increases in elevations to support marsh vegetation. Although sediment augmentation can add significantly to restoration project costs, and it may be a limiting factor, the beneficial reuse of dredged fine-sediment is one promising approach for salt marsh restoration that mitigates “sediment demand” and avoids recruitment of sediment from existing subtidal and intertidal habitats.

7.0 Conclusions and Future Work

This study improved our understanding of how salt marshes respond to changing sediment supply conditions in Humboldt Bay, CA. South Bay is shallower and rates of RSLR are higher due to tectonic subsidence, but this is balanced by a larger sediment supply and higher rates of marsh accretion and elevation change. North Bay is deeper, much larger volumetrically with lower rates of RSLR, sediment supply, accretion, and elevation change. Salt marshes are highly dynamic systems that keep pace with SLR by vertical accretion and horizontal retreat when space for retreat is available. Without an adequate sediment supply, the salt marshes in Humboldt Bay are more vulnerable to submergence due to accelerated SLR. Early results indicate short-term rates of elevation gain were lower than the long-term estimates of RSLR for all five of the study marshes.

Continued monitoring of the fine-sediment budget, marsh accretion and elevation change is essential to understand the trajectory of marsh formation within the framework of accelerated SLR and to determine whether future management actions will be needed to mitigate additional marsh loss. With informed regional sediment management and environmental planning, it may be possible to mitigate the sediment demand created by management activities and associated impacts. Marsh augmentation, using excess fine-sediment derived from maintenance dredging, is a potential approach for alleviating imbalances in the fine-sediment budget that impact the sediment supply available for marsh accretion and elevation gain.

8.0 References

Anderson, J.K., 2015. Humboldt Bay: Sea Level Rise, Hydrodynamic Modeling and Vulnerability Mapping. Prepared for the State Coastal Conservancy and Coastal Ecosystems Institute of Northern California. McKinleyville, CA: Northern Hydrology & Engineering.

Brown III, W. M., and Ritter, J. R. 1971. Sediment transport and turbidity in the Eel River Basin, California. U.S. Geol. Survey. Water Supply Paper 1986.

Buffington, K.J., Dugger, B.D., Thorne, K.M. and Takekawa, J.Y., 2016. Statistical correction of lidar-derived digital elevation models with multispectral airborne imagery in tidal marshes. *Remote Sensing of Environment*, *186*, pp.616-625.

Cahoon, D. 1997. Global warming, sea-level rise, and coastal marsh survival. USGS National Wetlands Research Center. USGS FS-09 1-97.

Cahoon, D.R., Lynch, J.C., Hensel, P., Boumans, R., Perez, B.C., Segura, B., and Day, J.W., 2002, High precision measurements of wetland sediment elevation—I, recent improvements to the sedimentation-erosion table: Journal of Sedimentary Research, v. 72, p. 730–733.

Cahoon, D.R., Hensel, P.F., Spencer, T., Reed, D.J., Mckee, K.L., and Saintilan, N., 2006. Coastal wetland vulnerability to relative sea-level rise: wetland elevation trends and process controls. Ecological Studies 190:271–292.

California Coastal Sediment Management Workgroup (CCSMW), 2017. Eureka Littoral Cell-Coastal Regional Sediment Management Plan, p. 176.

California State Coastal Conservancy (CA-SCC) 2012. California Coastal Conservancy Coastal Lidar Project Bare Earth Lidar Digital Elevation Data.

Callaway, J. C., J. A. Nyman, and R. D. DeLaune. 1996. Sediment accretion in coastal wetlands: A review and a simulation model of processes. Current Topics in Wetland Biogeochemistry 2:2-23.

Costa, S. L. 1982. The physical oceanography of Humboldt Bay. Proceedings Humboldt Bay Symposium. C. Toole and C. Diebel (ed.), HSU Center for Community Development, Arcata, CA.

Curtis, J, A., Flint, L.E., Stern, M.A., Lewis, J., and Klein, R.D. in review. Fine-sediment supply under current and future climates for Humboldt Bay, CA, submitted to Estuaries and Coasts

D'Alpaos A., Mudd, S.M., and L. Carniello, 2011. Dynamic response of marshes to perturbations in suspended sediment concentrations and rates of relative sea level rise: Earth Surface, v. 116, no. F4,

Dettinger, M.D., Ralph, F.M., Das, T., Neiman, P.J. and Cayan, D.R., 2011. Atmospheric rivers, floods and the water resources of California. *Water*, *3*(2), pp.445-478.

