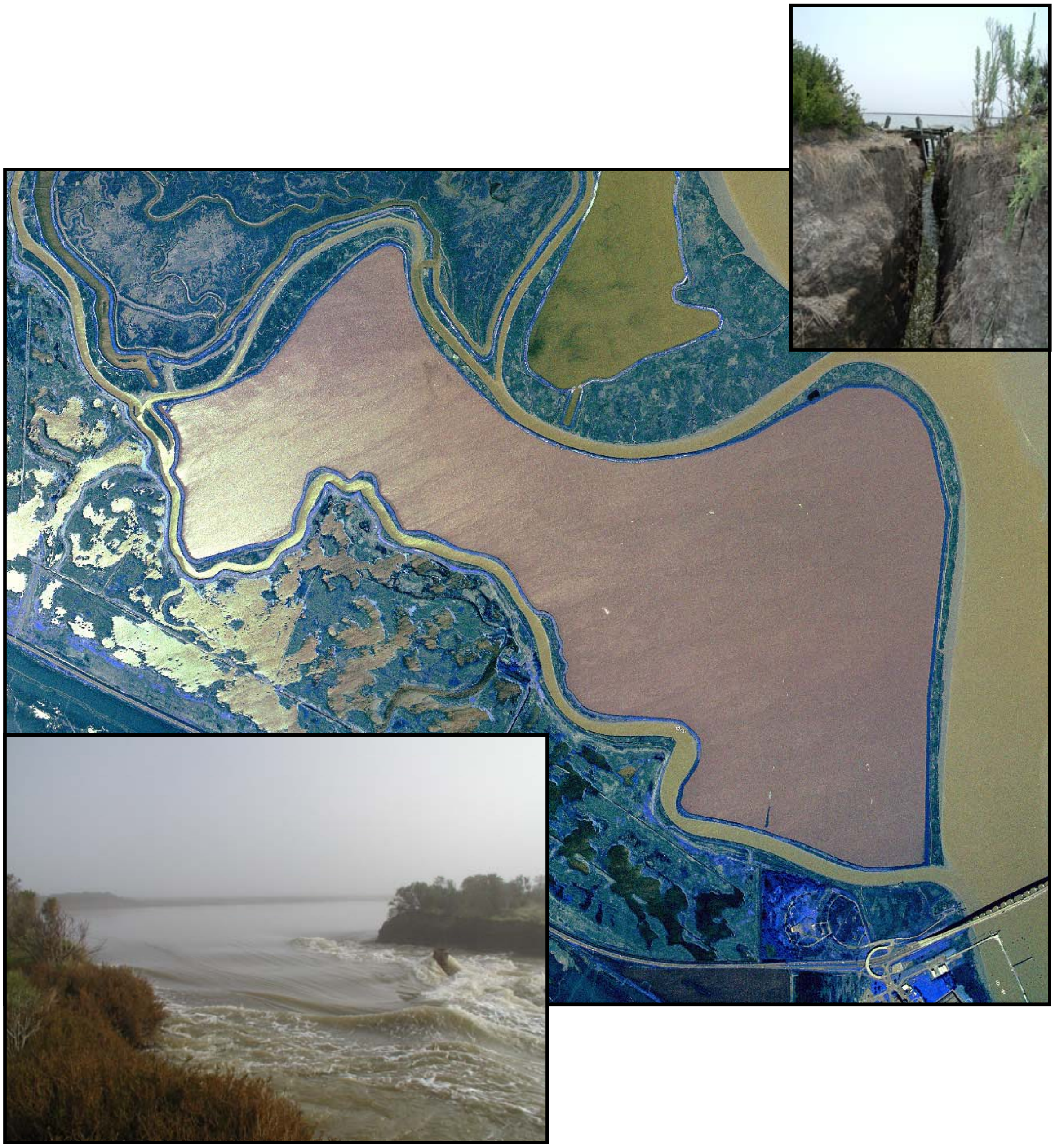
Initial Biophysical Changes after Breaching a Salt Pond Levee: Final Report on Napa-Sonoma Wildlife Area Pond 3 Breach



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U. S. Geological Survey, Western Region

Initial biophysical changes after breaching a salt pond levee: final report on Napa-Sonoma Wildlife Area Pond 3 breach

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[2004]

U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
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Please cite as: Takekawa, J. Y., D. H. Schoellhamer, A. K. Miles, G. G. Shellenbarger, N. D. Athearn, S. E. Spring, M. K. Saiki, C. A. Jannusch. 2004. Initial biophysical changes after breaching a salt pond levee: final report on the Napa-Sonoma Wildlife Area Pond 3 breach. Unpubl. Progr. Rep., U. S. Geological Survey, Vallejo, CA. 42pp.

****Preliminary Data, Please Do Not Cite or Distribute Without Permission****

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*****Preliminary Results. Do Not Cite Without Permission*****

EXECUTIVE SUMMARY

- The restoration of commercial salt production ponds to tidal habitats is challenging because hypersaline water can threaten biota in the receiving water when released; ponds can exhibit considerable changes in salinity and temperature, as well as tidal fluctuations in water level and altered biological habitats; and the increase in tidal prism increases currents and erodes the receiving basin around the breach and in portions of the pond.

- An unauthorized breach (< 0.45 m-wide) was excavated by unknown individuals in the levee between Pond 3 and South Slough on the north side of the pond during August 2002. This provided a unique opportunity to obtain empirical data from a small breach prior to the proposed restoration project. To provide up-to-date information for restoration planning and future management, we augmented our existing surveys to monitor biophysical changes in the ponds through the winter following the breaching of Pond 3. A second breach at Dutchman Slough was opened by CDFG as an emergency measure to allow water movement between the pond and the slough.

- The width of the South Slough breach did not change appreciably until November 2002, when it widened from 0.45 m to 0.55 m coincident with rains. The breach reached 5 m wide by the end of December and 23 m wide by March 2003, but only increased to 24 m by September 2003. The depth of the breach did not significantly increase until after the erosion enhanced by a mid-December storm. The higher thalweg of the Dutchman Slough breach limited water flow and erosion, therefore this breach did not widen or deepen significantly in the first year.

- Prior to breaching, Pond 3 was drying with increasing salinity. Post-breach, inflows at high tide allowed the pond to fill to the thalweg level of the breach. This created an initial salinity dilution from about 68 to 59 ppt. Changes in post-breach pond salinity can be explained by rainfall dilution until mid-December 2002. After December, further salinity declines were explained by rainfall and increased tidal action coincident with an increase in breach width. By the end of January, salinity in Pond 3 was less than 9 ppt.

- Immediately following a mid-December storm, water level fluctuations in Pond 3 began to vary semi-diurnally and showed muted tidal influence consistent with widening of the breach to South Slough. Tide range increased to more than 1 m tidal fluctuations near the breach and about 25 cm away from the breach by June 2003. The tide range (MLLW to MHHW) at nearby Mare Island Naval Shipyard was 1.8 m.

- Flow in South Slough seaward of the breach increased in response to the pond tidal prism. These fast, turbulent flows scoured the channel bed creating a hole in South Slough immediately in front of the breach that, in July 2003, was a maximum of 8 m deep and 45 m long. This scoured hole was about 4 m deeper than the original slough bottom. Between January and July 2003, 1,100 m^3 of sediment was lost from the South Slough bed near the breach. No erosion of the adjacent marsh or levee was observed.

- Sampling in Pond 3 in years prior to the breach indicated low invertebrate taxa richness but high numbers of a few species. Only *Polydora* and *Capitella*, (annelid worms), *Corophium* (amphipod crustacean), and occasionally Corixidae (insect) and *Streblospio* (annelid) were numerically common or detected during sampling periods prior to the breach. After the breach, the diversity of invertebrates common to the sloughs increased inside Pond 3 near the breach. These included the annelid worms Tubificoides, *Polydora*, and *Streblospio*; the crustaceans *Corophium*, *Ericthonius*, *Pancolus*, Gammaridae (amphipods), Sphaeromatidae (isopods), and *Mysis*, and the mollusks *Potamocorbula*.

- A substantial change in salinity and water depth immediately prior to the breach probably caused a decline in certain common organisms and an increase in others including *Artemia* (brine shrimp). *Artemia* was not found prior to summer 2002 but was the most common organism at the time of the breach in September 2002 when conditions were highly saline. *Artemia* was not detected after the breaching event.

- We caught nine fish species in Pond 3 during a single post-breach survey conducted in June 2003. Fish surveys conducted in July 1999 and in June-July 2000 yielded only four species: longjaw mudsucker, inland silverside, rainwater killifish, and Shimofuri goby. Seven supplemental fish surveys conducted during 1999 and 2000 yielded only two added species, striped bass and yellowfin goby. Although longjaw mudsucker dominated bag seine catches in 1999 and 2000, none were caught after the breach.

- A gradual reduction in Pond 3 use by diving benthivores and an increase in use by shorebirds correlated with declining water levels in Pond 3 from 1999 until the South Slough breach in August 2002. Although winter use of the pond eight months before the breach (2001) was heavily dominated by shorebirds, especially shallow probers, the net influx of water into the pond in winter 2002 was associated with an 89% reduction in shorebird numbers and the return of diving benthivores. However, winter 2002 encompassed the most dramatic changes to the pond habitat with widening of the breach.

- Prior to the breach, summer bird use was generally low and was dominated by terns and divers until 2001 and by terns and shallow probers by 2002. Following the breach, summer bird use of Pond 3 increased by approximately an order of magnitude over the previous four summers, with all foraging guilds represented and shorebirds (shallow probers, deep probers, and sweepers) comprising nearly 68% of all birds counted.

- An analysis of some of these data is summarized in:

  Shellenbarger, G.G., K. Swanson, D. Schoellhamer, J. Takekawa, N. Athearn, A.K. Miles, S. Spring, and M. Saiki. Desalinization, Erosion, Tidal, and Ecological Changes Following the Breaching of a Levee Between a Salt Pond and a Tidal Slough. In prep. Restoration Ecology.

TABLE OF CONTENTS

INTRODUCTION

In the San Francisco Bay (SFB) area, the past 150 years have been a period of increasing agricultural, industrial and human population growth at the expense of the natural environment. Water quality has degraded and habitats critical to native species have been destroyed. In the SFB estuary, over 90% of wetlands have been lost to diking and infill for development, agriculture, and salt production (Goals Project Report 1999). Over the past several decades, the perception of these impounded lands, located between the historic low and high tide levels, has shifted from that of industrial polders to areas of ecological and environmental benefit through managed restoration. The restoration of impounded lands not only recovers lost natural habitat, but also potentially improves water quality and flood risk mitigation (Carter 1997). The Netherlands, Great Britain, and the United States all have successfully restored both ecological and hydrological function to these types of impounded lands (Eertman et al. 2002, Crooks et al. 2002, Raposa & Roman 2001, Williams & Orr 2002).

The former Cargill salt evaporation ponds immediately west of the Napa River near Vallejo were purchased by the California Department of Fish and Game (CDFG) for their wildlife value in 1994. After a period of interim management, a Napa River Marsh Feasibility Study (Fish and Game, Coastal Conservancy, Corp of Engineers) was initiated in 1998 to study alternatives for maximizing wildlife values on the ponds. In that same year, the U. S. Geological Survey initiated a monitoring and research program of salt ponds under the Place-based Program of ecosystem studies. The intent of the study was to provide science support for better understanding of existing salt pond biological and physical characteristics and to develop information for restoration planning. Periodic monitoring of water quality, primary productivity, plants, invertebrates, fishes, and birds was conducted from 1999 to 2002.

The complex slough network surrounding the Napa-Sonoma Salt Ponds experiences temporally and spatially varying tidal forcing (Warner et al. 2003). The range of the semidiurnal tides is about 1.8 m. A sill at the mouth of Sonoma Creek on the west side of the pond complex can limit flow during ebb tide. Tidally averaged circulation in the complex is toward the east (Napa River) during spring tides and toward the west (Sonoma Creek) during neap tides (Warner et al. 2003). A phase difference between the tides at the mouths of Sonoma Creek and the Napa River sloughs creates a barotropic convergence zone in the middle of the slough network, where tidally-driven flows are in opposition. This convergence zone defines an area where suspended and dissolved constituents (e.g., sediment, salt and pollutants) may accumulate and could be detrimental to slough biota if a salt pond were to discharge to the slough network without sufficient dilution of the hypersaline water.

The restoration of commercial salt production ponds to tidal habitats is especially challenging because the pond water can be several times saltier than seawater and can threaten biota in the receiving water when released. In addition, the pond can exhibit considerable salinity and temperature changes, tidal fluctuations in water level, and altered biological habitats. Mixing of pond and receiving waters may also affect biota inside the pond. The increase in tidal prism increases currents and erodes the receiving basin around the breach and in portions of the pond. The pond may also serve as a sink or a source of sediment and contaminants (e.g., methyl mercury; Davis et al. 2003, Marvin-DiPasquale et al. 2003).

An unauthorized breach (<0.5 m-wide) was excavated by unknown individuals in the levee between Pond 3 and South Slough (SS) on the north side of the pond during the week of 5 August 2002. Management agencies met on 19 August 2002 and decided to retain the existing breach. On 12 September 2002, an emergency action was taken by CDFG to armor the breach near the siphon to prevent erosion, and to open an additional breach where a partial channel had been excavated at the mouth of Dutchman Slough (DS) on the Napa River. This provided a unique opportunity to obtain empirical data from a small breach prior to the proposed restoration project. At the request of the Coastal Conservancy (A. Hutzel) and with the assistance of Phillip Williams and Associates (PWA; M. Orr), we initiated studies to provide up-to-date information for the restoration planning and future management. We augmented our existing surveys to monitor biophysical changes in the ponds through the winter following the breaching of Pond 3.

