# DYNAMICS OF SEDIMENT ACCUMULATION IN POND A21 AT THE ISLAND PONDS

**John C. Callaway[1]**
**V. Thomas Parker[2]**
**Lisa M. Schile[3]**
**Ellen R. Herbert[2]**
**Evyan L. Borgnis[1]**

**Submitted to:**
Ann Buell
California State Coastal Conservancy
1330 Broadway, Suite 1300
Oakland, CA 94612

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[1]Department of Environmental Science
University of San Francisco
2130 Fulton St.
San Francisco, CA 94703
415.422.5702
callaway@usfca.edu

[2]Department of Biology
San Francisco State University
1600 Holloway Ave.
San Francisco, CA 94132

[2]Department of Environmental Science, Policy, and Management
University of California, Berkeley
Berkeley, CA 94720 USA

## INTRODUCTION

Understanding sediment accumulation within newly restored salt ponds in South San Francisco is critical because sediment accumulation, along with sea-level rise and *in situ* organic matter production, drives elevation change in intertidal habitats (Morris et al. 2002). Models have conceptualized the link between elevation, tidal inundation, and sedimentation rates (Krone 1987, French 1993), with the clear hypothesis that areas at lower elevations accumulate sediment more rapidly due to longer periods of tidal inundation. This has important implications for subsided ponds; "young" sites at low elevations are predicted to accumulate sediment most rapidly (e.g., see Figure 3 in Williams and Orr 2002). Data have been collected from San Francisco Bay marshes to evaluate this relationship (Williams and Orr 2002); however, a more quantitative understanding of this relationship is needed to fine tune predictions of the time period necessary for ponds to reach elevations appropriate for vegetation establishment. In addition, spatial variation in sediment processes within ponds is due not just to elevation, but to other factors including the distance from a tidal creek, suspended sediment concentrations, etc.

Additional uncertainties specific to the South Bay Salt Pond restoration project include effects of large-scale restoration on adjacent marsh communities and Bay dynamics and the effect of the existing gypsum layer on plant recruitment. First, there are concerns that the breaching of large salt ponds will create new sediment sinks that could shift sediment dynamics within the South Bay, potentially reducing sedimentation rates or eroding sediments from adjacent marshes, mudflats, and creeks. These existing areas offer habitat for endangered species as well as foraging areas for large migratory bird populations, and their preservation is a concern for the South Bay Salt Pond Restoration Project. Secondly, substantial gypsum ($CaSO_4$-$2(H_2O)$) deposits have accumulated in many of the ponds slated for restoration. It is uncertain how the gypsum layer may be affected by restoration, and how it may affect plant recruitment and channel development within the newly restored ponds. The gypsum layer varies across ponds in the Bay, with preliminary data indicating that it was at least 10 to 15 cm thick at Pond A21. This layer could affect root penetration and plant growth if it is located close to target plant elevations. The gypsum layer also may limit or alter the formation of new drainage creeks within restored ponds by resisting erosion.

The focus for our study was Pond A21, the westernmost of the three Island Ponds (the other ponds are Pond A19 and Pond A20). All three Island Ponds were reconnected to the tides in March 2006; Pond A21 was breached in two locations along Coyote Creek. We chose to focus our efforts on one site so that we could establish a dense network of sampling stations to better evaluate trends in sediment dynamics within a single pond.

In order to examine the aforementioned uncertainties for the Island Ponds and for future salt pond restoration projects, we measured net vertical sedimentation over month-to-year time scales for three years following the breach of Pond A21, as well as shorter-term (two week), mass-based measurements of sediment accumulation during the first year following the breach. Our first objective was to quantify sedimentation rates within Pond A21, including evaluating spatial variation of sediment rates within the pond as a function of proximity to tidal breaches and the initial elevation at each sampling site. We also examined effects on existing mudflats and tidal marshes surrounding Pond A21 by measuring sedimentation and erosion along Mud Slough (away from any breaches) and Coyote Creek (where new breaches were established).

Last, changes in the gypsum layer were monitored by evaluating the thickness of the gypsum over the first year post-breach in Pond A21.

## METHODS

Pond sedimentation

Sediment pins were established in a grid approximately every 100 m across Pond A21 (Figure 1). Coordinates for sampling locations were identified using GIS software in order to obtain even coverage across the site and to complement the existing pins that were installed by the Santa Clara Valley Water District (SCVWD). We established 27 stations at Pond A21, and SCVWD established 10 stations (Table 1). Stations were located in the field using a hand-held GPS receiver. At each station, a small hole was created in the existing gypsum layer using a sledge hammer and small pick. A 4-5 m length of PVC pipe (heavy duty, schedule 80, 3 inch diameter) was pounded through the gypsum and approximately 3 m into the existing sediment using a modified fence-post driver. Each pipe was capped, and approximately 1.8 m of pipe was left standing above the pond. Stations were established in March 2006. Following establishment, the height of each pin above the gypsum layer was measured on the east and west side to establish the baseline height (Figure 2). Small notches were cut on the cap of each pin so that future measurements would be made in exactly the same location on the east and west side. The height of each pin above the sediment surface was measured to the nearest mm approximately 1, 3, and 6 months, and 1, 2 and, 3 years after the breach. In cases where there was some localized erosion around the base of the sediment pin (typically a few cm), we measured the height based on the projected sediment surface from the area adjacent to the pin, rather than including the localized erosion in our measurements. This was done to reflect general conditions in the area, rather than very local changes around the pin. The two measurements of pin height (east and west side) were averaged for each date, and changes in sediment depth (sediment accumulation or erosion) were calculated based on changes in pin height relative to the initial measurements. Two pins broke at the sediment surface (pin #5 after 3 months and pin #16 after two years); these pins were dropped from further data analysis.

Sediment pins have been used in many studies; however, localized erosion around the pin can reduce the precision in measuring sedimentation rates. As an additional method for monitoring sediment accumulation, we used the existing thick layer of gypsum at the site as a "marker" for measuring the depth of newly deposited sediment. We decided to measure vertical rates of sediment accumulation using both sediment pins and the gypsum layer, although it was not clear initially if the gypsum layer would remain in place over the long term. When the project started, the gypsum layer was ubiquitous at Pond A21 (as well as at A20 and A19). As indicated below, the existing layer averaged over 15 cm throughout Pond A21. It was dense enough that a sledge hammer was needed to break through the gypsum layer. We measured the depth of sediment above the gypsum marker by inserting a small ruler through the newly deposited sediment until it hit the gypsum surface. A ruler was used initially to measure sediment depth to the nearest mm, but within a few sampling periods, the sediment was too deep to easily insert a ruler. In this case, a small piece of rebar was inserted until it hit the gypsum layer. The location of the sediment surface was marked on the rebar, and the depth was measured to the nearest mm. Eight replicate measurements of sediment depth were completed at locations located approximately 1 m away from the sediment pin. An initial location was chosen randomly and the subsequent sampling locations were evenly spaced radially around the pin (0° [initial location], 45°, 90°, 135°, 180°, 225°, 270°, and 315°).

In order to estimate short-term, mass-based rates of sediment accumulation in the first year post-breach, we used a modification of the "filter paper" method (Reed 1989). Rather than placing a filter paper on the existing substrate, we used a pre-weighed, thin rubber disk of approximately 12.5 cm diameter (Figure 3). The disk was a "handy can opener" and had a slight texture on the surface. This method had been used successfully on mudflats on the east coast (Jill Rooth, personal communication) where tidal currents and wind waves could remove or damage filter paper. The disks were attached to standard double light switch plates (approximately 12 x 12 cm) using thin rubber bands, and the light switch plates were attached to the gypsum using drywall screws. When sediment depths became deeper, the switch plates were placed directly on the sediment surface, and screws were inserted into the sediment to secure the switch plate and disk. A small piece of chicken wire was also anchored above the switch plate and disk to prevent gulls and other birds from disturbing the brightly-colored disks. Disks were left in place for a two-week period every two months over the course of one year from April 2006 to February 2007. A two-week period was chosen as this represents a full spring-neap sequence of tidal conditions. It was too time-consuming to set up the mass-based sediment stations at all 37 pin locations; instead, disks were placed in replicate pairs at 10 locations spread across Pond A21 (Figure 4). After two weeks, the pre-weighed disk and all sediment that had accumulated on it were placed into a ziplock bag, and the pre-weighed disks and all sediment were dried and weighed. Sediment weight was averaged across the replicate pairs at each pin. Although the particle size or texture of sediments was not measured, there were no obvious differences in sediment texture based on field observations across the pond.

Based on initial differences in sediment accumulation across the ponds, we averaged data from stations on the north and south side of the major tidal creek that bisected the pond. Groups of northern sites and southern sites are indicated in Table 1 for all pins, as well as the subset of pins that were used for the short-term, mass-based measurements. We used regression analysis to further evaluate spatial trends in sediment dynamics with rates of vertical accumulation as the dependent variable and included two separate independent variables: distance to the nearest breach and the initial elevation at each sampling location.

When we were completing sampling for sediment dynamics we also noted any new plants that were recruiting within Pond A21. Pictures were taken regularly within the ponds to document newly recruited vegetation. This included general pictures across the pond throughout the project, as well as individual pictures of each sediment sampling location during years two and three. Samples of *Spartina* spp. were collected and transferred to the *Spartina* Project in order to identify any potential hybrids at the pond. We measured the elevation at the sediment surface next to each pin, and at the gypsum surface in year two using a survey-grade Leica real-time kinematic (RTK) GPS receiver. We did not have access to the RTK GPS prior to year two. We used the elevation of the gypsum surface in year two as a measure of the initial elevation of the pond surface, assuming that no subsidence or other changes in the gypsum surface elevation occurred between breaching and our elevation survey. RTK GPS provides vertical accuracy of a few cm and will identify if any significant changes in the position of pins has occurred due to local subsidence or movement of pins.

Gypsum dynamics

Erosion or dissolution of the existing gypsum layer in Pond A21 was evaluated during the first year after the breach of the Island Ponds. The thickness of the initial gypsum layer prior to the breach was measured at all stations when pins were established. In the hole that was excavated for the sediment pin, we located the bottom of the gypsum layer by feel. We measured the thickness of the gypsum layer by inserting a ruler to the bottom of the layer and measuring the distance to the top of the layer. The thickness of the gypsum layer was measured in three random locations on the edge of each pin hole, and the average thickness was calculated for each pin location.

After 6 and 12 months, we re-measured the thickness of the gypsum layer. Measurements were made at the 27 pins that we established by breaking holes through the gypsum at a random location within approximately 5 m of the pin. We chose locations within 5 m of the pin so that we would be re-sampling in the same area but not close enough to the pin to create a disturbance that might affect local sedimentation rates or the local stability of the gypsum.

Sediment dynamics in existing, adjacent marshes and mudflats

In order to evaluate the potential for impacts to sediment dynamics in existing, adjacent ecosystems, we established stations along transects through existing salt marshes and mudflats on both Mud Slough and Coyote Creek (Figure 1). We chose Coyote Creek because the breaches occurred along this creek, and Mud Slough as a local comparison without any breaching. Three transects were established along each creek. Transects were located in three regions along Coyote Creek: 1) east (upstream) of the east breach, 2) between the east and west breach, and 3) west (downstream) of the west breach. Within each of these regions, a random starting location was chosen for a transect. Since there were no breaches on Mud Slough, the perimeter of Pond A21 along Mud Slough was divided into three equal-sized regions, and a random starting location was chosen for a transect in each of these three regions.

Along each transect, two stations were located in the marsh (one in the middle of the marsh [mid] and one closer to the adjacent levee [high]) and one station was located on the mudflat. At each station, a pin identical to those used in Pond A21 was pounded into the sediment to a depth of approximately 3-4 m. Approximately 60 cm of pipe was left standing above the sediment at the tidal marsh and mudflat locations in order to minimize visibility and potential of tampering or boat impacts. The height of the pins was measured when they were established, and approximately 1 and 6 months, and 1, 2, and 3 years after the breach.

At each marsh station, three feldspar plots (50 x 50 cm) were established to measure sediment accumulation. A thin layer of feldspar was sprinkled on the sediment surface at each plot, so that sediment accumulation above the feldspar marker could be measured (Cahoon and Turner 1989). Plots were located adjacent to each pin at approximately the same elevation. The corners of each plot were marked with small PVC pipes. On subsequent sampling dates (the same dates as marsh pin measurements), two small plugs of sediment (approximately 1x1 cm and 3 to 5 cm deep) were collected from random points within the feldspar plot. The depth to the feldspar layer was measured to the near 0.1 mm using a caliper on three edges of each plug.

These values were averaged for each plot, and the means from the three plots were averaged for each station. Sediment plugs were replaced to their original location to minimize disturbance.

Feldspar markers have low reliability at mudflat locations because of high rates of bioturbation and sediment re-suspension, so we established markers using very heavy, durable cloth (soil filter fabric that is used in landscaping to line drains). A 50 x 50-cm piece of fabric was placed directly on top of the existing sediment and anchored in place using large landscape staples. The corners of each plot were marked with small PVC pipes. The depth of newly accumulated sediment above the cloth marker was measured by inserting a ruler or calibrated rod (caliper) into the sediment until it was stopped by the cloth marker. Three measurements were made within 1-2 cm of a random point (to parallel data from the marsh feldspar markers), and two separate random points were sampled within each plot. These values were averaged for each plot, and the means from the three plots were averaged for each station. Mudflat markers were measured simultaneously with the marsh and mudflat pins. On some sampling occasions, the mudflat stations were underwater and pins and/or markers could not be measured. This was a particular issue on transect 2 at Coyote Creek, where we needed a relatively high tide to access the location by canoe. Mid and high marsh locations were accessible on these tides, but we were rarely able to sample the mudflat station here.

## RESULTS

### Pond sedimentation

Rates of sediment accumulation were highly variable spatially within Pond A21, with much more sediment consistently accumulating in the southern portion of the site (closest to the breach locations). We present the spatial data based on the sediment depth above the gypsum surface here; additional maps of spatial variation in sedimentation rates based on the change in height of the sediment pins are included in Appendix A. In the first three months, vertical sediment accumulation based on the depth of sediment above the gypsum surface at individual sampling locations ranged from 0.1 to 89 mm (Figure 5). The second sampling at six months proved to be just as variable with a range of 5 to 138 mm. By the six month sampling period the trend of higher accumulation in the southern portion of the pond was very clear (Figure 6). In the first year, vertical sediment accumulation at individual sampling locations was as high as 220 mm (Figure 7), although the average accumulation rate in the northern sites was 49 mm, 35% lower than the southern average of 140 mm. Similar trends in spatial patterns can be seen in maps of accumulation rates for both 2008 and 2009 (two and three years post-breach, respectively; Figures 8 and 9). Many individual locations had more than 200 mm of sediment after two or three years.

Averaging across the southern and northern portions of the pond, illustrates the temporal trends in sedimentation patterns in the three years since the opening of the Island Ponds. Average accumulation rates based on all sediment pins were: 52 mm (6 mo), 82 mm (12 mo), 115 mm (24 mo), and 131 mm (36 mo). Across the southern pond, average vertical accumulation of sediment has slowed down over the last two years with 130 mm accumulating in the first year post-breach, 56 mm from year one to year two, and 18 mm from year two to year three, totaling an average of 204 mm over three years. In the northern area accumulation rates have been much slower, with only 50 mm accumulating in three years (Figure 10); however, even this is much greater than the 3-5 mm/yr of sediment accumulation that occurs in natural salt marshes around San Francisco Bay and elsewhere (Patrick and DeLaune 1990, Callaway personal observation; see Table 3.1 in Callaway 2001 for compilation of multiple locations). The general temporal and spatial patterns of accumulation rates based on the depth of sediment over the gypsum surface were similar to rates based on sediment pins (i.e., see similarity of trends for Figures 10 and 11), although rates based on the depth of sediment over the gypsum surface were slightly higher than those based on the sediment pins.

A direct comparison of data from the change in pin heights and the depth of sediment over the gypsum surface showed strong correlation between these two different methods (Figure 12). This correlation is to be expected as both methods are measuring rates of vertical sediment accumulation. However, as noted above, the data based on the depth of sediment over the gypsum surface were consistently higher across the pond and over time. The gypsum surface creates a marker that allows for the direct measurement of sediment accumulation rates, whereas changes in the depth of the sediment pins are indicative of changes in the elevation of the sediment surface. If there is any consolidation or compaction of shallow materials (sediment or gypsum) this would be reflected in lower values in elevation measurements based on the changes in pin height, in comparison to those based on the gypsum surface. In comparison to measurements made in the marsh, the data based on the gypsum surface is analogous to sediment accretion measurements based on marker horizons (directly measuring sediment accretion), while the pin data are analogous to measurements made with a Surface Elevation Table or SET (measuring change in elevation). If the sediment is stable (no long consolidation or compaction), the two measurements will be identical. If there is substantial change occurring in surface sediments, then the pin-based measurements will be slightly lower than measurements based on the gypsum surface, with the difference between the two reflecting any consolidation that is occurring. If any local dissolution of gypsum is occurring at Pond A21, this could explain the slightly higher rates that we measured based on the gypsum surface.

In addition, some of the variation in the two methods is due to the fact that some pins that were established by the SCVWD were located in local depressions or ditches. These stations had higher rates of sediment accumulation as measured by the pins than in adjacent areas because of the pin location (these stations are the three points on Figure 12 that are substantially below the regression line).

Given that the depth above the gypsum surface is a direct measure of sediment accumulation, we feel that the rates based on this method are more representative of sedimentation patterns at the pond. The data relative to the gypsum surface are also based on eight replicates, while the pins are based on only two replicates (N and S sides of the pin). For future measurements, both methods would be useful where possible (in low salinity ponds there may not be a dense gypsum layer). In either case, the differences in measurements within the pond are quite small, and either method should give useful results, as long as pins are not placed in local depressions or creeks.

Evaluating trends from individual stations across Pond A21, there were significant correlations between the distance of the station to the nearest breach and the vertical rate of sediment accumulation (Figure 13). These patterns were relatively consistent across all three years (three panels on Figure 13), and there were similar patterns whether the evaluation was based on the depth of sediment over the gypsum surface (Figure 13) or sediment pins (not shown). Similarly, rates were highest for stations that were at lower initial elevations (Figure 14), although the correlation between these variables was weaker than the relationship between breach distance and accretion rates.

Short-term, mass-based rates of sediment accumulation over the first year post-breach also showed extremely rapid accumulation of sediment. As with the longer-term, vertical measurements of sediment accumulation, rates were substantially higher in the southern portion of Pond A21, with approximately 1000 to 3500 $g/m^2$ of sediment accumulating over each two-week period in the southern area and 500 to 1300 $g/m^2$ in the northern area (Figure 15; see Appendix B for spatial patterns of short-term accumulation rates across the pond). Averaging across the entire site, the annual rates of accumulation for Pond A21 were 1,562 $g/m^2$ per two-week interval, compared with 1000 to 5000 $g/m^2$ per year in a typical salt marsh (Turner et al. 2000). There was variation in deposition rates across the sampling intervals; however, there were not strong seasonal trends as might be expected (many Mediterranean-climate wetlands have very high winter rates of accumulation with little or no sediment accumulation in dry, summer months). We hypothesize that the lack of seasonal trend is due to wind-driven sediment resuspension which moves sediment in the Island Ponds, as there are often strong northwesterly winds across the South Bay throughout the year (J. Callaway, personal observation).

In general, the accumulation rates that were observed showed very rapid accumulation of sediment in Pond A21. Sedimentation rates have slowed down in years two and three although sediment continues to accumulate. Despite the small increase in vertical-based rates of accumulation in year three, we did observe that much of the sediment in Pond A21 has consolidated substantially over the last year: in previous years it was very difficult to walk in any of the southern areas of the pond with more than 20 or 30 cm of sediment; however, in 2009, it was much easier to walk across these deep sediments as they were much firmer.

Plant Recruitment

Vegetation established relatively quickly, although sporadically, throughout Pond A21 (see Figure 16 for pictures of plant recruitment over time). We observed a small amount of plant recruitment in each of the first two years following the breach. Mostly this was *Bolboschoenus maritimus* (which appear to establish from root or rhizome fragments rather than seeds) and *Sarcocornia pacifica* (formerly *Salicornia virginica*). Most of the *B. maritimus* was seen in 2006, and none is currently established at the pond. Other species that we have observed establishing at the pond include *Spartina foliosa,Salicornia europeae, Spergularia* sp., *Cotula coronopifolia*, and *Atriplex triangularis*. By year three, extensive patches of vegetation (primarily *Sarcocornia pacifica*) had established in three areas of the ponds: near the upper west part of the island near pins 1, 4, and 2102, the southwest corner near pins 2109 and 16, and in the north east portion of the island near pin 3. Given that these well-established patches will serve as propagule sources for future recruitment, we expect that further vegetation spread within the ponds will be quite rapid. This establishment also indicates that the sediment has consolidated enough to support vegetation in many areas of the pond.

Gypsum dynamics

The thickness of the gypsum layer was measured for one year post-breach, and data from that period indicate that there was little change in the average thickness of the gypsum layer across the pond (Figure 17). The average thickness of the gypsum layer was slightly greater in the northern portion of the site (18 cm) than in the southern portion (15 cm); however the average thickness in both areas remained constant over 6 months and 1 year (Figure 17). There were some changes in the gypsum layer over time as measured at individual sampling locations (see Appendix C for spatial patterns in the gypsum thickness across the pond); however, this is likely due to small-scale spatial variation in the original thickness of the gypsum layer, rather than any predictable changes in gypsum depth. We sampled in the same general location each time (with 5 m of the sediment pin); however it was not possible to relocate the exact location for previous measurements. Even within a single sampling hole, there was some variation in our measurements of the gypsum thickness (personal observations). In particular any measured increase in the thickness of the gypsum layer is due to spatial variation, as it is highly unlikely that the gypsum layer would be growing post breach. There could be some reduction in the gypsum layer that is occurring at particular locations within the pond; however, without much more intensive sampling it appears that large-scale dissolution of the gypsum layer at the pond did not occur in the first year following the breach.

Within Pond A21, we did observe that substantial undercutting and slumping of gypsum has occurred along small natural creeks, as well as along the borrow ditches. In addition, in some locations, we observed that the gypsum on the pond surface has softened somewhat, as our probe for measuring sediment depths occasionally broke through the gypsum. We also have observed that plants are getting established across the site, even in areas with a thin layer of sediment over the gypsum surface, indicating that the gypsum layer does not appear to inhibit plant establishment.