Fagherazzi, S., Kirwan, M.L., Mudd, S.M., Guntenspergen, G.R., Temmerman, S., D'Alpaos, A., van de Koppel, J., Rybczyk, J.M., Reyes, E., Craft, C. and Clough, J., 2012. Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors. *Reviews of Geophysics*, *50*(1).

Farnsworth, K.L., Warrick, J.A., 2007, Sources, Dispersal, and Fate of Fine Sediment Supplied to Coastal California: U.S. Geological Survey Scientific Investigations Report 2007–5254, 77 p.

Ganju, N. K., N. J. Nidzieko, and M. L. Kirwan, 2013. Inferring tidal wetland stability from channel sediment fluxes: Observations and a conceptual model, J. Geophys. Res. Earth Surf., 118, 2045.

Ganju, N. K., M. L. Kirwan, P. J. Dickhudt, G. R. Guntenspergen, D. R. Cahoon, and K. D. Kroeger, 2015. Sediment transport-based metrics of wetland stability, Geophys. Res. Lett., 42, 7992–8000.

Humboldt Bay Harbor Recreation and Conservation District (HBHRCD), 2015. Beneficial Reuse of Dredged Materials for Tidal Marsh Restoration and Sea Level Rise Adaptation in Humboldt Bay, California, Eureka, CA.

Kelsey, H.M., 1980. A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941–1975: summary. Geological Society of America Bulletin, Part I 91, 190–195.

Klein, R.D., Lewis, J. and Buffleben, M.S., 2012. Logging and turbidity in the coastal watersheds of northern California. *Geomorphology*, *139*, pp.136-144.

Kirwan, M. L., G. R. Guntenspergen, A. D'Alpaos, J. T. Morris, S. M. Mudd, and S. Temmerman (2010), Limits on the adaptability of coastal marshes to rising sea level, Geophys. Res. Lett., 37, L23401, doi:10.1029/2010GL045489.

Laird, A., B. Powell, J. Robinson and K. Shubert. 2007. Historical atlas of Humboldt Bay and the Eel River delta. Humboldt Bay Harbor, Recreation and Conservation District, Eureka, CA. Electronic document: DVD.

Laird, A. 2013. Humboldt Bay Shoreline Inventory, Mapping and Sea Level Rise Vulnerability Assessment. Prepared for State Coastal Conservancy. Trinity Associates, Arcata, CA.

Leithold, E.L., Perkey, D.W., Blair, N.E., Creamer, T.N., 2005. Sedimentation and carbon burial on the northern California continental shelf: the signatures of land-use change. Continental Shelf Research 25 (3), 349–371.

Lynch, J. C., P. Hensel, and D. R. Cahoon. 2015. The surface elevation table and marker horizon technique: A protocol for monitoring wetland elevation dynamics. Natural Resource Report NPS/NCBN/NRR—2015/1078. National Park Service, Fort Collins, Colorado.

Milliman, J.D., Farnsworth, K.L., 2011. River Discharge to the Coastal Ocean – A Global Synthesis. Cambridge University Press, Cambridge, UK, 384pp.

Montillet JP, Melbourne TI, Szeliga, WM (2018) GPS vertical land motion corrections to sea-level rise estimates in the Pacific Northwest. Journal of Geophysical Research: Oceans 123:1196−1212.

Morehead, M.D. and Syvitski, J.P. (1999) River-plume sedimentation modeling for sequence stratigraphy: application to the Eel margin, northern California. *Mar. Geol.*, **154**, 29–41.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. Ecology 83:2869-2877.

Orr, M., Crooks, S. and Williams, P.B., 2003. Will restored tidal marshes be sustainable? *San Francisco Estuary and Watershed Science*, *1*(1).

Patrick, W., & DeLaune, R., 1990. Subsidence, Accretion, and Sea Level Rise in South San Francisco Bay Marshes. *Limnology and Oceanography, 35*(6), 1389-1395.

Pethick JS. 1996. The geomorphology of mudflats. In: Nordstrom KF, Roman CT, editors. Estuarine shores: evolution, environment and human health. Chichester, UK: John Wiley. p 185-211.

Pethick JS, Crooks S. 2000. Development of a coastal vulnerability index: a geomorphological perspective. Environmental Conservation 27:359-367.

Pickart, A. 2001.The distribution of *Spartina densiflora* and two rare salt marsh plants in Humboldt Bay 1998-1999. Unpublished report, U.S. Fish and Wildlife Service, Humboldt Bay National Wildlife Refuge, Arcata, California.

