

**Sediment salinity distribution along the tidal channel networks  
of a restored salt pond in the San Francisco Bay-Delta Estuary system**

**Gregory Tseng**

**Abstract** As part of the South Bay Salt Pond Restoration Project, the levees of certain salt ponds in the Don Edwards San Francisco Bay Wildlife Refuge were breached in March 2006. Tidal inundation has deposited considerable amounts of sediment on the surface of the salt ponds over the past few years. Since tidal channels are the main conduits by which sediments enter and leave the pond and because sediment salinity is a basic indicator of favorable conditions for vegetation recruitment, I conducted a study of the tidal channels in Pond A21, investigating sediment salinity with respect to distance to nearest levee breach and along the assumed tidal channel flow path. However, I found no significant relationship between distance from the bay and sediment salinity within the sampled tidal channels. I attribute this to insufficient data and a parallel-to-channel sampling design. To improve this study, a perpendicular-to-channel sampling methodology may yield better results. Even though sediment salinity may be highly variable temporally and spatially, investigating sediment salinity distribution development is one step to understanding sediment dynamics and vegetation recruitment, and will help improve future restoration efforts.

## Introduction

Historically, salt marshes were regarded as only empty space or wastelands, and suffered human impacts such as dumping of construction materials and waste from urbanization, loss of area due to reclamation by agriculture, and sediment deposition from dredged channels (Boorman 1999, Callaway 2004, Kennish 2001, Neckles 2002, Vernberg 1993). Specifically, in the San Francisco Bay Area, over 85% of the original marshes have been altered by all of these methods within the last 150 years (US Fish & Wildlife Service 2003). Nowadays, salt marshes are known to help buffer against coastal storms, and sustain wildlife and marine communities (Boorman 1999). Salt marshes are considered to be one of the most biologically productive ecosystems on the Earth, providing sources of organic matter and nutrients (Kennish 2001). In light of advances in science and increasing research in this topic, more people recognize the value of salt marshes.

The key process in salt marsh development and survival can be attributed to the growth of vegetation, accretion events, and coastal submergence (Boorman 1999, Kennish 2001). Salt marshes depend on vegetation to stabilize the mud and trap additional sediment for growth (Boorman 1999, 2001). As more sediment accretes in an area, there is more potential for vegetation recruitment, and thereby an increase in more sedimentation. However, submergence, defined as any event which causes the water level to rise relative to the land level, may cause loss of marsh area (Kennish 2001). It is the balance of sedimentation and submergence that determine the survival of a salt marsh. Urbanization and sea level rise has affected salt marshes adversely.

As awareness of the importance of salt marshes and other coastal tidal wetland habitats increase, environmental groups, regulations, and laws to protect these delicate ecosystems have also increased. The Don Edwards San Francisco Bay National Wildlife Refuge, which was established in 1974, is a wildlife preserve that was founded out of the convergence of environmental awareness and political action. It is composed of 30,000 acres of open bay, mudflat, salt marsh, salt pond, upland and vernal pool habitats throughout south San Francisco Bay (US Fish & Wildlife Service 2003). The Refuge is home to endangered species such as the California clapper rail and the salt marsh harvest mouse, and is located along the Pacific Flyway, which is a common route for migratory birds. Over 280 species of birds stop in the Refuge each year to rest and refuel, utilizing the mud flats, salt ponds, and upland areas (US Fish & Wildlife

Service 2003). Restoration of damaged and altered habitats is one way the Refuge is helping to protect the various ecosystems along the edge of the Bay.

