Dissolved Oxygen in Guadalupe Slough and Pond A3W, South San Francisco Bay, California, August and September 2007

Open-File Report 2008–1097

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
acre	0.4047	hectare (ha)

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	1.094	yard (yd)

Datum

Some vertical coordinate information is referenced to the now superseded National standard geodetic reference for elevation, the National Geodetic Vertical Datum of 1929 (NGVD 29).

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Abstract

Initial restoration of former salt evaporation ponds under the South Bay Salt Pond Restoration Project in San Francisco Bay included the changing of water-flow patterns and the monitoring of water quality of discharge waters from the ponds. Low dissolved oxygen (DO) concentrations became evident in discharge waters when the ponds first were opened in 2004. This was a concern, because of the potential for low-DO pond discharge to decrease the DO concentrations in the sloughs that receive water from the ponds. However, as of summer 2007, only limited point-measurements of DO concentrations had been made in the receiving sloughs adjacent to the discharge ponds. In this report, we describe two short studies aimed at understanding the natural variability of slough DO and the effect of pond discharge on the DO concentrations in the sloughs. Pond A3W (a discharge pond) and the adjacent Guadalupe Slough were instrumented in August and September 2007 to measure DO, temperature, conductivity, and pH. In addition, Mowry and Newark Sloughs were instrumented during the August study to document DO variability in nearby sloughs that were unaffected by pond discharge. The results showed that natural tidal variability in the slough appeared to dominate and control the slough DO concentrations. Water-quality parameters between Guadalupe Slough and Mowry and Newark Sloughs could not be directly compared because deployment locations were different distances from the bay. Pond-discharge water was identified in Guadalupe Slough using the deployed instruments, but, counter to the previous assumption, the pond discharge, at times, increased DO concentrations in the slough. The effects of altering the volume of pond discharge were overwhelmed by natural spring-neap tidal variability in the slough. This work represents a preliminary investigation by the U.S. Geological Survey of the effects of pond discharge on adjacent sloughs, and the results will be used in designing a comprehensive DO study to determine normal variability for this region.

Introduction

In March 2003, 16,500 acres of salt evaporation ponds owned by the Cargill Corporation in San Francisco Bay were purchased for restoration purposes using State, Federal, and private funds. The California Coastal Conservancy has been leading a collaborative planning effort with the U.S. Fish and Wildlife Service (FWS) and the California Department of Fish and Game (DFG) to restore some of the ponds to tidal action, while providing for flood management, public access, and recreation. Other ponds in the system will remain and be managed as bird habitat. A long-term restoration plan has been developed for the acquired land, and pond restoration begins in 2008 (EDAW and others, 2007). The ponds have been operated and maintained according to the South Bay Salt Pond Restoration Project Initial Stewardship Plan (ISP; Life Science!, Inc., 2003) produced for the acquisition. The goal of the ISP was to maintain existing habitat and prevent a build up of salt in the ponds in a cost-effective manner until the long-term restoration plan is in effect.

One series of ponds, managed by FWS in southern San Francisco Bay, is the Alviso Salt Pond Complex (fig. 1). This complex is made up of 8,300 acres of ponds that have been altered into flow-through ponds connected in series, under the ISP. The flow-though design of water management for the ponds is critical to prevent the production of high concentrations of salt in the pond water. Certain ponds in the complex serve as intake ponds, drawing water in from San Francisco Bay at higher tides. The water then gravity feeds through subsets of ponds prior to entering a discharge pond. The discharge ponds discharge the water directly back to San Francisco Bay or to tidal sloughs that terminate in the bay. The discharged water, after its transit through the series of ponds, is chemically different from bay water because of physical and biological processes that occur in the ponds. Water in several of the sloughs in southern San Francisco Bay also includes discharge from water pollution control plants (WPCP). The WPCP discharge is also distinctly different from bay water and further complicates determination of the effect of pond discharge on the sloughs.