STUDY AREA

The present-day Napa-Sonoma salt ponds, positioned between San Pablo Bay and the Napa River (Fig. 1), are impounded former tidal marsh. Levees were constructed around these marshes in the 1870s (Thompson 1877) by excavating soil from borrow ditches inside the impounded regions adjacent to the levees. These impounded lands were flooded with water from San Pablo Bay in the 1950s to form evaporative salt production ponds. In 1994, CDFG acquired 12 production ponds from Cargill Inc. to manage as restored tidal marsh and wildlife ponds. Several of these former evaporation ponds have been returned to tidal or muted-tidal habitats (Williams & Orr 2002, Summary Status Report 2001). The Environmental Impact Report for the remaining restoration plans was completed in April 2004 (Jones & Stokes 2004).

OBJECTIVES

In this study, we described changes in salinity, water level, flow, ecology, and bathymetry caused by breaching a levee between a salt pond and a tidally influenced slough. We described hydrological and ecological changes in the pond and slough, and discussed several important factors to consider when planning, implementing, or monitoring a levee breach. This event created a rare opportunity to study physical and biological changes that result during salt pond restoration, and it has immediate implications for the largest urbanized tidal wetland restoration in the United States getting underway in South San Francisco Bay.

Following the breach of Pond 3, we augmented our studies to:

Objective 1: Monitor changes in salinity and flow of the Napa-Sonoma Marshes following the Pond 3 Breach in affected ponds, adjacent sloughs, and the Napa River.

Objective 2: Increase existing surveys of biota to document changes in the pond system on the west side of the Napa River following the breach.

METHODS

Objective 1: Monitor changes in salinity and flow of the Napa-Sonoma Marshes.

Site Evolution

Monthly measurements of breach width were made using laser level rods at three locations (slough-side, mid-levee, and pond-side) along the length of the breaches in the SS and DS levees. Breach depths were also measured with a laser level rod referenced to a nearby benchmark. After the SS breach dramatically widened, breach depths were measured with a less-precise Hondex depth sounder (Depthmate SM-5A, Speedtech Instruments, Great Falls, VA) from a boat and only during slack tide when conditions allowed.

Salinity and Flow

Salinity

Monthly measurements of water quality were performed using a Hydrolab Minisonde CTD (Hydrolab, Loveland, CO). We collected specific conductivity, dissolved oxygen, pH, salinity, temperature and turbidity at 2-6 locations in Ponds 3, 4, and 5. Water depth at the sampling location was measured with a depth recorder or meter stick, and pond water level was measured using the pond's existing staff gage (surveyed to NGVD29).

Conductivity-temperature-depth meters (CTDs, DataSonde 4, Hydrolab, Loveland, CO) were deployed in Pond 3 on a dock near the SS breach from late August 2002 until March 2003. CTDs measured and recorded specific conductance, temperature, depth and turbidity every 15 minutes and were cleaned and calibrated monthly. After tidal range inside Pond 3 increased, the instrument was dry for extended periods. The instrument was repositioned to a lower elevation in late January 2003, but the sensors were still exposed during low tide. In February, the CTD was relocated to the southeastern edge of Pond 3 near DS. CTDs were also deployed at the Can Duck Club (CAN) in SS, the Napa River at the Mare Island Causeway (MIC), Carquinez Strait (CAR), and Channel Marker 9 (CM9) in San Pablo Bay (Fig. 1; Buchanan 2000) in order to determine far-field salinity effects resulting from Pond 3 desalinization.

To evaluate slough and pond water mixing in Pond 3, salinity transects were conducted in the pond between the two breaches on 17 September 2002 and on 15 January 2003. Surface and bottom salinities were measured with a Hydrolab Minisonde CTD and averaged at each of seven locations between the two breaches (Fig. 1). We obtained daily rainfall records from the California Irrigation Management Information System (CIMIS) for Station #109, Carneros (http://www.ipm.ucdavis.edu) to calculate salinity dilution in Pond 3. Rainfall dilution calculations were done assuming an initial pond salinity of 54 ppt, depth of 0.5 m and area of 5 km^2. Evaporation was not considered but is much less than rainfall in December (Lionberger et al. 2004).

Tide Range

Because the CTD in Pond 3 was not consistently deployed at the same elevation, we calculated changes in water surface height relative to the instrument. However, during site visits, water level where the CTD was deployed was referenced to a permanent staff gauge of known elevation. In addition, temporary staff plates were installed and monitored on the plateau in the northwest corner of Pond 3 and in SS west of the breach for nearly one tidal cycle on 19 June 2003. Water level measurements were referenced to a nearby benchmark (Towill, Inc. 2001 survey, #1001, 2.95 m NAVD88) to obtain concurrent water surface elevations from four locations in the pond.

Flow

Flow in SS seaward (towards the Napa River) and landward (away from the Napa River) of the breach was measured on 19 June 2003 over most of one tidal cycle using a vessel-mounted 1200 KHz shallow water acoustic Doppler current profiler (ADCP, RD Instruments, San Diego, CA). Flow rates were calculated using the WinRiver software package (RD Instruments, San Diego, CA). Discharge from Pond 3 was calculated as the difference between seaward and landward flow rates. Because the seaward and landward measurements were collected sequentially and not simultaneously, flow rates were interpolated to the same time prior to calculating Pond 3 discharge. Tidal exchange between Pond 3 and Dutchman Slough was observed to be minimal and not measured during our study.

Site Infrastructure

Slough Erosion

The bathymetry of SS and the breach was surveyed on 28 January 2003 and 10 July 2003 using a vessel-mounted ADCP interfaced with a Leica differential global positioning system (DGPS). The difference between January and July measurements represents loss or gain of sediment in SS near the breach. Depths were measured in SS with the ADCP both seaward and landward of the breach and within the breach when slack tide allowed for a safe approach. A contour plot of bathymetry was developed for each sampling period with Geographic Information System (GIS) software (ArcMap8.3, Environmental Systems Research Institute, Redlands CA). The amount of erosion was calculated by creating triangulated area network (TIN) three-dimensional spatial coverages for each sampling period, then computing the volumetric differences between these two times. Volumetric differences within the study area were then plotted as a separate spatial coverage for display purposes.

Levee Wall Erosion

To measure erosion or deposition along the interior levee walls in Pond 3, we placed 5 sets of 3 erosion pins (2" PVC pipe buried to 3') spaced 1 m apart along transects of levee walls. The lowest erosion pin was placed in the water, the middle erosion pin was placed at the water's edge, and the high erosion pin was placed above the water level on the levee. The erosion pins were installed in February 2003 and measured monthly with a flat-bottomed measuring pole.

Objective 2: Increase existing surveys of biota to document changes in the pond system.

Chlorophyll and Nutrient levels

We measured primary productivity (chlorophyll-*a*) and nutrients inside Ponds 3 and 4 and in SS adjacent to the breach on Pond 3. Duplicate samples were collected in October and December

2002 and in February, April, and May 2003, and analyzed for total and soluble phosphorous (TP, SP), sulfate (SO_4), ammonium (NH_4), and nitrate (NO_3) by the University of California (UCD) Department of Natural Resources Analytical Laboratory. We determined chlorophyll-*a* levels using a Turner Designs SCUFA® submersible fluorometer, calibrated with a spectrophotometer. The SCUFA was submerged in each sample and temperature corrected fluorescence values were recorded. Water samples were placed on ice and filtered in a laboratory within 24 hours of collection using 1.2-µm glass fiber filters. Filters were frozen at least 24 hours. Extraction solvent (90% acetone) was then added to the filters at least 48 hours after filtration. Absorbance of the extracts was read using a spectrophotometer at 750, 660, and 664 nm. Chlorophyll-*a* was calculated using the Monochromatic method (Wetzel &Likens 1991).

Benthic macroinvertebrates

Ponds 1, 2, 3, and 4 were sampled in November 2001 and in May and November 2002 and 2003. Three benthic and sweep samples were collected from each of five locations in each pond, and the invertebrates were identified and enumerated for these samples through 2002. The SS breach at Pond 3 and Pond 4 were sampled in September 2002 after the breach was discovered. Subsequent samples from Pond 3 were collected in March, May, and July 2003. Three benthic samples each were collected from 3 randomly selected locations inside Pond 3 near the breach and 3 locations in the slough outside the breach.

Benthic macroinvertebrates were sampled from a 3.5-m flat bottom boat powered by a modified shallow water outboard motor, using a standard Ekman grab sampler (15.2 cm x 15.2 cm x 15.2 cm) to collect invertebrates. Samples were collected by lowering the dredge into the water slowly, holding it level on the substrate and releasing the trigger. Muddy soft substrates consistently produced samples that filled the dredge, whereas on hard substrates only a small portion of the dredge was filled. Two of the three samples at each location were washed in the field using a 1-mm mesh screen and preserved in 70 % ethanol with dye (rose bengal). The third sample was washed through a 0.5-mm mesh sieve and the organisms preserved as stated above. Sweep samples were collected from the slowly moving boat by placing a D-ring dip net (0.5-mm mesh) in the water column for a distance of 10 m. Collected samples were processed (sorted from debri and identified to taxa) at UCD. Wet weight and dry weight biomass of selected groups of organisms were determined using an Ohaus, Model 3130 scale.

Fishes

Fish were surveyed bimonthly in Pond 3 from July 1999 until December 2000, and a post-breach survey was conducted in June 2003. We used a 5.5-m bag seine with 6.4-mm mesh in the bag and 12.7-mm mesh in the wings. We performed five seine hauls at each of 4-6 sites near the shoreline where water depth was <1.5 m by hauling the seine about 8 m perpendicular or parallel to shore. We counted and identified to species all fish, then released them in the capture vicinity. Representative specimens were preserved in 10% formalin to verify species identities using standard taxonomic keys (Miller & Lea 1972; Moyle 2002; Eschmeyer et al. 1983; McGinnis 1984).

Avian Abundance and Distribution

We conducted monthly or bimonthly bird counts at Ponds 1, 2, 2A, 3, 4, and 7 from January 1999 to July 2003 with binoculars and spotting scopes. In October 2002, monthly bird surveys were expanded to include Ponds 1A, 5, 6, 6A, and 7A. Locations of waterbirds were identified within 250-m x 250-m (6.25 ha) UTM grid cells superimposed on a graphical schematic of the pond. Surveys were conducted during daylight within 3 hours of the highest high tide, when the largest number of waterbirds roosted in the salt ponds.

Identified waterbirds were separated into guilds to examine differences among foraging groups rather than differences among species. These foraging guilds included: 1) sweepers – obtained prey from the surface e.g., *Recurvirostra americana* (American avocet); 2) shallow probers – foraged in the top layer (< 3 cm) of sediments, e.g., *Calidris mauri* (western sandpiper); 3) deep probers – reached deeper into the substratum than shallow probers, e.g., *Limosa fedoa* (marbled godwit); 4) dabblers – fed in the upper water column, e.g., *Anas acuta* (northern pintail); 5) diving benthivores – fed in deeper water on benthic invertebrates, e.g., *Aythya affinis* (lesser scaup); 6) piscivores – fish consumers, e.g., *Pelecanus erythrorhynchos* (American white pelican); and 7) other – omnivores and incidental species including gulls.

Months were assigned to seasons to encompass the major migration chronology in spring (February-March) and autumn (September-October) (Takekawa et al. 2001). To reduce potential bias caused by large numbers of birds moving quickly through the area during fall and spring migration, we examined differences among foraging guilds at Pond 3 during the winter (November-January) and summer (April-August) seasons. The year of the first month of the season was used as the yearly identifier (e.g., winter 2002 is November 2002 – January 2003).

RESULTS

Site Evolution

The width of the SS breach remained static prior to November 2002. Coincident with the onset of rain in November, the breach eroded and widened from 0.45 m to 0.55 m. By the end of December 2002, it was > 5 m wide (Fig. 2E), and by March 2003, the breach eroded to 23 m wide (Fig. 12). By September 2003, the breach growth had slowed and the width was 24 m. The depth of the SS breach did not significantly increase until after erosion was enhanced by a mid-December storm. By January 2003, the thalweg of the breach was below mean lower low water (MLLW), and turbulent conditions prevented depth measurements except during slack tide. The higher thalweg of the Dutchman Slough breach limited water flow and erosion; thus, this breach did not widen or deepen significantly during the first year.

Salinity and Flow

Salinity

Prior to breaching, Pond 3 was gradually drying with a subsequent increase in salinity. Post-breach, the flow of water into the pond at high tide allowed it to fill to the thalweg level of the breach. This caused salinity in the pond to initially decline from about 68 ppt to 59 ppt. Rain in November further diluted the salinity to about 48 ppt before substantial breach erosion occurred (Figs 2A, B). Beginning on 9 December 2002 and continuing for the next seven days, storms delivered over 16 cm of rain - 27% of Napa's average annual rainfall - to Pond 3. Changes in post-breach pond salinity can be explained by rainfall dilution until 17 December 2002, when salinity in the pond dropped below what could be explained by rainfall alone. Data suggest that the breach to SS significantly widened on this date and allowed additional salinity dilution through large inputs of fresher slough water (slough salinity was less than 15 ppt at the time).

By 23 December 2002, the salinity in the pond near the breach was 21 ppt, while an average of five locations throughout the pond showed the salinity to be just over 19 ppt (Table 1). By the end of January, the four-corner-averaged salinity in Pond 3 was less than 9 ppt (Table 1).