The South Bay Salt Pond Restoration Project (SBSRP) is one project focused on restoring salt ponds back into salt marsh in this area. In 2003, as part of this restoration effort, the Refuge purchased over 15,000 acres of salt ponds from the solar salt manufacturing company Cargill Inc., which has been manufacturing salt for decades. Cargill, which has production facilities based in Newark and Redwood City, still owns 11,000 acres of salt ponds and continues to produce salt in the area. These historic salt ponds were created by building levees around sections of natural salt marsh, which impeded tidal flow and allowed accumulated salt water to evaporate. During construction of these salt ponds, the material for the levees was taken from the perimeter of the pond, creating a deep “borrow ditch” (the levee material was borrowed from the ditch) that surrounds the entire pond plateau (Callaway pers. comm. 2008, Stacey pers. comm. 2008). The plateau of the pond therefore is the elevated part of the pond which is surrounded by the borrow ditch. It is here where salt is produced and harvested. Freshwater from creeks and urban runoff mix with seawater to produce a range of water salinity where extremely high levels (over 300 ppt, seawater is 35 ppt) can be reached in the most saline ponds (US Fish & Wildlife Service 2006). As water from the ponds evaporate, the brine (water with high salt content) is moved through ponds of increasing levels of salinity through an intricate network of pumps until it is ready for harvesting. Producing one batch of salt (650,000 tons) can take up to 5 years (Cargill Salt 2009). Over the decades of solar salt harvesting, precipitation of the salts in the brine water have formed a layer of gypsum (calcium sulfate) at the bottom of the pond (Callaway, pers. comm. 2008, US Fish & Wildlife Service 2006). The effects of a gypsum layer in these ponds have not been documented comprehensively. Despite these unnatural alterations and setbacks, the goal of the SBSRP is to restore these thousands of acres of salt pond back into salt marsh or tidal mudflats by opening the ponds to tidal inundation (South Bay Salt Pond Restoration Project 2008).

Tidal inundation from bay water influences the sediment salinities inside these former salt evaporator ponds. In a natural salt marsh, the salinity gradients are generally linear, increasing with distance from the Bay and increasing in elevation. Marsh areas that are higher in elevation are less frequently inundated and commonly have higher soil salinities due to evapo-transpiration (Callaway 2007). However, in a salt pond with unnatural barriers, tidal inundation is affected.

During high tide, water fills up in the borrow ditch around the perimeter before inundating the rest of the pond through tidal channels and creeks (Callaway pers comm. 2008, pers. obs. 2009). This difference in inundation from a natural salt marsh may have effects on the soil salinity gradients that will develop. This is an important consideration in a restoration setting where vegetation is just beginning to recruit because newly recruiting plants suffer greater impacts from salinity shifts than well-established vegetation (Callaway 2007). Even though vegetation in these marshes are salt-tolerant, salinities still affect their seed germination and initial seedling growth (Noe 2001, Zedler 2003). Also, exposure to hypersaline conditions can adversely affect the viability of seeds and therefore, marsh restoration potential can be linked to adequate freshwater input (Shaw 2008). Salinity is an important factor to consider in salt marsh restoration.

In this paper, I conducted a study on a salt pond which used to be owned by Cargill, but is currently undergoing restoration by adaptive management. Adaptive management is acknowledging that insufficient information is known to make the correct decisions in restoration projects. It is a iterative process, where data is collected and analyzed about a particular site, and suggestions are made to management. From the results of the management step, more questions and further research is done (Zedler 2001). In March 2006, two breaches were made in the levee of this salt pond, restoring tidal inundation. Consequently, over the past three years, sediment deposition has increased gradually and has been monitored (Callaway unpublished data 2009, pers. comm. 2009). One problem of restoring salt ponds back into salt marsh is sedimentation inputs. Callaway *et. al* (2008) found a correlation between sediment deposition and distance from nearest levee breach (Callaway presentation Sep 25, 2008). Sediments are being deposited at different depths across the surface of the pond, and one reason for this may be related to distance from inundation. Sparse and sporadic vegetation recruitment is present in some areas of the pond – an good indicator that salinity levels are reaching levels favorable for vegetation – but there have been no systematic data collected regarding salinity development in the sediments across the plateau of this particular pond.