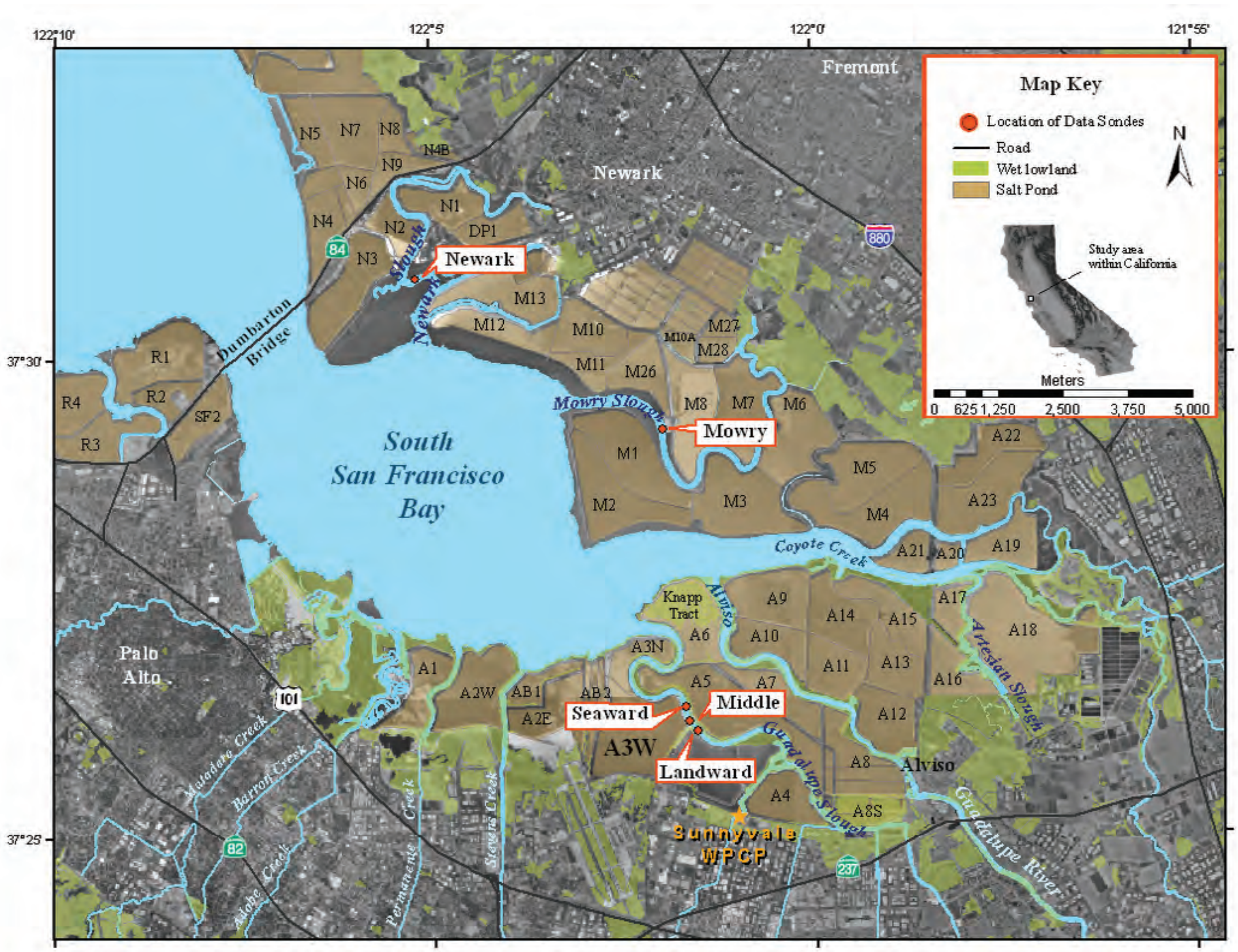

Figure 1. Study area in southern San Francisco Bay. Salt ponds labels that begin with "A" are part of the Alviso Salt Pond Complex. The data sondes deployed for the study measured temperature, conductivity, pH, and dissolved oxygen.

San Francisco Bay waters are generally considered to be high in nutrient concentrations and low in chlorophyll concentrations (Cloern, 1996; Wilkerson and others, 2006). However, when this water enters the shallow, typically non-tidal pond systems, changes in physical habitat contribute to conditions that are favorable for algal growth (Thebault and others, in review at Wetlands). These conditions lead to the establishment of macrophytic algae and the potential for periodic chlorophyll blooms in the ponds. In fact, large mats of filamentous green algae have been found in a number of the ponds. As these mats develop, some portion of the algal biomass dies. This leads to localized areas of increased respiration in the water column, owing to microbial decomposition of the organic matter, which results in subsequent decreases in dissolved oxygen (DO) concentrations. This issue is typically more severe in the summer and can lead to suboxic and anoxic conditions in sections of the ponds.

When suboxic or anoxic conditions occur in a discharge pond, there is the potential for release of low-DO water to the bay or adjacent sloughs, in violation of the discharge permits granted by the San Francisco Bay Regional Water Quality Control Board. The concern is that releasing large volumes of low-DO water into the adjacent sloughs could affect the slough-water quality by decreasing the DO concentrations to the detriment of the slough biota. Summertime low-DO conditions were noticed in parts of several of the FWS discharge ponds beginning in 2004. Monitoring has included summertime continuous (specifically, 15-min frequency) measurements of DO concentrations inside the discharge ponds at the discharge location and periodic point samples collected in the sloughs. The DO trigger for management activity (specified by a decrease in pond discharge) is when DO concentrations fall below 3.3 mg/L in greater than 10 percent of discharge readings, as calculated on a calendar-weekly basis. Given that the regulatory requirement is written as a DO concentration, instead of the more intercomparable and biologically relevant percent saturation, this document reports DO in units of concentration. Two issues of concern exist with the current monitoring and regulatory strategy: (1) some reaeration of the discharge water occurs as the water passes through the discharge structure, so the true DO concentrations of the water entering the slough from the pond are not known; and, (2) the naturally occurring and pond-influenced time-series of DO concentrations in the tidal sloughs is unknown, so the effect of pond discharges on water quality in the receiving sloughs is unknown. In 2007, the U.S. Geological Survey (USGS) conducted two short studies (referred to in this report as “first deployment” and “second deployment”) designed to gather data necessary to address to these concerns about the current monitoring and effects of pond discharge on the receiving water.

Purpose and Scope

This study and report were designed to explore three questions: (1) what are the natural DO concentrations in South Bay sloughs that are not subjected to pond discharge, and how do they compare to DO concentrations in Guadalupe Slough, which receives discharge from Alviso pond A3W; (2) is there a discernable impact of pond discharge on slough DO concentrations; and (3) does changing the volume of pond discharge have a corresponding change in impact on the slough DO concentrations?

This report presents the results from a preliminary study on the impact of discharge from one pond on dissolved oxygen concentrations in an adjacent tidal slough. The results are derived from the conditions during two limited deployments during late summer 2007. Vertical variation of water quality in the water column (both pond and slough) was not measured. DO concentrations were measured only inside the pond at the discharge structure, so spatial variability of DO within the pond was not quantified. This report provides the results of the data collection effort and some interpretation of the data with regard to management activities.

Acknowledgements

Paul Buchanan, Neil Ganju, and Jessica Wood provided assistance with the field work. Clyde Morris and Eric Mruz of the Don Edwards San Francisco Bay National Wildlife Refuge provided access and information on pond A3W. John Johnston of California State University, Sacramento, kindly analyzed our biochemical oxygen demand (BOD) samples. Dave Grabiec provided us with data from the Sunnyvale Water Pollution Control Plant. Eric Mruz, Tara Schraga, and Lisa Olsen provided reviews that improved the manuscript. Funding was provided by the U.S. Geological Survey Priority Ecosystem Science Program.