Between-breach transects in Pond 3 for salinity differed before and after the widening of the SS breach (Fig. 3). In September, we recorded a large gradient with the lowest salinity of about 50 ppt near the SS breach that increased to over 60 ppt in the southeast corner near the Dutchman Slough breach. In January, cross-pond salinity levels and gradient were greatly reduced, with salinities near the SS breach about 10 ppt and about 15 ppt near the middle of the transect. Differences between surface and bottom salinities were minor for both transect periods.

Salinity from the pond entered SS in December 2002. Salinity did increase in the barotropic convergence zone near CAN 4.1 km (linearly) to the west of Pond 3 in SS (Fig. 2C). The salinity pulse persisted in this location for ten days, but the measured salinities never exceeded the local summer high of about 20 ppt. No far-field salinity increase from the pond desalination was distinguished at sites MIC, CAR or CM9. All sites exhibited decreasing salinities with the rainfall in mid-December, and tidal variation (both flood-ebb and spring-neap timescales) was visible in all records.

Water exchange through a siphon from Pond 3 affected salinity in Pond 4. The four-corner salinity averaged 210 ppt in September 2002 and decreased to 131 ppt by 23 December 2002. By the end of January, the four-corner-averaged salinity in Pond 4 was less than 82 ppt (Table 1) and by July 2003, Pond 4 salinity was 37 ppt. After the breach, average water quality parameters in Ponds 3 and 4 were more similar to pre-breach values in Ponds 1 and 2 (Table 2).

Tide Range

Diurnal wind-driven variations were about 10 cm prior to the storm on 13 December 2002. Immediately following the storm, water level fluctuations in Pond 3 began to vary semi-diurnally and showed muted tidal influence (Fig. 2D). These tidal fluctuations are consistent with widening of the breach to SS at this time and increased tidal exchange between Pond 3 and SS. Tidal fluctuations increased to more than 1 m near the breach and about 25 cm away from the breach by June 2003 (Fig. 4). The tide range (MLLW to MHHW) at nearby Mare Island Navel Shipyard was 1.8 m (http://co-ops.nos.noaa.gov).

Flow

The widened breach altered flow in SS. The maximum flow seaward of the breach was more than double the flow rate landward of the breach (Fig. 5). Low slack water (12:00 to 13:00 h in Fig. 5) in SS occurred at least an hour earlier landward of the breach than seaward (a distance of <100 m), indicating that the volume and momentum of discharge from the pond was sufficient to delay the turning of the tide in SS seaward of the breach. After the slough completely turned to ebb at 13:30 h, the pond continued to ebb for about 2 hours, until it began to flood and fill at 15:30 h.

Site Infrastructure

Slough Erosion

Flow in SS seaward of the breach increased in response to the pond tidal prism. These fast, turbulent flows scoured the channel bed creating a hole in SS immediately in front of the breach that, in July 2003, was a maximum of 8 m deep and 45 m long (Fig. 6). This scoured hole was about 4 m deeper than the original slough bottom. Between January and July 2003, 1,100 m^3 of sediment was lost from the SS bed near the breach. No erosion of the adjacent marsh or levee was observed.

Levee Wall Erosion

Erosion pins showed some changes in ground height from March 2002 to March 2003, particularly on the northern side of Pond 3. The upper pole on the northern portion of the pond showed a decrease of 1.5 cm in local ground height. The middle elevation erosion pin at the same north pond site indicated a similar decrease, whereas the low erosion pin showed a 2.5 cm increase in ground height. Other site differences were minimal and could be accounted for by measurement error, although monitoring should identify slower changes.

Chlorophyll and Nutrient levels

Primary productivity

Chlorophyll *a* concentration was highest in Pond 3 during December 2002 at 245 mg/m^3 (Table 4). Productivity varied seasonally in SS and within Ponds 3 and 4. The highest concentrations in both ponds and SS occurred during February 2004.

Nutrients

Nutrient concentrations varied among ponds and seasons (Table 3). Ammonium (NH_4) concentrations varied most widely among Ponds 3 and 4 and SS, with values in Pond 4 ranging from 0.35 – 8.07 mg/L compared to < 0.05 - 0.22 mg/L in Pond 3 and SS. Nitrate (NO_3) concentration in SS ranged from less than 0.05 to 0.88 mg/L, whereas Pond 3 (<0.05 - 0.47 mg/L) and Pond 4 (<0.05 - 0.56 mg/L) showed slightly less variation. Soluble phosphorous in Pond 4 was high in October 2002 (0.95 mg/L) relative to Pond 3 and SS (0.07 – 0.16 mg/L).

Benthic macroinvertebrates

Sampling in Pond 3 in years prior to the breach indicated low invertebrate taxa richness but high numbers of a few species. We identified 49 taxonomic groups, most to the genus or family level (Table 5). Only *Polydora* sp.and *Capitella* sp., (annelid worms), *Corophium* sp. (amphipod crustacean), and occasionally Corixidae (insect) and *Streblospio* sp. (annelid) were numerically common or detected during sampling periods prior to the breach (Fig. 9). After the breach, the diversity of common invertebrates increased inside Pond 3 near the breach. These included the annelid worms *Tubificoides* sp., *Polydora* sp., and *Streblospio* sp.; the crustaceans *Corophium*, *Ericthonius* sp., *Pancolus* sp., Gammaridae (amphipods), Sphaeromatidae (isopods), and *Mysis* sp., and the mollusks *Potamocorbula* sp. and, to a lesser extent, *Macoma* sp. (Table 5). Other organisms detected occasionally in Pond 3 included Anthozoa, Bryozoa, Hydrozoa and Nematoda (the most abundant of the occasional organisms). Some of these organisms were absent or rare prior to the breach. Certain common organisms, e.g., *Polydora* sp. and *Capitella* sp., declined considerably well before the breach indicating a substantial change in habitat (e.g., water quality or level). This pre-breach habitat change also probably affected *Artemia* sp. (brine shrimp). *Artemia* was not found prior to summer 2002 but was the most common organism (81.7 per sweep sample) at the time of the breach in September 2002. *Artemia* was not detected after the breach. *Potamocorbula* was absent in all samples prior to the breach but was the most common organism just inside Pond 3 after the breach (Fig. 9). All of the organisms that recruited to Pond 3 were common in the slough adjoining the breach (Table 5).

We identified only 6 lower taxonomic groups within 2 orders (Fig. 10) in Pond 4 during June 2001 and 2002 (Table 6). Although taxonomic diversity was low, *Artemia* comprised about 84% of the sample before the Pond 3 breach, with the remainder primarily made up by *Ephydra.* By September 2002, *Artemia* declined to 5% of the sample while *Ephydra* comprised 31%. However, this does not likely indicate in increase in numbers of *Ephydra*, because the total number of animals per sample had declined significantly as salinity decreased (Fig. 10). *Artemia*, which thrives in higher salinity conditions, was probably more severely affected by changing water chemistry than was *Ephydra*, which is more tolerant of lower salinity.

Fishes

We caught nine fish species in Pond 3 during a single post-breach survey conducted in June 2003 (Fig. 8). No pre-breach fish surveys were made during the summer of 2002 to allow a direct seasonal comparison. However, fish surveys conducted in July 1999 and in June-July 2000 yielded only *Gillichthys mirabilis* (longjaw mudsucker), *Menidia beryllina* (inland silverside), *Lucania parva* (rainwater killifish), and *Tridentiger bifasciatus* (Shimofuri goby). Seven supplemental fish surveys conducted in other months during 1999 and 2000 yielded only two additional species, *Morone saxatilis* (striped bass) and *Acanthogobius flavimanus* (yellowfin goby). Although *G. mirabilis* dominated bag seine catches in 1999 and 2000 (354 out of 780 captured fish or 45% of the total catch), none were caught in June 2003. The catch in June 2003 was dominated by *Gasterosteus aculeatus* (threespine stickleback, 38%), *A. flavimanus* (20%), and *M. beryllina* (17%), with *L. parva* and *Leptocottus armatus* (Pacific staghorn sculpin) contributing 8% and 7% of the catch respectively. Other species captured in June 2003 included *Cottus asper* (prickly sculpin), *Gambusia affinis* (western mosquitofish), *T. bifasciatus* and *Carassius auratus* (goldfish).

Avian Abundance and Distribution Surveys

A gradual reduction in pond use by diving benthivores and an increase in use by shorebirds (especially shallow probers; Fig. 7) correlated with declining water levels in Pond 3 from 1999 until the SS breach in August 2002. Although winter use of the pond eight months before the breach (2001) was heavily dominated by shorebirds, especially shallow probers, the net influx of water into the pond in winter 2002 was associated with an 89% reduction in shorebird numbers and the return of diving benthivores (Fig. 7B). However, winter 2002 encompassed the most dramatic changes to the pond habitat with widening of the breach. By the end of December 2002, bird communities may not have fully responded to the mid-December events and the rapidly changing habitat conditions. Prior to the breach, summer bird use was generally low and was dominated by terns (piscivores) and divers until 2001 (Fig. 7A) and by terns and shallow probers by 2002 (Fig. 7A). Following the breach, summer bird use of Pond 3 increased by approximately an order of magnitude over the previous four summers, with all foraging guilds represented and shorebirds (shallow probers, deep probers, and sweepers) comprising nearly 68% of all birds counted (Fig. 7A).

In Pond 4, declining water levels and increasing salinity resulted in changing species composition before the Pond 3 breach. Dabbling and diving ducks comprised 52% of the overall count during winter 1999 (Fig. 8B), but were virtually absent during winter 2000 and 2001. Instead, approximately 79% of birds counted during this period were small shorebirds, with the remainder made of larger shorebirds (deep probers) and sweepers. After the breach during summer 2002, the greater variability in water depth enabled divers to return to Pond 4, where they comprised approximately 10% of the total count during winter 2002 and 2003. The effect of pond drying on bird use prior to the breach on Pond 4 was even more pronounced during the summer, where total bird numbers in 2002 were only about 25% of the previous 3 summers and were represented primarily by shallow probers (97%). Following the breach, summer bird use increased nearly 8-fold and the pond supported a wider variety of foraging guilds (Fig. 8A).

DISCUSSION

Site Evolution

The width of the breach to SS grew rapidly with winter storms and increased exposure to tidal action, but stabilized after the onset of the dry season in April 2003. Williams et al. (2002) developed empirical relationships for channel width, depth and cross-sectional area based on either the area of marsh or the tidal prism for marshes in San Francisco Bay. Treating the breach as a channel between the slough and the pond, the predicted equilibrium width and maximum depth (below MHHW) of the SS breach are 106 m and 4.60 m, respectively, based on a marsh area of 500 ha. If we assume that the tidal elevation change from the northwest corner is representative of the change throughout the majority of the pond (i.e., 0.25 m), then we calculate a tidal prism of 1.25×10^6 m^3 (5x106 m^2 pond area, 0.25 m water elevation change). However, this most likely underestimates the actual tidal prism because our water surface elevation data did not cover the entire range from high tide to low tide, and regions of the pond nearer the breach exhibited greater than 0.25 m surface fluctuations. With an estimated tidal prism of 1.25x106 m^3, the equilibrium channel width is 95.1 m and depth is 4.59 m. The SS breach is much narrower and deeper than predicted by both equilibrium estimates. We suggest that the levee will continue to erode until breach size and tidal prism equilibrate (Williams et al. 2002, Orr et al. 2003). Possibly, saturation of the levee by rainwater (Thorne & Osman 1988) and the energy associated with storms might weaken the breach, allowing for additional erosion during the next wet season. Continued erosion and slumping of channel banks will probably continue for decades (Ellery & McCarthy 1998; Williams et al. 2002).

The widening of the SS breach resulted from the migration of the breach nick point (an incised headcut in the bed indicated by a sudden drop in bed level) from the slough into the pond. The nick point advanced into the pond radially from the breach and appeared as a ledge about 20 m inside the pond. The pattern of sediment removal by the migrating nick point left a hole in the pond near the breach that was about 20 m wide and up to 2 m deep. The lost sediment appeared to come predominately from the sediment-filled borrow ditch that lines the inside levee and from flushing of a sediment-filled relic channel near the breach. This has left the majority of the pond bottom as a plateau about 2 m above the pond bottom near the breach.

The southern breach to DS has not significantly eroded. The thalweg is too high to allow water exchange except during the highest tides. A shallow hole (< 0.50 m) has formed on the pond side of the breach. At low tide, a tiny rivulet channel was observed in the slough mudflat, but even here, erosion has not been substantial. This breach probably will erode to allow increased water exchange, but the timescale is uncertain.

Salinity and Flow

Salinity

Pond Desalinization

The between-breach salinity transect conducted in September 2002 (Fig. 3) indicated that only the SS breach allowed substantial input of slough water to the pond. The salinity was depressed by over 10 ppt adjacent to SS breach, but most of the pond had not decreased in salinity. Diurnal fluctuations of salinity and temperature in the pond were driven by diurnal winds and associated wind setup (J. Bricker, unpublished data). Substantial pond-wide salinity dilution began with rain in November 2002, when about 6 cm of rain diluted the pond salinity from the mid-50s ppt down to the upper 40s ppt, and continued with more rain in December and the widening of the SS breach.

The desalination of this pond was controlled by rainfall, the widening of the breach and the subsequent flushing of the pond. The most critical event was the large rainfall in December. Not only did this serve to dilute the saline pond water, but also possibly contributed to weakening the levee around the breach. This allowed for rapid levee erosion and breach widening. These events in concert led to the discharge of water from Pond 3 that had a maximum salinity of 35 ppt, which is higher than summer high salinities at MIC. However, most of the discharged water had salinities less than 25 ppt, which is a typical summertime high for this region.