Sediment dynamics in existing, adjacent marshes and mudflats

Sediment dynamics were more variable in the mudflat stations than in marsh stations both along Coyote Creek and Mud Slough, and whether measured with pins (Figures 18 and 19) or markers (Figures 20 and 21). This is to be expected as mudflat areas are naturally more dynamic and temporally variable than vegetated marshes, both in terms of water flow and sedimentation patterns (Bouma et al. 2005). Along Mud Slough, mudflat stations on Transect 1 and 2 had very rapid accumulation with approximately 300 mm in two years as measured with pins (Figure 18). The pins at these transects appeared to be completely buried by year three, indicating more than 600 mm of accumulation over three years. The cloth markers in the mudflat stations on both creeks were not as reliable as the pins as they are susceptible to being washed out or buried so deeply that they can not be relocated in this dynamic environment. Markers at mudflat stations on Mud Slough indicated rapid accumulation during the first two year with some evidence of erosion in year three (Figure 20).

Mudflat stations at Coyote Creek Transect 3 (west of both breaches) had very rapid accumulation, but both Transect 2 (in between the two breaches) and Transect 1 (east of both breaches) were erosional (Figure 19). On some occasions, markers were washed out, or pins and markers were not accessible. This is indicated by missing data in the figures for the low stations. For example, markers at the mudflat stations were eroded on Transect 1 and 2 of Coyote Creek before the 6-month reading, and the re-established markers were also washed out (Figure 21). This erosion was confirmed by changes measured with the sediment pins (Figure 19). The data from Coyote Creek are preliminary but could indicate that there is some local reduction in sediment inputs associated with the new breaches (i.e., sediment is moving into the ponds rather than accumulating on nearby mudflats). It is likely that the immediate sediment source for these areas is from the Bay rather than from upstream, watershed sources (Mark Stacey, personal communication, September 2008). Sedimentation rates at the mudflat station on Transect 3 at the far western station on Coyote Creek were quite high, and, if the sediment source is from the west, these would be unaffected by the new breaches. The other two sampling locations are further east of the breaches, and local sediment may be moving into the ponds rather than accumulating on the mudflats east of the breaches. Further data collection is needed to confirm these preliminary trends on the mudflats.

The mid and high stations on all transects were much less variable. Marker data from Mud Slough indicated continuous accumulation of sediment in mid and high stations with 20-30 mm of material accumulating over three years (Figure 20). The pin data from Mud Slough showed more variation than the marker data but also indicated a depositional environment over the long term (Figure 18). Well developed, vegetated marshes typically are consistently depositional due to the dense vegetation and in the south Bay rates are typically in the 3-6 mm/yr range (J. Callaway, personal observation). Given the low sedimentation rates and the lack of fine-scale resolution with the sediment pins, we feel that the data from the markers are more reliable for the mid and high stations in the vegetated marsh.

Mid and high stations on Coyote Creek were also depositional. Markers indicated rates of 15-25 mm over three years (Figure 21), slightly lower than those measured on Mud Slough (Figure 20). Data from the sediment pins on Coyote Creek were highly variable in year two at mid elevations, with a large increase on transects 2 and 3 and a subsequent drop in year three. This may have been due to some data error, as we do not expect to see such large changes in sediment elevation in vegetated marshes, and these changes were not reflected in the marker data. Pin data for high stations on Coyote Creek show very slight deposition and erosion over the three-year period (less than 15 mm), and these values are probably in the range of error for measurements with the sediment pins. Figures illustrating spatial patterns of these dynamics over time are included in Appendix D (based on pin data) and Appendix E (based on marker data).

In general, the data from the adjacent habitats indicated that adjacent marshes (mid and high stations) continue to be depositional. There were no substantial differences in marsh sediment dynamics between Mud Slough and Coyote Creek stations, indicating no substantial effects of the breaches on existing marshes over this three-year period. Given the stability of vegetated marshes, it may take a much longer time period to identify an impact of breaches, if any is actually occurring.

On the mudflats, sediment dynamics are much more variable and difficult to interpret given the natural variation that is inherent in these areas. Mud flat locations on Mud Slough have been more consistently depositional than Coyote Creek locations, with two sites on Coyote Creek showing significant erosion. This could be due to impacts associated with the new breaches; however, without any data prior to the breach it is difficult to evaluate if this is an inherent spatial pattern between Mud Slough and Coyote Creek, or if it is a real effect of the breach location.

Given the highly dynamic nature of changes on mudflat locations, and the likelihood that markers (whether cloth, feldspar, or other material) will be washed out on the mudflats, we recommend using pins in mudflat locations for future studies. On the other hand, markers are more precise and work very well in the marsh, which is almost always depositional. We also recommend that data be collected prior to future breaches at adjacent mudflats so that baseline conditions on mudflat dynamics can be established prior to restoration.

## CONCLUSIONS

Based on the observations of sediment accumulation over three years post-breach at Pond A21, subsided ponds clearly have the potential for very rapid accumulation of sediment. It is likely that Pond A21 is at the high end of possible accumulation rates compared to other salt ponds, as winds in South Bay resuspend material off local mudflats, and winds and tides likely carry this material into Pond A21 (Mark Stacey, personal communication, September 2008). Furthermore, historical evidence from Foxgrover et al. (2004) and Jaffe and Foxgrover (2006) indicates that shallow subtidal areas south of the Dumbarton Bridge are usually depositional, while similar subtidal areas in other parts of the South Bay may switch back and forth from depositional to erosional over time. Rates within Pond A21 were much higher than are found in well-developed salt marshes, as is to be expected, but the rates within the pond were even more rapid than we expected for a newly restored site. As indicated above, sedimentation rates were greatest at stations close to the breaches and at those that were at lower initial elevations. Sedimentation rates have slowed down at stations that started with very high initial rates, as these sites build in elevation and sediment consolidates. Plant recruitment also has been rapid at Pond A21, with some recruitment occurring in the first year post-breach. In following years, more and more vegetation has established (primarily *S. pacifica*), with dense patches of vegetation that are currently established likely to serve as seed sources for further recruitment throughout the pond.

Based on our measurements, the gypsum layer at Pond A21 appears to have remained intact in the first year post-breach. The only evidence of significant gypsum erosion in the first year was along creek banks and borrow ditches. Given the erosion and slumping of gypsum along creek banks, it is unlikely that the gypsum would restrict establishment of new creek channels within the pond. Although there was no measured change in the thickness of the gypsum layer in the first year following the breach, the gypsum surface appears to have softened in some areas of the pond. On a small number of occasions during sampling in years two and three, our rebar "probe" for measuring sediment depth above the gypsum surface has broken through the gypsum layer. We also have run into occasional soft spots in the gypsum when walking across the ponds, particularly in the north-east part of the site. However, this has been quite sporadic across the pond, indicating that the gypsum remains primarily intact throughout the pond. In addition, no negative effects of the gypsum layer on vegetation recruitment have been observed at Pond A21. We observed plants recruiting during the first and second years post-breach in areas with just a few cm of sediment on top of the gypsum.

The breaches at Pond A21 appear to have no significant impacts on adjacent marshes, as we saw similar rates of sediment accumulation at the mid and upper stations for transects along both Coyote Creek and Mud Slough, and these rates were similar to those found in other South Bay marshes. There were differences in sediment dynamics for the mudflat stations along Coyote Creek that were closest to the two breaches at Pond A21, indicating that some local dynamics may be affecting adjacent mudflat stations. However, mudflats are naturally very highly dynamic, and without some background data on local spatial variability in mudflat sediment dynamics, it is difficult to evaluate if these changes are primarily due to inherent spatial variation or to impacts associated with the breach.

As more salt ponds are opened to tidal action within particular local regions of the South Bay, it would be very useful to evaluate regional patterns of both sedimentation rates within ponds and effects on existing adjacent mudflats before and after breaching. If there are limitations to sediment availability that either restrict pond accumulation rates or cause impacts to existing mudflats or marshes, it is likely that these will become apparent through observations of cumulative effects of multiple restored ponds within a region.

**ACKNOWLEDGMENTS**

We thank the following students who helped in the field and laboratory for this project: Theresa Engle, Zooey Diggory, Rob Genova, Russell Hilkene, Amber Finley, and Vivek Dharne. Also thanks to the U.S. Fish and Wildlife Service for providing access, and to Lisa Porcella and others at the Santa Clara Valley Water District for collaboration and support on this project.

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**Table 1.** Grouping of sampling locations for the north and south portions of Pond A21. Vertical rates of sedimentation were measured at all stations using sediment pins and the depth of sediment above the gypsum surface. Short-term, mass-based sedimentation rates were measured using rubber disks at the 10 stations indicated with an asterisk. See Figure 1 for location of stations within the pond.

| North Site | South Site |
|---|---|
| 1 | 11 |
| 2* | 12* |
| 3 | 16* |
| 4* | 17 |
| 5 | 19 |
| 6 | 20 |
| 7 | 21* |
| 8* | 22 |
| 9 | 23 |
| 10 | 24* |
| 13 | 25 |
| 14 | 26* |
| 15 | 27 |
| 18* | 2106 |
| 2101 | 2108 |
| 2102 | 2109 |
| 2103* | 2110 |
| 2104 | |
| 2105 | |
| 2107 | |

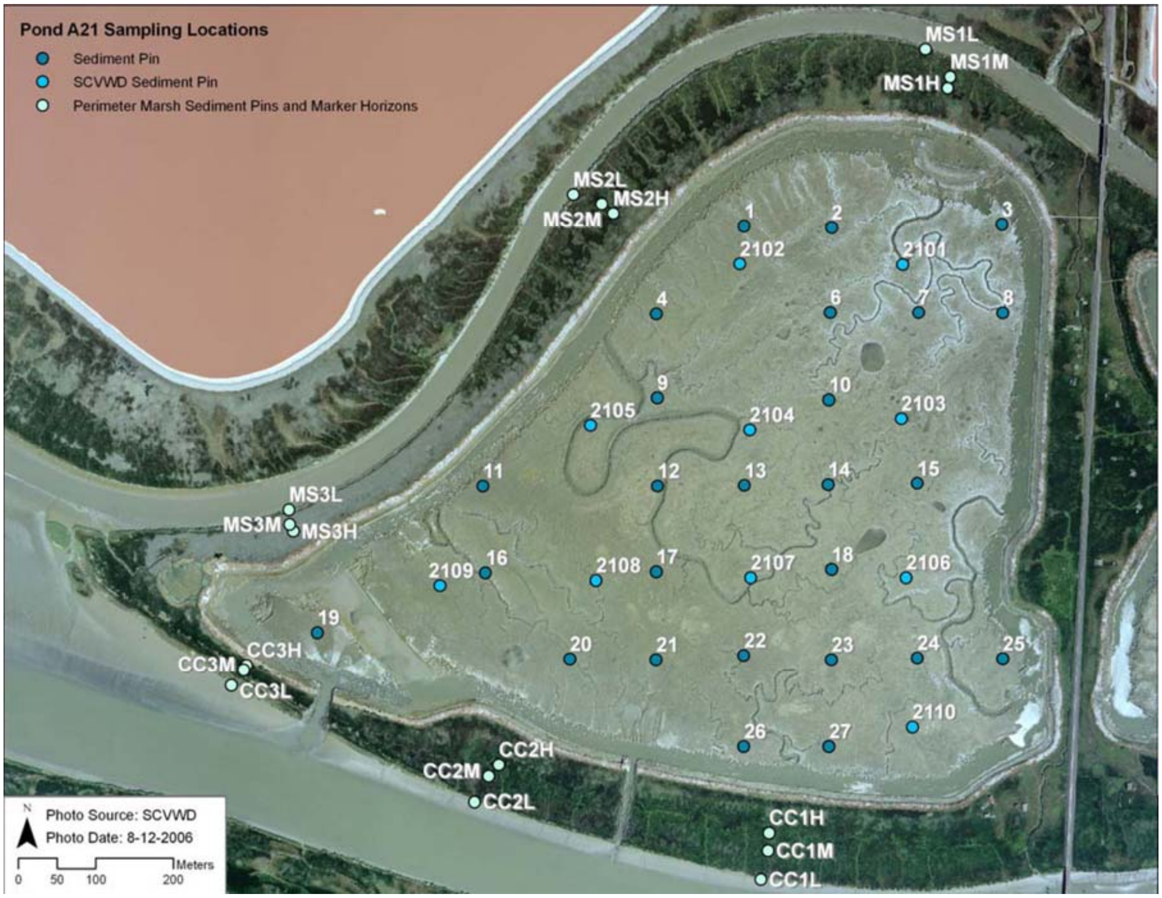



**Figure 1**. Sampling locations at Pond A21, including locations within the pond and perimeter marsh and mudflat locations along Coyote Creek (indicated with CC as station location on the figure) and Mud Slough (indicated with MS as station location on the figure). Locations within Pond A21 were sampled using sediment pins and measuring the depth of sediment above the gypsum layer. Pond locations established as part of this research project are numbered 1 to 27, and those from the Santa Clara Valley Water District are 2101 to 2110. Locations along both Coyote Creek and Mud Slough have three transects containing a low, middle, and high marsh sample site.

**Figure 2**. Sediment pins used to measure vertical rates of sediment accumulation at Pond A21. PVC pipes were pounded into the sediment approximately 3 meters, with approximately 1.8 meters remaining above ground. Measurements of pin heights relative to the surrounding sediment surface were recorded on two sides of each pin prior to the breach and approximately 1, 3, and 6 months and 1, 2, and 3 years post breach.

**Figure 3**.  Rubber disks used to measure short-term, mass-based rates of sediment accumulation.  Disks (approximately 12.5 cm diameter) accumulated sediment over a two-week period and were deployed every two months in the first year post breach.  Wire screens prevented disturbance of disks and sediment by birds at the pond.

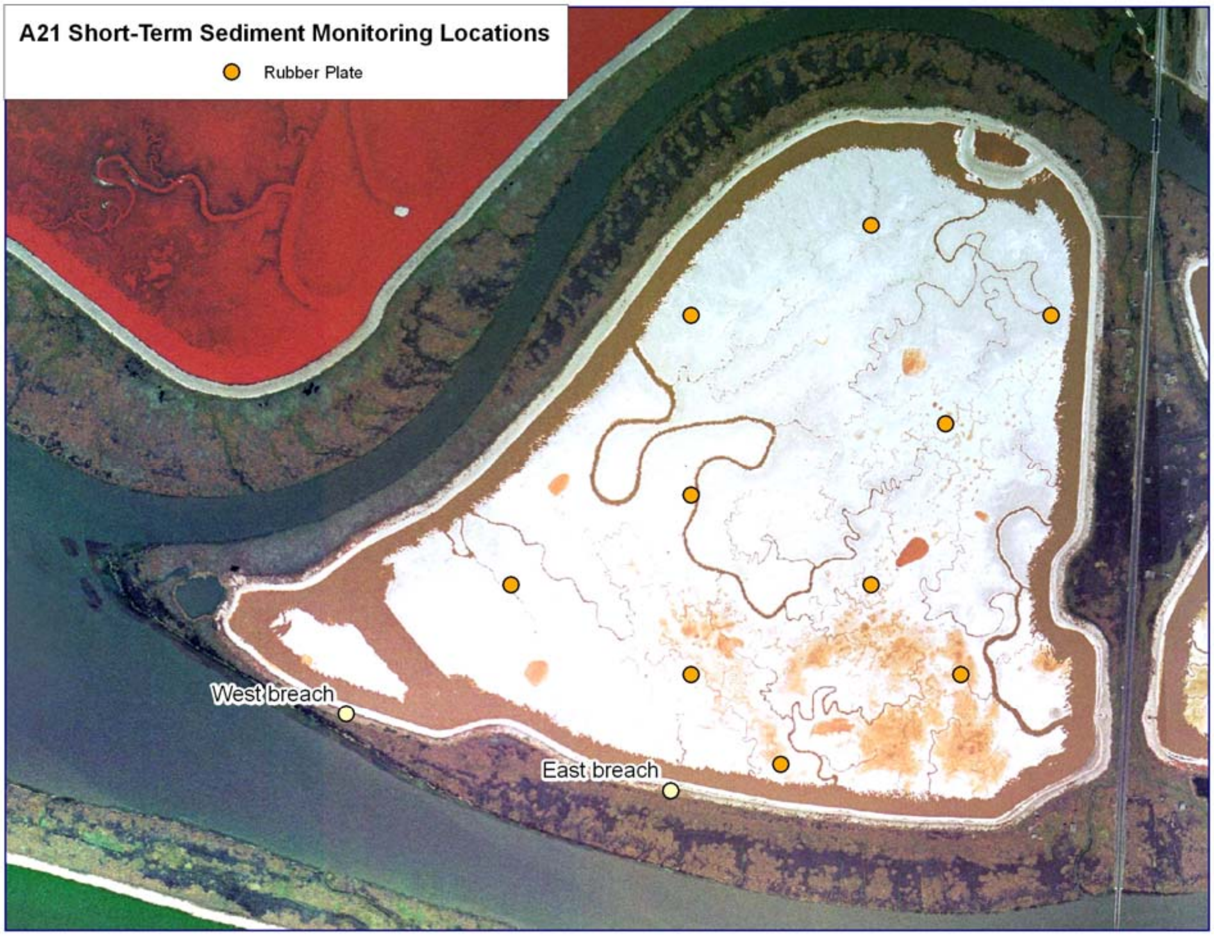



**Figure 4**. Sampling locations for short-term monitoring of mass-based sediment accumulation, using rubber disks. This includes stations number 2, 4, 8, 12, 16, 18, 21, 24, 26 and 2103.

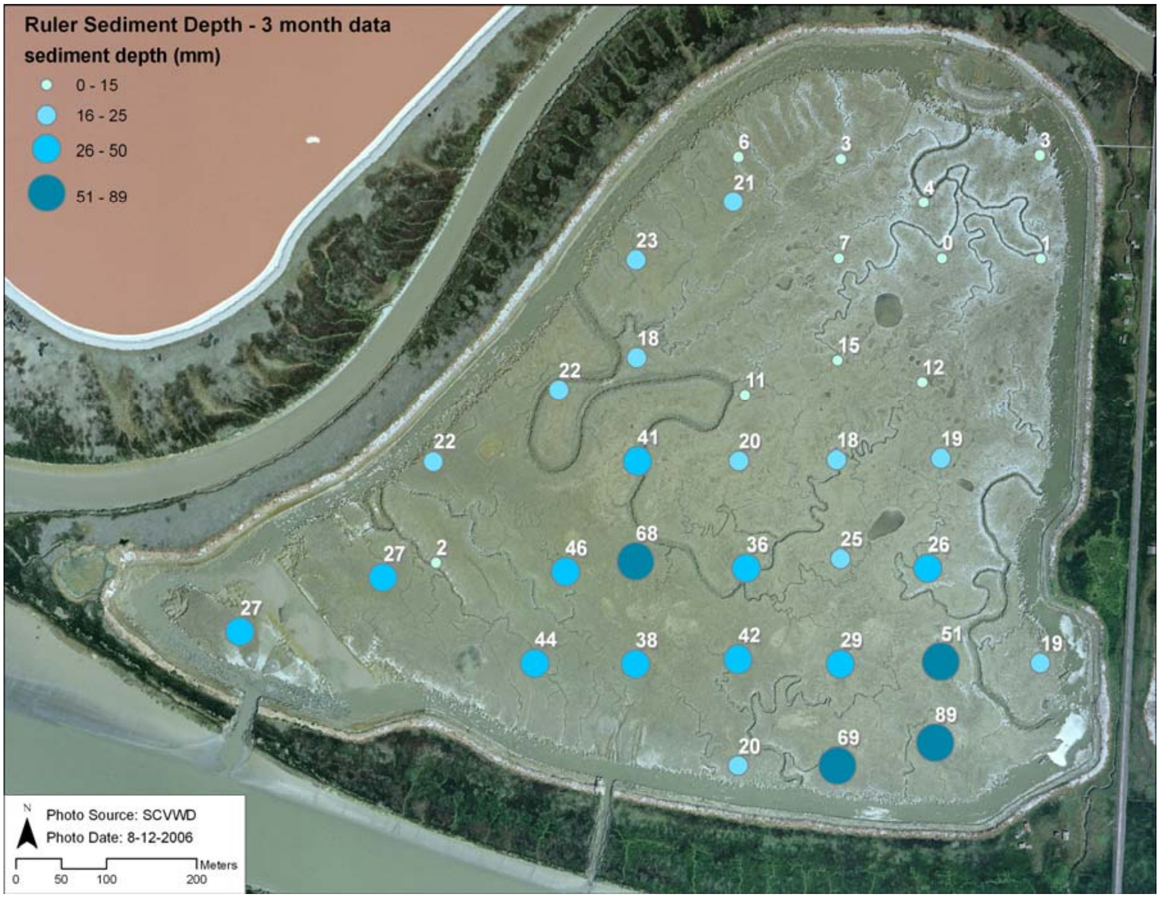



**Figure 5**. Depth of accumulated sediment (mm) above gypsum surface at each sampling location, three months following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

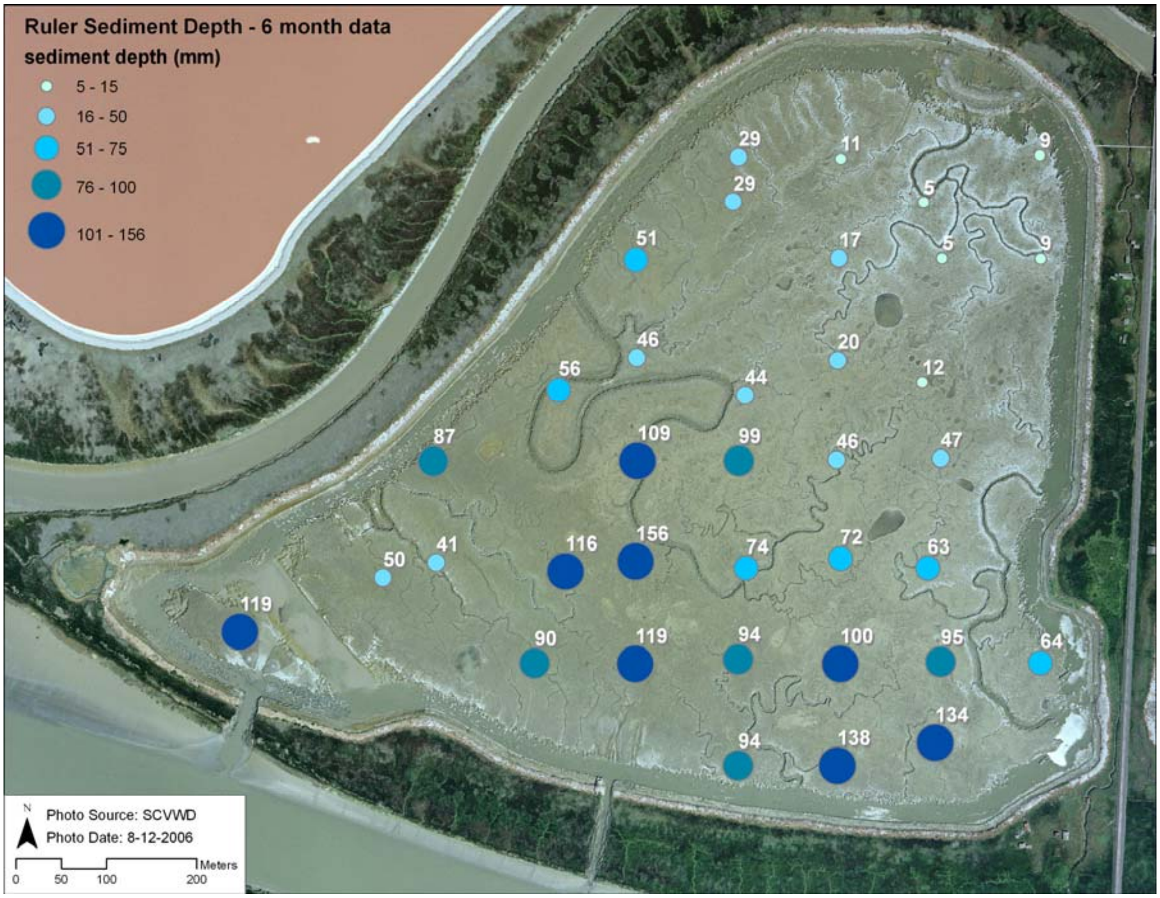



**Figure 6**. Depth of accumulated sediment (mm) above gypsum surface at each sampling location, six months following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