Methods

Data sondes that measured temperature, conductivity, pH, and DO (YSI 6920v2, YSI, Incorporated, Yellow Springs, Ohio) were deployed about 0.75 m above the bottom in the thalweg (deepest point) of some southern San Francisco Bay sloughs. Three sondes were deployed in Guadalupe Slough: one landward, one adjacent to (called middle), and one seaward of the pond A3W discharge structure (figs. 1 and 6). The middle sonde was deployed intentionally in the mixing zone of the slough and discharged pond water. The USGS maintained a data sonde just on the pond side of the A3W discharge culverts as part of the FWS self-monitoring program (Hydrolab 4a, Hach Company, Loveland, Colorado). This instrument recorded measurements every 15 minutes. Calibration of these sondes prior to deployment followed the manufacturer's recommended methods and conformed to Wagner and others (2006). Checks were conducted after the deployment period to verify that sondes were still calibrated. The deployments were of short duration, and no fouling or drift corrections were required. All data collected from the sondes were accepted with no edited data points. An acoustic Doppler velocimeter (Argonaut-XR ADV, Sontek/YSI, Inc., San Diego, California) was deployed in Guadalupe Slough. Biochemical oxygen demand (BOD) values for the Sunnyvale WPCP discharge reported by the City of Sunnyvale (David Grabiec) were carbonaceous BOD_5 (5-day, $CBOD_5$) analyzed following Standard Methods 5210 (American Public Health Association, 2006). Estimates of pond discharge were obtained from PONDCALC (Shellenbarger and others, 2007), a tool developed for FWS by the USGS to calculate pond discharge based on water surface elevation in the pond and tidal stage in the slough.

First Deployment

The first deployment occurred August 13–17, 2007. Instruments were deployed in Guadalupe, Newark, and Mowry Sloughs and recorded measurements every 15 minutes. One sonde was deployed in each of Mowry and Newark Sloughs (fig. 1). These sites served as control sites, because they experienced neither pond nor water pollution control plant discharge. Guadalupe Slough receives discharge from the City of Sunnyvale WPCP landward of our deployment locations. The Sontek ADV recorded water depth above its pressure transducer every 15 minutes. Water velocities were not measured successfully in August.

Second Deployment

Data sondes were deployed in Guadalupe Slough during September 11–24, 2007, (figs. 1 and 6). These instruments recorded measurements every 7.5 minutes. The Sontek ADV measured and recorded water depth above its pressure transducer and depth-integrated velocity in the slough every 7.5 minutes. Several water samples were collected to measure biochemical oxygen demand (BOD) on September 13: three samples were collected from different spots in pond A3W (fig. 6): sites BOD 1 (southeastern side near a thick algae mat), BOD 2 (adjacent to the discharge structure), and BOD 3 (at the levee bend north of the discharge structure). Two samples were collected from Guadalupe Slough (both collected from the NASA dock just landward of the pond A3W discharge at BOD 4, one from early flood and the second about 2 hours later during flood tide). These unfiltered samples were analyzed for BOD_5 (5-day, sum of carbonaceous and nitrogenous demand) by Dr. John Johnston, California State University, Sacramento, following Standard Method 5210 (American Public Health Association, 2006). The difference in analysis methods between the pond and slough samples (BOD_5 analyzed by John Johnston) and those of the Sunnyvale WPCP ($CBOD_5$ analyzed by the City of Sunnyvale) suggests that the numbers are not directly comparable. However, BOD_5 is likely to overestimate oxygen demand, relative to $CBOD_5$. Since our BOD_5 results are quite low, this difference did not affect the interpretation of these data.

Question 1: Are Dissolved Oxygen Concentrations in Guadalupe Slough Similar to Dissolved Oxygen Concentrations in Newark and Mowry Sloughs?

Technical Considerations

- This question was addressed only during the first deployment.
- Guadalupe Slough is affected by discharge from pond A3W, pond A5, and the City of Sunnyvale water pollution control plant (WPCP).

- Newark and Mowry Sloughs serve as control sites, because they experience neither pond nor WPCP discharge.
- Guadalupe Slough is longer than the control sites and the measurement site was further from the bay (table 1).
- Pond A3W discharged through one of three 48-inch culverts, and the flap gate on the slough side had a 10-inch opening above the invert to allow some flow into the pond during higher tides in the slough.
- The pond A5 discharge was seaward of our Guadalupe Slough measurement sites.

Table 1. Distances from the sonde locations to the corresponding slough mouths for the first deployment (August).

Site	Distance to slough mouth (meters)
Newark Slough	1,800
Mowry Slough	2,140
Guadalupe Slough-seaward	3,800
Guadalupe Slough-middle	4,090
Guadalupe Slough-landward	4,320

Results

- Average DO concentrations were greatest in Newark Slough and least in Guadalupe Slough (fig. 2).
- DO varied semidiurnally, and the lowest DO concentrations occurred during low tides and the highest DO concentrations during high tides. This indicates that bay water generally has higher DO concentrations than slough water. Low-DO slough water moves toward the bay during ebb tide, and higher-DO water moves from the bay into the sloughs during flood tide.
- DO increased to the north (toward the Golden Gate) in the South Bay. DO concentrations were 6.2–6.6 mg/L (85–92 percent saturation) on July 23, 6.8–6.9 mg/L (94–95 percent saturation) on August 22 off Calaveras Point in South Bay (fig. 1) and generally increased northward (USGS *Polaris* cruise data, http://sfbay.wr.usgs.gov/access/wqdata/query/index.html).
- The water level in pond A3W was -0.8 ft (NGVD 29) on August 13.