I conducted two case studies of the tidal channels of Pond A21, investigating sediment salinity with respect to the distance along the tidal channel flow path to the levee breaches. My research question is: Does distance from originating point of tidal input affect sediment salinity

distribution along tidal channels? I investigated the fact that tidal waters filled up the borrow ditch before inundating the rest of the pond through tidal channels, and whether that has an effect on sediment salinity. I hypothesize that distance from the point of tidal input affects sediment salinity distribution along tidal channels. I further hypothesize that there is a positive correlation between sediment salinity levels and distance from the bay.

## Methods

Salt Pond A21 is located at approximately  $+37^{\circ} 27' 55''$ ,  $-121^{\circ} 58' 45''$ , in the southernmost reach of the San Francisco Bay-Delta Estuary system (Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma Counties, California); nearby cities include Fremont, Milpitas, and Mountain View. It is part of the complex known as the “Island Ponds” and includes Pond A19 and A20 – as identified previously by Cargill. Pond A21 has a roughly triangular shape and its levees are bordered on the south by Coyote Creek, on the east by the Pacific Union railroad, and along the north and west by a smaller creek known as Mud Slough. The pond has two breaches – one near the south-westerly corner and the other in the

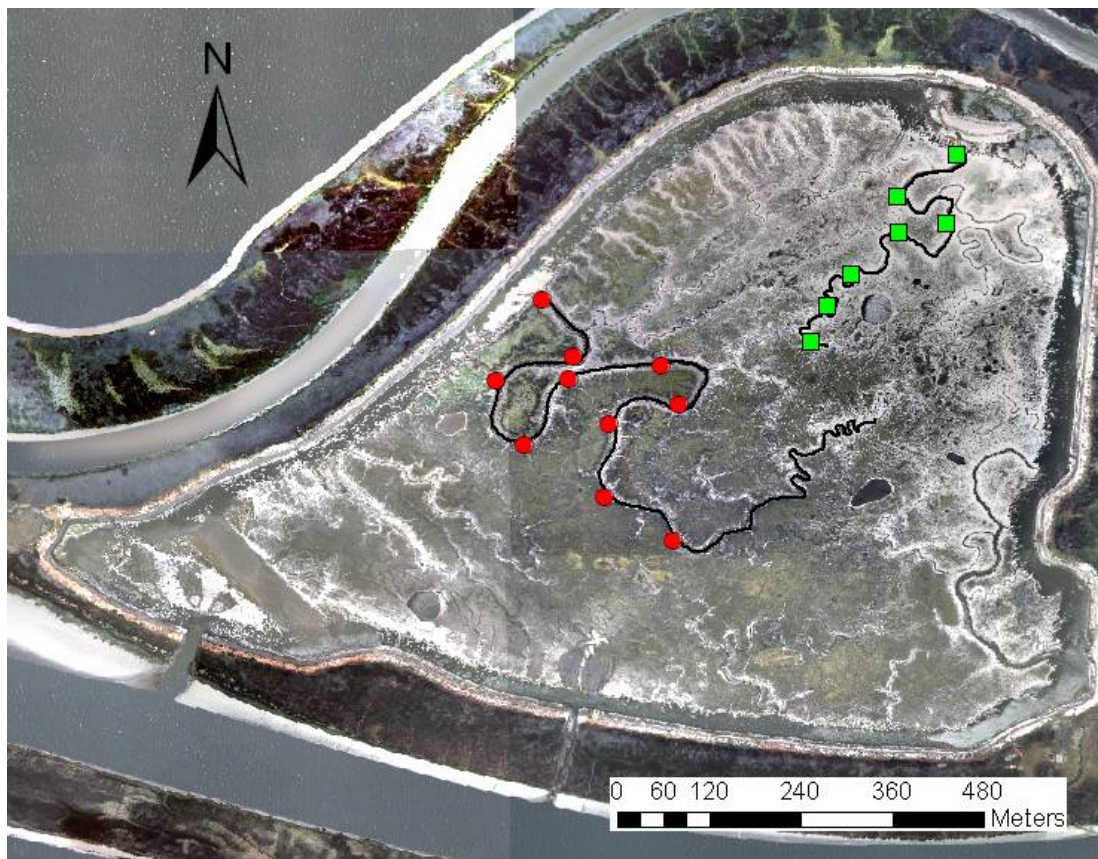


Fig 1: Map showing Pond A21. Channels studied are outlined in dark black, with red circles designating west channel sampling points and green squares north channel sampling points