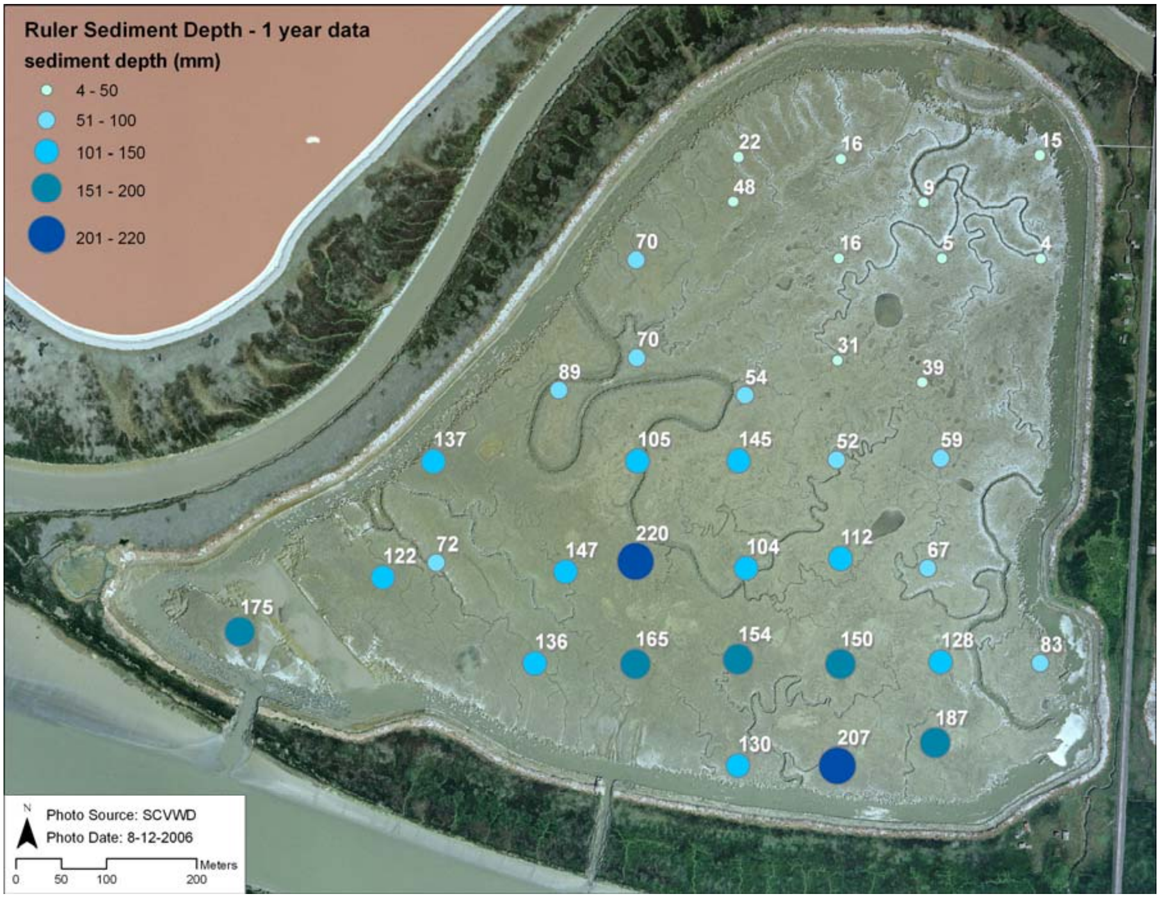



**Figure 7**. Depth of accumulated sediment (mm) above gypsum surface at each sampling location, one year following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

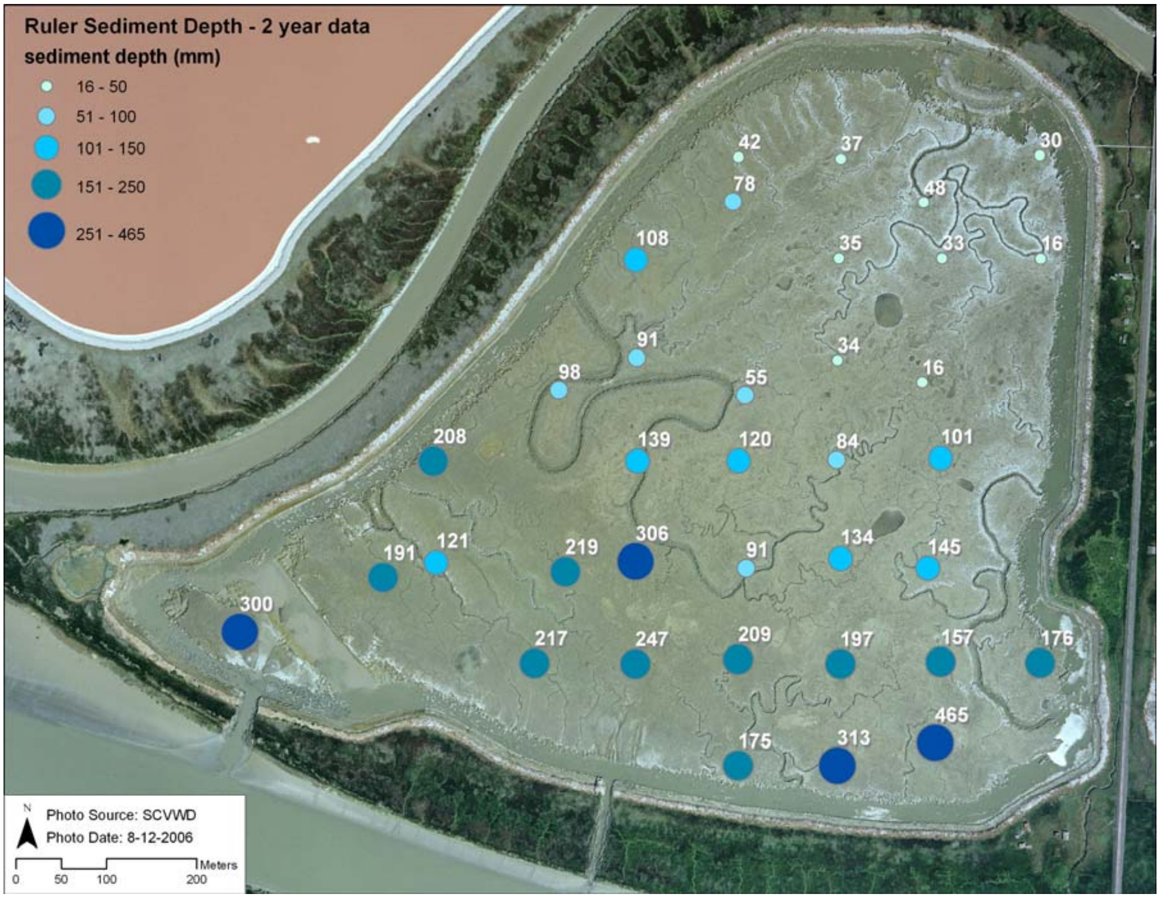



**Figure 8**. Depth of accumulated sediment (mm) above gypsum surface at each sampling location, two years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

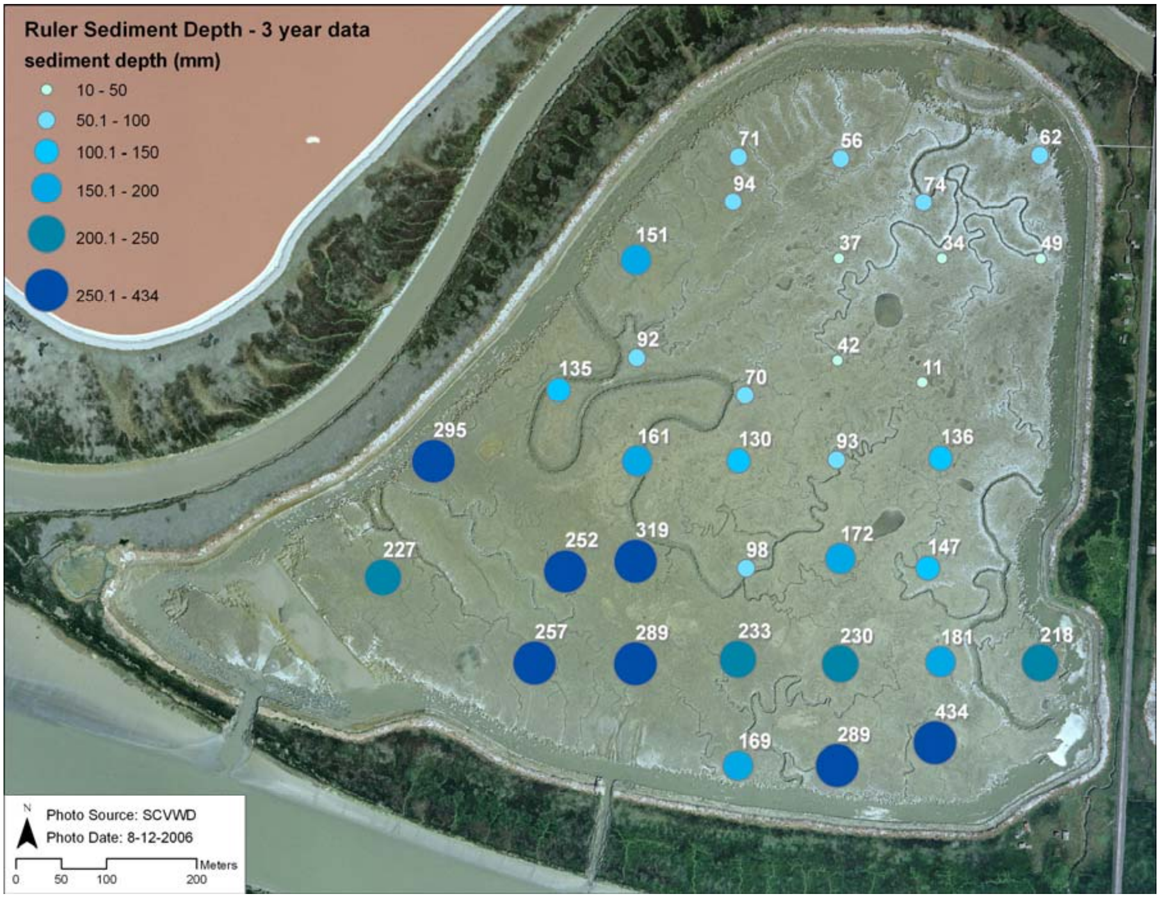



**Figure 9**. Depth of accumulated sediment (mm) above gypsum surface at each sampling location, three years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

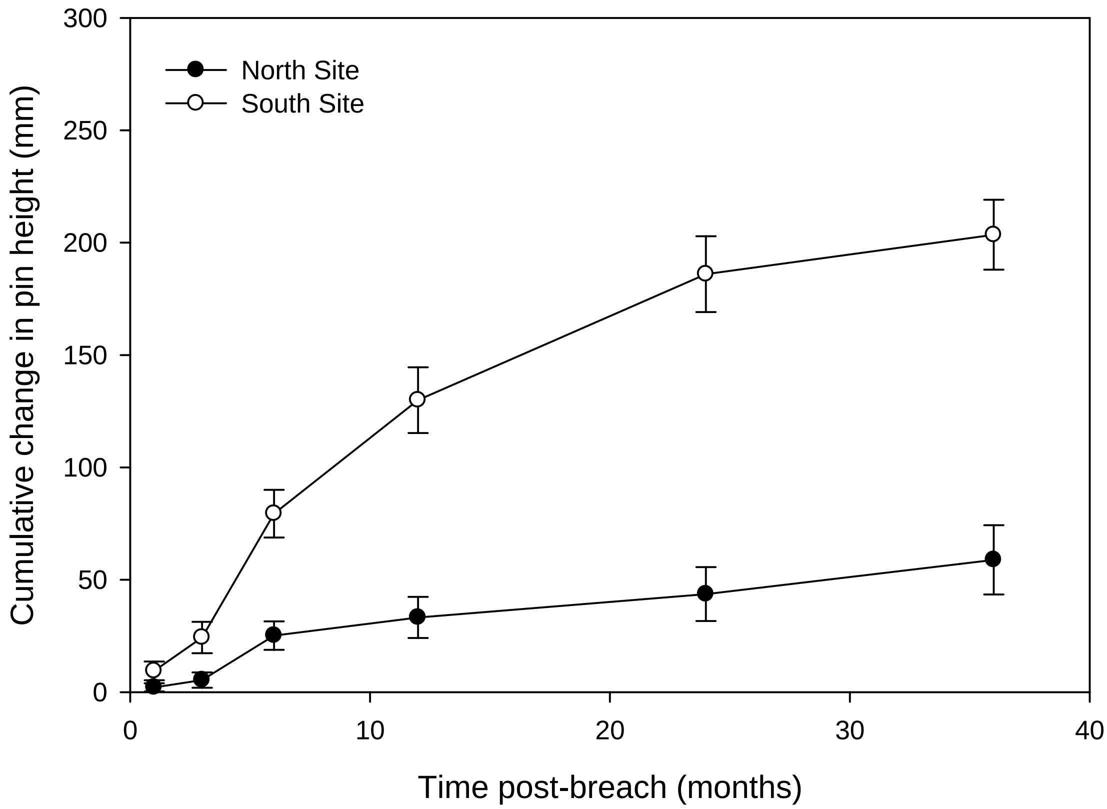



**Figure 10**. Cumulative change in pin heights (mm) from sediment burial (y-axis) at 1, 3, 6, 12, 24, and 36 months following breach (x-axis). Data are averaged for North and South portions of Pond A21 (see Table 1 for North and South groups of sampling locations).

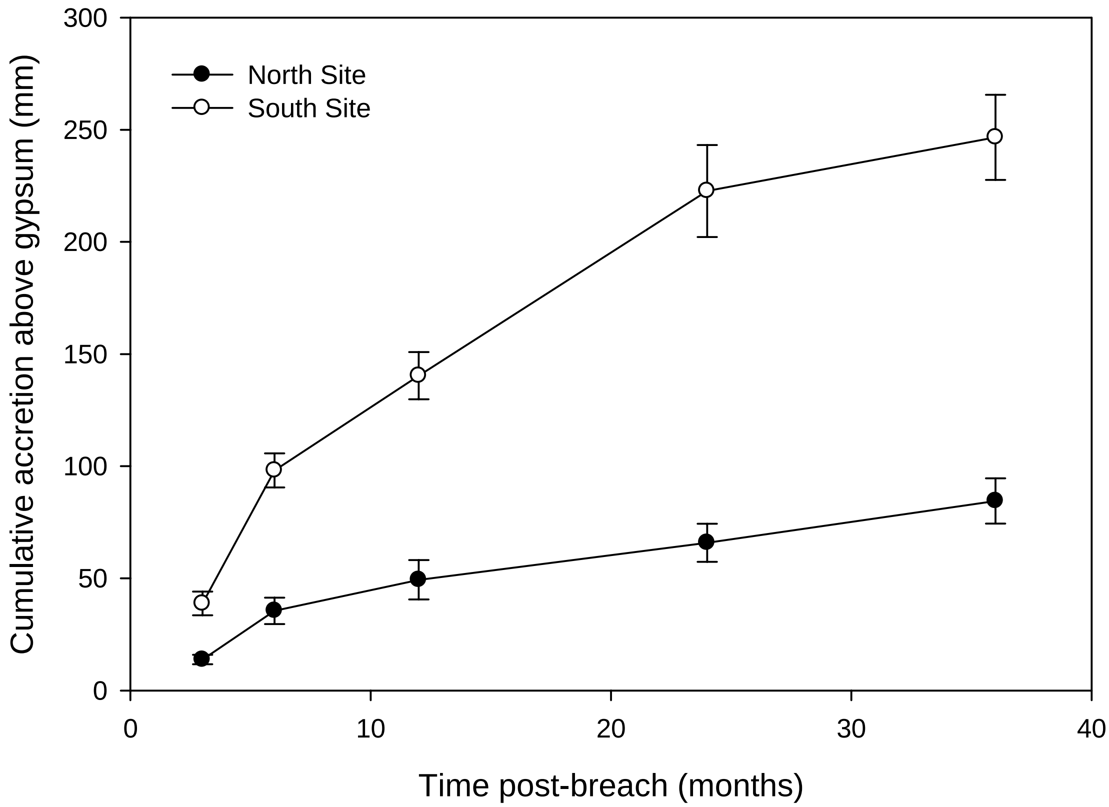



**Figure 11**. Cumulative sediment accretion depths (mm) above the gypsum surface (y-axis) at 1, 3, 6, 12, 24, and 36 months following breach (x-axis). Data are averaged for North and South portions of Pond A21 (see Table 1 for North and South groups of sampling locations).

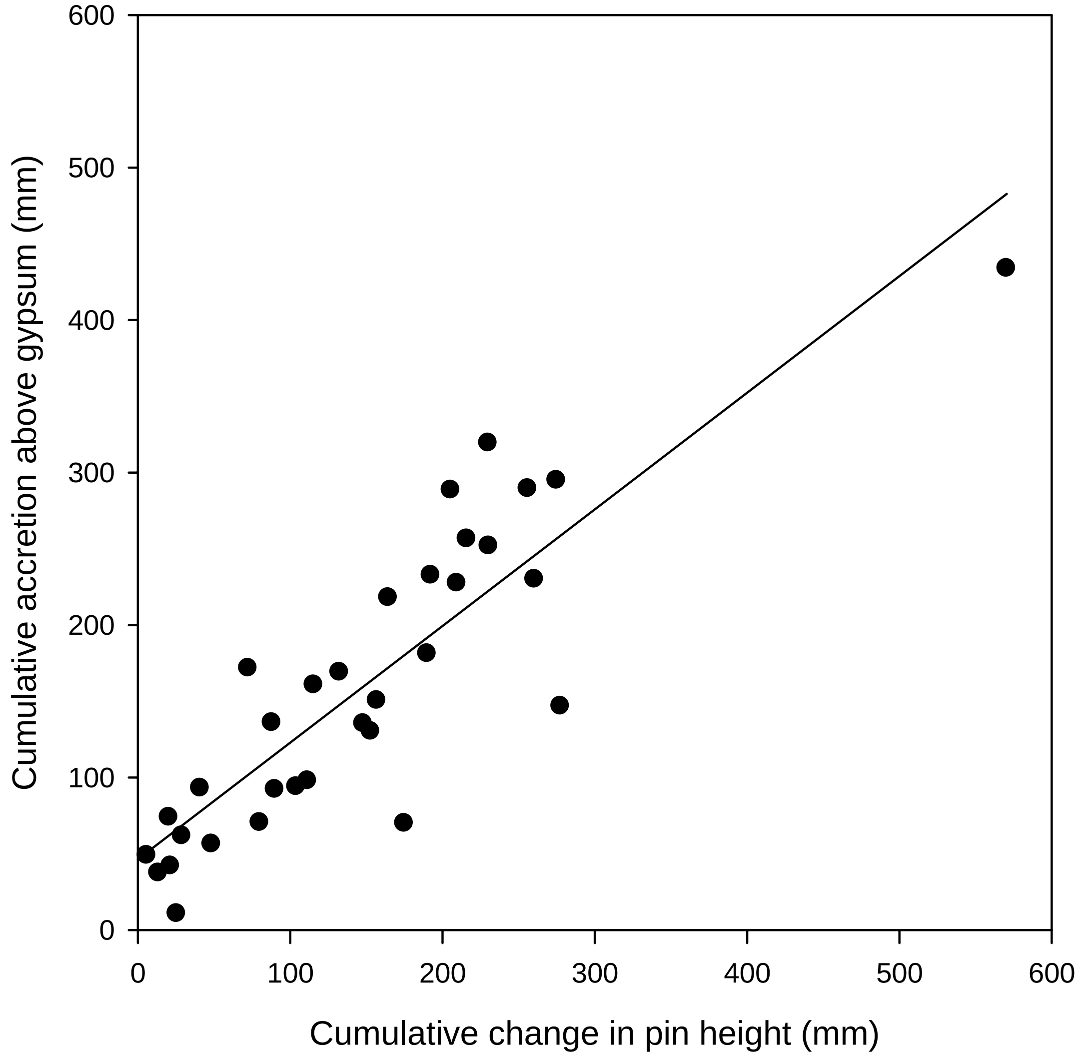



**Figure 12**. Comparison of sedimentation rates after three years, as measured by pin heights (x-axis) and the depth of sediment above the gypsum surface (y-axis). Data for all sampling locations are illustrated ($r^2$ = 0.78 for all data and $r^2$ = 0.87 excluding SCVWD pins).