Salinity in Receiving Waters

Our results show that future controlled breaches in the Napa-Sonoma Marsh should be properly timed relative to the flood-ebb and spring-neap tidal cycles and located to avoid high salinity discharge that will collect in the baroclinic convergence zone. These findings stress the importance of understanding and considering the local phenomenon created by spatially and temporally varying tides at each site when planning a restoration.

Although the sudden widening of the SS breach in December was naturally controlled and occurred on a time scale of hours to days, timing an intentional breach to occur during ebb tide would be advantageous in this system. Flood flow in SS is landward and ebb flow is seaward toward the Napa River. By timing a breaching event with the ebb tide, pond water is removed from the slough system and mixed into the larger Napa River. This decreases the likelihood of pond water becoming entrained in the baroclinic convergence zone, and it increases the mixing and dilution of the pond water.

The spring-neap tidal processes exert major control on water flow in this slough system. A sill at the mouth of Sonoma Creek truncates the low spring tides, limiting the extent of the ebb from Sonoma Creek and creating an earlier low tide. This condition creates a tidally averaged flow in SS seaward toward the Napa River. Low neap tides are above the sill, do not limit ebb, and create tidally averaged landward flow in SS (Warner et al. 2003). The breach widening occurred during a spring tide with a 2 m tide range. The salinity exiting the pond was carried by tidal excursion to the baroclinic convergence zone near CAN, where it remained tidally trapped for ten days. The salinity levels at CAN never exceeded the summer salinity levels around 20 ppt because of the additional dilution of pond water by slough water. The salinity pulse remained in the convergence zone until a strong neap tide (range of 1.4 m) most likely flushed the salt west (i.e., landward) out Sonoma Creek into San Pablo Bay.

The location of a levee breach can be as critical as timing. A breach located so that the pond discharged into the Napa River rather than into the interconnected sloughs that host the convergence zone would increase dilution by mixing with the larger body of water. This would decrease the likelihood of high salinity water being trapped in the slough system. Locating the breach away from the slough would prevent increased tidal prism, scour, and potential marsh degradation in the sloughs. Proximity of a breach to the Napa River also provides increased water flow and possibly increased tidal action in the pond.

Site Infrastructure

Slough Erosion

Morphological processes in the pond-slough system occur over much longer timescales than chemical changes such as salinity. Drastic changes in breach size and channel depth were observed in the year following breaching. The slough geometry also changed with the formation of a scour hole in SS adjacent to the breach. In five months, about 1100 m^3 of sediment was scoured to enlarge the hole in SS that was observed in late January 2003. However, geomorphic changes are expected to continue for decades and stabilize slowly (Simenstad & Thom 1996, Ellery & McCarthy 1998, Williams et al. 2002). Although we have not yet observed effects on the adjacent marsh and levee, continued scouring in SS would steepen the banks on both sides of the slough and potentially lead to slumping of the banks and degradation of the nearby marsh and levee.

Changes in Biota

Following the breach at SS, changes in Pond 3 water quality and hydrology were accompanied by shifts in invertebrate, fish, and bird communities in the pond. Changes in the ecological community also resulted from drying conditions and increasing pond salinity in the years immediately preceding the breach. Changes in water quality parameters, most notably salinity, had the major influence on species diversity and composition of invertebrates and fish. Changes in invertebrate and fish assemblages, as well as water depths – a major determinant of guild-specific predator use (Takekawa et al. 2000) – probably influenced changes in bird use of Pond 3. As water depth influenced water quality (e.g., salinity, temperature, or dissolved oxygen), this in turn affected prey use and availability.

Pre-Breach Changes

In Pond 3, pre-breach changes in the invertebrate community were likely caused by water regime changes in early 2001 or late 2000. *Polydora* and *Capitella* nearly disappeared in 2001 after being common in 1999 and 2000. Conversely, *Artemia* flourished by summer 2002, probably in response to sustained high salinity conditions, and subsequently crashed in response to the influx of water associated with the breach. Although fish surveys were not conducted in 2001 or 2002, it is likely that water quality changes that were reflected in changes in invertebrates, also affected fish species composition.

Bird use of Pond 3 underwent a shift concurrent with pre-breach changes in the invertebrate assemblage. Tern numbers were relatively stable in all years, but these and other piscivores were accompanied in summer 1999 and 2000 by diving benthivores and in 2001 and 2002 by shallow probers. Although salinity can drive invertebrate assemblage changes, its impact on higher trophic levels is more variable (Takekawa et al. 2004). Bird guilds require water depths consistent with their foraging strategy to utilize a food source. The shift from diving benthivores, which use the deepest water, to shallow probers, which use the shallowest, was apparently related to changing water depths in the pond. This may not have influenced tern numbers because breeding terns nested on islands in Pond 3 and did not exclusively forage in this pond. Changes in invertebrate prey may have also contributed to the shift, as *Artemia* was first found in high numbers in summer 2002.

Post-Breach Changes

The SS breach initially resulted in a net influx of slough water that increased pond water level and decreased salinity (Fig. 11, Table 1). The introduction of common slough invertebrates, accompanied by changing water quality, changed invertebrate species composition and increased species richness inside the pond in the region of the breach. *Artemia* was not detected after the levee was breached. Some species, although common in the adjacent slough, were rare or not detected in the pond prior to the breach. *Potamocorbula* was absent in all samples prior to the breach but was the most common organism after the breach just inside Pond 3.

The fish in Pond 3 changed from a low-diversity, salt-tolerant assemblage to more diverse, lower salinity species. Prior to the breach, *G. mirabilis* comprised over half the catch during summer months. Moreover, just six species were caught during ten fish surveys between May 1999 and December 2000. *G. mirabilis* was not detected after the breach, presumably because this marine species cannot survive for more than a few days in freshwater (Moyle 2002). The fish survey in June 2003 captured nine species, several of which were previously absent from Pond 3. *C. auratus*, a previously absent freshwater species (Moyle 2002), occurred in Pond 3 after the breach.

Following the breach, summer bird use of the pond increased and more foraging guilds began using Pond 3. Water depth increased in winter 2002 and enabled use by diving benthivores. By the first post-breach summer (2003), bird use increased dramatically. All foraging guilds were represented in the pond but were dominated by shorebirds, especially shallow probers. Increased, though muted, tidal action in the pond resulted in shallow water depths during summer 2003 and created an appropriate foraging environment for shallow probers. Although salt ponds generally receive the highest shorebird use during high tide when the bay's mud flats are inundated (Warnock & Takekawa 1995), shorebirds now forage on the pond during low tide as well as high tide. Increased tidal action in the pond probably provides larger areas of shoreline accessible for shorebird foraging.

Pre-breach changes on Pond 4 were similar to those on Pond 3, as the pond underwent a similar period of drying and increasing salinity. Post-breach, salinity and water depth became more similar to 1999-2000 conditions, and the pond underwent the associated species composition changes as well. Diving benthivores were once again using the pond, and all birds were present in higher numbers. Invertebrate diversity was lower on Pond 4 than on Pond 3, but salinity-tolerant specialists *Artemia* and *Ephydra* were present in large numbers. Salinity reduction following the breach may have driven a shift from *Artemia* to *Ephydra* in the pond, and as salinity continues to decrease, changes in the invertebrate community are likely to continue.

Although fish were not present in Pond 4 in 1999 or 2000, declining salinity may set the stage for colonization in the near future.

Future Changes

Sterna caspia and *S. forsteri* (Caspian and Forster's terns) use pond islands for breeding, but these populations may not be sustainable. Tidal action in early spring 2003 reduced the effective size of the Pond 3 islands and eliminated more than 50% of tern nests in the northern portion of the pond (C. Strong, San Francisco Bay Bird Observatory, personal communication). Although the pond may continue to support a limited number of breeding terns, eventual marsh development is likely to introduce mammalian predators and hinder predator avoidance activities. The initial high waterbird use of Pond 3 will probably decline as sediment deposition and vegetation establishment continue. This change was seen at Napa Pond 2A, a neighboring salt pond that was breached in 1995 (Williams & Orr 2002). Waterbirds can have advantages in salt ponds not found in tidal marsh habitat. For example, *C. mauri* benefits from salt ponds because shallow, sheltered impoundments create a favorable microclimate for roosting and foraging, whereas large, open expanses of water enable birds to avoid predators and human disturbance (Warnock & Takekawa 1996). Conversion to tidal marsh habitat will benefit some avian species, including the listed *Rallus longirsotris obsoletus* (California Clapper Rail) and *Laterallus jamaicensis coturniculus* (California Black Rail). However, these benefits will come at the expense of shorebird and breeding tern habitat, which should be considered in restoration planning in the Bay. Further, biologically important prey assemblages (e.g., *Artemia*) exist in massive numbers at higher salinity salt ponds and are relatively rare in other environments within San Francisco Bay. Particularly in Pond 4, the loss of this biomass to the prey base and carbon cycling requires assessment.

Vegetation Colonization

The most important determinant for colonization of marsh plants in Pond 3 is surface elevation of the sediments (Simenstad & Thom 1996; Cornu & Sadro 2002, Williams & Orr 2002). Mean elevation of the bottom of Pond 3 is about 1.2 m NAVD88 (Towill, Inc. 2001 survey), which corresponds to local mean low water (MLW; 1.20 m elevation at Mare Island Causeway, http://coops.nos.noaa.gov/epoch_datum_check.shtml?stnid=9415218). This is just below the average elevation of Napa Pond 2A (elevation =1.6 m), a neighboring salt pond in the same system (Williams & Orr 2002). Pond 2A was naturally restored to greater than 50 percent salt marsh vegetation cover within three years of a levee breach. MLW is generally recognized to be below the minimum elevation for marsh colonization (Williams & Orr 2002), whereas the transition from mud flat to low marsh usually occurs at mean tide level (MTL, Orr et al. 2003). Generally, salt marsh plants are concentrated in the range from MHW to MHHW. Around the Napa Ponds, this ranges from 1.87 m (MTL) to 2.53 m (MHW) to 2.70 m (MHHW), suggesting that high points of the pond bottom that are near MTL may now be suitable for colonization. However, Crooks et al. (2002) suggested that poorly drained regions, even at elevations suitable for marsh plant colonization, will not be colonized. This is mostly a consequence of waterlogged sediments, which reduces required photosynthetic gas exchange. In fact, the first noticeable vegetation in Pond 3 was the green alga *Enteromorpha* spp. when it appeared in February 2003. This alga is associated with waterlogged sediments and reduced colonization of the early colonizing halophyte *Salicornia* spp. in England (Reading et al. 2000 as reported in Crooks et al. 2002). Pickleweed (*Salicornia virginica*) was observed in August 2003 (Fig. 13) to colonize some of the higher points and edges of Pond 3. However, the mean pond elevation must increase through sedimentation, and the drainage must improve before a restored salt marsh can flourish.

CONCLUSIONS

Based on our experience with the breaching of Napa Pond 3, the following general conclusions can be made:

- Physical processes (the tidal cycle) must be considered when planning the timing of a breaching event.

- Local conditions, such as the existence of the baroclinic convergence zone in our study region, should be understood prior to breaching.

- Erosion can be significant at the location of the breach and could contribute to contaminant mobilization and degradation of nearby marsh and levees.

- A decreasing salinity regime in the pond drove a rapid change in invertebrates and fish in the pond.

- Changing pond water levels and prey items drove a rapid change in the bird community.

LOGISTICAL ISSUES

After the SS breach widened during winter 2002, water movement through the breach was turbulent and made the breach dangerous to approach during any period except slack tide, about a 15-minute window. Additionally, water movement in the breach was too fast to obtain many accurate depth readings during the period of this study. Fish sampling was constrained because tide action and fluctuating water levels prevented sampling with gill nets, which were typically set for 2-hour periods during our study. Pond 3 was difficult to access during low tide because of the need to cross soft mud flats, and this hindered our ability to read staff gages at low tide.

FUTURE RESEARCH

We will continue to monitor birds, fish, water quality, and invertebrates in the Napa-Sonoma salt ponds, under support from the California State Coastal Conservancy and the USGS San Francisco Bay Priority Ecosystem Science Program, through the spring of 2007. As plans proceed for restoration, we will summarize and continue baseline monitoring of primary productivity, macroinvertebrate, fish, and bird use to assess effects on wildlife. We will conduct construction and post-construction surveys with emphasis on Ponds 3-5 to track changes during the Phase I Restoration. Finally, we will establish avian point counts for passerines and rails and small mammal surveys on Ponds 3-5 to characterize fringing marshes and determine construction effects on tidal marsh species.

ACKNOWLEDGMENTS

This research was supported by the California State Coastal Conservancy (Amy Hutzel and Nadine Hitchcock) and the USGS San Francisco Bay Priority Ecosystem Science Program (J. Cloern, J. Thompson). Tom Huffman and Larry Wyckoff were instrumental with logistical assistance (California Department of Fish and Game). Paul Buchanan was responsible for monthly water quality measurements, and Greg Brewster and Brad Sullivan assisted him. Neil Ganju and Megan Lionberger provided assistance with the collection and analysis of bathymetry and flow data. Scott Demers was responsible for bird surveys and monthly measurements of breach dimensions. Jodi Despot, Martin Stafford and Deb Jaouen led the benthic macroinvertebrate collection and identification. Danika Tsao assisted with chlorophyll-*a* and nutrient data collection and laboratory work. Jeff Schlosser was mostly responsible for fish collections during 1999-2000, whereas Francine Mejia oversaw fish collections in 2003. Jim Orlando assisted with GIS and provided the scour figure. The use of firm, trade and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

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Tables and Figures

Table 1. The salinity in the four corners and near the SS breach of Pond 3 measured during three sampling events.