Pickart, A. 2012. *Spartina densiflora* invasion ecology and the restoration of native salt marshes, Humboldt Bay, California. unpublished report, U.S. Fish & Wildlife Service, Arcata, California

Pickart, A, 2013, A Comparison of Mechanical Treatments for the Control of *Spartina densiflora* at Jacoby Creek Unit, Humboldt Bay National Wildlife Refuge**,** unpublished report, U.S. Fish & Wildlife Service, Arcata, California.

Rasmussen, P.P., Gray, J.R., Glysson, G.D., and Ziegler, A.C., 2009, Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. C4, 52 p.

Russell, N.; Griggs, G., 2012. Adapting to Sea Level Rise: A Guide for California's Coastal Communities. Prepared for the California Energy Commission Public Interest Environmental Research Program, University of California Santa Cruz. 50 pp.

Schlosser, S., and A. Eicher. 2012. The Humboldt Bay and Eel River Estuary Benthic Habitat Project. California Sea Grant Publication T-075, 246 p.

Stralberg, D., Brennan, M., Callaway, J.C., Wood, J., Schile, L., Jongsomjit, D., Kelly, M., Parker, V.T., and Crooks, S. (2011). Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. PLOS ONE, 6.11: e27388.

Takekawa, J.Y., Thorne, K.M., Buffington, K.J., Freeman, C.M., Powelson, K.W., and Block G. 2013. Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge. Unpubl. Data Summary Report. USGS Western Ecological Research Center, Vallejo, CA. 44pp + Appendices.

Thom, R. M. 1992. Accretion rates of low intertidal salt marshes in the Pacific Northwest. Wetlands

Thorne, K.M., MacDonald, G.M., Ambrose, R.F., Buffington, K.J., Freeman, C.M., Janousek, C.N., Brown, L.N., Holmquist, J.R., Gutenspergen, G.R., Powelson, K.W., Barnard, P.L., and Takekawa, J.Y., 2016, Effects of climate change on tidal marshes along a latitudinal gradient in California: U.S. Geological Survey Open-File Report 2016-1125, 75 p.

Thorne, K.M., G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C. Freeman, C. Janousek, L. Brown, J. Rosencranz, J. Holmquist, J. Smol, K. Hargan, and J. Takekawa. 2018. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise: Science Advances, v. 4, no. 2.

van Proosdij, D., Lundholmb, J., Neatt, N., Bowron, T., Graham, J., 2010. Ecological reengineering of a freshwater impoundment for salt marsh restoration in a hypertidal system. Ecological Engineering 36, 1314e1332.

Waananen, A.O., Harris, D.D. and Williams, R.C., 1971. *Floods of December 1964 and January 1965 in the Far Western States; Part 1 Description* (No. 1866-A). US Govt. Print. Office. 276p.

Wagner, R.J., Boulger, R.W., Jr., Oblinger, C.J., and Smith, B.A., 2006, Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, 51 p.

Warrick, J.A., Madej, M.A., Goñi, M.A., Wheatcroft, R.A., 2013. Trends in the suspended sediment yields of coastal rivers of northern California, 1955–2010. Journal of Hydrology 489, 108–123.

Warrick, J.A., 2014. Eel River margin source-to-sink sediment budgets: Revisited. *Marine Geology*, *351*, pp.25-37.

Webb, E.L., Friess, D.A., Krauss, K.W., Cahoon, D.R., Guntenspergen, G.R., and Phelps, J., 2013, A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise: Nature Climate Change, v. 3, p. 458–465.

Wheatcroft, R.A., Sommerfield, C.K., Drake, D.E., Borgeld, J.C., Nittrouer, C.A., 1997. Rapid and widespread dispersal of flood sediment on the northern California margin. Geology 25, 163–166.

Wheatcroft, R.A., Borgeld, J.C., 2000. Oceanic flood deposits on the northern California shelf: large-scale distribution and small-scale physical properties. Continental Shelf Research 20, 2163–2190.

Appendix A-2. Methods from Curtis, J.A., Flint, L.E., Stern, M.A., Lewis, J. Klein, R.D. In review. Amplified impacts of climate change on fine-sediment supply and tidal marsh resiliency, Humboldt Bay, California.

Methods: Our objective was to investigate the impact of climate change on hydrology, fine sediment supply and salt marsh resiliency, using Humboldt Bay as a case study, which required developing a modeling approach that could be projected into the future on the basis of climate alone. We developed an integrated modeling approach that uses empirical and statistical methods to investigate whether documented declines in the regional supply of fine sediment under current conditions may be offset under future climates by projected increases in the magnitude and requency of extreme runoff events and increases in the fine-sediment supply.