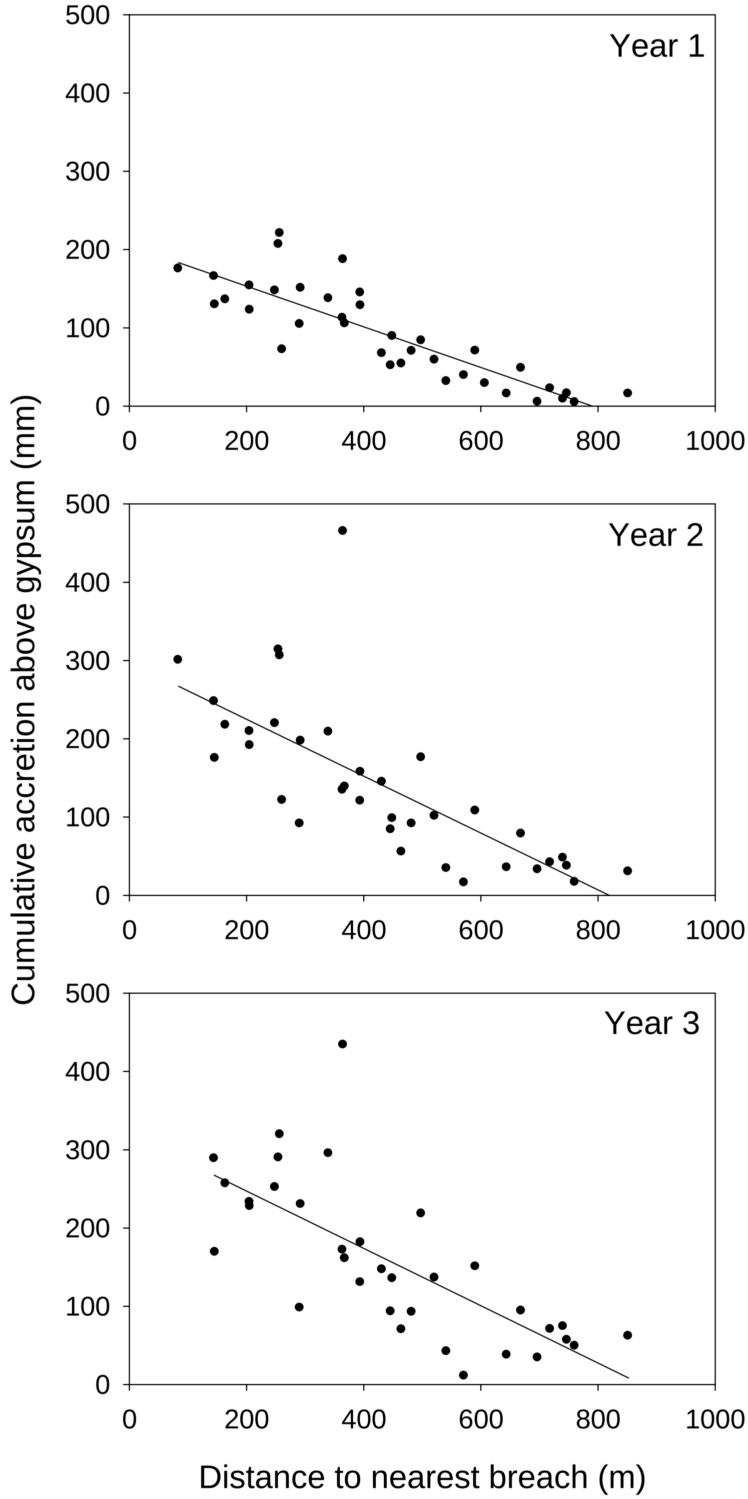



**Figure13**. Comparison of cumulative sediment accretion rates (mm) above the gypsum layer (y-axis) and site proximity (m) to the nearest breach (x-axis) for year one ($r^2$=0.73), year two ($r^2$=0.53), and year three ($r^2$=0.52).

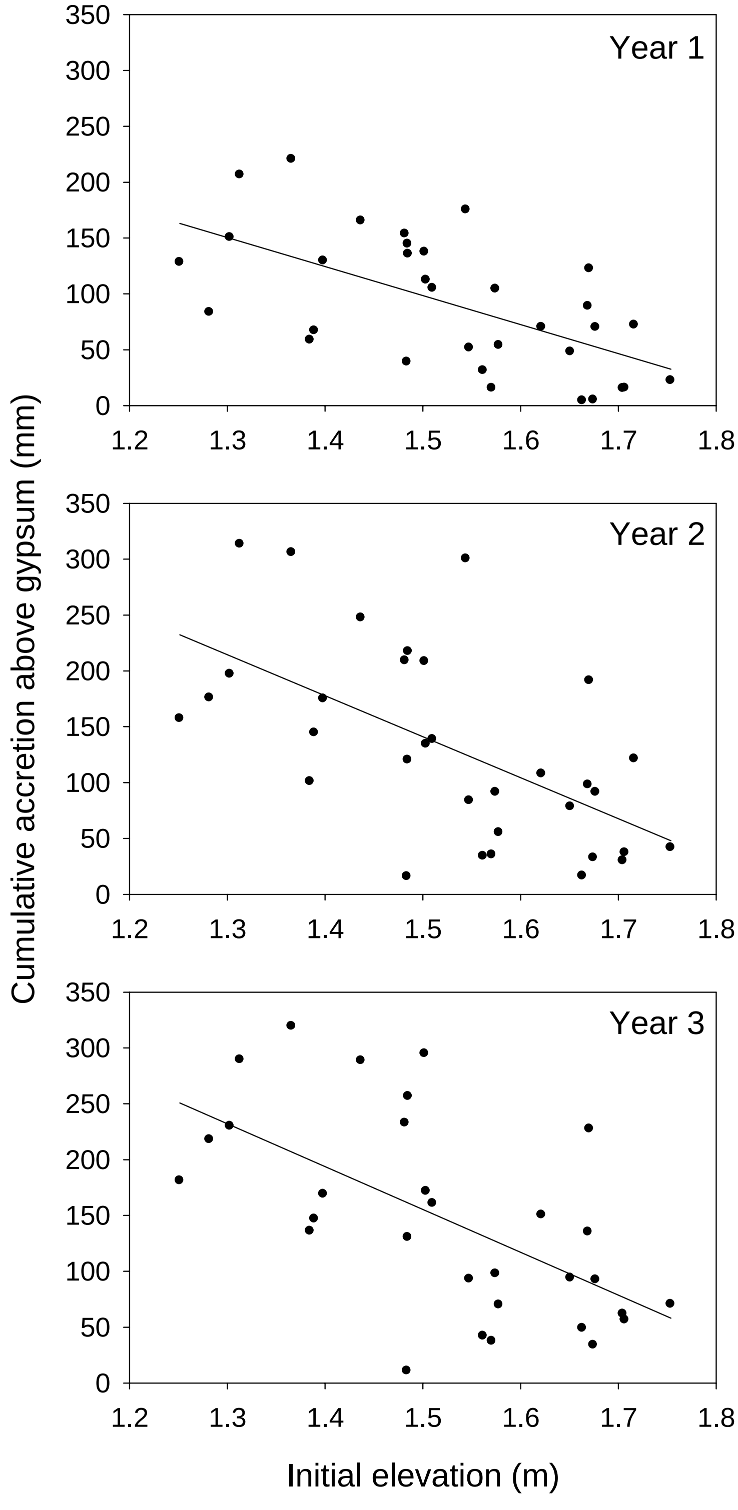



**Figure 14**. Comparison of cumulative sediment accretion rates (mm) above the gypsum surface (y-axis) and initial site elevation (x-axis) for year one ($r^2$=0.37), year two ($r^2$=0.35), and year three ($r^2$=0.36).

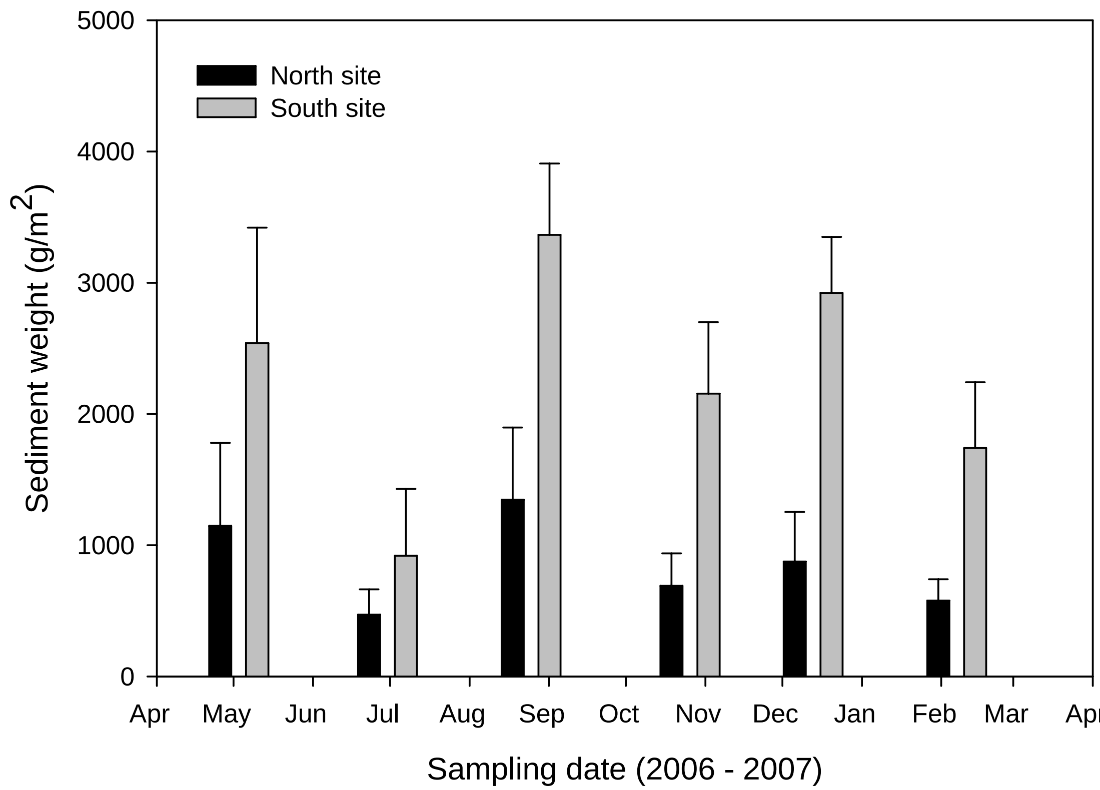



**Figure 15**. Short-term, mass-based sedimentation rates (g/m$^2$) over two-week sampling intervals during the first year post-breach. Data are averaged for North and South portions of Pond A21 (see Table 1 for North and South groups of sampling locations).

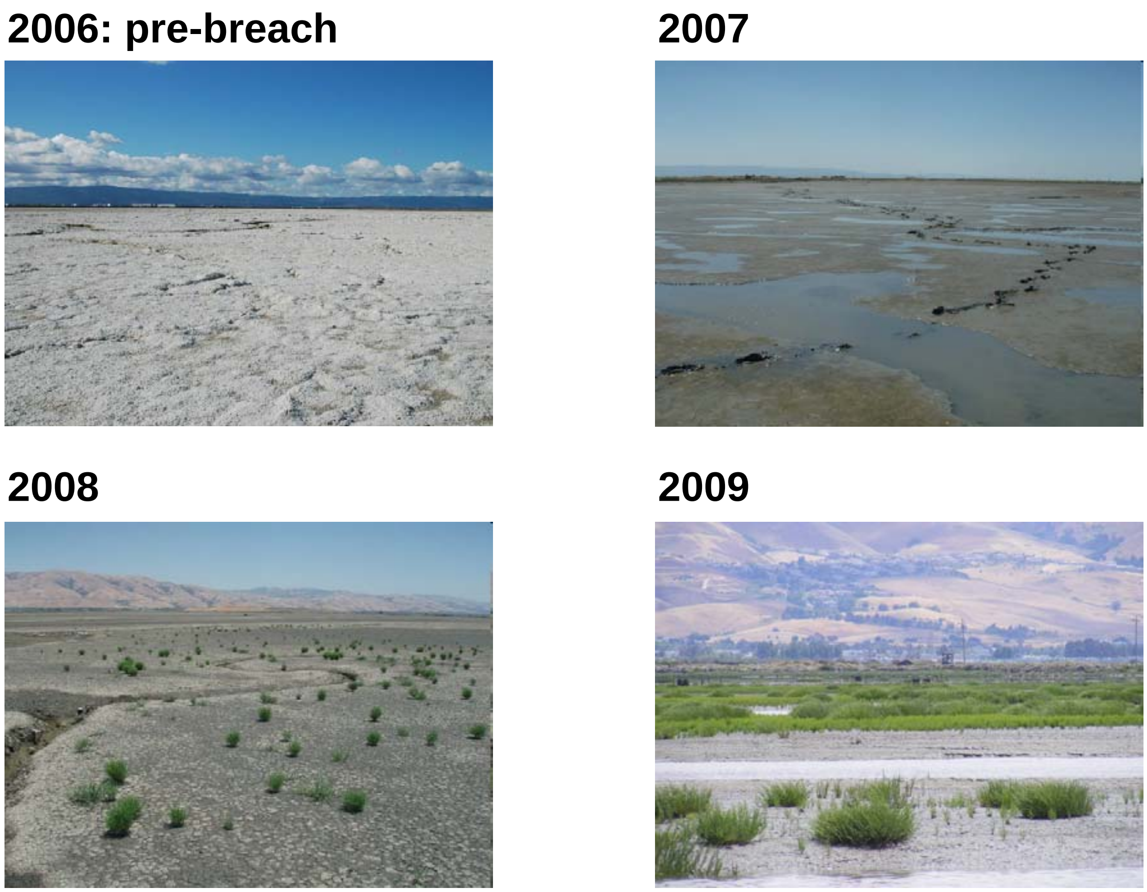



**Figure 16**. Pond A21 before the breach in 2006, and annually until 2009. The surface in 2006 consisted of bare gypsum, but by 2008 enough sediment had accumulated for plants to establish in multiple areas within the pond.

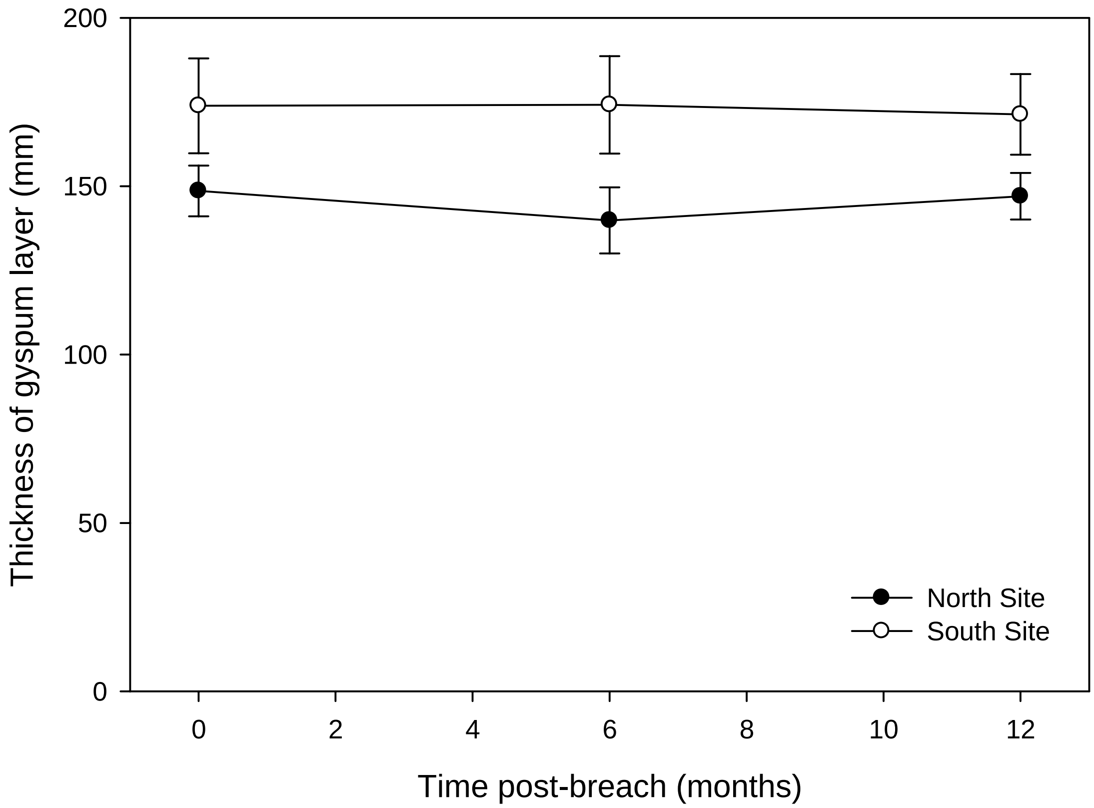



**Figure 17**. Thickness of gypsum layer (mm) just prior to the breach, six months and one year post-breach. Data are averaged for North and South portions of Pond A21 (see Table 1 for North and South groups of sampling locations).

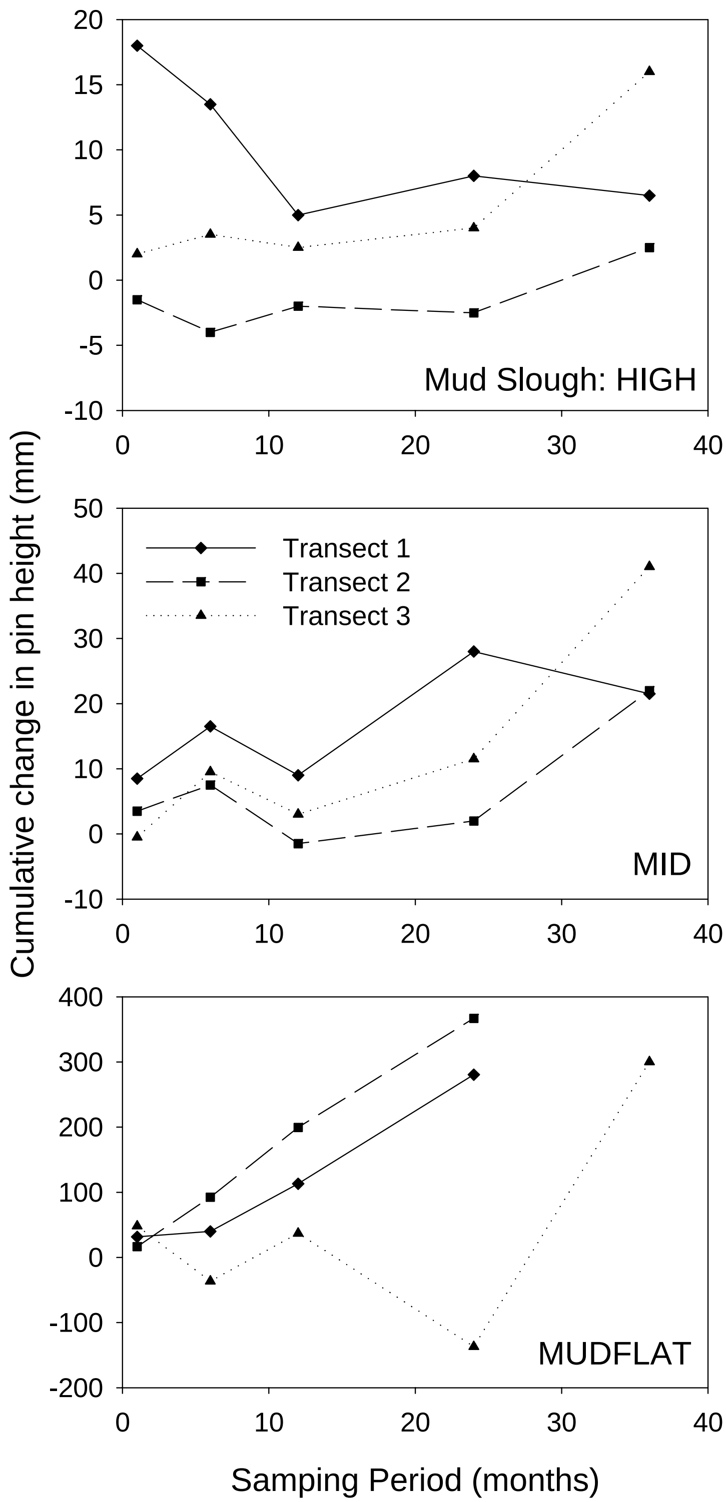



**Figure 18**. Cumulative change in pin heights (mm) from sediment burial (y-axis) in mudflat, middle, and high marsh zones of Mud Slough. Data were collected 1, 6, 12, 24, and 36 months following breach (x-axis).

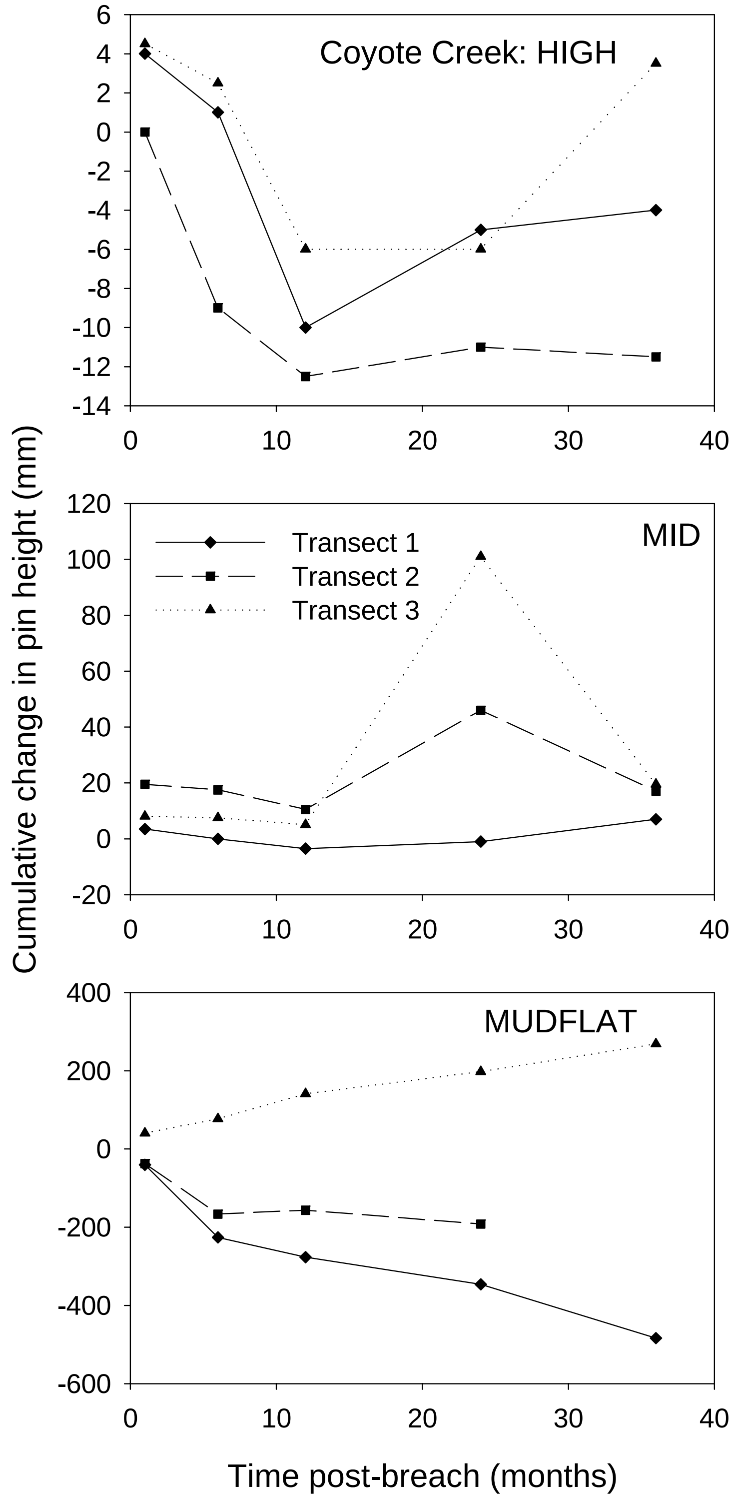



**Figure 19**. Cumulative change in pin heights (mm) from sediment burial (y-axis) in mudflat, middle, and high marsh zones of Coyote Creek. Data were collected 1, 6, 12, 24, and 36 months following breach (x-axis).