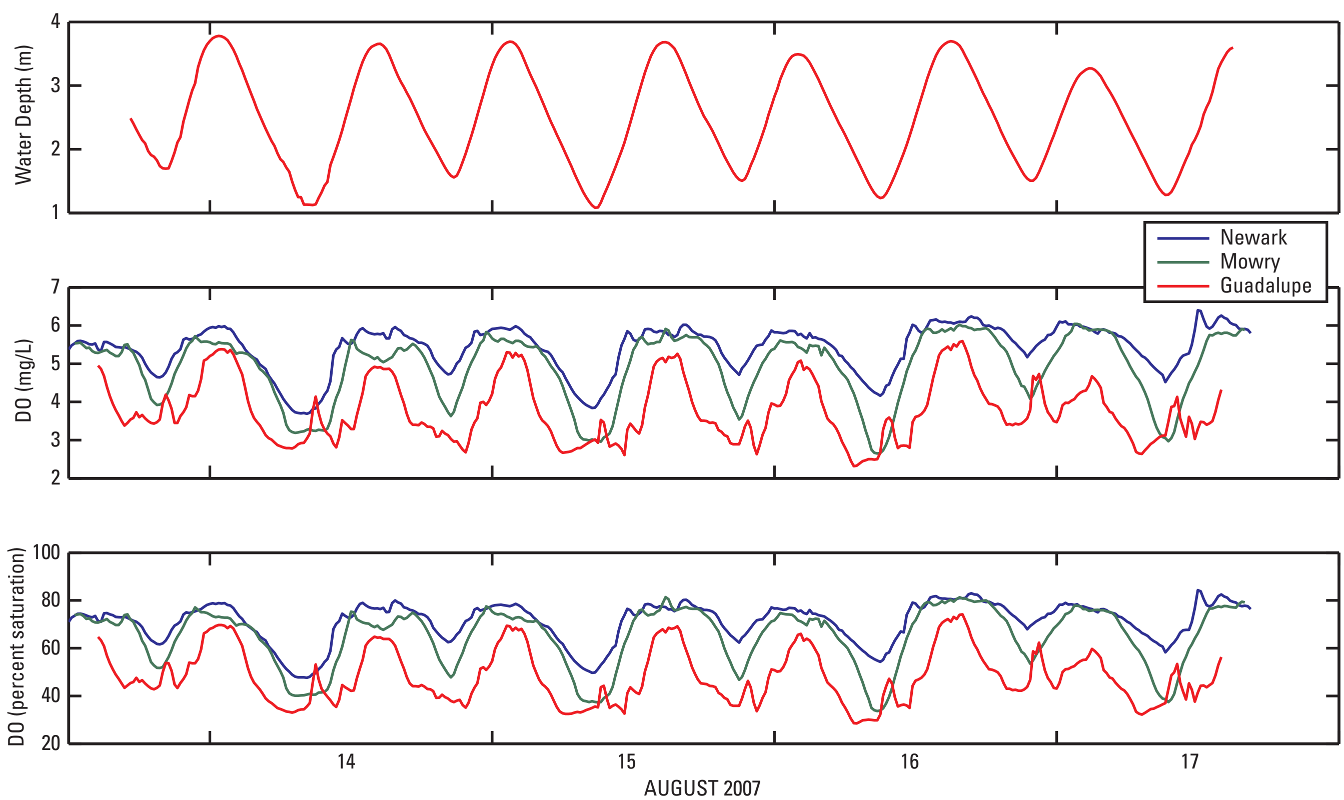

Figure 2. Water level and dissolved oxygen (DO) in Newark, Mowry, and Guadalupe (middle site) Sloughs.

Discussion

- Potential explanations prior to data collection in the first deployment and discussions based on collected data after the first deployment for the presence of lower DO concentrations in Guadalupe Slough than in control sloughs include (explanations other than pond A3W discharge):

    1. Measurement sites in Guadalupe Slough were further from the bay than in the control sloughs (table 1). DO in tidal creeks often is depleted, relative to open bay waters (MacPherson and others, 2007), and DO concentrations tend to decrease with increasing distance from open water (Boto and Bunt, 1981). Thus, lower DO concentrations in Guadalupe Slough, relative to the control sloughs, could be due to increased distance from bay water.

    2. The Sunnyvale WPCP could release water with lower DO than that measured in Guadalupe Slough. For the study period, however, the average discharge from the Sunnyvale WPCP was 15 MGD, and the average effluent DO was 4 mg/L (50 percent saturation, David Grabiec, City of Sunnyvale WPCP, written commun., October 5, 2007). This DO concentration was higher than the average concentration measured at any of the three Guadalupe Slough sites. PONDCALC (Shellenbarger and others, 2007) estimated an average of 15 MGD discharged from the pond August 13–17. Thus, the discharge volume of the pond and WPCP were similar, so it is not expected that the WPCP effluent chemistry could be masked completely by pond discharge.

    3. Biochemical oxygen demand (BOD) of pond discharge or Sunnyvale WPCP discharge potentially could decrease DO in Guadalupe Slough. However, the average Sunnyvale WPCP effluent BOD for August 13–15 was 3 mg/L (David Grabiec, City of Sunnyvale WPCP, written commun., October 5, 2007). The effluent BOD was low enough that, assuming reasonable deoxygenation and reaeration coefficients, it should produce an increase (not a decrease) in DO in the receiving waters after discharge (Dr. John Johnston, CSUS Civil Engineering, written commun., September 13, 2007). Later in this report we describe some limited measurements of BOD in A3W and Guadalupe Slough that suggest that BOD in the pond water and discharge is not a significant consumer of DO.

    4. Sediment oxygen demand (SOD) in Guadalupe Slough might have been larger than in the control sloughs. We found a layer of decaying vegetation below the surface sediment (fig. 3) in Guadalupe Slough that could act as a source of SOD; however, SOD was not measured.

Figure 3. Guadalupe Slough surface sediment (tan) lying on top of decaying vegetation (black).

Question 2: Does Discharge From Pond A3W Affect Dissolved Oxygen Concentrations in Guadalupe Slough?

Technical Considerations - First Deployment

- Pond A3W discharged through one of three 48-inch culverts.
- The flap gate on the slough side of the culvert had a 10-inch opening above the invert to allow some muted tidal flow into the pond during higher tides in the slough.