A regional water-balance model was used to simulate mean daily stream discharge (Q_w) under current and future climates for all of the hydrology basins within the Humboldt Bay-Eel River (HBER) study region (Figure 1). Because our objective was to assess the impact of climate change on fine-sediment supply, model runs used a daily time-step and optimization of high flow conditions was prioritized over baseflows. Sediment-transport models were used to estimate sediment-discharge (Q_{ss}) under current and future climates for all of the HBER sediment reporting basins. Model parameters defined for gaged basins under current conditions were used to estimate Q_w and Q_{ss} in ungaged basins and for future climate projections.

2.1 Stream discharge under current and future climates

The Basin Characterization Model (BCM; *Flint et al., 2013*) is a regional water-balance model that mechanistically models the hydrologic response to climate (e.g. precipitation and air temperature) using measured landscape attributes (e.g. topography, soils, and bedrock geology). The BCM is a fine-scale (270-meter) spatially-gridded model, which converts daily climate data into hydrologic response variables (snow accumulation, snowmelt, actual evapotranspiration, soil moisture storage, surface runoff, and groundwater recharge) for each 270-meter cell (*Figure 2*). Potential evapotranspiration (PET) is calculated from solar radiation with topographic shading and cloudiness (*Flint and Flint, 2007*). Snow is accumulated, sublimated, and melted. Excess water infiltrates and moves through the soil profile, dynamically changing soil-water storage. Changes in soil-water storage are used to calculate actual evapotranspiration (AET). The difference between PET and AET provides an estimate of climatic water deficit, which represents the stress on the subsurface landscape water supply. Depending on the soil properties and bedrock permeability, available water is then partitioned into recharge or runoff and aggregated into unimpaired stream discharge for each basin. Unimpaired stream discharge is then calibrated using a series of post-processing calibration equations described in Section 2.1.2.

2.1.1 Daily climate grids for current and future conditions

To enhance the spatial and temporal accuracy of the daily climate data available for the historical model runs, we used a method developed by *Stern et al.* (*2016*) that uses measured daily precipitation and air temperature data and monthly maps of precipitation and air temperature (PRISM; http://prism.oregonstate.1 edu/; *Daly et al., 2008*). Measured data were downloaded for 94 climate stations from the National Weather Service Cooperative Observer Program (COOP, www.ncdc.noaa.gov/), the Remote Automated Weather Stations (RAWS, www.raws.dri.edu/), and the California Irrigation Management Information System (CIMIS, www.cimis.water.ca.gov/). A quality review was performed using a jack-knifing statistical method (Efron and Stein, 1981) that identifies and removes poor quality stations or data points. We selected five global climate models (GCMs; *Table 2*) from the full ensemble of the GCMs used in the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Inter9 comparison Project Phase 5 (CMIP5). The GCMs were selected on the basis of the historical performance and their ability to produce realistic simulations of California-specific climate features (CADWR-CCTAG, 2015). Available climate projections for the five GCMs used in this study were statistically downscaled (Pierce et al., 2014) from 2°, which is approximately 222-km resolution, to a 6-km resolution using the LOcalized Constructed Analog (LOCA) method. Each of the LOCA projections, for the period from 1950 to 2005, were bias-corrected (Pierce et al., 2014), using gridded climate data from measured climate observations (Livneh et al., 2013). Theses bias-corrected LOCA projections produce better estimates of extreme events and reduce the common downscaling problem of too many light-precipitation days (Pierce et al, 2014). The LOCA projections and a description of the methods are available at http://caladapt.org/data/loca/. A Gradient and Inverse Distance Squared (GIDS; Nalder and Wein, 1988) weighting was used to downscale spatially distribute the PRISM and LOCA climate data across the HBER BCM modeling domain. The GIDS method develops a regression for each day using northing, easting, and elevation and interpolates values for each 270-meter grid cell. This method adjusts for local gradients such a 1 s lapse rates, inversions, or rain shadows at scales from tens of meters to kilometers and produces accurate maps with sparse data; and the data requirements are far fewer than required for techniques such as kriging (Hughes and Lettenmaier 1981). Finally, the GIDS maps were scaled to monthly climate grids using a ratio, which ensures that the daily maps sum (precipitation) or average (air temperature) to the monthly grids.