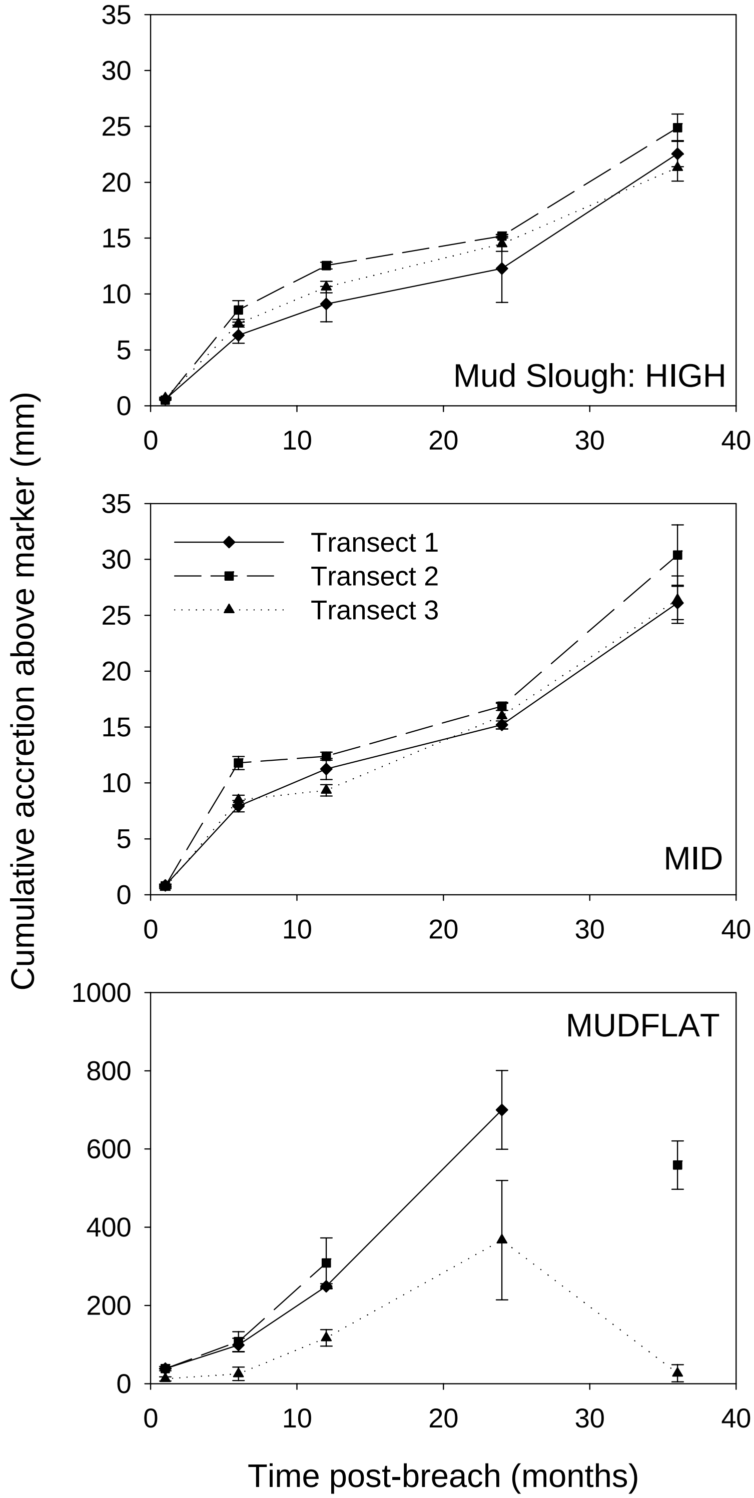



**Figure 20**. Cumulative sediment accretion (mm) above feldspar or cloth markers (y-axis) in mudflat, middle, and high marsh zones of Mud Slough. Data were collected 1, 6, 12, 24, and 36 months following breach (x-axis).

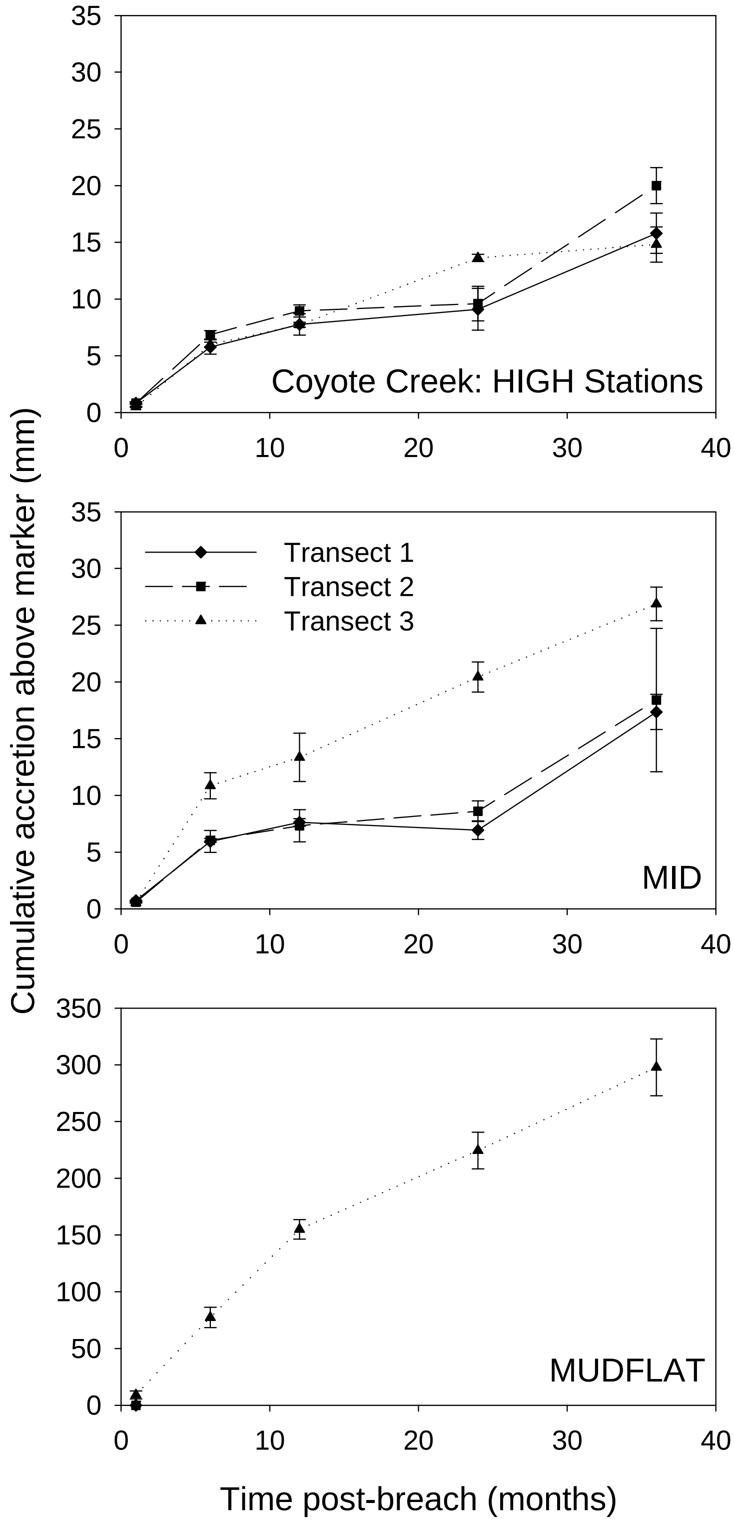



**Figure 21**. Cumulative sediment accretion (mm) above feldspar or cloth markers (y-axis) in mudflat, middle, and high marsh zones of Coyote Creek. Data were collected 1, 6, 12, 24, and 36 months following breach (x-axis).

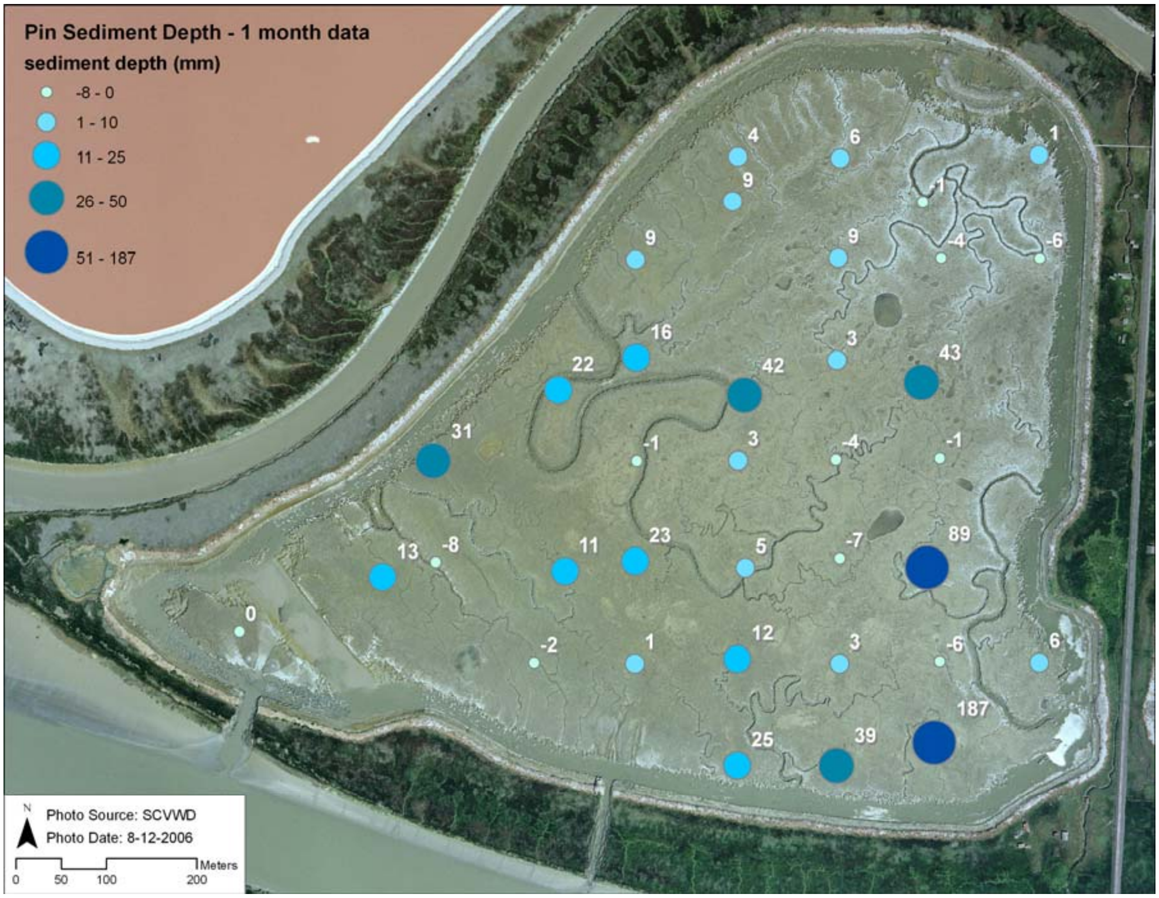
# APPENDICES FOR:

## DYNAMICS OF SEDIMENT ACCUMULATION IN POND A21 AT THE ISLAND PONDS

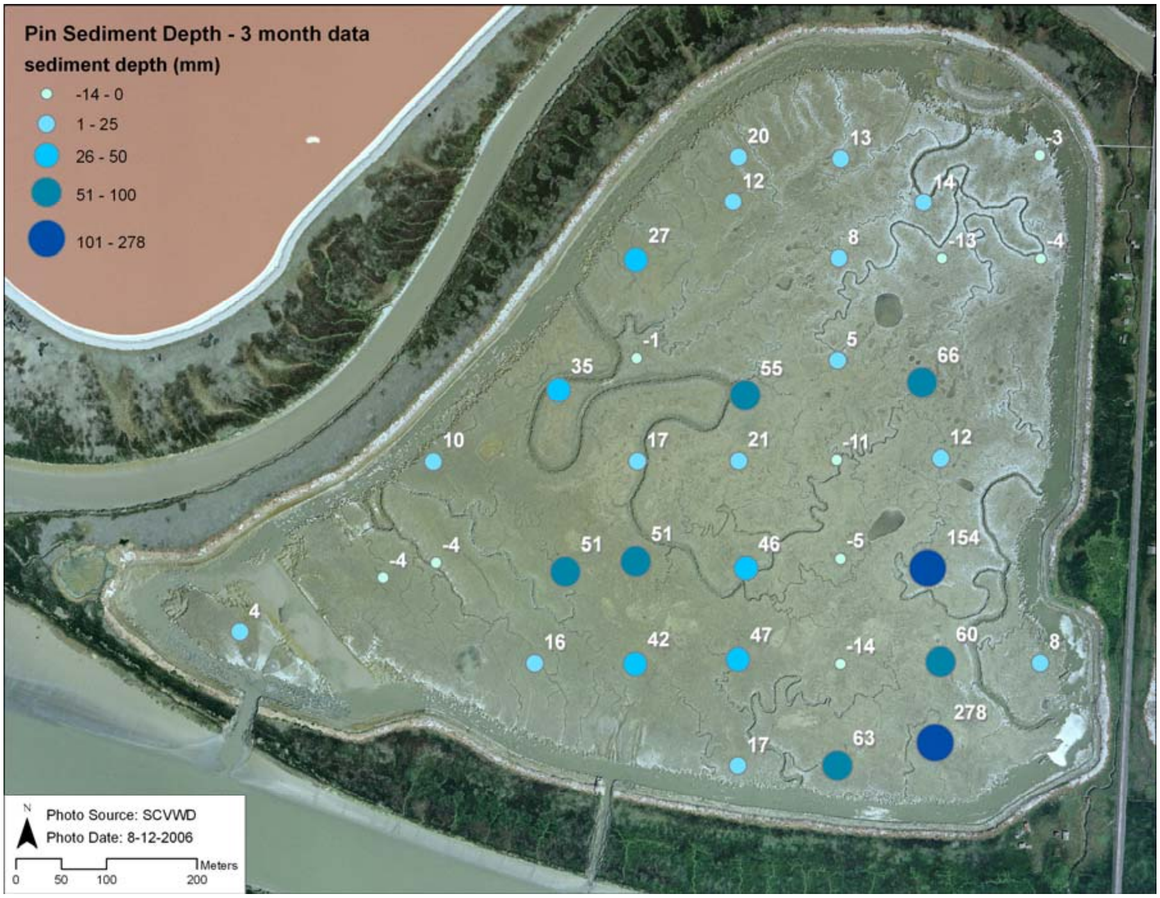
**John C. Callaway**
**V. Thomas Parker**
**Lisa M. Schile**
**Ellen R. Herbert**
**Evyan L. Borgnis**

# APPENDIX A:

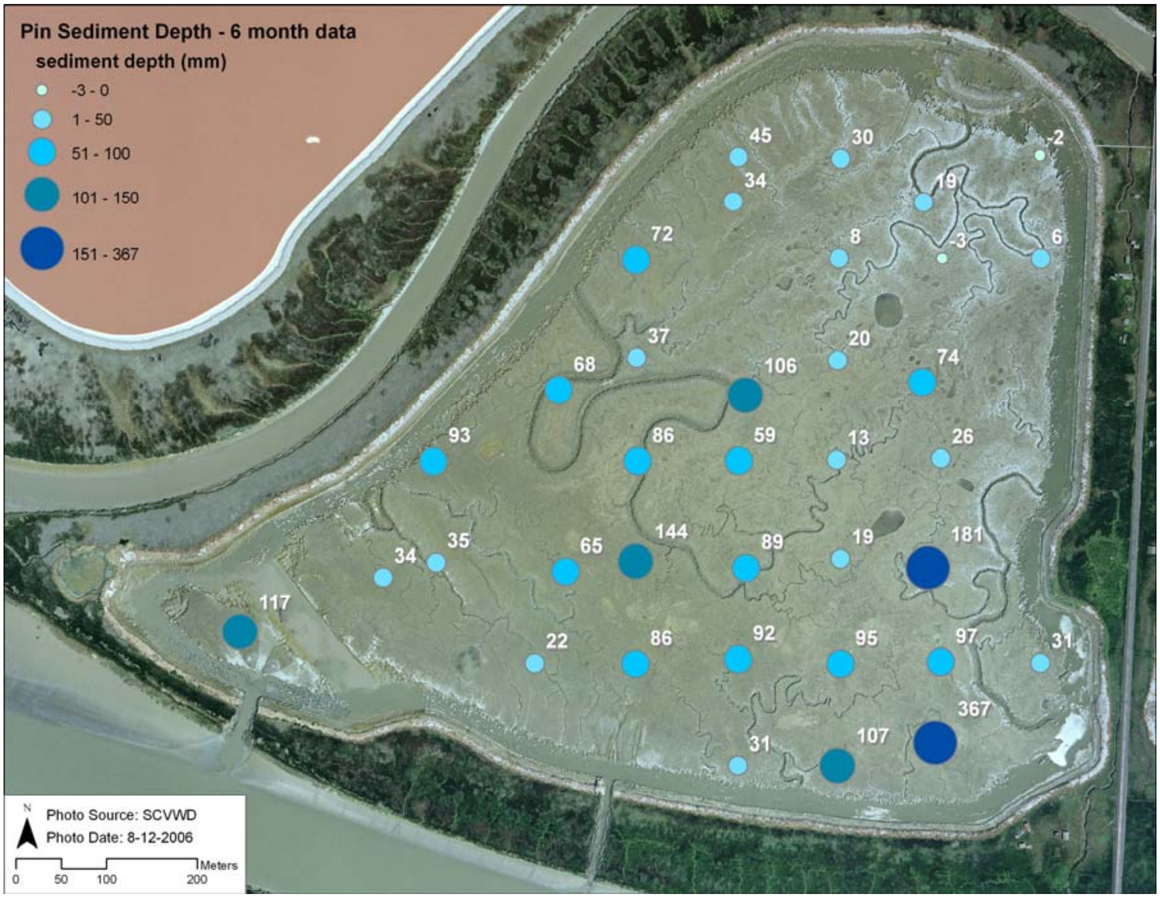
# Maps of pond sedimentation rates based on heights of sediment pins



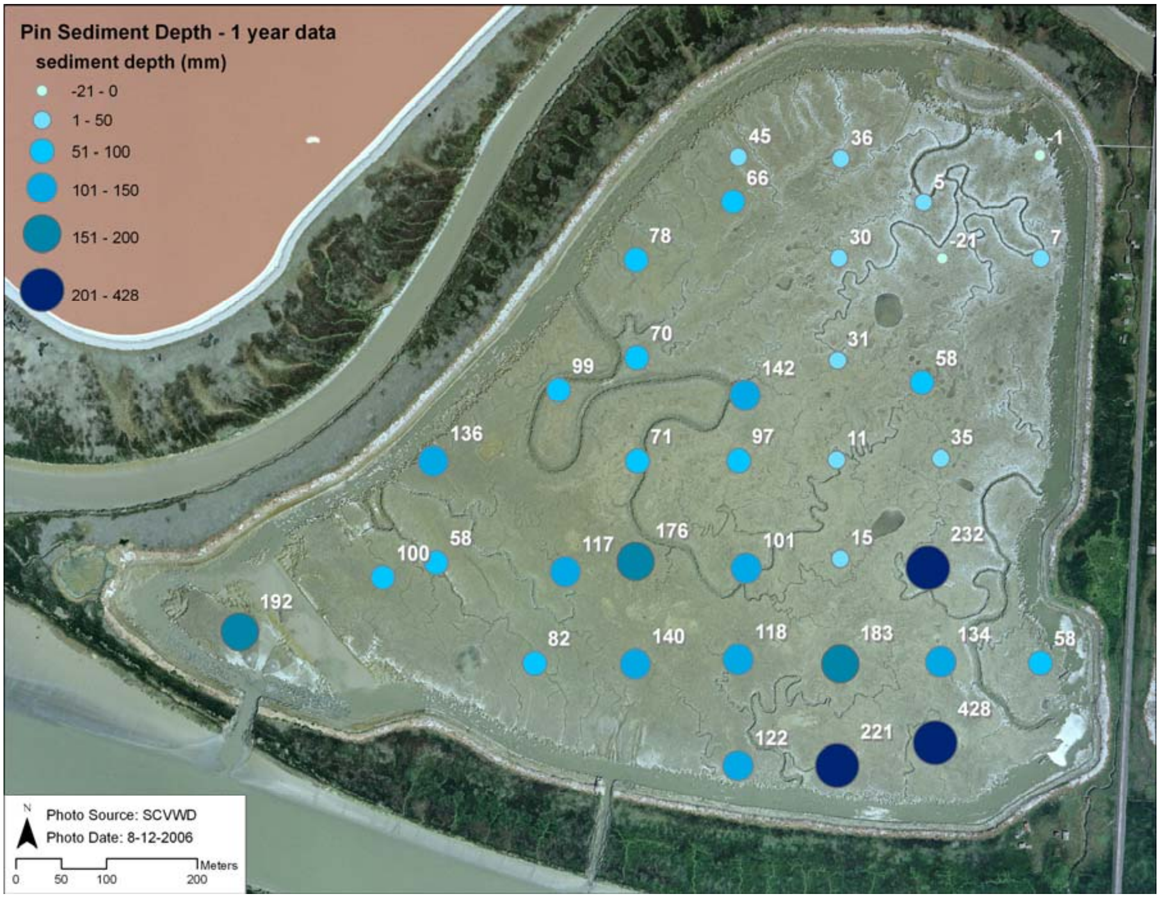

Appendix A.1. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each sampling location, one month following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.