middle of the southern levee wall. Surrounding the levees on the outboard side are batches of fringing marsh; these are also starting to develop on the inboard side due to restored tidal action.

Due to time restraints, weather impediments, and limited resources, I only selected two of the largest tidal channels in the pond – the west channel and the north channel – to test my research question of distance versus sediment salinity. These tidal channels serve as the main conduits for tidal inundation into the pond from the perimeter borrow ditch. I treated each of these channels as a nonlinear transect for my data sampling. I designated sampling stations at approximately 100-m intervals heading into the center of the pond from the start of the channel (Fig 1). Heading towards the center of the pond, each sample was collected from the right side of the channel. At each station, I collected three soil samples with a PVC core with an inside diameter of 5.08 cm to an depth of approximately 8 cm. Samples were taken on a 1-m transect parallel to and 1-m away from the channel bank. The first sample was at the midpoint of the transect, the second sample was at the left endpoint, and the third sample

was at the right endpoint (Fig 2). The reason for doing this was to get an average reading across the sampling point; each point was the same distance away from the channel, so the soil salinities would be comparable. I used a 5.08-cm inside diameter PVC core to collect all soil samples to an approximate depth of 8-cm. I extracted each sample into a labeled plastic zipper bag. On some sampling points, the amount of material collected was limited

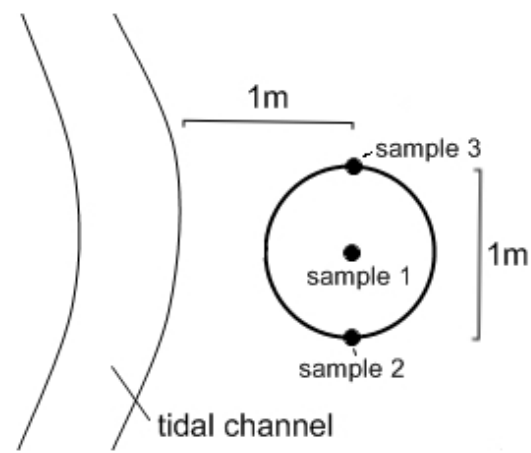


Fig 2: Diagram of sampling station showing placement of samples relative to channel

to fewer than 5 cm in depth because of the hard gypsum layer below. In these cases, I collected material around the point with my spatula, but still within the 1-m circle. Between sites, I used a new core to prevent cross-site contamination. For the north channel, I collected my samples on February 27, 2009 during the wet season. For the west channel, I collected the samples on March 20, 2009 during a dry period. All samples were collected at low tide when the surface of the pond was exposed.

Each soil sample was prepared for analysis by the saturated soil paste extraction method. (Richards 1954, Zhang 2005) The saturated soil paste extract method allows for comparison

across different sites and different times and simulates conditions present directly following rainfall or tidal inundation (Zedler 2001). Soil samples were mixed with deionized water until point of saturation, then allowed to sit covered (to prevent evaporation) for 24 hours (to allow paste to stabilize). A vacuum line was used to extract the supernatant, which was then measured with a YSI electrical conductivity meter in units of mS/cm (For reference, 53 mS/cm is approximately equal to 35 ppt). The electrical conductivity meter was over 20 years old, so I tested with known concentrations to be sure it was accurate enough for my purposes. Linear regression was used to analyze salinity data against distance data (OpenOffice.org Calc). An average of each of the three samples per sampling site was used as the salinity measurement for that site. Distance was obtained with a GPS unit (Trimble GeoXT, Trimble Navigation Limited, Sunnyvale, CA).