Location in Pond	August 20, 2002	December 23, 2002	January 24, 2003
Northeast Corner P3	64.7	19.8	5.3
Southeast Corner P3	75.2	19.1	13.2
Southwest Corner P3	48.2	13.2	12.5
Northwest Corner P3	54.6	23.1	4.6
Near Breach P3	54.5	21.1	6.2
Pond 3 Average	59.4	19.3	8.4
Northeast Corner P4	209	137	70.6
East Side P4	209	132	82.5
Northwest Corner P4		137	71.3
Southwest Corner P4	217	132	87.8
South Side P4	205	117	97.2
Pond 4 Average	210	131	88.9

Table 2. Average water quality parameters measured pre-breach (January 2001-July 2002) and post-breach (August 2002-October 2003).

		Pond 1	Pond 2	Pond 3	Pond 4	Pond 5	Pond 7
pre-breach	Salinity (ppt)	30.8	26.6	62.2	178.6		258.2
	D.O. (mg/L)	8.5	8.5	8.6	5.6		3.7
	Temperature (°C)	19.2	17.8	19.3	21.0		20.2
	pH	8.2	8.8	8.4	7.6		5.6
	Turbidity (NTU)	78	86	187	73		155
post-breach	Salinity (ppt)			26.9	124.3	92.4	
	D.O. (mg/L)			8.4	7.2	3.9	
	Temperature (°C)			17.2	16.2	18.7	
	pH			8.4	8.1	8.5	
	Turbidity (NTU)			63	72	101	

Table 3. Nutrients for Oct and Dec 2002, Feb, Apr, May 2003 in South Slough (SS), breached Pond 3 and Pond 4.

		NH_4-N (ppm)	NO_3-N (ppm)	P (Soluble; ppm)	P (Total; ppm)	S (Total; ppm)	SO_4-S (ppm)	Turbidity (NTU)
Oct-02	SS	0.06	<0.05	0.09	0.3	980	--	--
Dec-02	SS	0.12	<0.05	--	<0.1	920	--	--
Feb-03	SS	<0.05	0.88	0.16	--	--	271	--
Feb-03	SS	<0.05	0.88	0.15	--	--	269	--
Apr-03	SS	<0.05	0.58	0.08	0.3	--	--	417.0
May-03	SS	<0.05	0.29	0.07	0.1	--	--	58.6
Oct-02	Pond 3	0.08	<0.05	0.14	0.5	1320	--	--
Oct-02	Pond 3	0.06	<0.05	0.13	0.4	1300	--	--
Dec-02	Pond 3	0.22	0.21	--	<0.1	600	--	--
Feb-03	Pond 3	0.08	0.47	0.12	--	--	304	--
Apr-03	Pond 3	<0.05	0.42	0.07	0.2	--	--	182.0
May-03	Pond 3	<0.05	0.27	0.07	0.1	--	--	118.0
Oct-02	Pond 4	8.07	0.22	0.95	2.1	8160	--	--
Oct-02	Pond 4	8.05	0.23	0.96	2.1	7930	--	--
Dec-02	Pond 4	2.82	0.22	--	0.8	4030	--	--
Dec-02	Pond 4	2.85	0.17	--	0.9	3870	--	--
Feb-03	Pond 4	0.36	0.56	0.14	--	--	480	--
Feb-03	Pond 4	0.35	0.56	0.14	--	--	480	--
Apr-03	Pond 4	1.87	<0.05	0.12	0.4	--	--	72.8
Apr-03	Pond 4	1.87	<0.05	0.16	0.4	--	--	69.5
May-03	Pond 4	1.24	<0.05	0.13	0.4	--	--	131.0
May-03	Pond 4	1.25	<0.05	0.14	0.5	--	--	127.0

Table 4. Chlorophyll-*a* data (mg/m^3) measured in breached Pond 3 and Pond 4. Oct and Dec 2002, Feb, Apr, and May 2003.

Chlorophyll-*a*	Oct-02	Dec-02	Feb-03	Apr-03	May-03
Pond 3	159.35	244.959	8.68	9.49	3.898
South Slough	147.82	124.912	12.382	9.75	42.161
Pond 4		47.072	30.82	71.96	2.893

Table 5. Invertebrate Species list for Pond 3 Pre- and Post- Breach. Pre-Breach species list includes samples collected April 1999 – June 2002; Post-Breach samples were collected September 2002 – July 2003; slough samples were collected in the slough at the breach site, March, May, and July 2003 ("x" indicates species present).

Phylum	Classification	Organism	Pond 3		South Slough
			Pre-Breach	Post-Breach	Post-Breach
Crustacea	Genus	*Ampithoe*		x	x
Crustacea	Genus species	*Artemia*	X	x	x
Mollusca	Genus species	*Assiminea californica*			x
Bryozoa	Phylum	Bryozoa	X		
Annelida	Genus	*Capitella*	X		X
Insecta	Family	Ceratopogonidae			x
Insecta	Family	Chironomidae			x
Crustacea	Family	Cirripidae		x	x
Crustacea	Subclass	Copepoda	X		
Insecta	Family	Corixidae	X	x	x
Crustacea	Genus	*Corophium*	X	x	x
Crustacea	Genus species	*Crangon franciscorum*		x	
Crustacea	Order	Cumacea	X	x	x
Anthozoa	Genus	*Diadumene*		x	x
Insecta	Order	Diptera	X	x	
Cnidaria	Genus	*Edwardsia*	X		x
Arthropoda	Genus	*Ephydra*	X	x	x
Crustacea	Genus	*Ericthonius*	X	x	x
Annelida	Genus	*Eteone*		x	x
Crustacea	Family	Gammaridae	X	x	x
Mollusca	Genus species	*Gemma gemma*			x
Crustacea	Genus species	*Hemigrapsus oregonensis*			x
Annelida	Genus	*Heteromastus*	X	x	x
Insecta	Family	Hydrophilidae	X	x	x
Hydrozoa	Class	Hydrozoa		x	
Crustacea	Family	Idoteidae		x	
Nemertea	Family	Lineidae	X		x
Mollusca	Genus species	*Macoma balthica*		x	x
Insecta	Family	Muscidae	X		x
Crustacea	Genus	*Mysis*		x	x
Mollusca	Family	Mytilidae			x
Nematoda	Class	Nematoda	X		x

Table 5. Continued.

Annelida	Genus	*Nereis*		x	x
Hydrozoa	Genus	*Obelia*	X		
Crustacea	Order	Ostracoda	X	x	
Crustacea	Genus species	*Palaemon macrodactylus*			x
Crustacea	Genus species	*Pancolus californiensis*	x	x	x
Annelida	Genus	*Polydora*	x	x	x
Annelida	Genus	*Pseudopolydora*	x		
Mollusca	Genus	*Potamocorbula*		x	x
Annelida	Genus	*Pseudopolydora*			x
Insecta	Family	Psychodidae			x
Annelida	Family	Sabellidae			x
Crustacea	Family	Sphaeromatidae		x	x
Annelida	Family	Spionidae			x
Annelida	Genus	*Streblospio*	x	x	x
Crustacea	Family	Synidotea		x	x
Annelida	Order	Tubificoides	x	x	x

Table 6. Invertebrate species list for North Bay Salt Ponds. Samples collected at all Ponds in Feb, Jun, and Nov 2001, and Jun 2002. Pond 3 and Pond 4 also include data from Sep 2002.

Order	Taxonomic Group	Pond 1	Pond 2	Pond 3	Pond 4
Nematoda	Nematoda	x	X	x	
Oligochaeta	Oligochaeta	x			
	Tubificoides	x	X	x	
Polychatea	Capitella	x	X	x	
	Cirratulus	x	X		
	Eteone	x	X		
	Heteromastus	x	X	x	
	Nereis	x	X		
	Pancolus			x	
	Polydora	x	X	x	
	Pseudopolydora	x	X	x	
	Spionidae	x	X		
	Streblospio	x	X	x	
Bivalvia	*Macoma balthica*	x	X		
	Mya arenaria		X		
	Potamocorbula	x			
Crustacea	Ampelisca	x	X		
	Ampithoidae	x	X		
	Artemia			x	x
	Barnacle		X		
	Cirripidae		X		
	Copepoda	x			
	Corophium	x	X	x	
	Crangon franciscorum		X		
	Cumacea	x		x	
	Ericthonius	x	X		
	Gammaridae	x	X		
	Mysis	x	X		
	Ostracoda	x	X	x	
	Palaemon macrodactylus		X		
	Pancolus californiensis		X		
	Sphaeromatidae		X		
	Synidotea	x			
Insecta	Corixidae	x	X	x	x
	Diptera			x	x
	Dolichopodidae				x
	Drosophilia		X		
	Ephydra		X	x	x
	Hydrophilidae			x	x
	Muscidae			x	x
Other	Lineidae		X	x	
	Assiminea californica		X		
	Diadumene	x	X		
	Bryozoa	x	X	x	

Table 6. Continued.

	Coelomate			x	
	Edwardsia	x	X		
	Anthozoa		X		
	Obelia		X	x	
	Mitrella carinata	x			
	Opisthobranchia	x			
	Poynoidae	x			
TOTAL TAXA		31	36	21	7

Table 7. Bird Species list for North Bay Salt Ponds 3 and 4. Pre-breach surveys conducted January 2001-July2002; and post-breach surveys conducted August 2002-November 2003.

			Pond 3		Pond 4	
Guild	Common Name	Genus and species	Pre-Breach	Post-Breach	Pre-Breach	Post-Breach
Dabbler	American coot	*Fulica americana*	x	x	x	X
	American wigeon	*Anas americana*	x	x	x	X
	cinnamon teal	*Anas cyanoptera*		x		
	gadwall	*Anas strepera*	x	x	x	X
	green-winged teal	*Anas crecca*	x	x	x	
	mallard	*Anas platyrhynchos*	x	x	x	X
	northern pintail	*Anas acuta*	x	x	x	X
	northern shoveler	*Anas clypeata*	x	x	x	X
Diver	bufflehead	*Bucephala albeola*	x	x	x	X
	canvasback	*Aythya valisineria*	x	x	x	X
	Clarke's grebe	*Aechmophorus clarkii*	x		x	
	common goldeneye	*Bucephala clangula*	x	x	x	x
	eared grebe	*Podiceps nigricollis*	x	x	x	x
	horned grebe	*Podiceps auritus*	x		x	
	pied-billed grebe	*Podilymbus podiceps*	x	x	x	x
	redhead	*Aythya americana*	x			
	ruddy duck	*Oxyura jamaicensis*	x	x	x	x
	scaup (lesser, greater)	*Aythya affini, marila*	x	x	x	x
	western grebe	*Aechmophorus occidentalis*	x	x	x	x
piscivore	American white pelican	*Pelecanus erythrorhynchos*	x	x	x	x
	black-crowned night heron	*Nycticorax nycticorax*	x			
	black skimmer	*Rynchops niger*		x		
	Caspian tern	*Sterna caspia*	x	x	x	x
	common merganser	*Mergus merganser*	x			x
	double-crested cormorant	*Phalacrocorax auritis*	x	x	x	x
	Forster's tern	*Sterna forsteri*	x	x	x	x
	great blue heron	*Ardea herodias*	x	x	x	x
	great egret	*Casmerodius albus*	x	x	x	x
	red-breasted merganser	*Mergus serrator*	x	x	x	
	snowy egret	*Egretta thula*	x	x	x	x
shallow prober	Baird's sandpiper	*Calidris bairdii*				x
	black-bellied plover	*Pluvialis squatarola*	x	x	x	x
	dunlin	*Calidris alpina*	x	x	x	x
	killdeer	*Charadrius vociferous*		x	x	x
	least sandpiper	*Calidris minutilla*	x	x	x	x
	red knot	*Calidris canutus*			x	
	ruddy turnstone	*Arenaria interpres*			x	
	sanderling	*Calidris alba*				x
	semipalmated plover	*Charadrius semipalmatus*		x	x	x
	semipalmated sandpiper	*Calidris pusilla*				x
	snowy plover	*Charadrius alexandrinus*				x
	western sandpiper	*Calidris mauri*	x	x	x	x

Table 7. Continued.

deep prober	dowitchers	*Limnodromus scolopaceus,griseus*	x	x	x	x
	greater yellowlegs	*Tringa melanoleuca*		x	x	x
	Lesser yellowlegs	*Tringa flavipes*		x		
	long-billed curlew	*Numenius americanus*		x	x	x
	marbled godwit	*Limosa fedoa*	x	x	x	x
	White-faced ibis	*Plegadis chihi*				x
	whimbrel	*Numenius phaeopus*			x	x
	Willet	*Catoptrophorus semipalmatus*	x	x	x	x
sweeper	American avocet	*Recurvirostra americana*	x	x	x	
	black-necked stilt	*Himantopus mexicanus*	x	x	x	x
	red-necked phalarope	*Phalaropus lobatus*	x	x	x	x
other	Bonaparte's gull	*Larus philadephia*	x	x	x	x
	California gull	*Larus californicus*	x	x	x	x
	Canada goose	*Branta canadensis*	x	x	x	x
	greater flamingo	*Phoenicopterus roseus*	x	x	x	x
	herring gull	*Larus argentatus*		x		
	mute swan	*Cygnus olor*		x		
	northern harrier	*Circus cyaneus*		x		x
	osprey	*Pandion haliaetus*	x	x		
	peregrine falcon	*Falco peregrinus*		x		x
	ring-billed gull	*Larus delawarensis*	x	x	x	x
	western gull	*Larus occidentalis*	x	x	x	x