2.1.2 Basin Characterization Model Calibration and Validation

The HBER-BCM was developed using a modified version of a previously published monthly model (Flint et al., 2013). The computational period for the historical model runs (PRISM-BCM) spanned water years 1961 to 2016 and the model runs for the ten future climate scenarios (LOCA-BCM) span water years 1961 to 2099 with greenhouse gas forcings imposed beginning in 2006. The model domain (*Figure 1*) included twelve flow calibration gages (green dots; Table 1), four non-USGS sediment gages (yellow triangles; Table 3) and one USGS sediment gage (yellow squares). Reporting basins that discharge directly to Humboldt Bay (green area; Table 3) are collectively referred to hereafter as the bay basins (Jacoby Creek, Freshwater Creek, Elk River and Salmon Creek). The PRISM-BCM model was calibrated from 2009 to 2016 and validated from 2000 to 2008 using unimpaired-streamflow measurements. Calibration involved an iterative adjustment of parameters to match modeled stream discharge to measured streamflow using a series of post processing equations (eq. 1 - 7). An additional adjustment of bedrock permeabilities was used, if necessary, to improve the goodness-of-fit statistics. A schematic describing the post-processing steps for partitioning $\mathbf{BCM_{rch}}$ and $\mathbf{BCM_{run}}$ into stream discharge is shown in *Figure 3* and a description of the complete workflow was published by Flint et al. (*2013*).

The following post-processing equations are used to calibrate $\mathbf{BCM_{rch}}$ and $\mathbf{BCM_{run}}$ (shown in bold) using adjustable parameters (*shown in italics*).

$SW_{surface(i)} = SW_{surface(i-1)} + \mathbf{BCM_{run(i)}} – Surfaceflow_{(i-1)}$ (eq. 1)

$Surfaceflow_{(i)} = (SW_{surface(i)})^{\mathit{SurfaceExp}}$ (eq. 2)

$GW_{shallow(i)} = GW_{shallow(i-1)} + \mathbf{BCM_{rch(i)}} – Surfaceflow_{(i)} – Deepflow_{(i)}$ (eq. 3)

$Shallowflow_{(i)} = (GW_{shallow(i-1)})^{ShallowEx}$ (eq. 4)

$Deepflow_{(i)} = (GW_{shallow(i-1)})^{DeepExp}$ (eq. 5)

$Stream_{(i)} = Surfaceflow_{(i)} + Shallowflow_{(i)} + Deepflow_{(i)}$ (eq. 6)

$Discharge_{(i)} = AquiferRch * Stream_{(i)}$ (eq. 7)

Equation (1) accumulates surface runoff ($SW_{surface(i)}$) for each calibration basin using modeled runoff (**BCM_{run}**). Equation (2) applies an exponential decay function (*SurfaceExp*) to match peaks and winter hydrograph recessions to represent flow into the surface groundwater reservoir. Shallow subsurface flow ($GW_{shallow(i)}$) is accumulated with equation (3) using modeled recharge (**BCM_{rch}**) to calculate shallow recharge ($Shallowflow_{(i)}$). Equation (4) uses exponential decay (*ShallowExp*) to match the springtime hydrograph recessions to simulate flow into the shallow groundwater reservoir. Equation (5) uses exponential decay (*DeepExp*) to match modeled base flows ($Deepflow_{(i)}$) and maintain a mass balance between the measured streamflow and modeled stream discharge by adjusting the contribution of the shallow groundwater reservoir to streamflow. Total streamflow ($Stream_{(i)}$) is calculated using Equation (6), which sums surfaceflow, shallowflow, and deepflow. Finally, modeled stream discharge ($Discharge_{(i)}$) is calculated by scaling the calculated streamflow (*$Stream_{(i)}$*) by *AquiferRch* to match total measured flow volume for the period of record and to account for losses to the groundwater system as well 1 as unknown impairments, diversions, or pumping using Equation (7). The adjustable parameters *SurfaceExp, ShallowExp, DeepExp,* and *AquiferRch* are manually changed for each calibration station (Table 1) to match unimpaired measured streamflow and flow volumes and to optimize two goodness-of-fit statistics, the coefficient of determination (R^2) and the Nash Sutcliffe Efficiency coefficient (NSE), for the daily and monthly time series.

Table 1. Streamflow basin identifier (see Figure 1), USGS station ID and name, and period of record for measured mean daily streamflow used to calibrate and validate the modeled daily stream discharge for the Humboldt Bay-Eel River study.