## Results

For the north channel, there seemed to be no relationship between distance and salinity (Fig 3). For the west channel, there was a small relationship between distance and salinity (Fig 4). EC values for the soil samples ranged from 10 to 27 mS/cm.

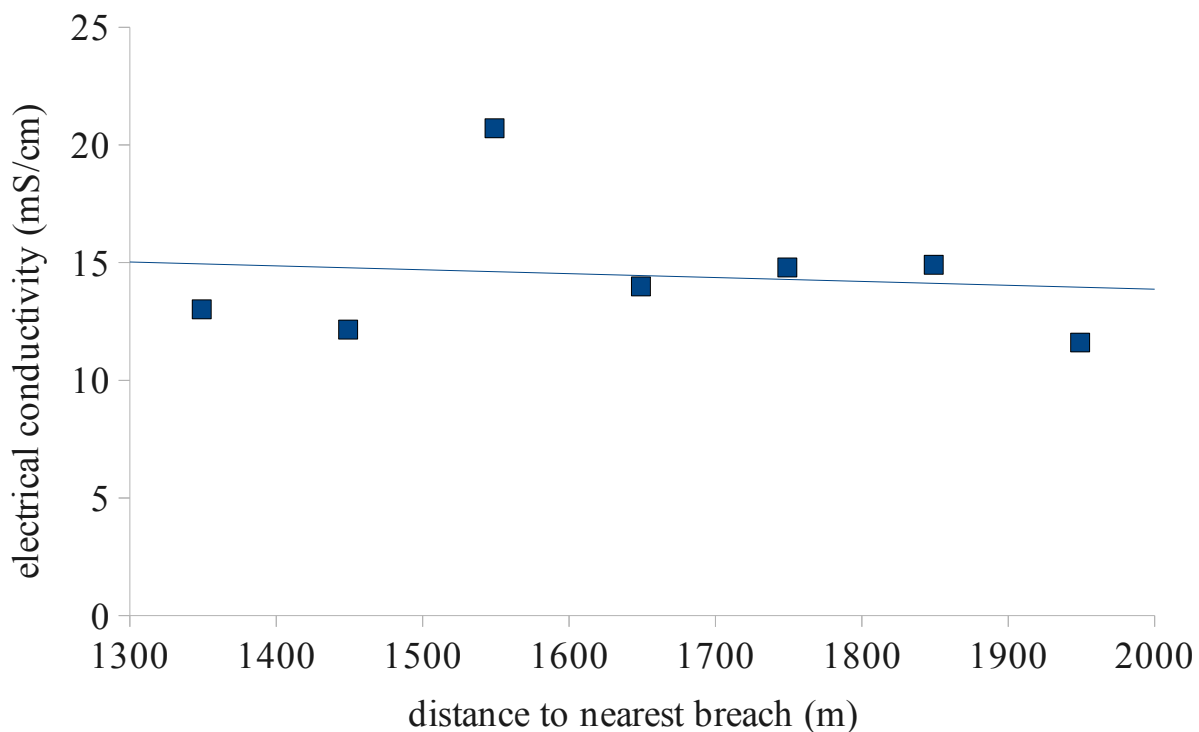


Fig 3: North channel salinity data versus distance. R-squared value = 0.01. p-value = 0.802.