Results – First Deployment

- Specific conductance (SC) and pH proved to be good indicators of pond water in the slough. The average SC of the pond was slightly greater than 45,000 µS/cm (fig. 4), the SC of bay water was 40,000 µS/cm, and the SC of the landward slough water was no more than 10,000 µS/cm; the low SC in the slough probably results from the low SC of water discharged from the WPCP (not measured in this study but assumed to be fresh water). The average pH of the pond was about 8.7 and the average pH of slough water was about 8.2. The pH time series offers more detail so it could be used to differentiate pond water in the slough. At high tide, water from the bay filled the slough and entered the pond through the slightly open culvert, lowering pH to the bay value (roughly a value of 8).

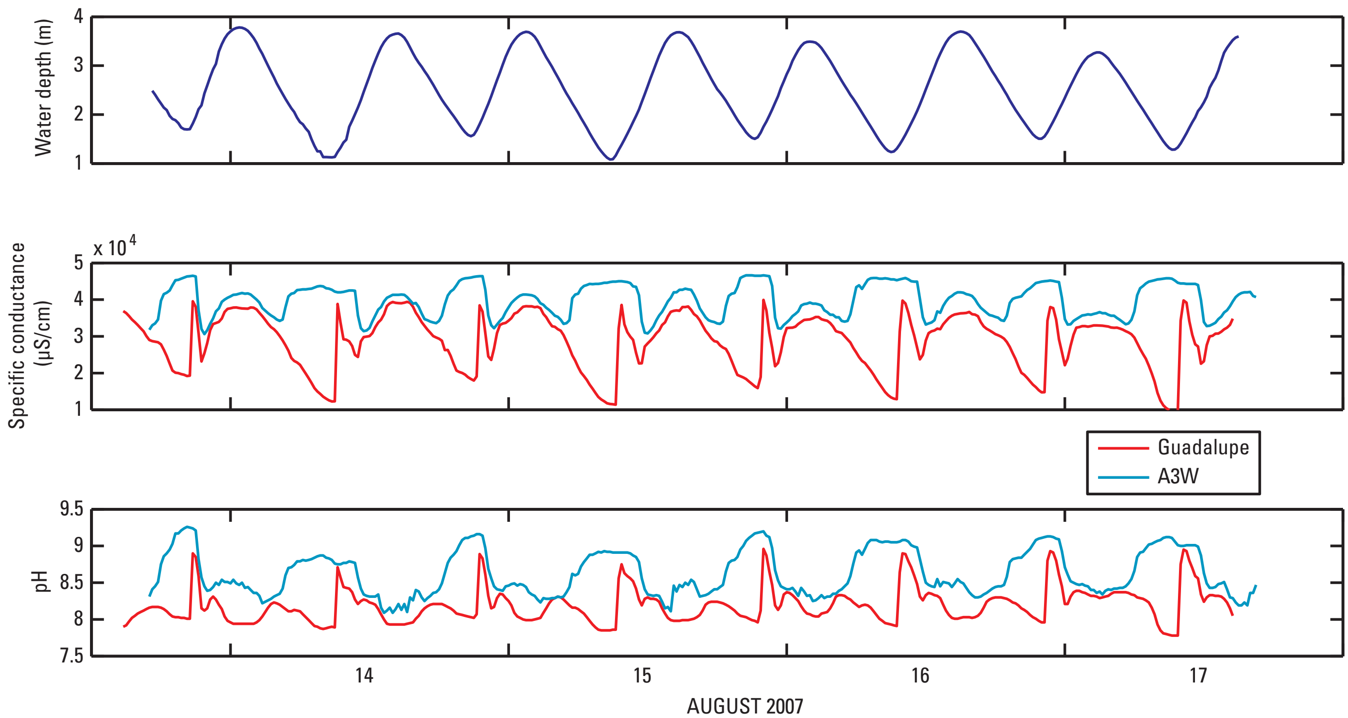

Figure 4. Time series of water depth, specific conductance, and pH in pond A3W and in Guadalupe Slough (middle site).

At low tide, bay water was pulled out of the pond and slough and pH rose to the pond value (approaching a value of 9).

- During seven of the eight low tides observed, slightly aerated pond water entered the slough (fig. 2). During these low tides, SC (fig. 4) and pH (fig. 5) spiked when high-SC and high-pH water from the pond appeared at the middle site in the slough adjacent to the discharge structure. pH did not increase either landward or seaward of the discharge point (0900 h, fig. 5). Photosynthesis increased DO in the pond in the late morning when lower low water (LLW) occurred. DO increased in the slough at LLW concurrent with the spike in pH (0900 h, fig. 5). Discharged pond water hit the culvert flap gate, passed through the trash rack, and flowed down a wide shallow channel into the slough. Aeration along this flow path increased DO roughly 1 mg/L. The subsequent floodtide transported the higher pH and DO water to the landward site (red line, fig. 5). The higher pH and DO water was not observed at the seaward site.

- The high-pH water that came out of the pond during low tide was transported upstream during the subsequent floodtide. During the following ebb tide, that water returned to the middle site, increasing pH at that location (fig. 4). The ebb tide pH peak was lower and more diffuse than the flood tide pH, owing to mixing and dilution.