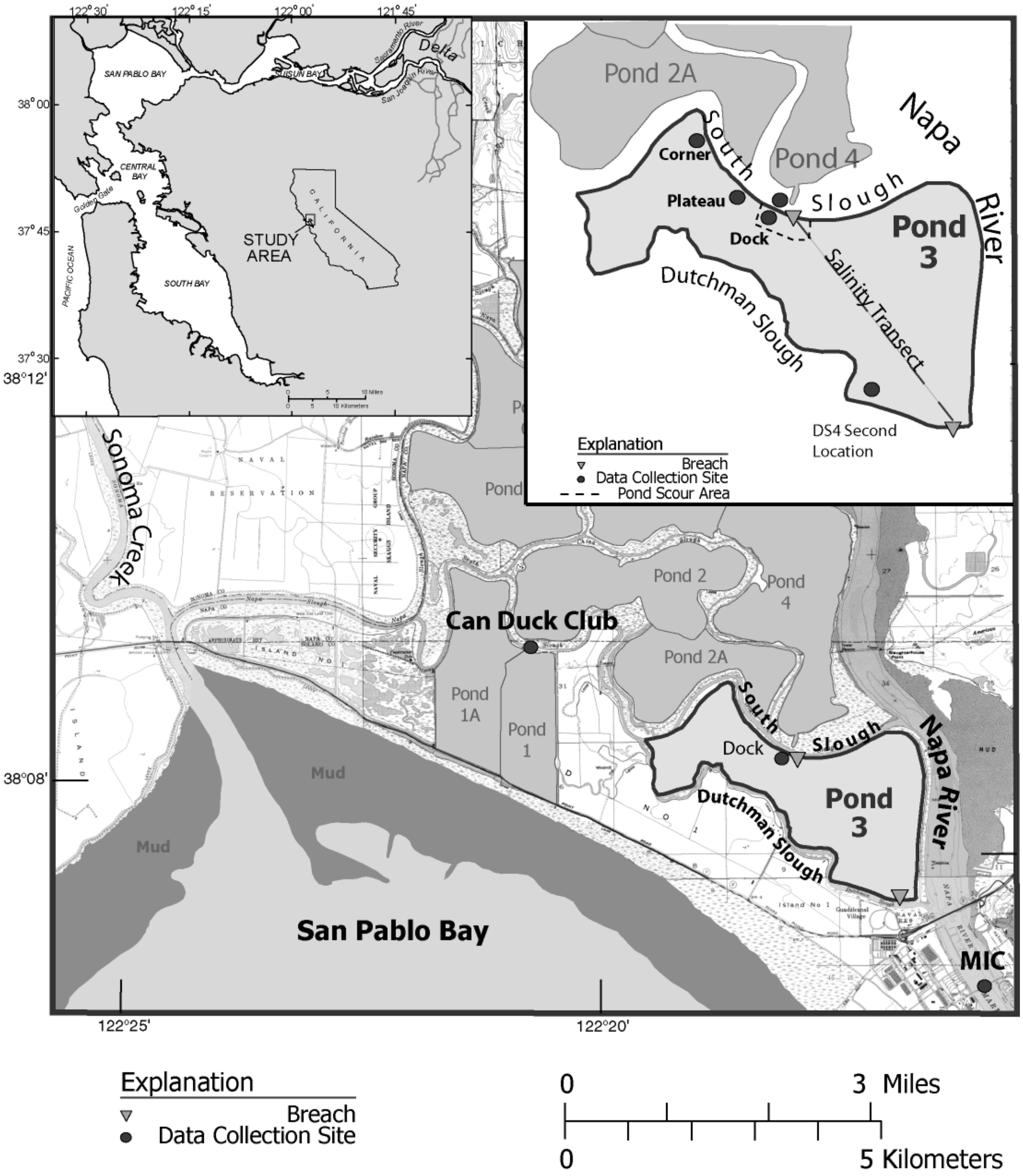

Figure 1. Location of the study area in northern San Francisco Bay. MIC is the Mare Island Causeway. The inset in the upper right corner is a detail of the Napa Pond 3 study area. The ‘Corner’ and ‘Plateau sites were utilized during the measurement of the pond and slough discharge (19 June 2003).

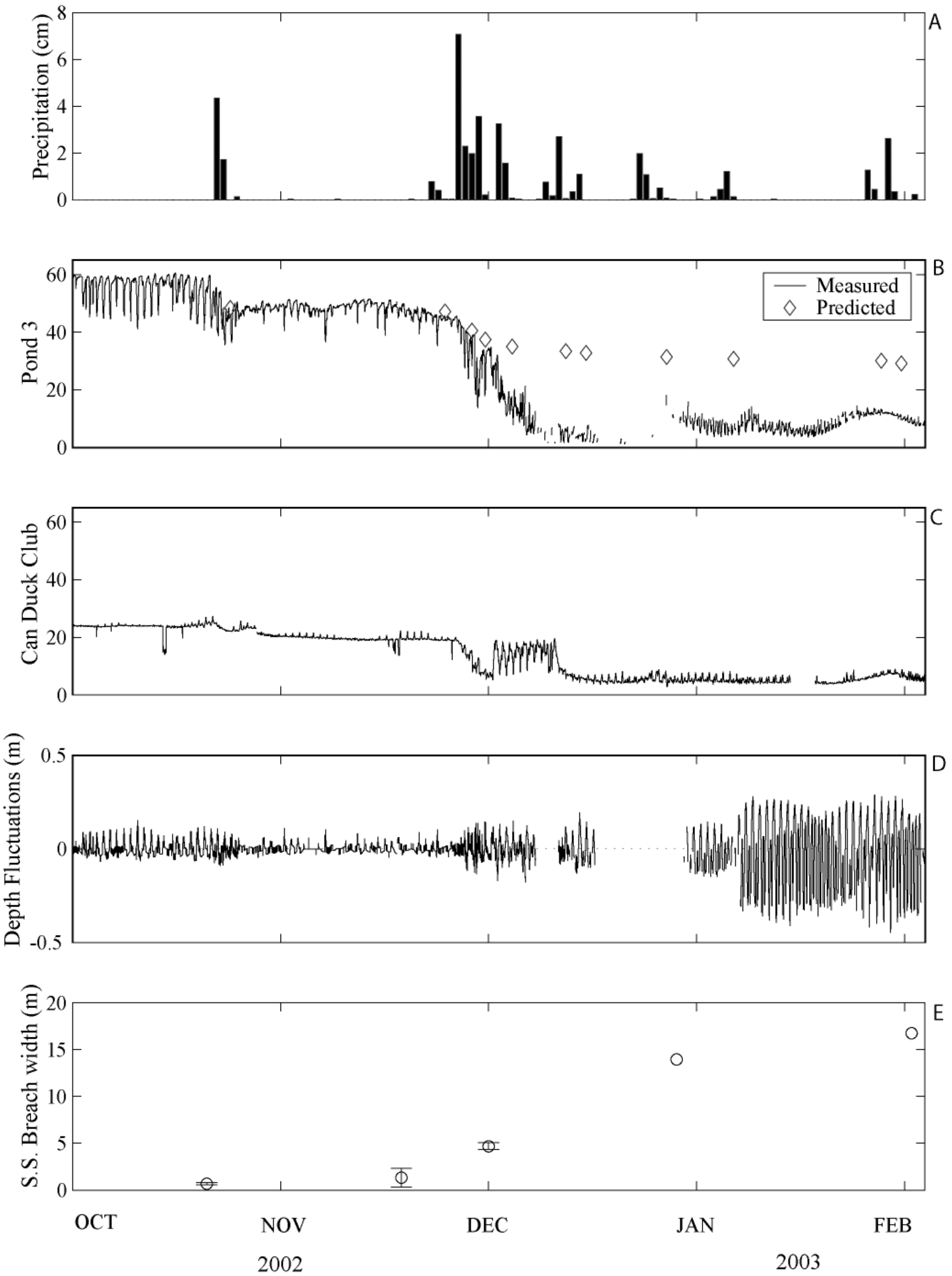

Figure 2. A) Daily rainfall as recorded at Carneros (CIMIS station 109). B) Salinity measured in Pond 3. Prediction of salinity is based on dilution by rainfall only. C) The 30-hour running mean of salinity measured at the Can Duck Club in SS to the west of Pond 3. D) Water surface fluctuations in Pond 3. E) Width of the breach to SS. Error bars represent one standard error (n=3).

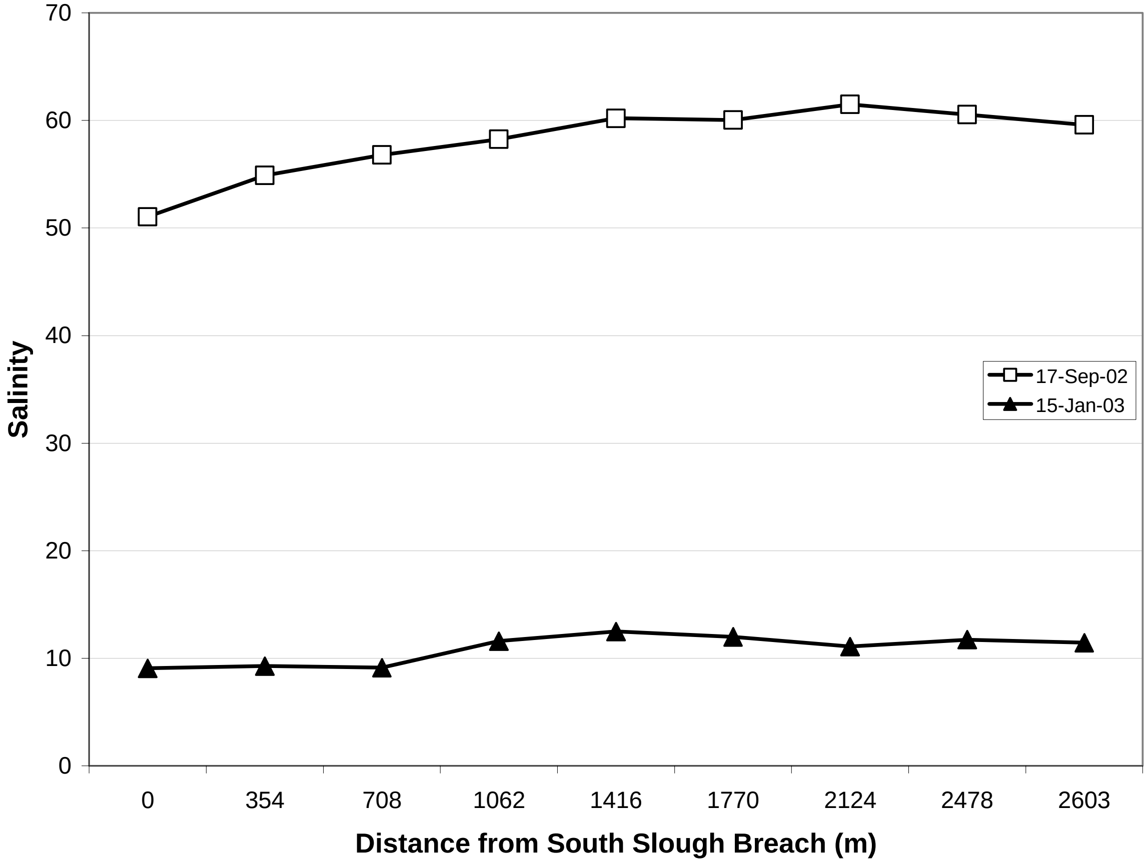

Figure 3. Between-breach salinity transects in Pond 3 one month post-breach and one month post-breach widening. Measurement starts at the South Slough breach and ends at the Dutchman's Slough breach.

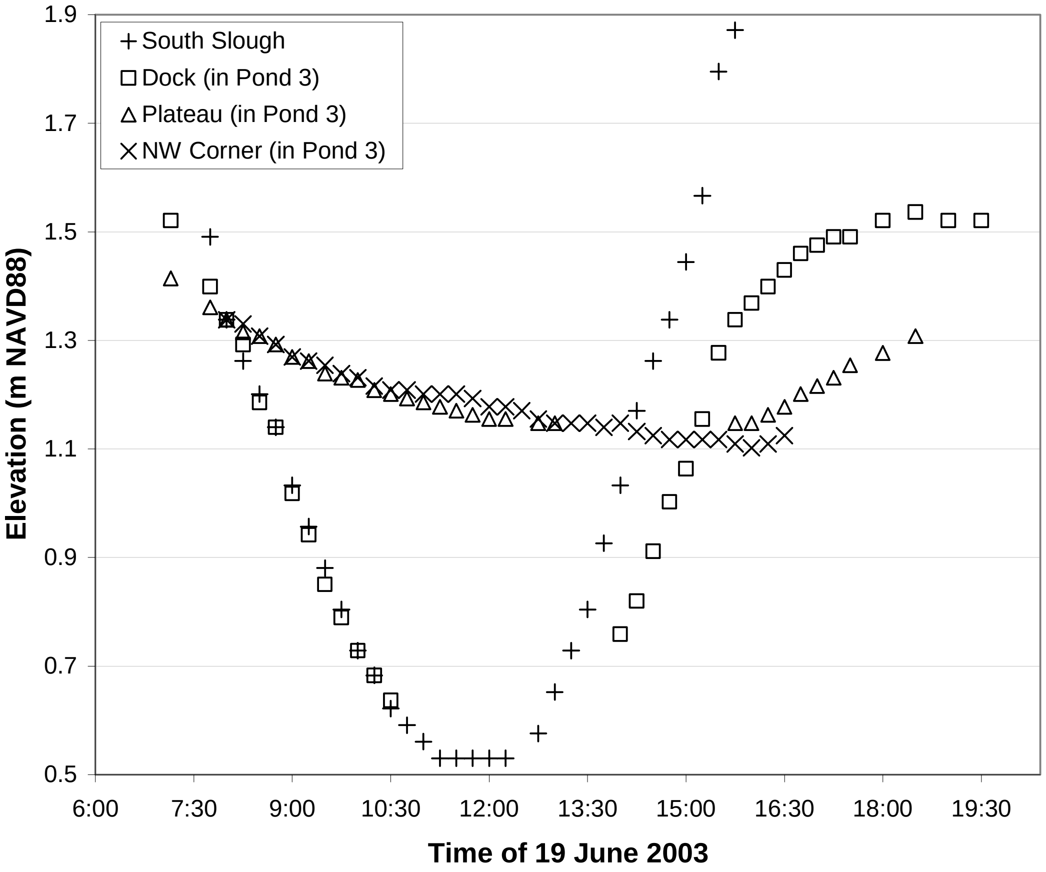

Figure 4. Water surface elevation for most of one tide in June 2003. Data gaps represent periods when the tide level fell below the minimum staff gauge reading.