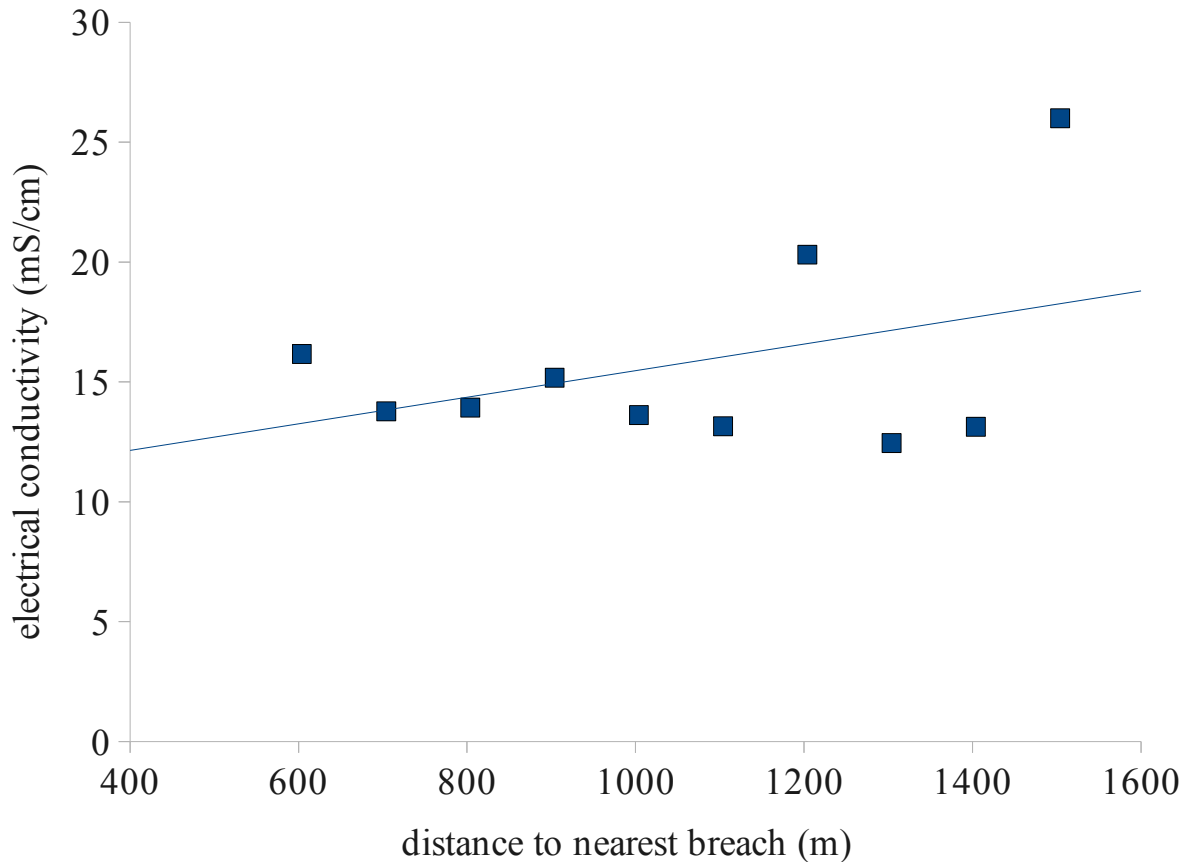


Fig 4: West channel salinity data versus distance. R-squared = 0.16. p-value = 0.259.

## Discussion

The results suggest that there is no real significant relationship between distance from point of tidal inundation and sediment salinity levels. My hypothesis that distance would affect the sediment salinity levels was not supported, but my results are partially supported by previous studies. It is known that soil salinities increase at higher elevations in a marsh, due to less frequent flushing by the tides and exposure to more surface evaporation (Callaway 2007). The general trend from my data seems to agree with this fact, but only to a certain extent. Areas further away was not inundated as long as areas closer to the point of tidal inundation. I hypothesized that distance would play a role in the less frequent inundation, but this seemed to not be the case. Noe and Zedler (2001) concluded that soil salinity and moisture did not explain a significant amount of the spatial variability of vegetation recruitment, but this study was done in three already established intertidal salt marshes, not restored salt ponds. I believe that a higher



resolution study of sediment salinity in this salt pond may reveal more useful spatial data. I attribute the difference from my study compared with previous studies to the fact that my model is too simple for this system.