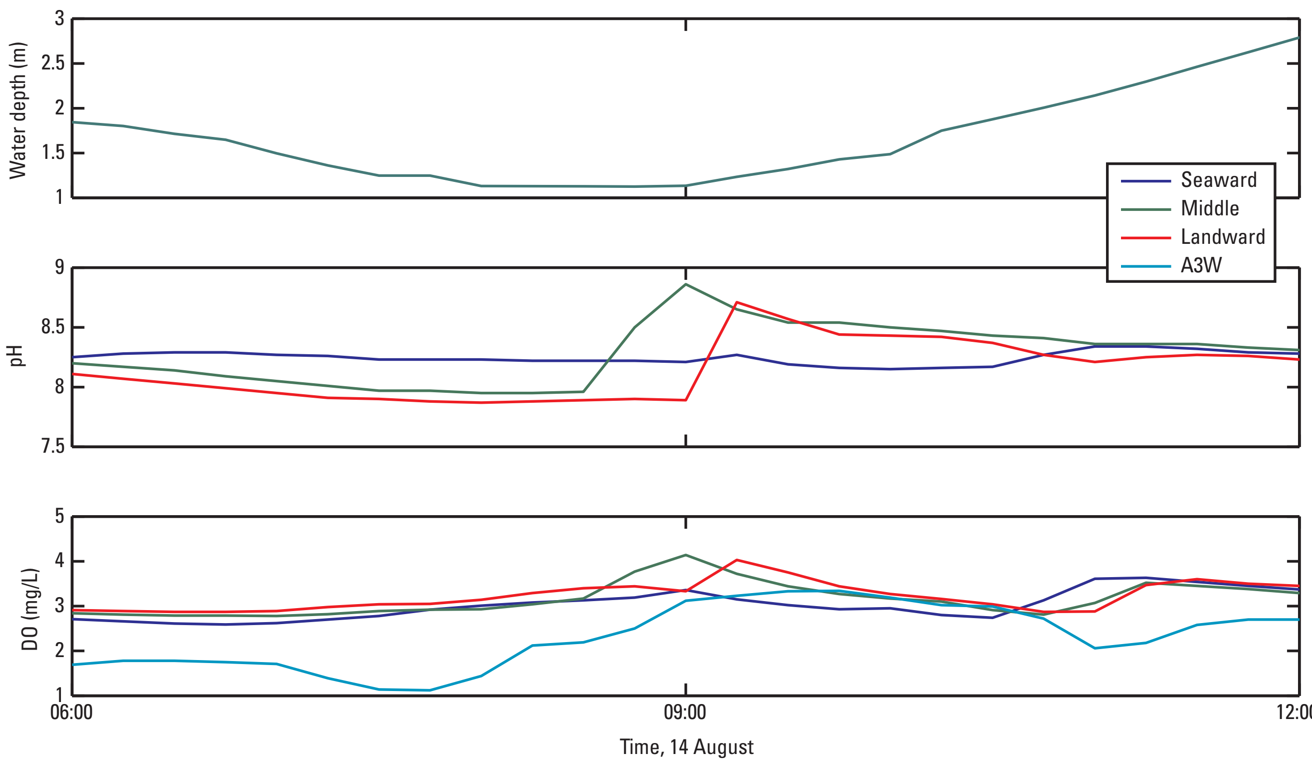

Figure 5. Depth, pH, and dissolved oxygen (DO) around lower low water in Guadalupe Slough and pond A3W during the morning of August 14, 2007. These results were typical of seven of the eight low tides observed during the first deployment.