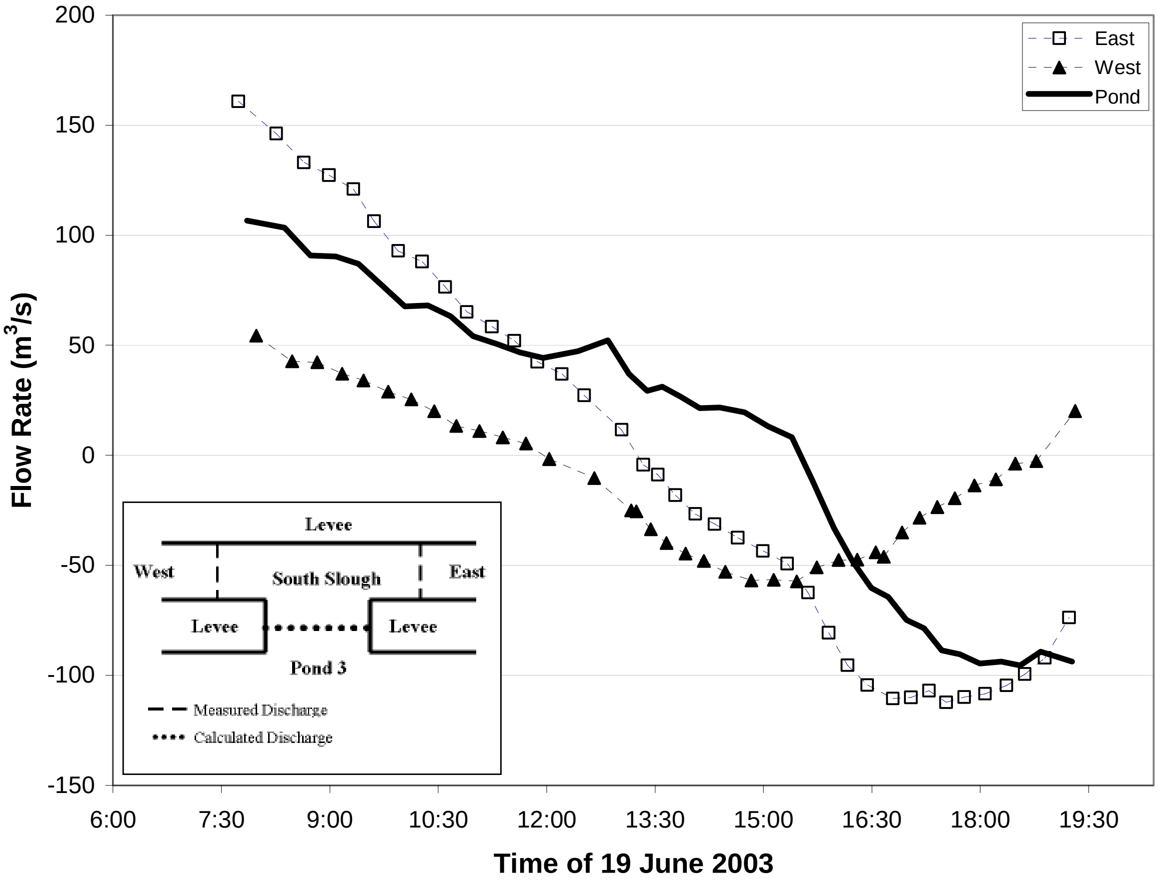

Figure 5. The flow rates in SS and the breach. 'East' and 'West' refer to directions in SS relative to the breach. The solid line represents the flow rate through the breach as calculated as a difference between east and west flow rates. Positive flow is out of the pond and to the east (toward the Napa River). Inset shows a schematic of the system.

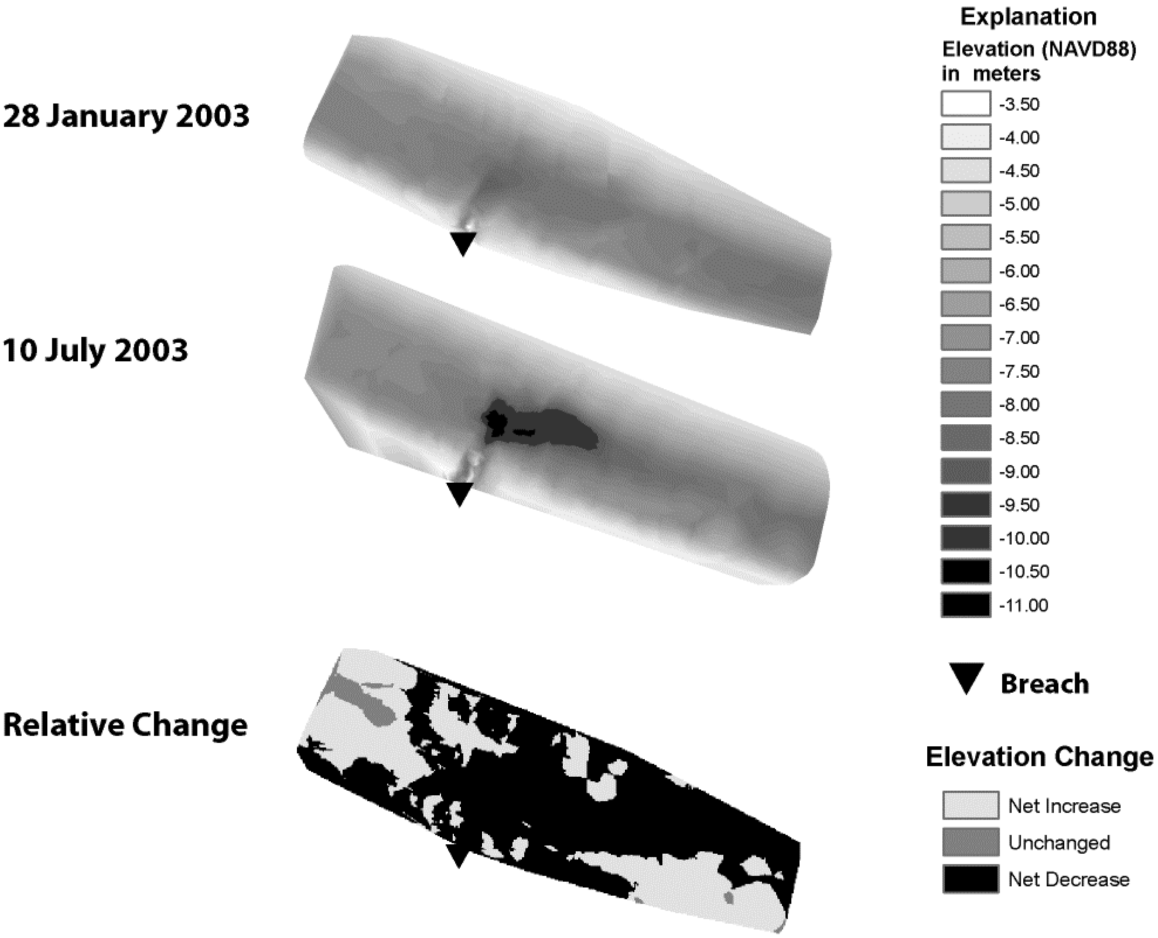

Figure 6. Change in SS bathymetry between January and July 2003. About 1,100 m^3 of sediment was scoured from SS in nearly 6 months.

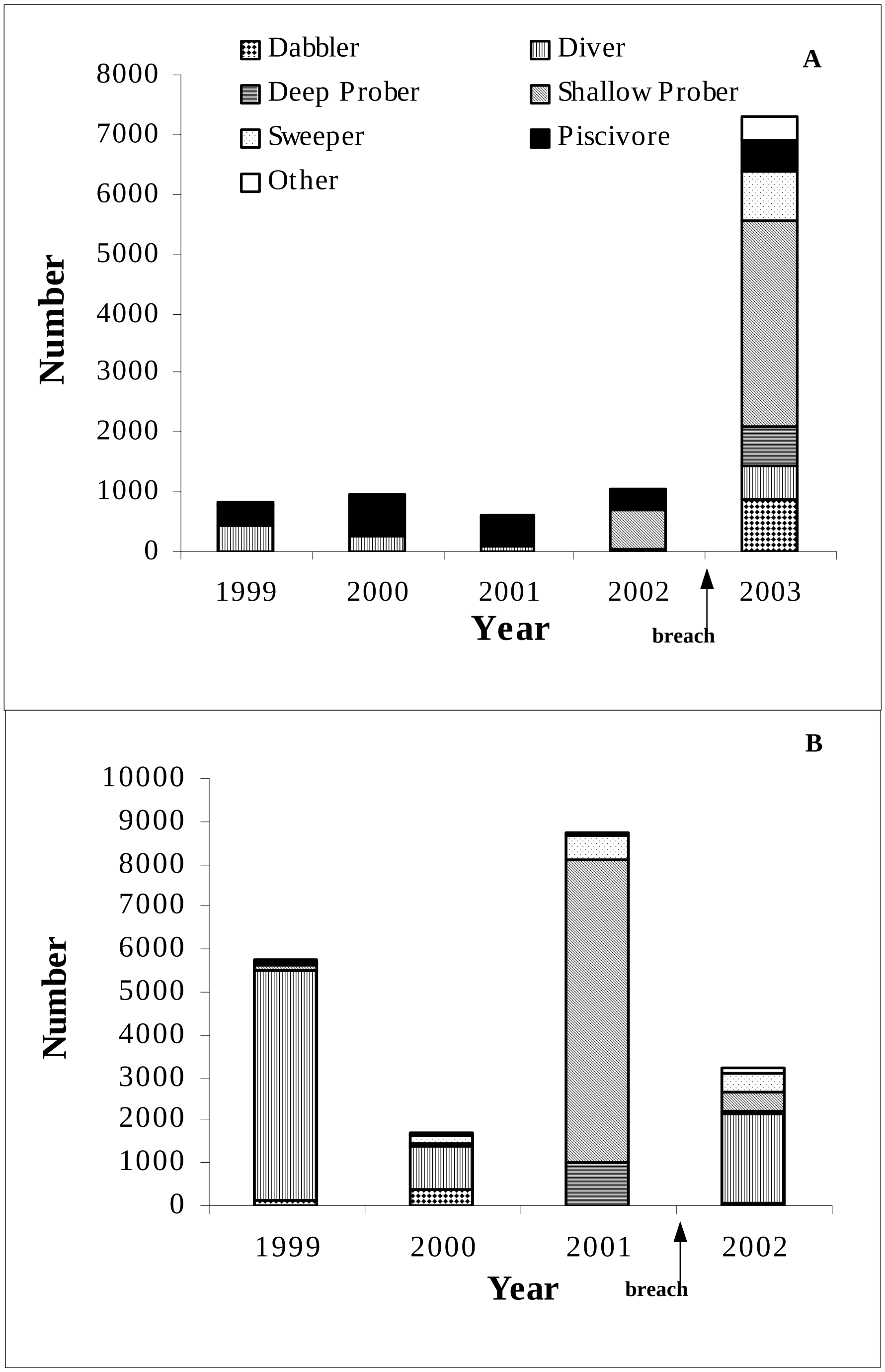

Figure 7. Changes in mean number of birds counted per month during A) summer (April-August) and B) winter (November-January) on Pond 3 in the Napa-Sonoma Marsh, 1999 – 2003. The SS breach occurred in August 2002. Birds were separated into guilds to examine differences among foraging groups rather than differences among individual species (see Methods).