Streamflow Basin ID (Figure 1)	USGS Station ID	USGS Station Name	Period of record		
1	11481000	MAD R NR ARCATA	10/01/1910	-	06/05/2018
2	11481200	LITTLE R NR TRINIDAD	10/01/1955	-	06/05/2018
3	11473900	MF EEL R NR DOS RIOS	10/01/1965	-	06/05/2018
4	11478500	VAN DUZEN R NR BRIDGEVILLE	10/01/1950	-	06/05/2018
5	11476500	SF EEL R NR MIRANDA	10/01/1939	-	06/05/2018
6	11475800	SF EEL R A LEGGETT	10/01/1965	-	06/05/2018
7	11477000	EEL R A SCOTIA	10/01/1910	-	06/05/2018
8	11475000	EEL R A FORT SEWARD	09/01/1955	-	06/05/2018
9	11475560	ELDER C NR BRANSCOMB	10/01/1967	-	06/05/2018
10	11468900	MATTOLE R NR ETTERSBURG	06/21/2001	-	06/05/2018

11	11469000	MATTOLE R NR PETROLIA	10/01/1911	-	06/05/2018
12	11482500	REDWOOD C A ORICK	09/01/1911	-	06/05/2018

Table 2. Description of the global climate models used to simulate stream discharge and sediment supply under future climates for the Humboldt Bay-Eel River study region (see Taylor et al., 2012 for model descriptions).

Model name	Institute ID	Modeling center or group
CanESM2	CCCMA	Canadian Centre for Climate Modeling and Analysis
CCSM4	NCAR	National Center for Atmospheric Research, United States of America
CNRM-CM5	CNRM-CERFACS	Centre National de Recherches Météorologiques (CNRM) / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CERFACS), France
HadGEM2-ES	MOHC	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais), United Kingdom
MIROC5	MIROC	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology

2.2 Fine-sediment supply under current and future climates

Warrick et al. (2013) identified a regional decline in the suspended-sediment discharged (Q_{ss}) from coastal rivers of northern California. In the presence of time-dependent trends stationary sediment-transport models can produce biased estimates of Q_{ss} (*Porterfield, 1972*). To mitigate this problem of non-stationarity (*Milly et al., 2008*), while providing a robust and representative dataset for estimating fine-sediment supply under current conditions, we followed the approach of Warrick (*2014*) and used 1981 as beginning of the computational period for current conditions. There are numerous methods for developing sediment-transport models (*Glysson, 1987; Asselman, 2000; Horowitz, 2003; Gray and Simões, 2008, Warrick et al., 2014*). In this study,we developed a series of sediment-transport models, which can be used to estimate Q_{ss} from modeled Q_w, using the following linear regression model:

$$\mathrm{Log}_{10}\, Q_{ss} = \mathrm{Log}_{10}\, a + b\,(\mathrm{Log}_{10}\, \mathrm{BCM\text{-}}Q_w) \quad \text{(eq. 8)}$$

where Q_{ss} is suspended-sediment discharge (metric tonnes/day), BCM-Q_w is modeled stream discharge (m^3/s), and a and b are regression coefficients. Because our objective was to estimate the changes in the sediment supply under future climates, we necessarily used modeled Q_w in the regression analysis to compute Q_{ss}.

Sediment-transport models were developed for five HBER basins with measured sediment data, which include four bay basins (JBW, HHB, KRW, and SFM) and the Eel River at Scotia (Eel,

Figure 1). Standard statistical m 1 ethods (*Helsel and Hirsh, 1991*) were used to test for linearity and equal variance in the residuals (i.e. homoscedasticity). Fitting the regression models required logarithmic transformation of Q_{ss} and Q_w. Results were bias-corrected to account for retransformation bias (*Helsel and Hirsch, 2002*) using a non-parametric "smearing estimator", which is insensitive to non-normality in the regression residuals (*Duan, 1983*). Retransformation bias causes underprediction of Q_{ss} and the degree to which Q_{ss} is underpredicted is a function of the goodness-of-fit of the regression.

The mean daily Q_{ss} dataset used in the sediment-transport models (eq.8) for each of the five sediment reporting basins was estimated using two different methods. Continuous turbidity and streamflow measurements were available for the four bay basins, but only discrete measurements of SSC and associated instantaneous Q_w were available for the Eel River at Scotia (Table 3).

For the four bay basins, continuous turbidity measurements were used as a surrogate for SSC (*Rasmussen et al., 2009*) to estimate a mean daily Q_{ss} (*Table 3*). These turbidity stations were operated and maintained following standard procedures (*Lewis and Eads, 2009*) and available data includes continuous 10-minute records of turbidity, SSC and streamflow (*Klein et al., 2012; Lewis, 2013*). We aggregated the 10-minute SSC data and estimated a discharge-weighted mean daily Q_{ss} time series for each of the four sediment stations (*Supplemental Material*).