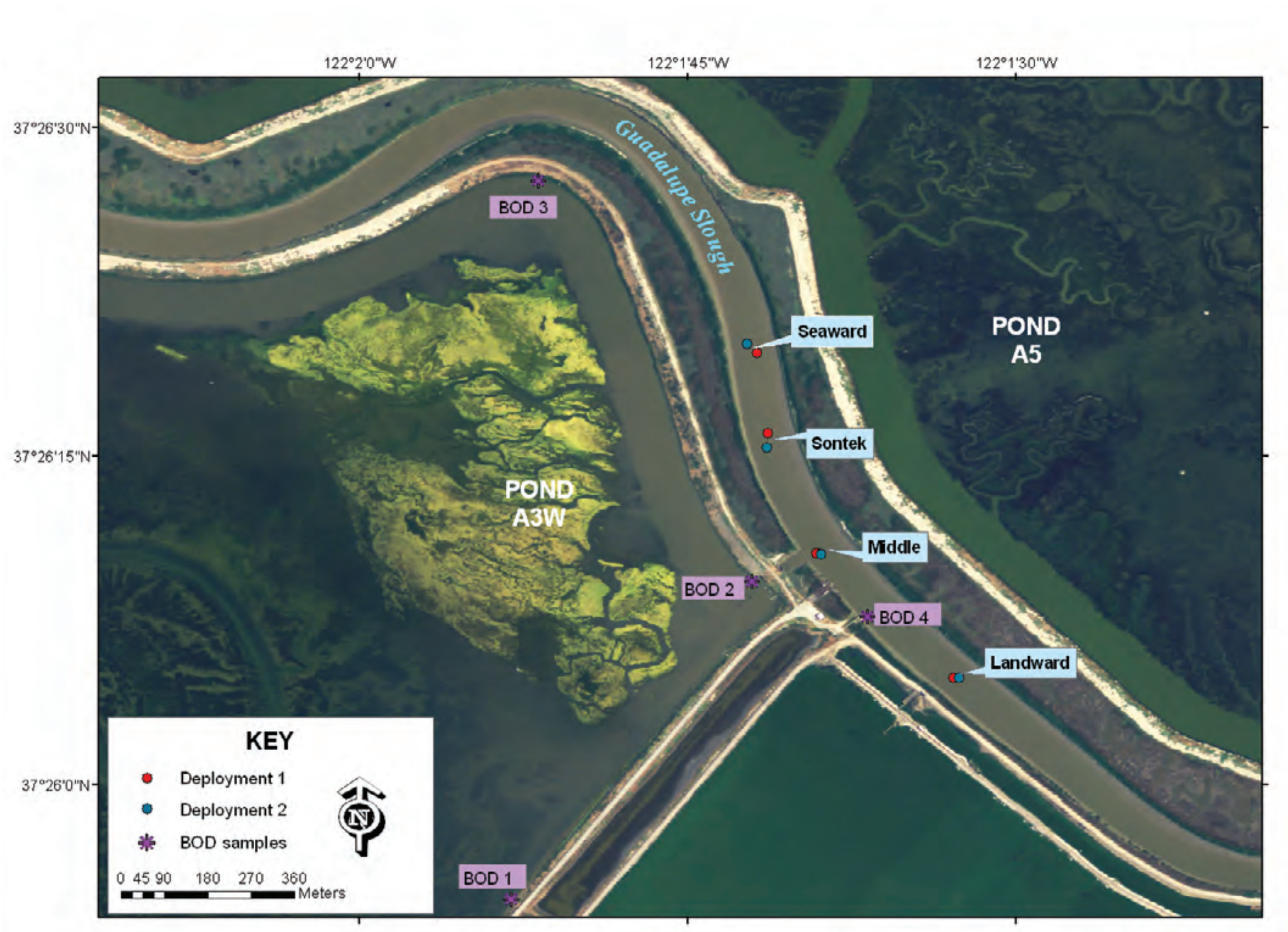

Figure 6. The deployment locations in Guadalupe Slough during both deployment periods. The seaward sonde, middle sonde, and landward sonde sites were the locations of the conductivity, temperature and depth sondes, while "Sontek" was the location of the current meter. BOD sites were locations where the BOD samples were collected on September 13; BOD 1–3 were in pond A3W, while BOD 4 was in Guadalupe Slough.

Discussion – First Deployment

- Pond discharge affected the slough at low tide when pond discharge was greatest and dilution by slough water was smallest.
- It is unknown whether the correspondence of minimum slough DO and low water was caused by pond discharge, upstream Sunnyvale WPCP, or sediment oxygen demand. If the pond discharge were responsible, closing the pond discharge for several days should cause DO to increase in the slough. If there were no increase, then either the pond discharge was not responsible or the pond discharge was not closed long enough to allow recovery of DO. This experiment could be the basis of a subsequent deployment, if it would be ecologically feasible to close the pond.
- Scope of findings: The results were for only one tidal condition and one discharge point. Discharge points from other ponds are located closer to or further from the bay and upstream freshwater sources (including WPCPs). This deployment helped explain details of the pond A3W discharge, and it served as a reconnaissance for deploying these instruments and for designing a comprehensive monitoring program for DO in the sloughs.

Technical Considerations – Second Deployment

- For pond A3W discharge, three 48-inch culverts were open prior to the start of the deployment until the afternoon of September 13. One 48-inch culvert remained opened from the afternoon of September 13 until the afternoon of September 20 (the other two culverts were closed). The two closed culverts were reopened on the afternoon of September 20, and all three culverts remained opened though the end of the deployment on September 24.
- The pond was closed to direct water input from the slough (the pond was not opened to tidal action).

Results – Second Deployment

- DO in the slough varied semidiurnally (fig. 7*E*), and the lowest DO concentrations occurred near low tide and highest DO concentrations during high tide. However, not all low tides were associated with low DO (fig. 8), mostly owing to the discharge of high DO pond water (see below for a more detailed description of DO dynamics in pond A3W). In general, bay water had greater DO than slough

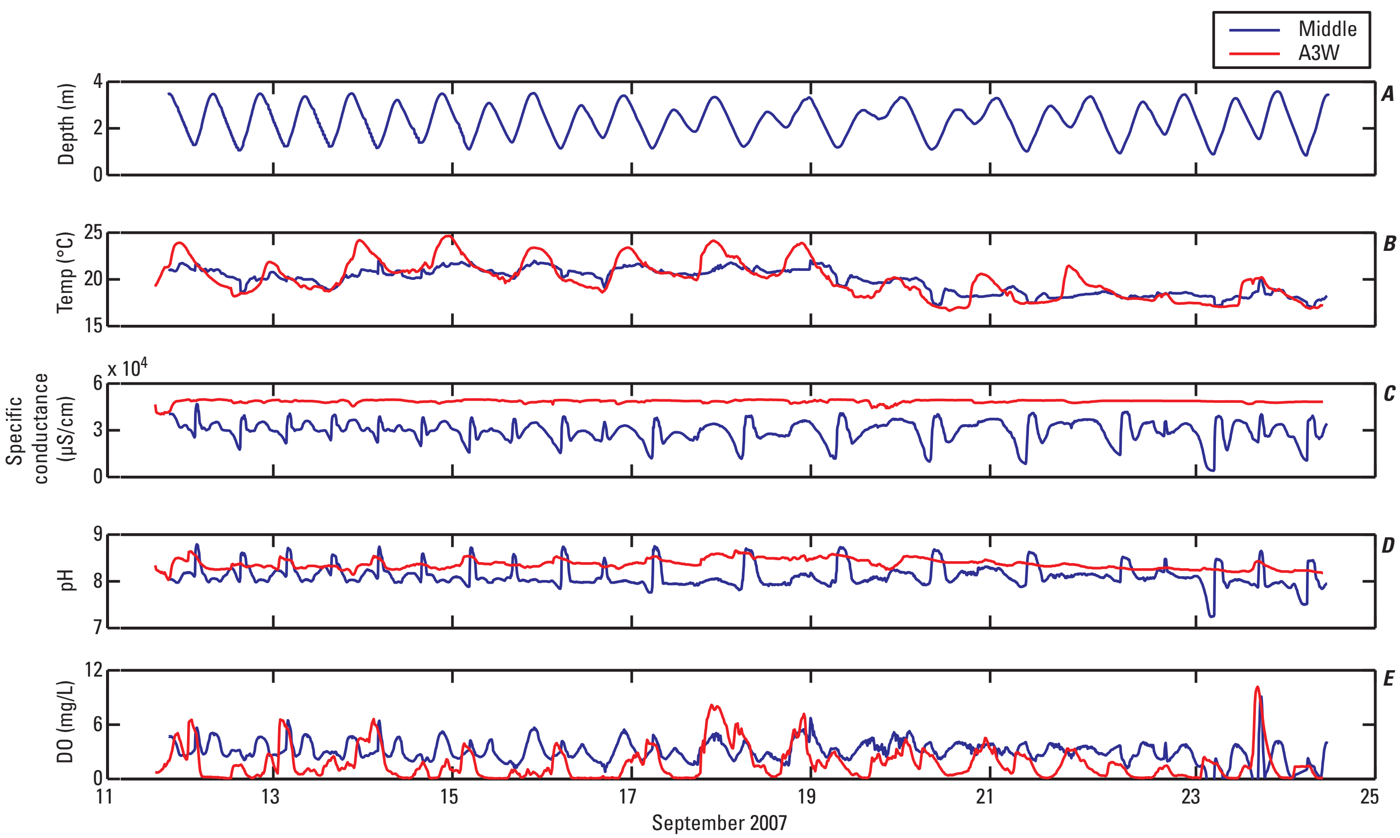

Figure 7. Overview of Guadalupe Slough (middle site) and pond data for the second deployment. Pond A3W discharge gate operations changed on the afternoon of September 13 and 20 (see text for details).