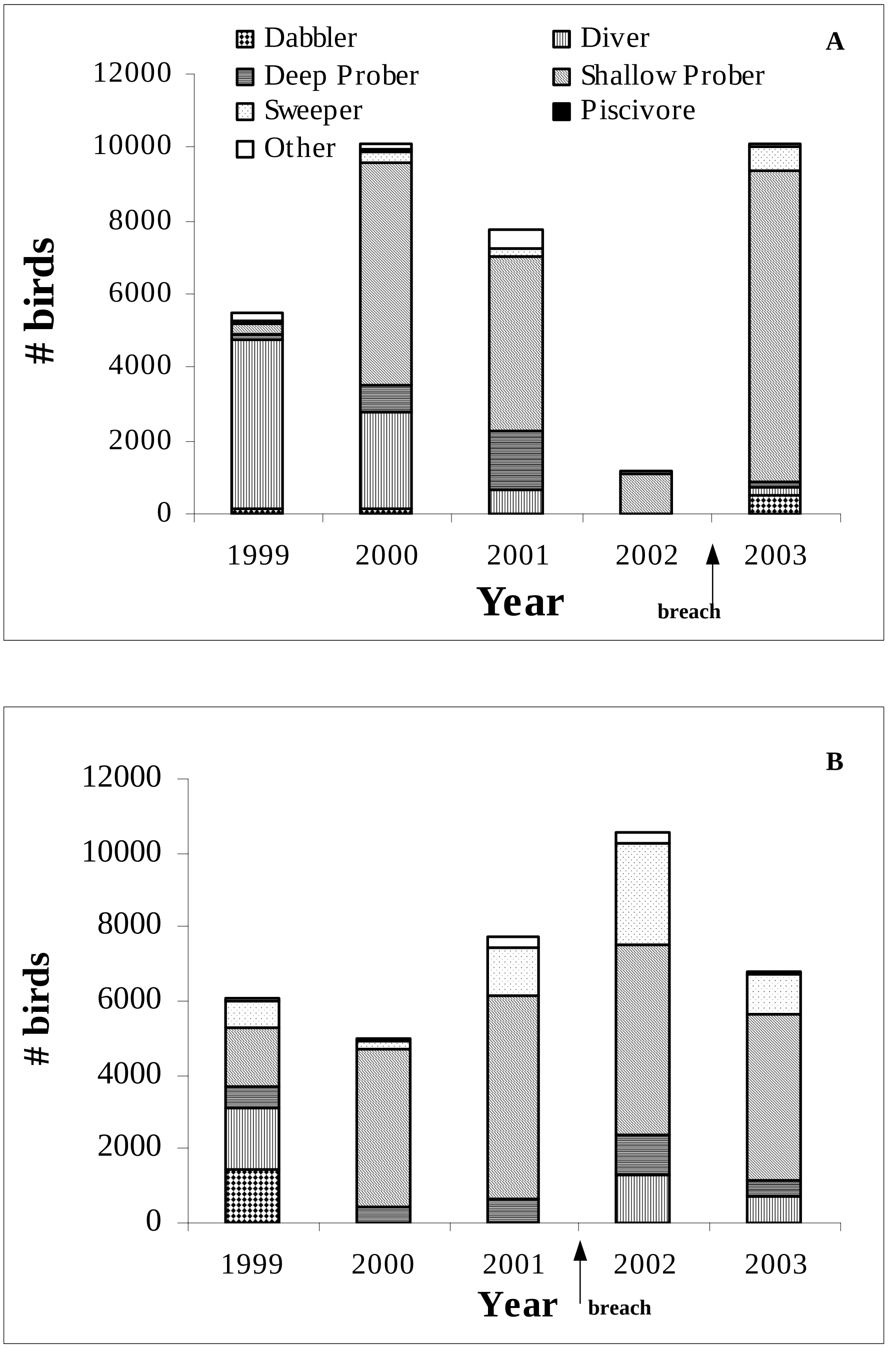

Figure 8. Changes in mean number of birds counted per month during A) summer (April-August) and B) winter (November-January) on Pond 4 in the Napa-Sonoma Marsh, 1999 – 2003. The SS breach occurred in August 2002. Birds were separated into guilds to examine differences among foraging groups rather than differences among individual species (see Methods).

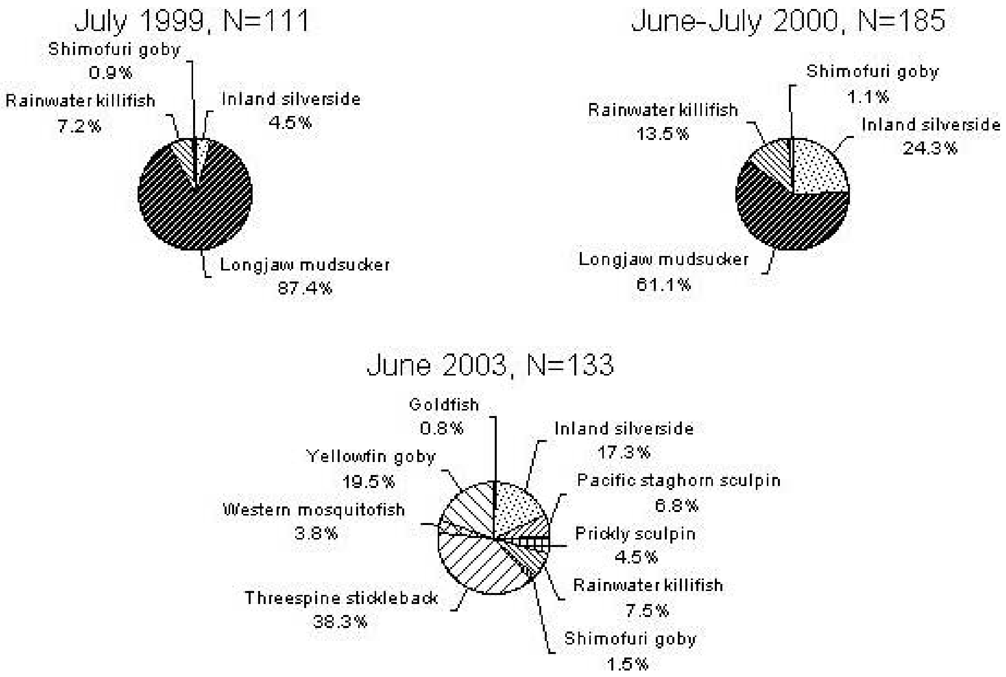

Figure 8. Percent composition of fish caught with bag seines in Pond 3 in the Napa-Sonoma Marshes, 1999 – 2000 and 2003. The SS breach occurred in late summer 2002. July 1999 and June-July 2000 are provided as pre-breach summer comparisons to June 2003.

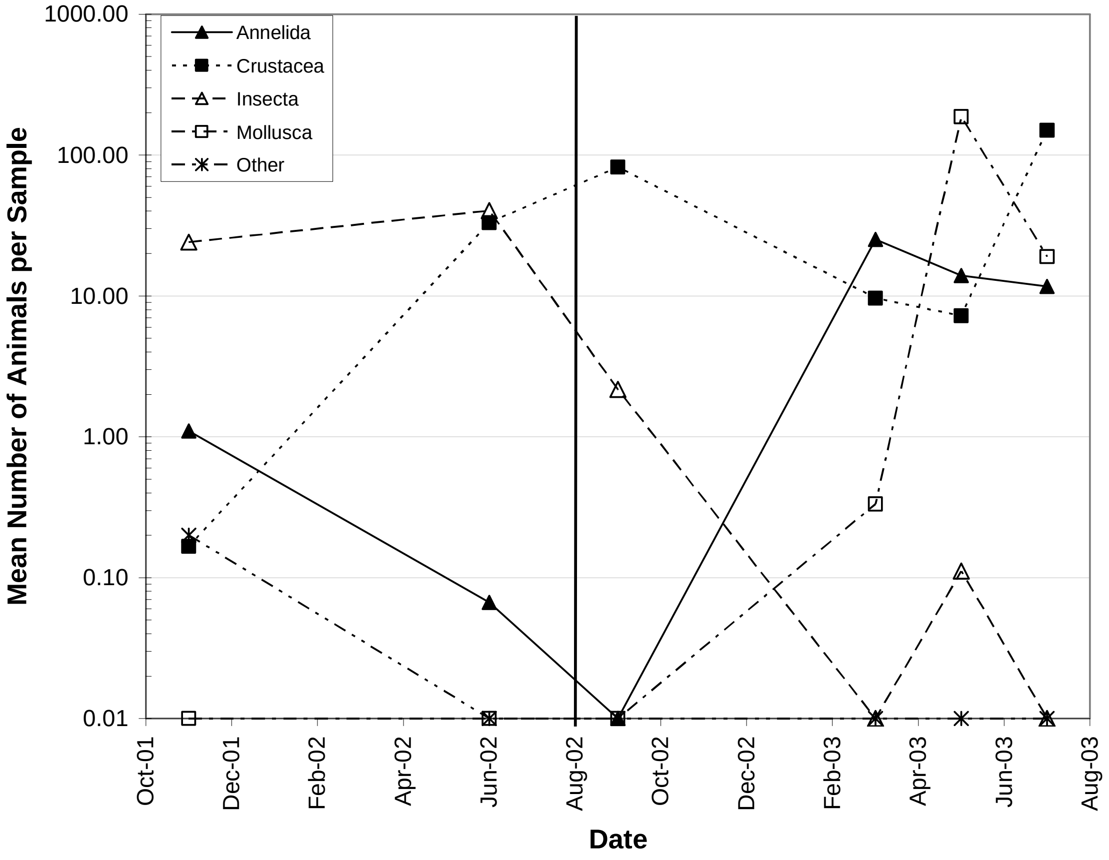

Figure 9. Pond 3 invertebrate composition. Vertical line marks the initial breaching event in August 2002. The breach greatly widened in December 2002.

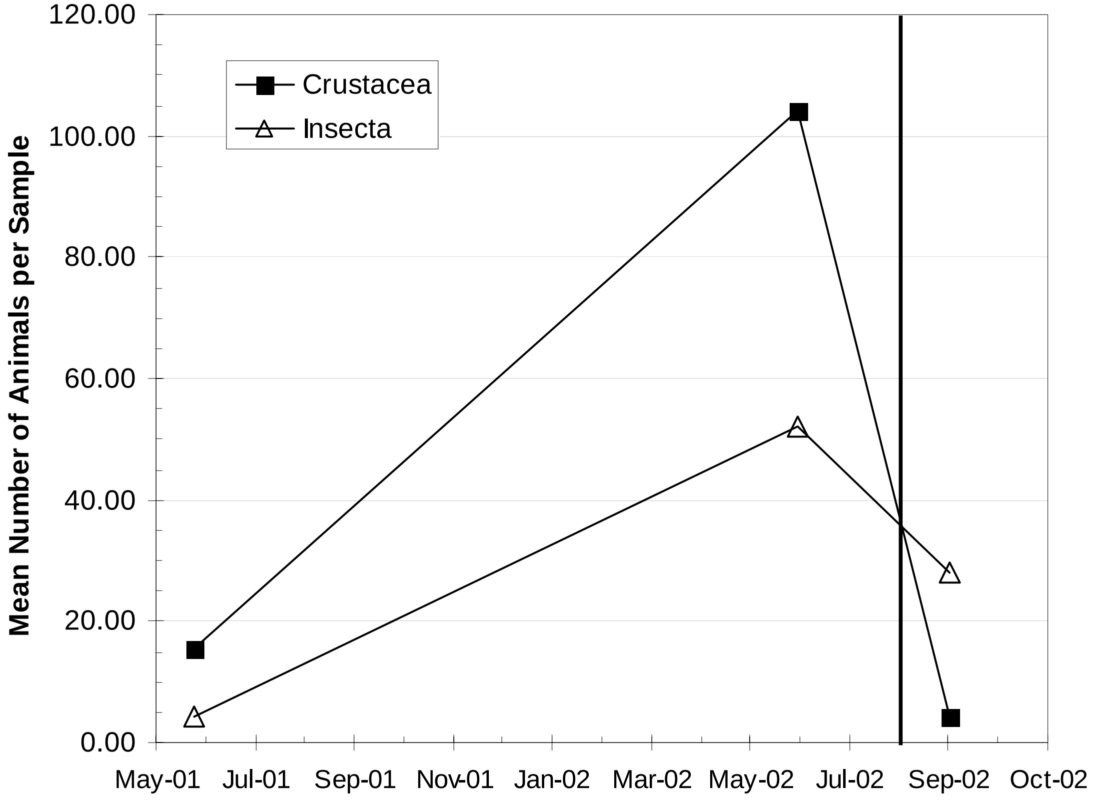

Figure 10. Pond 4 invertebrate composition. Vertical line marks the initial breaching event in August 2002.

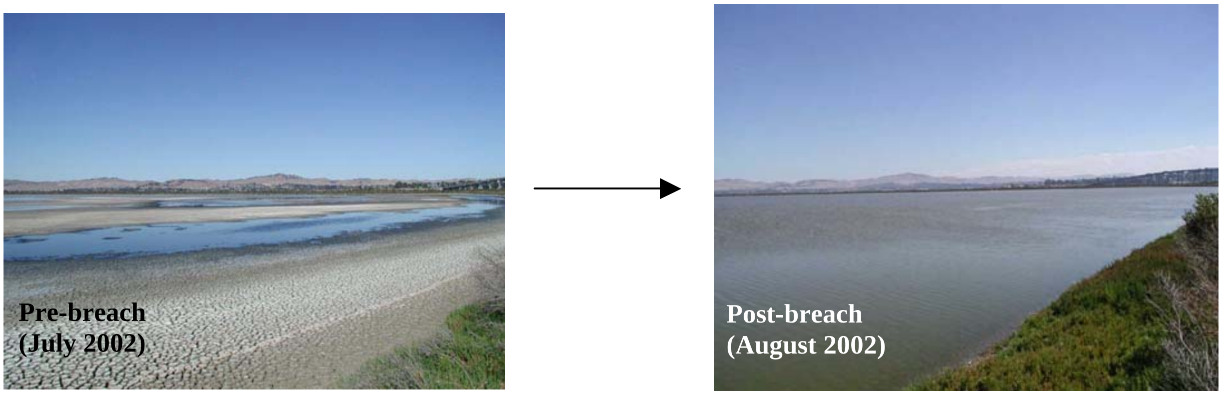

Figure 11. Pond 3 in the Napa-Sonoma salt ponds was drying in summer 2002 before the SS breach caused flooding in August.

South Slough Breach

Figure 12. Images showing the sequence of changes in the South Slough breach, August 2002 – June 2003.

Figure 12 (continued). Images showing the sequence of changes in the South Slough breach, August 2002 – June 2003.

Figure 13. Initial vegetation growth in Pond 3, August – December 2003.