I assumed that water from tidal inundation filled up the perimeter borrow ditch before entering the historical tidal channels. Through the channels, water and sediment is transported to the central portions of the pond. However, this model may be too simple and not reflective of real-world morphology. During the return of the high tide, the direction of water flow in the west channel was toward the middle of the pond coming from the borrow ditch as I expected, but I also noticed an opposite water flow coming from what seemed to be the middle of the pond. It is highly likely that water velocities and bank elevation are variable in different parts of the borrow ditch, which would lead to some areas being inundated before others. Since I only was able to investigate one north channel and one west channel, a revised hypothesis would include that water flow is higher on the eastern part of the pond, which can explain the seemingly backward flow of water in the west channel.

#### *Limitations and errors encountered*

As previously mentioned, on some sampling points, the amount of material was not obtained directly from the cores. However, the saturated soil paste method allows for differences in starting material as long as the saturation point is relatively similar. Human error during the preparation of the saturated paste extract could be a factor in error. The saturated paste extract method simulates the soil conditions immediately following rainfall or tidal inundation. All samples were prepared and determined to be at the point of saturation by myself; however, fatigue could have influenced the amount of saturation from the first sample to the last sample.

The composition of the mud at various sampling sites throughout the salt pond may have had an effect on the measured EC. One indicator of this was the color variance in the samples, which ranged from medium brown to pitch black. The source of the sedimentation in the pond is mixed suspended sediment from Coyote Creek watershed and Bay waters. However, it was beyond the scope of this project to evaluate sediment composition. Determining sediment sample composition would be an interesting future investigation, although it is known that most of the sediment are clay and Bay mud.

Seasonality also may have played a part in influencing the salinity levels measured, not to

mention the daily tidal cycles. The data from the north channel was taken between bouts of precipitation, while the data from the west channel was obtained approximately after one week of no rainfall. This was due to the limitations of tidal cycles and daylight hours. Even though the saturated paste method allows for comparison across different sites and at different times, I speculate that perhaps the rainy season altered or leached some salts from the sediment. For this reason, no direct comparison between the two channels was made. These two channels are separate case studies. Only intra-channel data was analyzed and compared to each other. For the most part, sub-samples within sampling sites had salinity levels relatively close to each other. I did not find a significant relationship, but I did collect sediment salinity data that may be useful in future studies.

#### *Concluding remarks*

Although I did not find a strong relationship between sediment salinity and distance from point of tidal input, it is a first step in discovering the effects of tidal water in these salt pond tidal channels after years of no inundation. Without specific prior knowledge on how levee breaching affects restoration methods on salt ponds, conducting further studies on tidal inundation will be useful in refining adaptive management efforts. Future research analyzing the entire pond surface could provide a better picture as to how salinity changes throughout the plateau. Looking into tidal inundation levels and patterns as well as seasonal changes in precipitation is another step. Future studies could include sampling perpendicularly from the tidal channel as well as alongside it. It may be the case that sediment salinity and vegetation patterns may not be crucial in the development of the salt marsh in the long run, but it is still worthwhile to learn as much as possible about these ecosystems. Restoration by adaptive management requires persistent research to be conducted in order to gain better insight into how to manage these sites for future generations.

#### **Acknowledgements**

I express my gratitude towards my mentor Ronald Amundson for guiding me throughout my research, and for providing the supplies and equipment needed to complete my analysis. I thank Mark Stacey for being a great advisor, helping me revise my methodology many times, and focusing my research direction. I acknowledge John Callaway, who provided insights and shared

with me his first-hand experience of working in the salt ponds, and for letting me borrow his “mudders” - which kept me from sinking into the mud. I thank Jeremy Freund and Kevin Koy of the Geospatial Innovation Facility for their advice and knowledge regarding GPS equipment and GIS mapping. I also thank the U.S. Fish and Wildlife Service for allowing me to conduct my study within the Don Edwards San Francisco Bay National Wildlife Refuge. Many thanks to my field sampling assistants Ricky Wang, Phillip Chang, Serena Tseng, and Joy Yang. Lastly, I thank the ES196 instructors and GSIs – Shelly Cole, Robin Turner, Gabrielle Wong-Parodi, Tim De Chant – for their continuous understanding, for their patience and respect during difficult times, and for their guidance throughout the entire process of my research