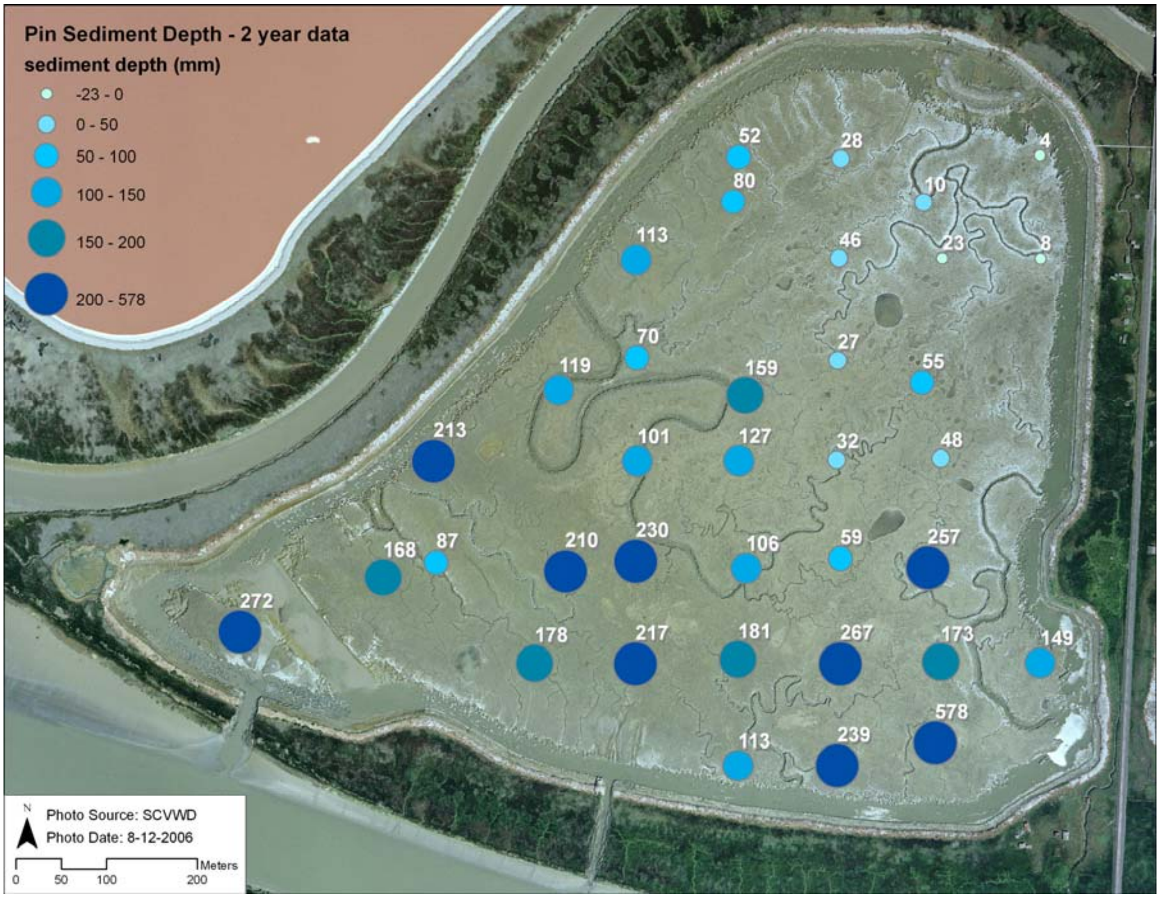

Appendix A.2. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each sampling location, three months following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.



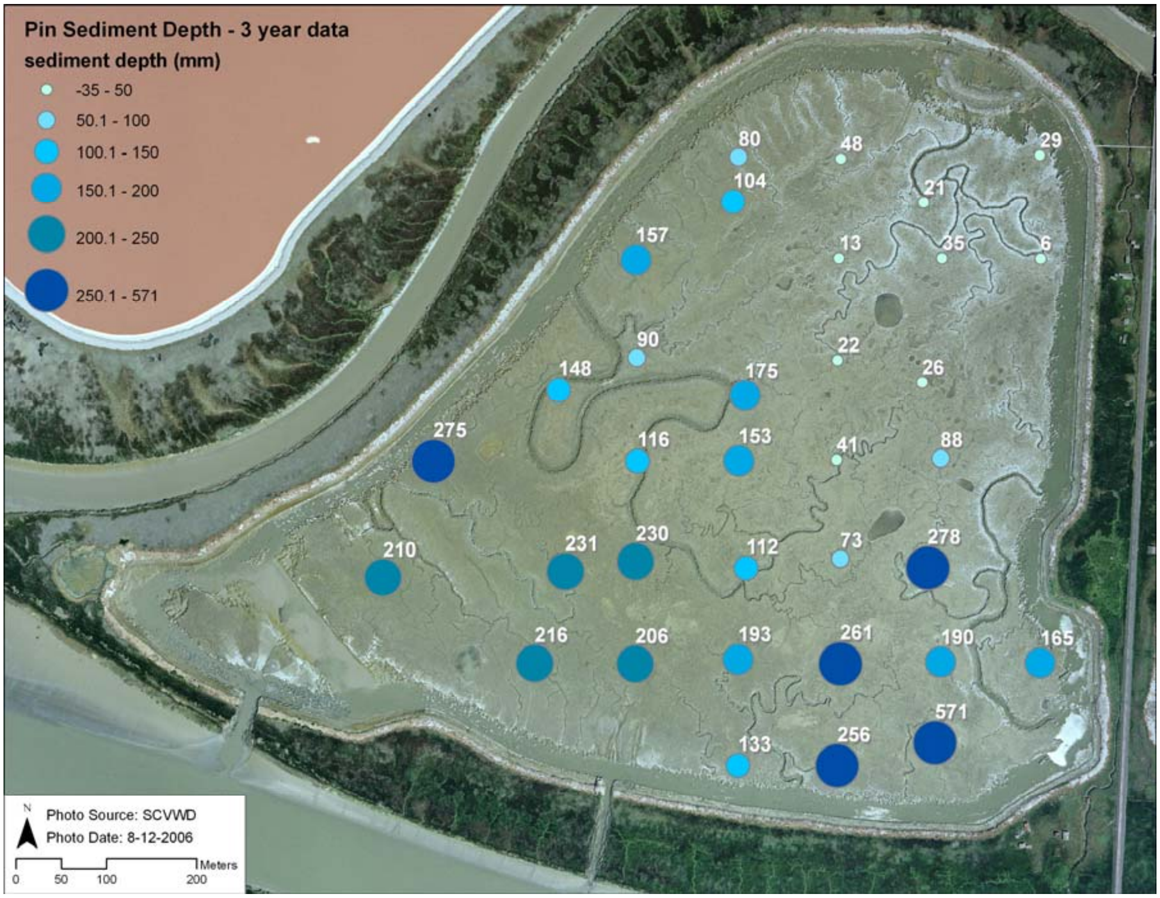

Appendix A.3. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each sampling location, six months following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.




Appendix A.4. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each sampling location, one year following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.



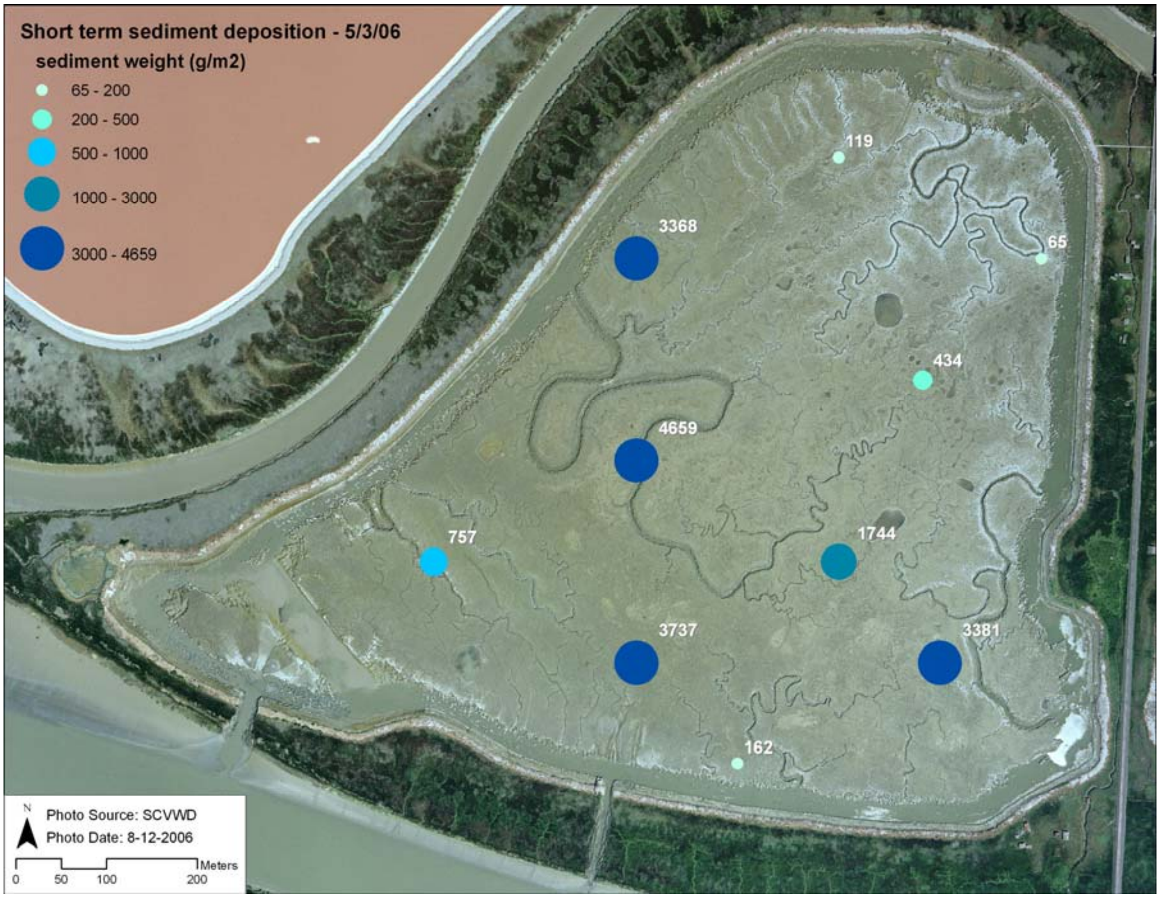

Appendix A.5. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each sampling location, two years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.



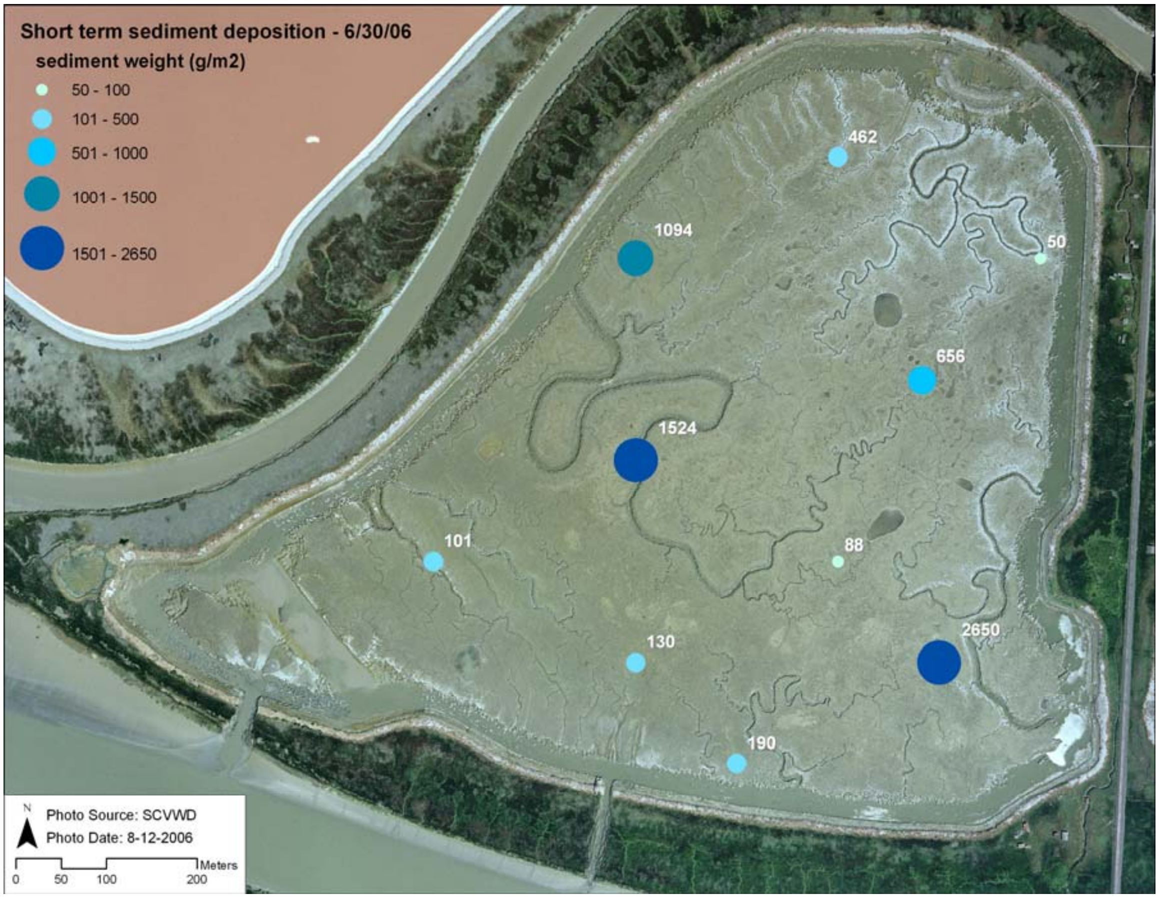

Appendix A.6. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each sampling location, three years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

# APPENDIX B:

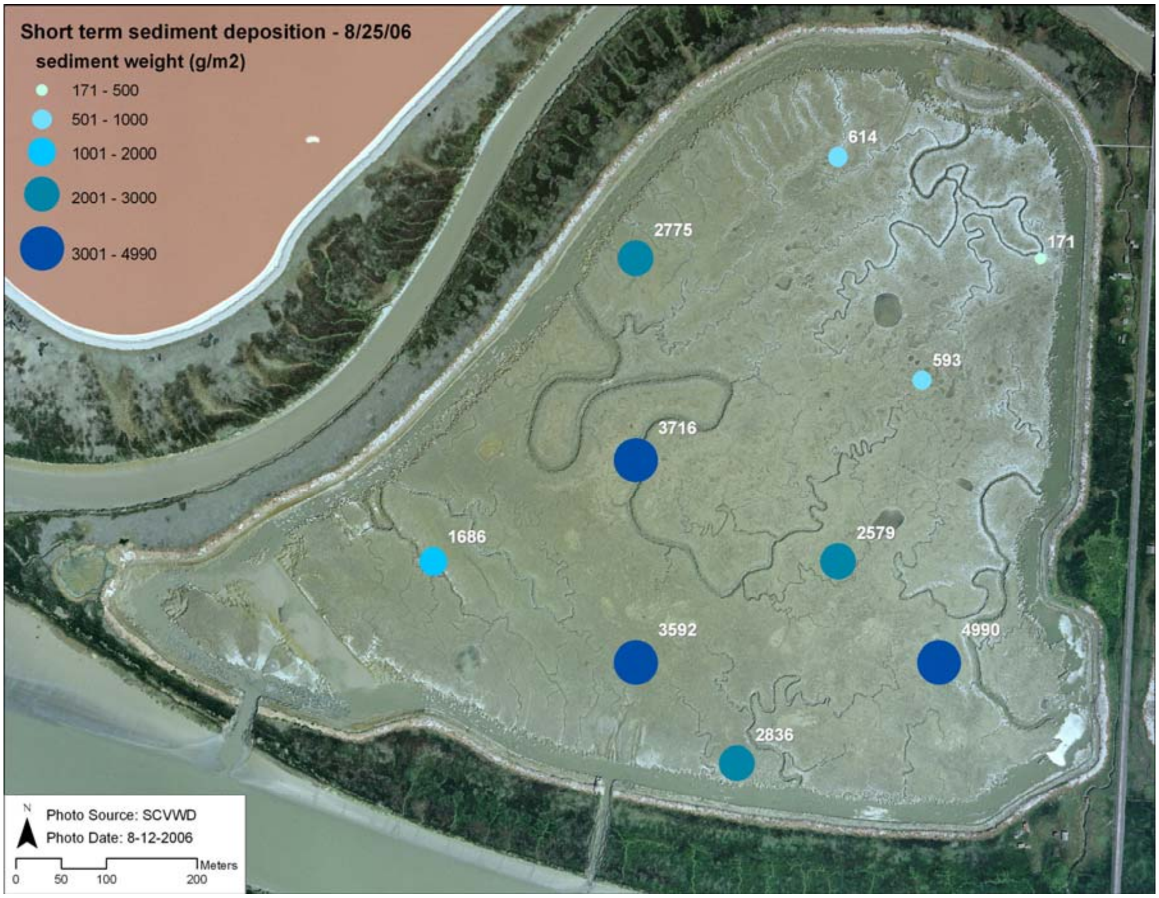
# Maps of short-term, mass-based rates of sedimentation



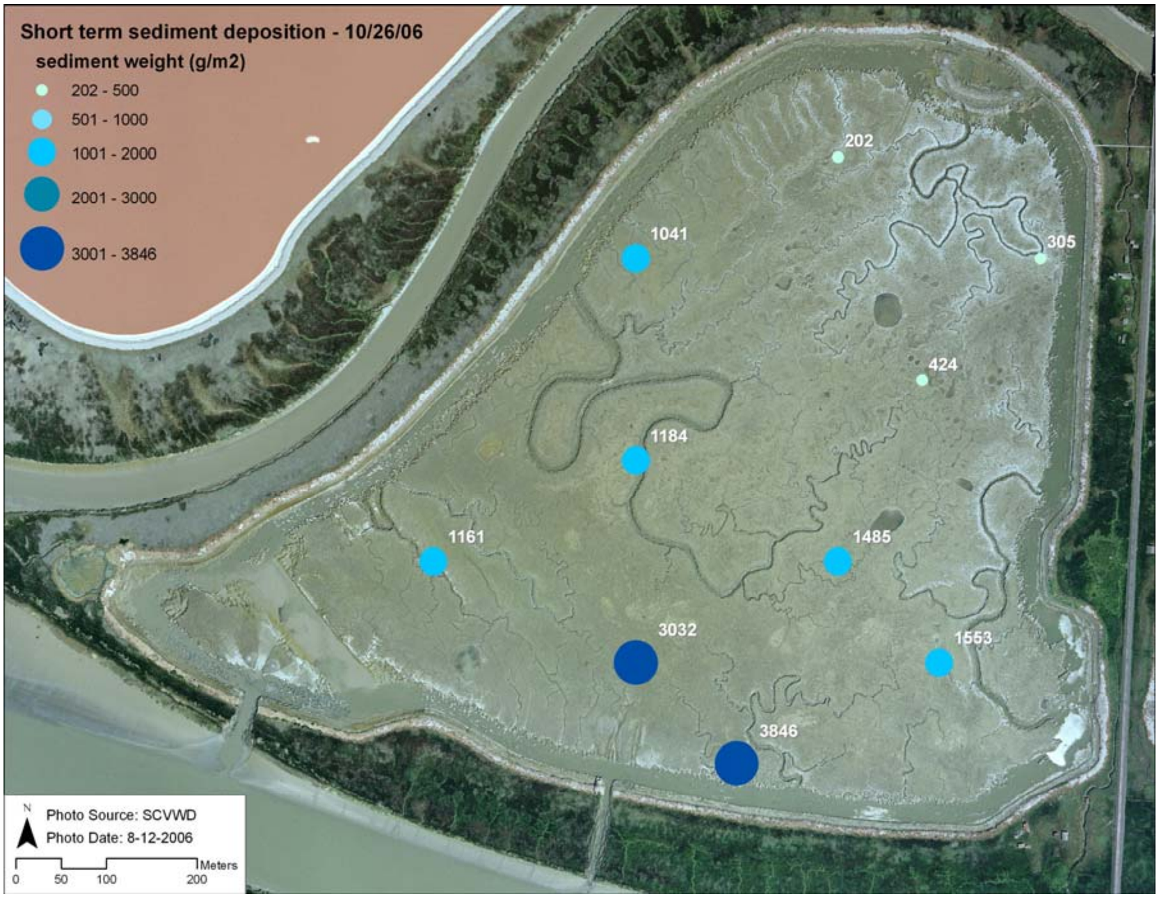

Appendix B.1. Mass of accumulated sediment ($g/m^2$) on rubber disks collected over a two-week period in April-May, 2006. The larger and darker circles indicate greater weights of sediment on top of the rubber disks, and the number above each circle indicates the grams of sediment per meter square from each station.



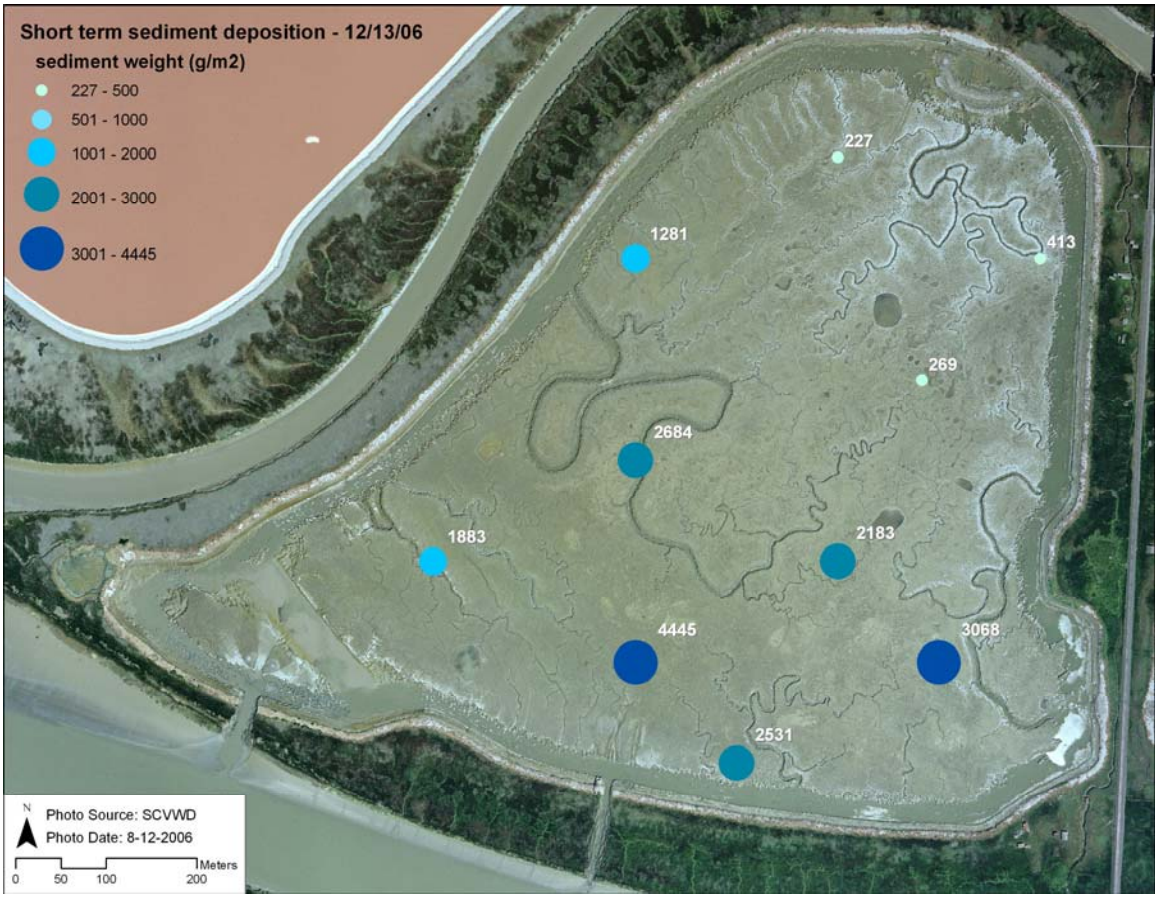

Appendix B.2. Mass of accumulated sediment ($g/m^2$) on rubber disks collected over a two-week period in June 2006. The larger and darker circles indicate greater weights of sediment on top of the rubber disks, and the number above each circle indicates the grams of sediment per meter square from each station.