For the Eel River at Scotia, in the absence of continuous SSC data, we used discrete measurements of SSC and instantaneous streamflow to develop a sediment rating curve (eq.9; *Horowitz, 2003*) to estimate a mean daily record of SSC. This required an additional regression model for the Eel River at Scotia:

$$\mathrm{Log}_{10}\,\mathrm{SSC} = \mathrm{Log}_{10}\,c + d\,(\mathrm{Log}_{10}\,Q_w) \quad \text{(eq. 9)}$$

where SSC is suspended-sediment concentration (1 mg/L) corrected for percent fines (diameter <0.63 µm), Q_w is instantaneous streamflow (m^3/s), and c and d are regression coefficients. Because our goal was to estimate the potential sediment contribution to Humboldt Bay from Eel River coastal river plumes, the SSC data were corrected for percent of fines (diameter <63 µm) to exclude the non-buoyant sand-sized sediment. The SSC, percent fines, and streamflow data are available at *https://waterdata.usgs.gov/nwis*.

We used eq.9 to estimate a continuous 15-minute record of SSC from 1988 to 2017 for the Eel River at Scotia and accounted for a sampling bias associated with the post-1980 sampling strategy at this gaging location. After 1980 the USGS began collecting bimonthly sediment samples on a regular time-step, which resulted in the collection of more samples at low to moderate flows. A flow threshold was defined at 10 m^3/s and all samples below the threshold were removed from the Eel River SSC dataset to match methods used in previous studies (*Warrick, 2014*). The 15-minute SSC data, estimated using eq.9, was then converted to Q_{ss} and aggregated into a record of mean daily Q_{ss} for the Eel River at Scotia.

Sediment-transport models (eq.8) for each of the five sediment reporting basins were developed using a group-average approach (*Glysson, 1987; Curtis, 2005*), which is appropriate when there are a large number of low to moderate data values that strongly influence the slope of the regression model. The group-average method removes this influence and improves predictions at the upper end of the transport models. This is an extremely important consideration because slight errors in the slope of a transport model can generate large errors in Q_{ss} predictions. The Q_{ss} and BCM-Q_w data were log-transformed, binned, and group-averages determined. The group averages were used to create separate transport models for low and high flow conditions for each reporting basin.

The transport models were optimized 1 for the best form and fit and were then used to estimate daily Q_{ss} from Q_w using the historical (PRISM-BCM) and future (LOCA-BCM) modeling results. Although we addressed non-stationarity in the development of the transport models, we assumed no time-dependent trends under future climates. The regression coefficients for the transport models defined for historical conditions were used to estimate Q_{ss} under future climates.

Table 3. Sediment station identifier (see Figure 1 for locations), station name, number of mean daily Q_{ss} values, available data and the period of record used to develop sediment-transport models for five sediment stations in the Humboldt Bay-Eel River study region.

Sediment Station ID (Figure 1)	Sediment Station Name	Number of mean daily Q_{ss} values	Available Data	Period of Estimated Q_{ss} Record
Eel	Eel R at Scotia	10,715	Discrete SSC measurements Continuous 15-minute streamflow	09/17/1955 – 03/02/1988 09/17/1988 - 02/28/2017
JBW	Jacoby Creek	1,718*	Continuous 10-minute turbidity and streamflow	11/02/2003 - 09/30/2017
HHB	Freshwater Creek	977*	Continuous 10-minute turbidity and streamflow	11/26/2004 - 05/04/2011
KRW	North Fork Elk River	1,454*	Continuous 10-minute turbidity and streamflow	11/18/2002 - 04/17/2013
SFM	South Fork Elk River	1,993*	Continuous 10-minute turbidity and streamflow	11/16/2002 - 04/08/2013

* Bay basin stations were operated seasonally, and percent missing values are provided in supplemental material

References

Asselman, N.E.M., 2000. Fitting and interpretation of sediment rating curves. Journal of Hydrology 234, 228–248. http://refhub.elsevier.com/S0025-3227(14)00052-8/rf9000

California Department of Water Resources-Climate Change Technical Advisory Group (CADWR-CCTAG) 2015. Perspectives and guidance for climate change analysis. California Department of Water Resources Technical Information Record, 142 p. https://water.ca.gov/LegacyFiles/climatechange/docs/2015/Perspectives_Guidance_Climate_Change_Analysis.pdf

Curtis, J.A., Flint, L.E., Alpers, C.N., Wright, S.A., and Snyder, N.P., 2006, Use of Sediment Rating Curves and Optical Backscatter Data to Characterize Sediment Transport in the Upper Yuba River Watershed, California, 2001–03: U.S. Geological Survey Scientific Investigations Report 2005–5246, 74 p.