## References

- Adam, P. 2002. Saltmarshes in a time of change. *Environmental Conservation* 29:39-61.
- Boorman, L. A. 1999. Salt marshes - present functioning and future change. *Mangroves and Salt Marshes* 3:227-241.
- Boorman, L. A., J. Hazelden, and M. Boorman. 2001. The effect of rates of sedimentation and tidal submersion regimes on the growth of salt marsh plants. *Continental Shelf Research* 21:2155-2165.
- Callaway, J. C., V. T. Parker, M. C. Vasey, and L. M. Schile. 2007. Emerging issues for the restoration of tidal marsh ecosystems in the context of predicted climate change. *Madrono* 54:234-248.
- Cargil Salt – San Francisco Bay. <<http://www.cargill.com/static/sb/index.htm>>. Accessed 2009 July 1.
- Goals Project. 1999. Baylands Ecosystem Habitat Goals. A report of habitat recommendations prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. U.S. Environmental Protection Agency, San Francisco, Calif./S.F. Bay Regional Water Quality Control Board, Oakland, Calif.
- Kennish, M. J. 2001. Coastal salt marsh systems in the US: A review of anthropogenic impacts. *Journal of Coastal Research* 17:731-748.
- Neckles, H. A., M. Dionne, D. M. Burdick, C. T. Roman, R. Buchsbaum, and E. Hutchins. 2002. A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales. *Restoration Ecology* 10:556-563
- Noe, G. B., J. B. Zedler. 2001. Spatio-Temporal Variation of Salt Marsh Seedling Establishment in Relation to the Abiotic and Biotic Environment. *Journal of Vegetation Science* 12:61-74
- Richards, L. A. 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. USDA Agricultural Handbook 60, Washington, 160 pp.
- Shaw, G. A., J. B. Adams, and T. G. Bornman. 2008. Sediment characteristics and vegetation dynamics as indicators for the potential rehabilitation of an estuary salt marsh on the arid west coast of South Africa. *Journal of Arid Environments* 72:1094-1106.
- Thom, R. M. 2000. Adaptive management of coastal ecosystem restoration projects. *Ecological Engineering* 15:365-372
- Vernberg, F. J. 1993. Salt-Marsh Processes - A Review. *Environmental Toxicology and Chemistry* 12:2167-2195.
- Zedler, J.B. 2001. *Handbook for Restoring Tidal Wetlands*. CRC Press, Boca Raton, FL.

Zedler, J. B., H. Morzaria-Luna, and K. Ward. 2003. The challenge of restoring vegetation on tidal, hypersaline substrates. *Plant and Soil* 253:259-273.

Zhang, H., J. L. Schroder, J. J. Pittman, J. J. Wang, and M. E. Payton. 2005. Soil salinity using saturated paste and 1 : 1 soil to water extracts. *Soil Science Society of America Journal* 69:1146-1151.

South Bay Salt Pond Restoration Project. <<http://www.southbayrestoration.org/>>. Accessed 2009 April 1.

US Fish & Wildlife Service. 2003 Mar. Don Edwards San Francisco Bay National Wildlife Refuge <<http://library.fws.gov/refuges/DEsanfran.pdf>>. Accessed 2009 April 1.

US Fish & Wildlife Service, Don Edwards National Wildlife Refuge, Santa Clara Valley Water District. 2006. Restoration and Mitigation Monitoring Plan for the Island Ponds Restoration Project.