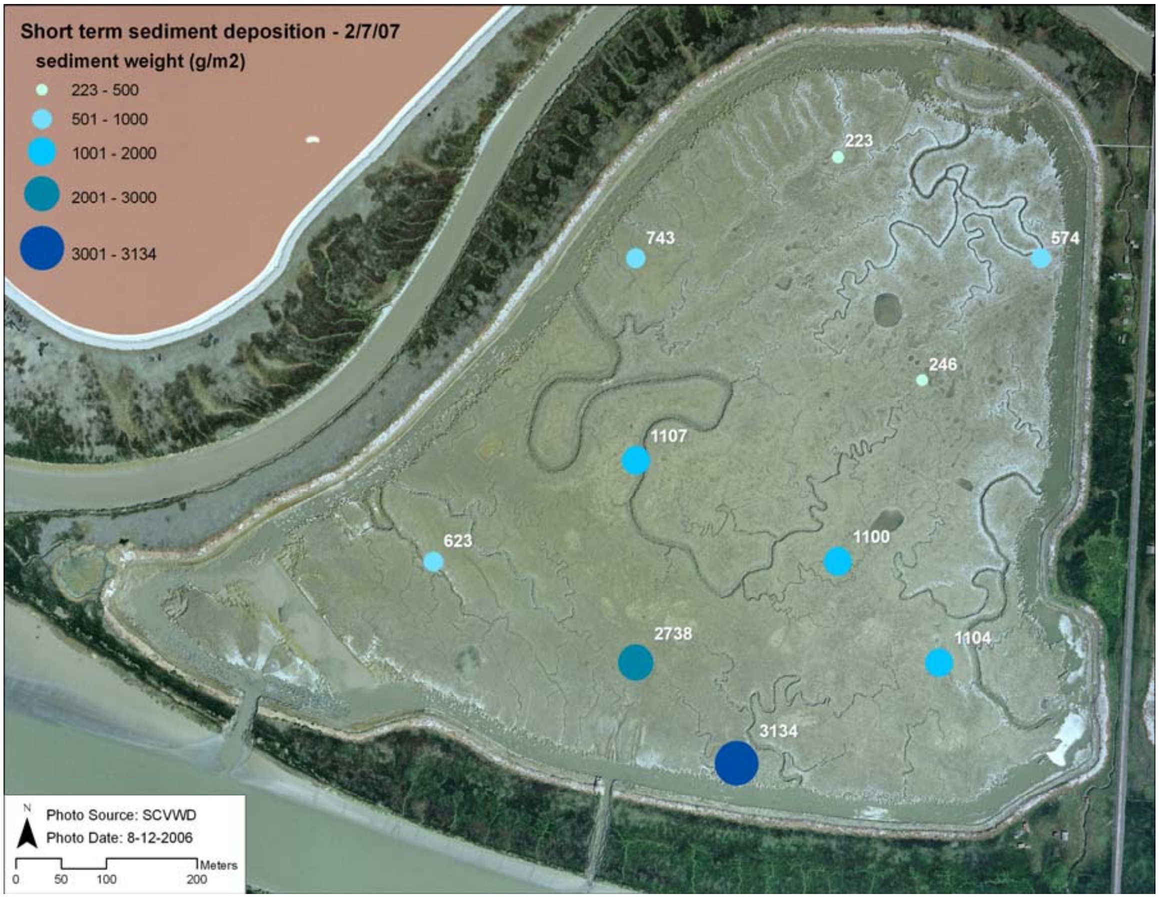

Appendix B.3. Mass of accumulated sediment ($g/m^2$) on rubber disks collected over a two-week period in August, 2006. The larger and darker circles indicate greater weights of sediment on top of the rubber disks, and the number above each circle indicates the grams of sediment per meter square from each station.




Appendix B.4. Mass of accumulated sediment ($g/m^2$) on rubber disks collected over a two-week period in October, 2006. The larger and darker circles indicate greater weights of sediment on top of the rubber disks, and the number above each circle indicates the grams of sediment per meter square from each station.



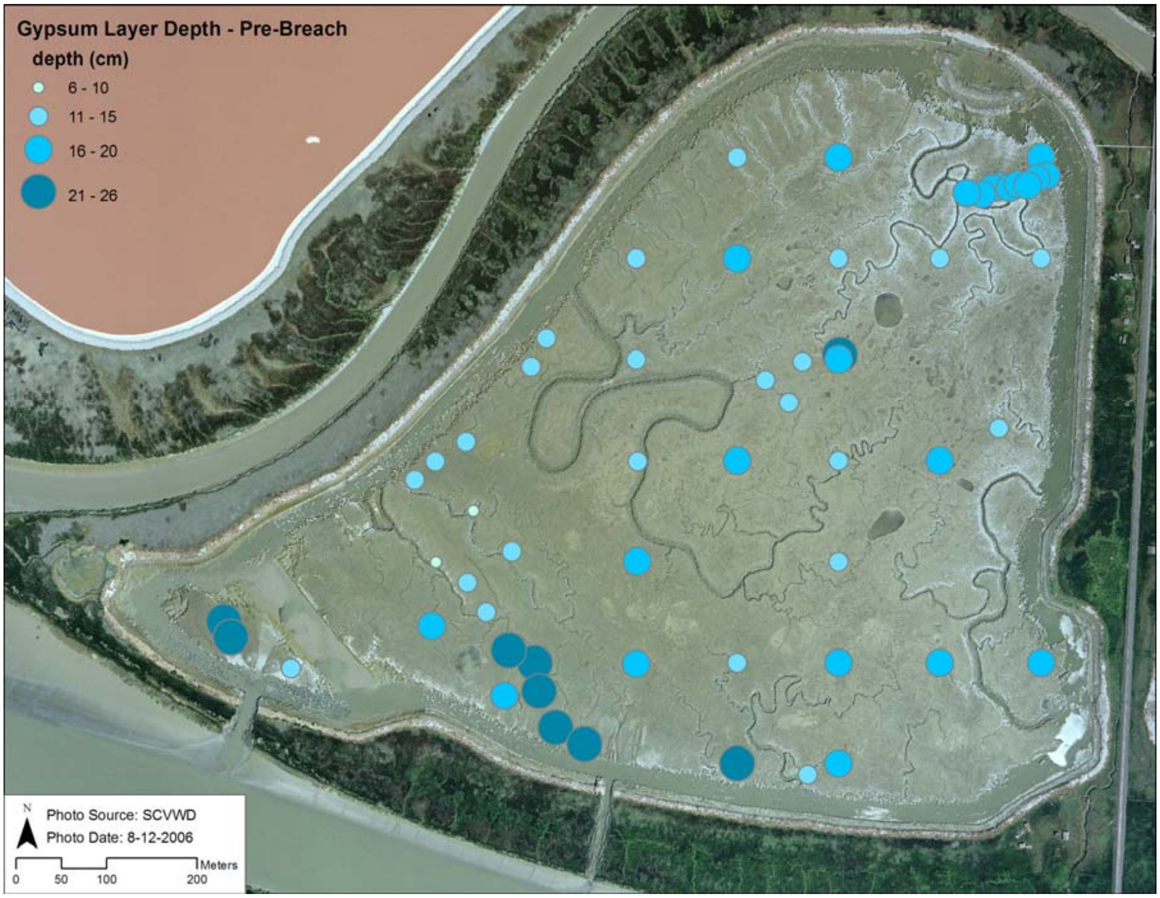

Appendix B.5. Mass of accumulated sediment (g/m$^2$) on rubber disks collected over a two-week period in December, 2006. The larger and darker circles indicate greater weights of sediment on top of the rubber disks, and the number above each circle indicates the grams of sediment per meter square from each station.



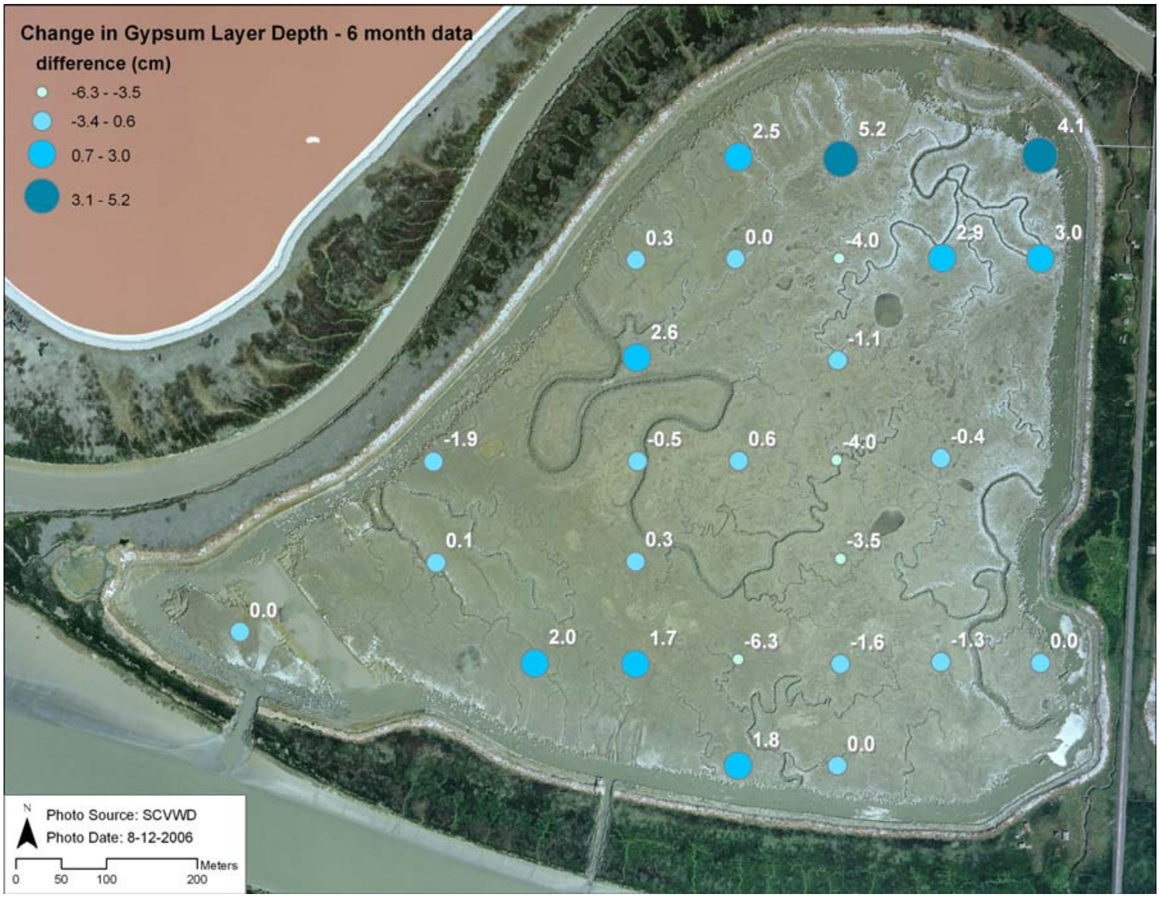

Appendix B.6. Mass of accumulated sediment (g/m$^2$) on rubber disks collected over a two-week period in January-February, 2007. The larger and darker circles indicate greater weights of sediment on top of the rubber disks, and the number above each circle indicates the grams of sediment per meter square from each station.

# APPENDIX C:

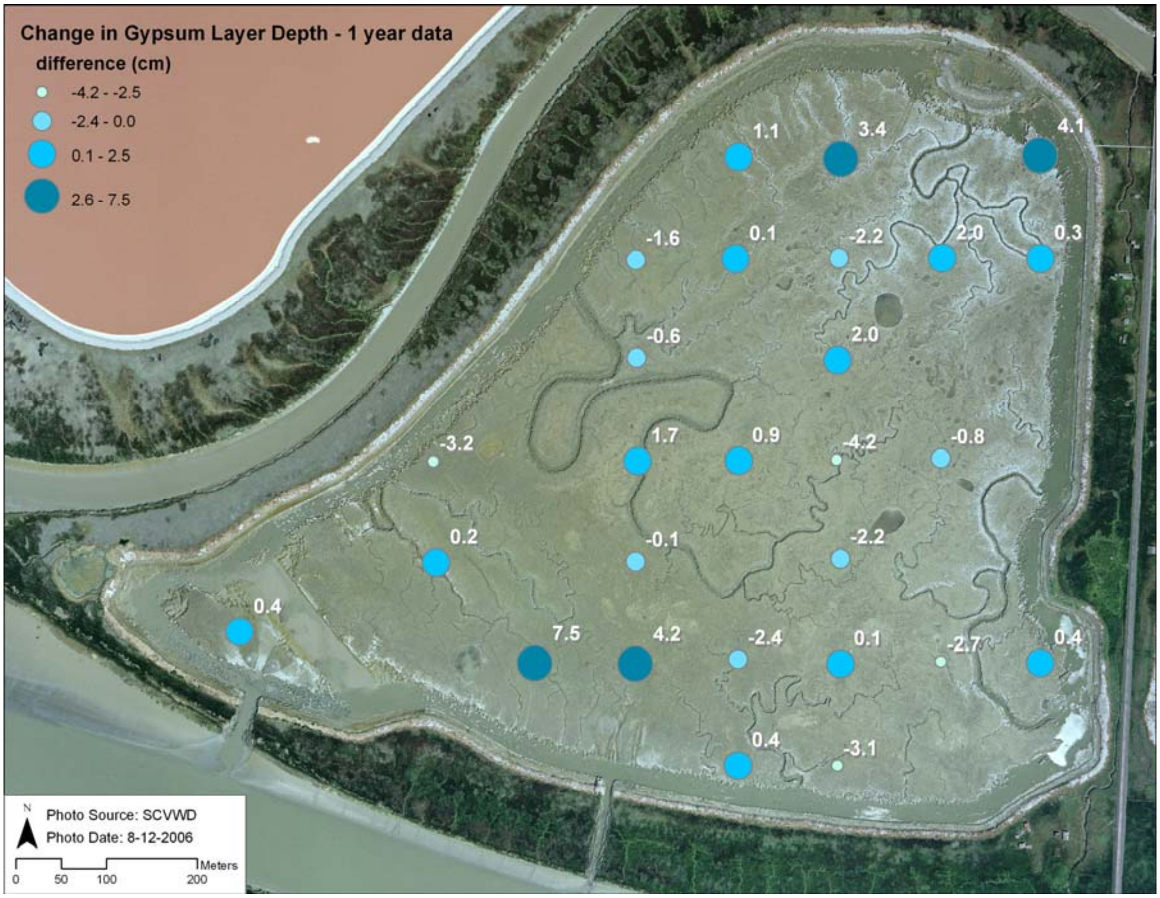
## Maps of changes in the thickness of the gypsum layer




Appendix C.1. Thickness (cm) of gypsum layer at each sampling location before any tidal breaching occurred. Larger and darker circles represent thicker layers of gypsum. Some locations in addition to the sediment sampling locations were included in our initial survey.



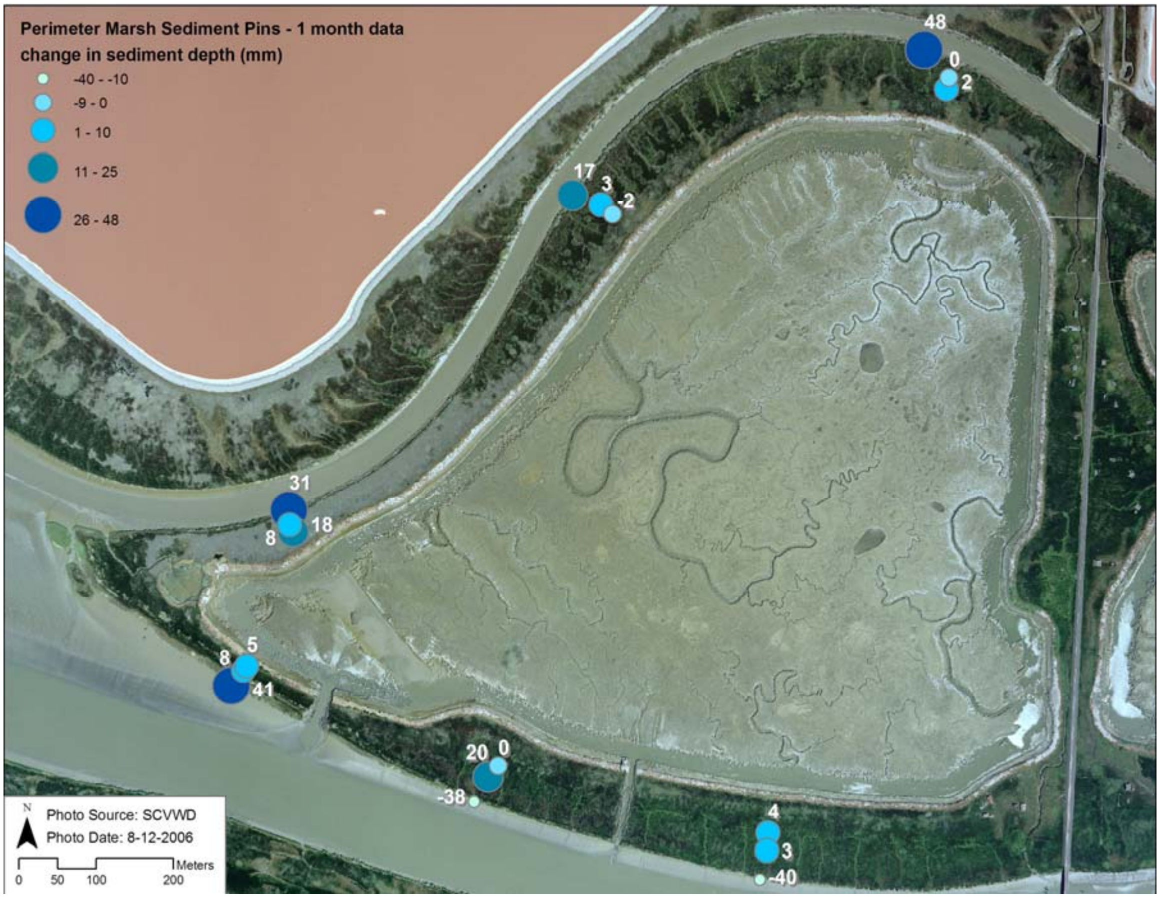

Appendix C.2. Change in the thickness (cm) of gypsum layer at each sampling location, six months following the tidal breach. Smaller, lighter circles represent a decrease in the thickness at a particular location; larger and darker circles represent an increase in the thickness. Numbers above each circle indicate the average change at each sampling location. Increases in thickness are probably due to spatial variation in the gypsum layer rather than any actual accumulation of gypsum.



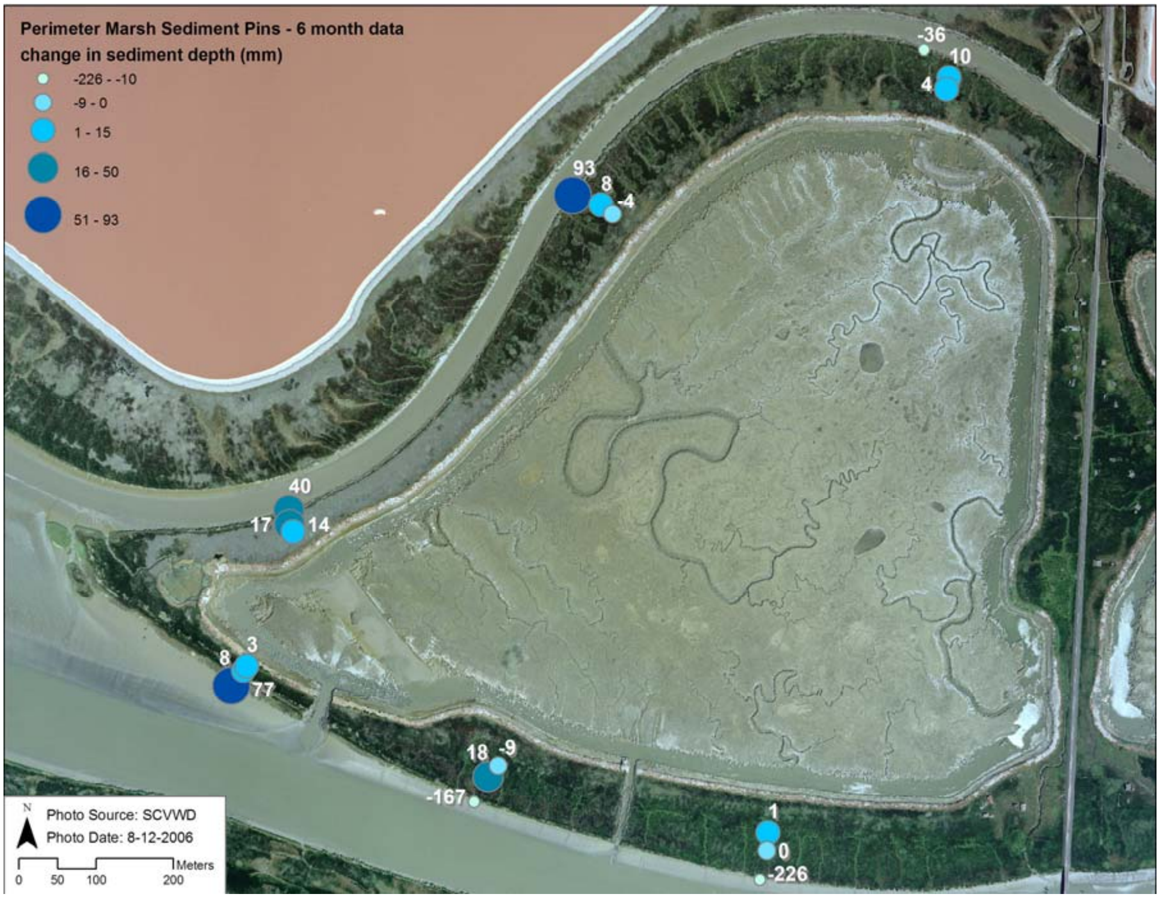

Appendix C.3. Change in the thickness (cm) of gypsum layer at each sampling location, one year following the tidal breach. Smaller, lighter circles represent a decrease in the thickness at a particular location; larger and darker circles represent an increase in the thickness. Numbers above each circle indicate the average change at each sampling location. Increases in thickness are probably due to spatial variation in the gypsum layer rather than any actual accumulation of gypsum.