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., and Pasteris, P.A. 2008, Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. International Journal of Climatology, 28: 2031-2064. DOI: 10.1002/joc.1688

Duan, N. (1983). “Smearing estimate: A nonparametric retransformation method.” *Journal of the American Statistical Association* , 78(383), 605–610.

Efron, B. and Stein, C., 1981. The jack knife estimate of variance. *The Annals of Statistics*, pp.586-596.

Flint, L.E. and Flint, A.L., 2007, Estimation of hourly stream temperatures in unmeasured tributaries to the lower Klamath River, California: J. of Environmental Quality, 37:57-68.

Flint, L.E., Flint, A.L., Thorne, J.H., and Boynton, R., 2013, Fine-scale hydrologic modeling for regional landscape applications: the California Basin Characterization Model development and performance: Ecol. Processes 2:25.

Glysson, G. D., Gray, J. R., and Schwarz, G. E. (2001). “Comparison of load estimates using total suspended solids and suspended sediment concentration data.” *Proc., ASCE World Water & Environmental Resources Congress* , ASCE, Reston, Va. https://water.usgs.gov/osw/techniques/sedimentpubs.html

Glysson, G. D. (1987). “Sediment-transport curves.” *Open-File Report 87-218* , U.S. Geological Survey, Reston, Va., https://pubs.er.usgs.gov/publication/ofr87218

Gray, J.R. and Simões, F.J., 2008. Estimating sediment discharge. In *Sedimentation engineering: Processes, measurements, modeling, and practice* (pp. 1067-1088).

Helsel, D.R. and Hirsch, R.M., 2002. *Statistical methods in water resources* (Vol. 323). Reston, VA: US Geological survey.

Horowitz, A.J., 2003. An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. Hydrological Processes 17, 3387–3409. http://refhub.elsevier.com/S0025-3227(14)00052-8/rf0095

Hughes, J.P. and Lettenmaier, D.P., 1981. Data requirements for kriging: estimation and network design. *Water Resources Research*, *17*(6), pp.1641-1650.

Klein, R.D., Anderson, J.K., 2012. Declining sediment loads from Redwood Creek and the Klamath River, north coastal California. Proceedings of the Coastal Redwood Forests in a Changing California: A Symposium for Scientists and Managers, U.S. Department of Agriculture, Forest Service General Technical Report PSW-GTR-238, pp. 79–88.

Lewis, J. and R.E.Eads. 2009. Implementation Guide for Turbidity Threshold Sampling: Principles, Procedures, and Analysis. General Technical Report PSW-GTR-212, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://www.fs.usda.gov/treesearch/pubs/30732

Livneh, B., Rosenberg, E.A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K.M., Maurer, E.P. and Lettenmaier. D.P. 2013. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: Update and extensions. Journal of Climate, 26(23), p. 9384-9392.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity is dead: whither water management? Science 319, 573–574. http://dx.doi.org/10.1126/science.1151915.

Nalder, I.A., Wein, R 1 .W., 1998. Spatial interpolation of climatic Normals: test of a new method in the Canadian boreal forest. Agricultural and Forest Meteorology 92, 211–225. https://doi.org/10.1016/S0168-1923(98)00102-6

Pierce, D.W., D.R. Cayan and B.L. Thrasher 2014. Statistical Downscaling Using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology 15:2558-2585. http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-14-0082.1

Porterfield, G., 1972. Computation of fluvial-sediment discharge. In: Techniques of Water-Resources Investigations of the U.S. Geological Survey. Book 3. Applications of Hydraulics. U.S. Gov't Printing Office, Washington, DC, p. 71.

Rasmussen, P.P., Gray, J.R., Glysson, G.D., and Ziegler, A.C., 2009, Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. C4, 52 p.

Stern, M.A., Flint, L.E., Minear, J.T., Flint, A.L., Wright, S.A. 2016. Characterizing Changes in Streamflow and Sediment Supply in the Sacramento River Basin, California, Using Hydrological Simulation Program—FORTRAN (HSPF). Water. 2016; 8(10):432. doi:10.3390/w8100432

Warrick, J.A., Madej, M.A., Goñi, M.A., Wheatcroft, R.A., 2013. Trends in the suspended sediment yields of coastal rivers of northern California, 1955–2010. Journal of Hydrology 489, 108–123.

Warrick, J.A., 2014. Eel River margin source-to-sink sediment budgets: Revisited. *Marine geology*, *351*, pp.25-37.