# APPENDIX D:

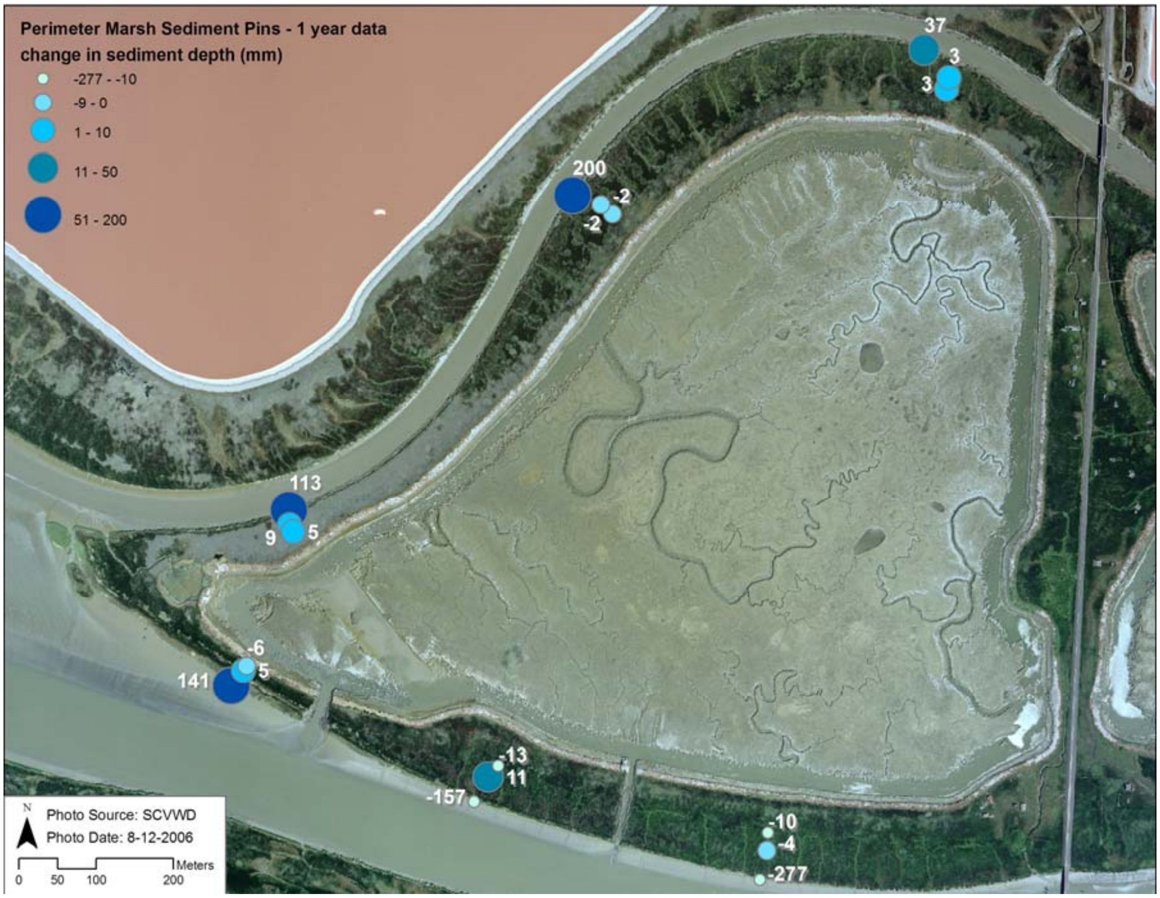
# Maps of sedimentation rates in adjacent marshes and mudflats based on heights of sediment pins



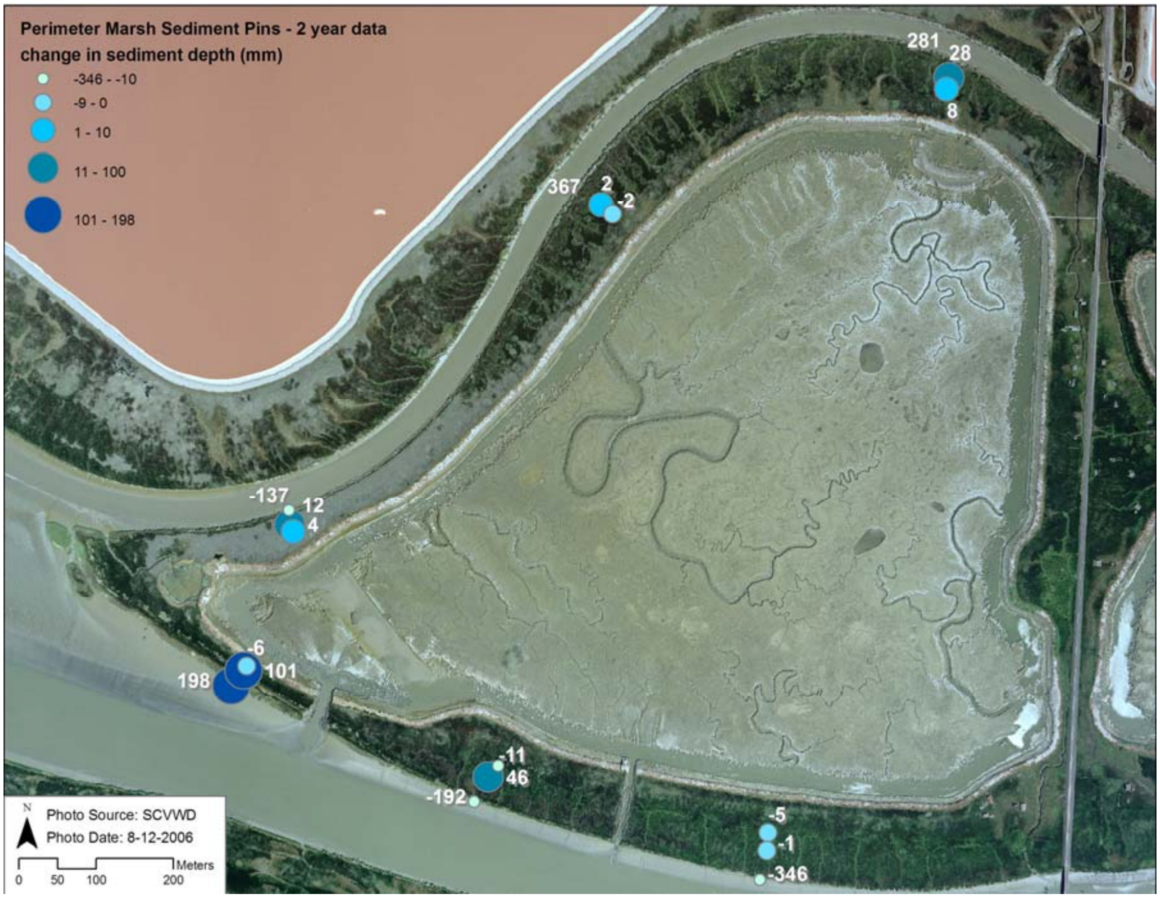

Appendix D.1. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each perimeter sampling location of Coyote Creek and Mud Slough, one month following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.



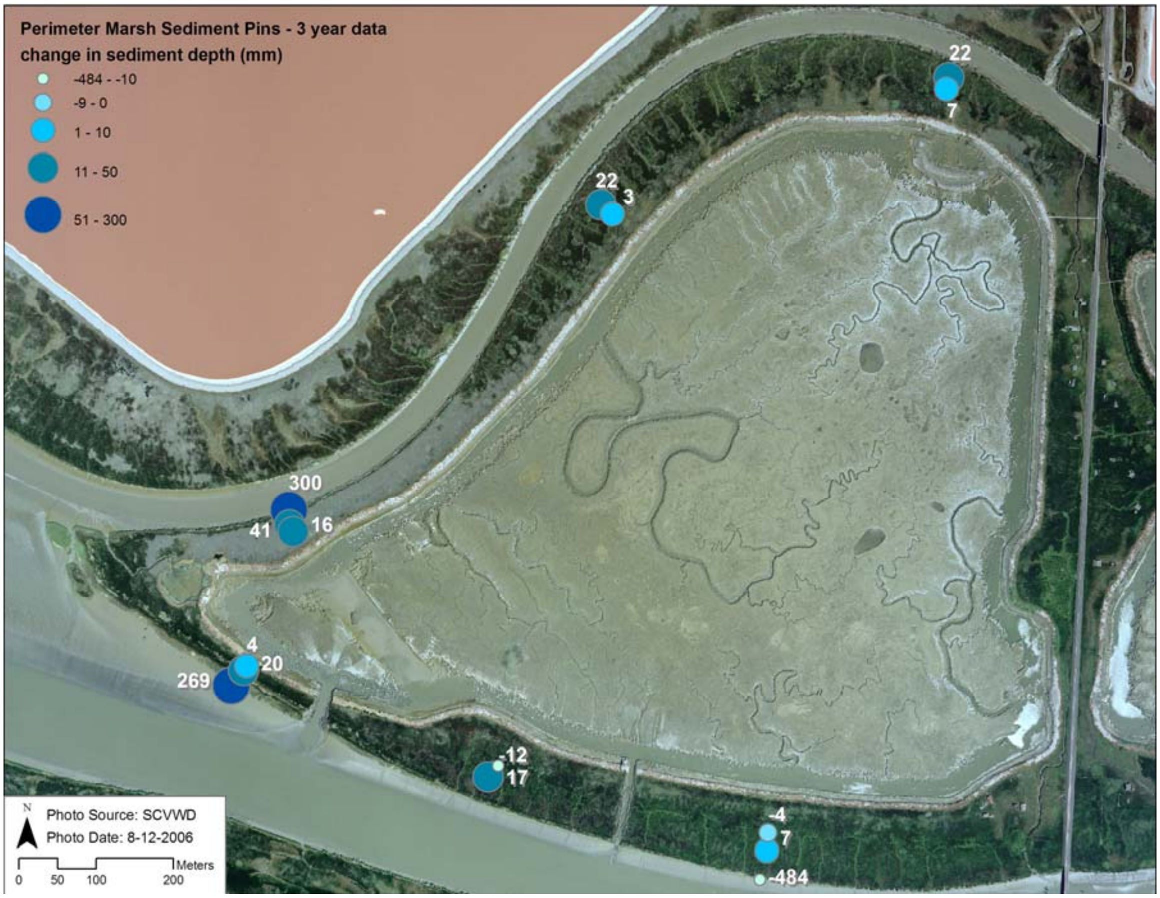

Appendix D.2. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each perimeter sampling location of Coyote Creek and Mud Slough, six months following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.




Appendix D.3. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each perimeter sampling location of Coyote Creek and Mud Slough, one year following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.




Appendix D.4. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each perimeter sampling location of Coyote Creek and Mud Slough, two years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.



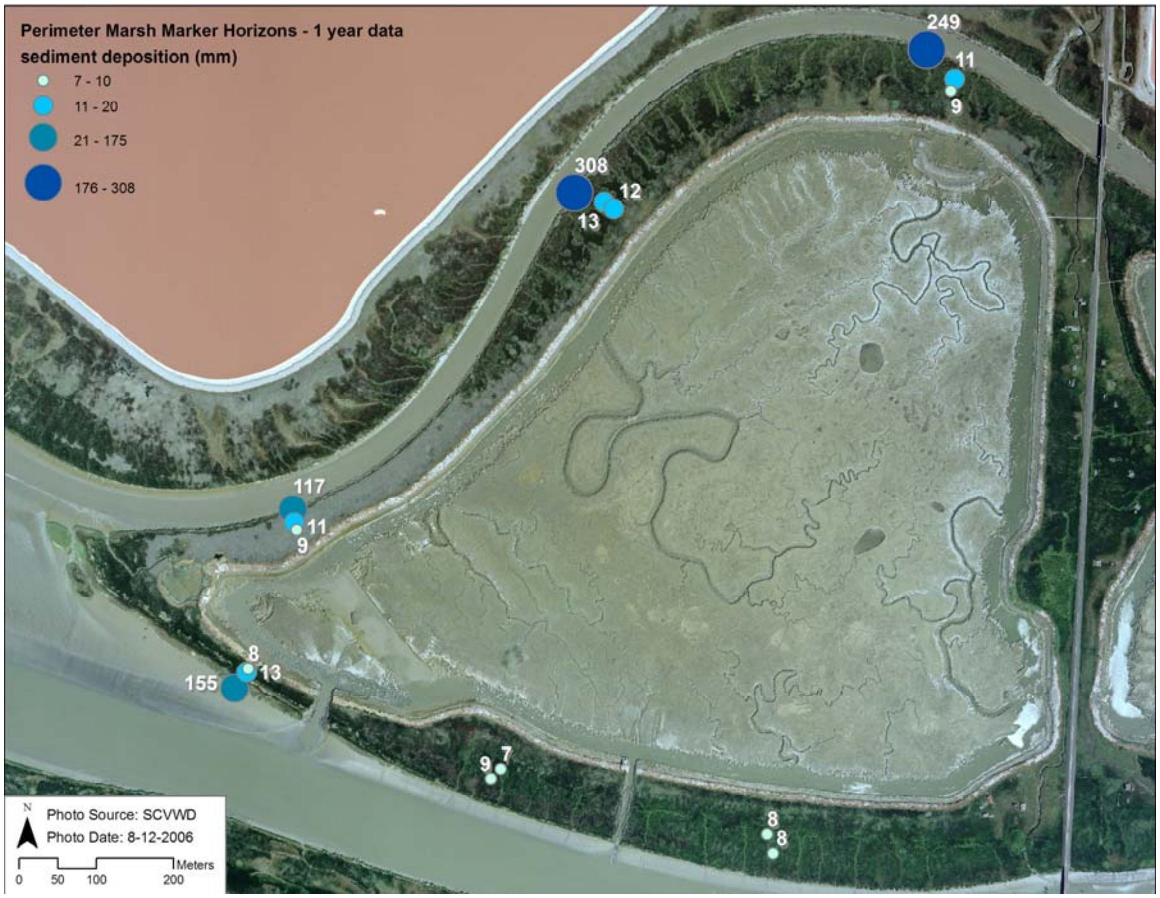

Appendix D.5. Depth of accumulated sediment (mm) based on changes in height of sediment pins at each perimeter sampling location of Coyote Creek and Mud Slough, three years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

# APPENDIX E:

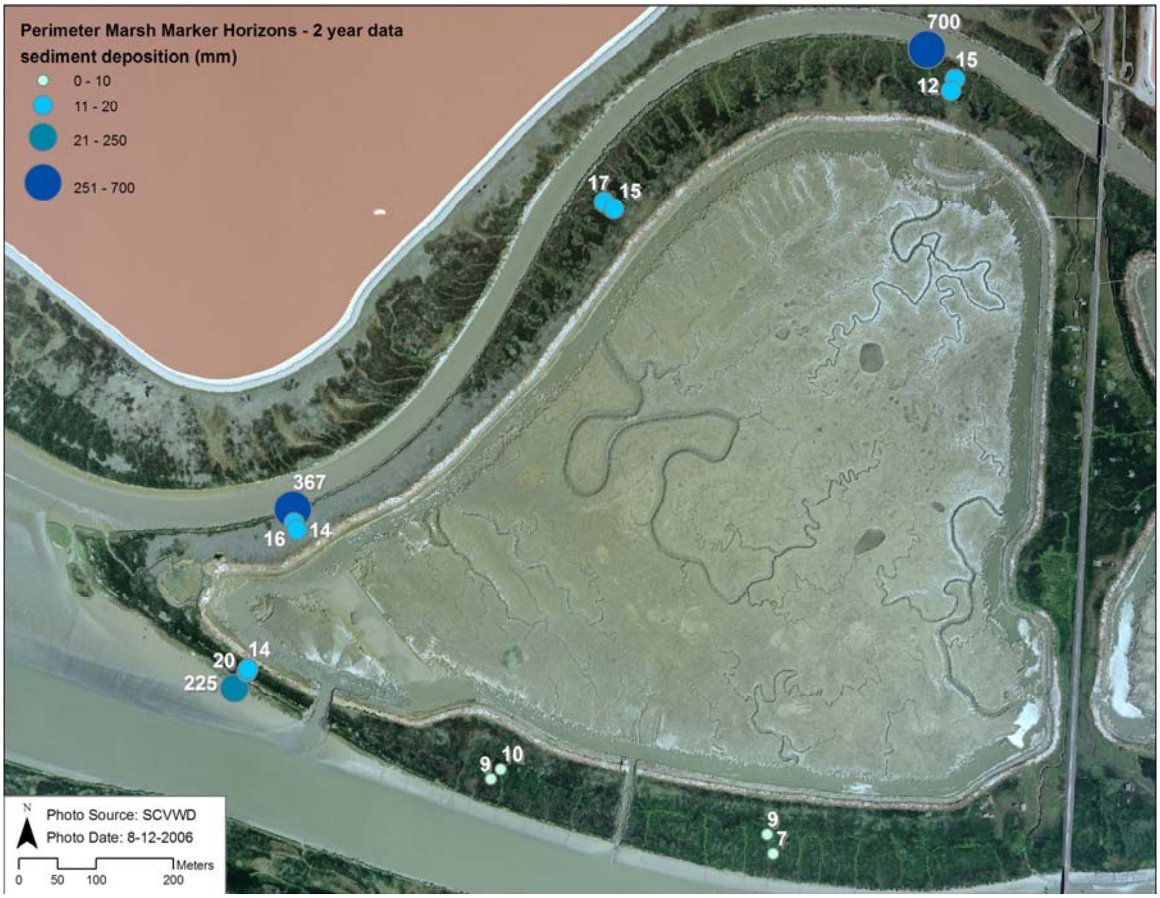
# Maps of sedimentation rates in adjacent marshes and mudflats based on feldspar and cloth markers


Appendix E.1. Depth of accumulated sediment (mm) above feldspar and cloth markers at each perimeter sampling location of Coyote Creek and Mud Slough, one month following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.

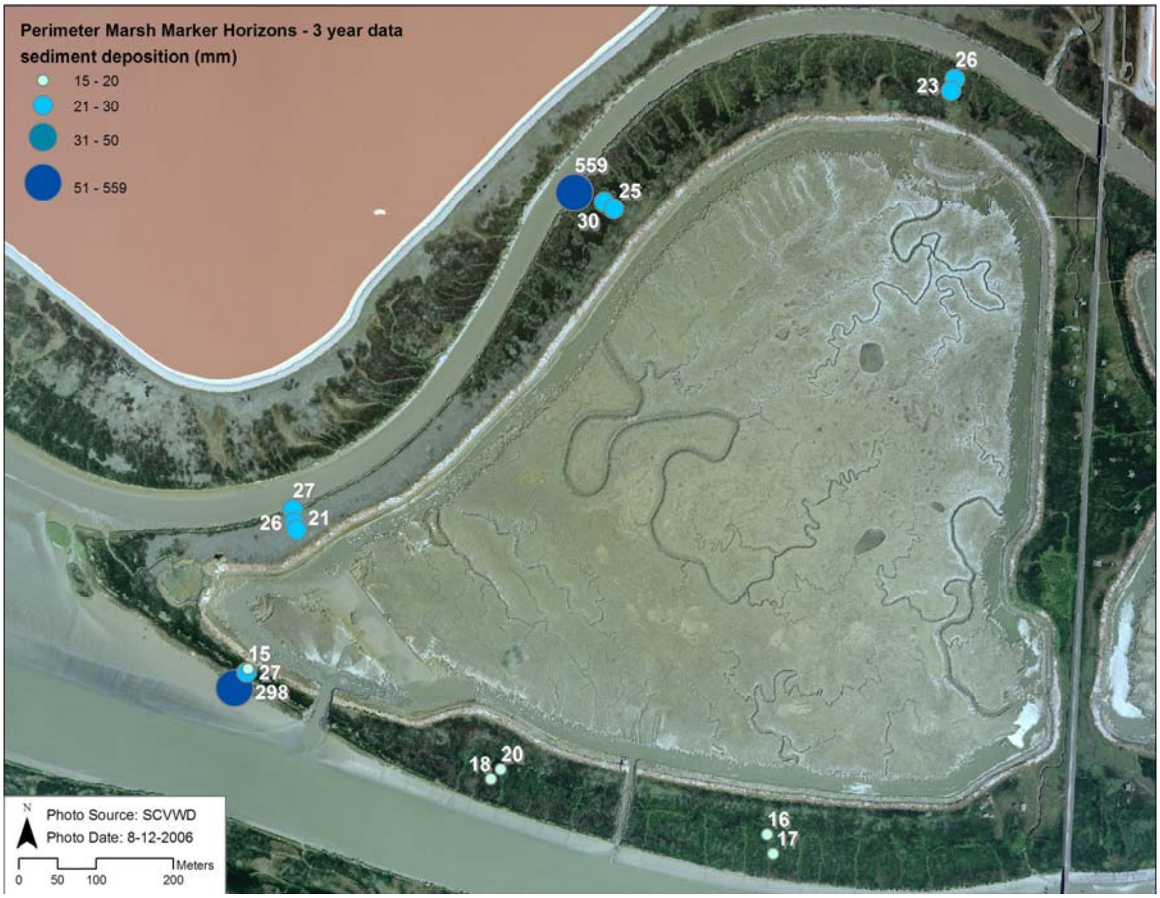

Appendix E.2. Depth of accumulated sediment (mm) above feldspar and cloth markers at each perimeter sampling location of Coyote Creek and Mud Slough, six months following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.




Appendix E.3. Depth of accumulated sediment (mm) above feldspar and cloth markers at each perimeter sampling location of Coyote Creek and Mud Slough, one year following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.




Appendix E.4. Depth of accumulated sediment (mm) above feldspar and cloth markers at each perimeter sampling location of Coyote Creek and Mud Slough, two years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.




Appendix E.5. Depth of accumulated sediment (mm) above feldspar and cloth markers at each perimeter sampling location of Coyote Creek and Mud Slough, three years following the breach. Larger and darker circles indicate greater rates of sediment accumulation, and numbers above each circle indicate the average measurement at each sampling location.