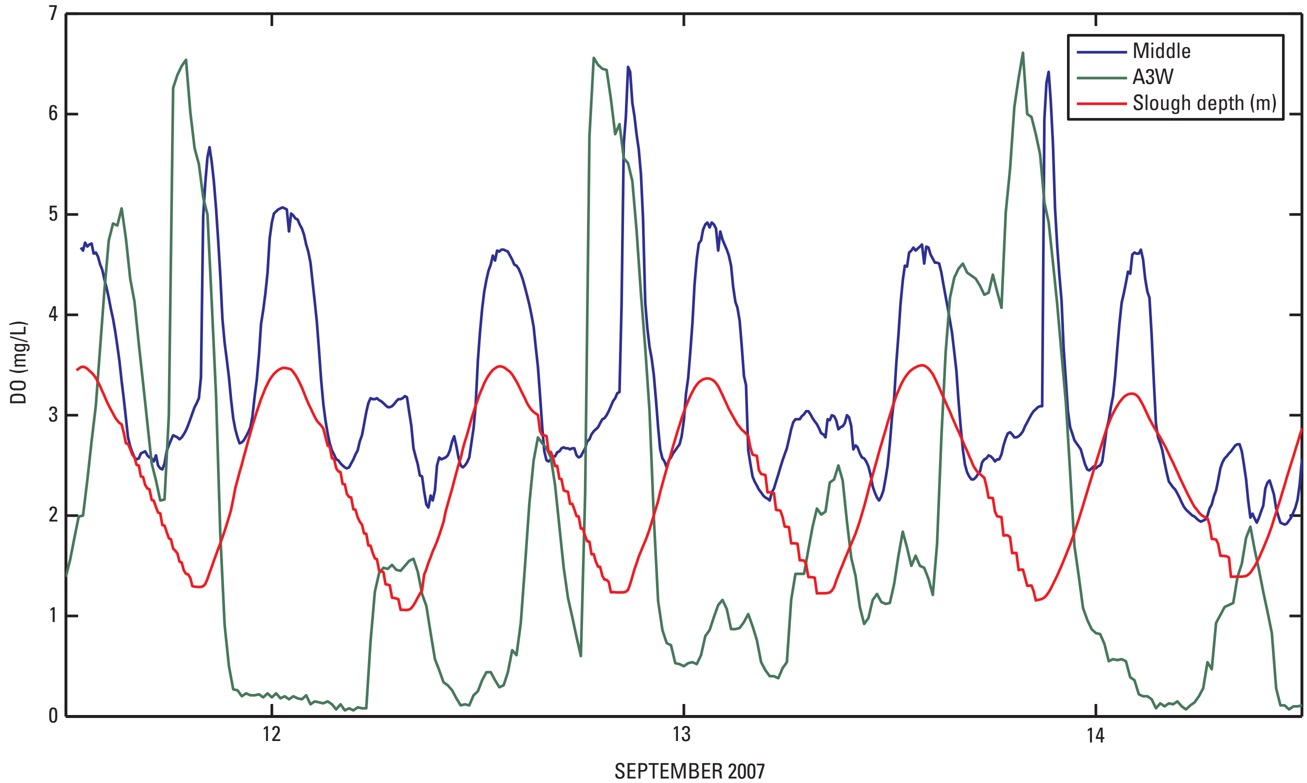

Figure 8. Dissolved oxygen (DO) concentrations in Guadalupe Slough (middle site) and pond. The red curve is the water depth (meters) above the current meter and corresponds to the tidal level. These data run from noon on September 11 until noon on September 14. When water level was decreasing, the tide was ebbing. When water level was increasing, the tide was flooding. The depicted results are typical for spring (displayed) and neap tidal conditions, although the dissolved oxygen (DO) response to discharge during neap conditions is muted.

water. Low DO slough water moved toward the bay during ebb tide and higher DO water moved from the bay into the slough during flood tide.

- DO concentrations at the discharge structure in the pond mostly varied diurnally. However, weaker semidiurnal variations did occur. DO peaks at the discharge structure in the pond typically corresponded to low tide in the slough, with the larger peaks associated with the lower tides (fig. 8).

- Water temperatures at all locations were significantly lower at the end of the study than at the beginning (fig. 7*B*).

- There was a precipitation event during the study period. Moffett Field (fig. 1) experienced 0.74 cm of rainfall on September 22 (http://www.wunderground.com/). Rainfall could have changed the flow, conductivity, and mixing dynamics in the slough and pond.

- Similar to the first deployment, pond discharge was identified clearly in the slough on the basis of conductivity, pH, and DO data.

- The increase in DO concentrations at the middle and landward locations that typically accompanied the beginning of flood tide peaked at the middle site prior to the landward site (roughly 30 minutes after low tide). This is suggestive of high-DO pond water (higher than the slough) discharging to the slough and being transported upstream. See below for an explanation for this higher-DO pond water.

- The DO concentration averaged over the entire study period was significantly lower in the pond than in the slough ($p<0.0001$, t-test).

- The BOD in the slough was 4–5 mg/L (at BOD 4), while the BOD in pond A3W was approximately 19 mg/L at BOD 1, approximately 1 mg/L at BOD 2 (discharge structure), and approximately 6 mg/L at BOD 3 (Dr. John Johnston, CSUS Civil Engineering, written commun., September 18, 2007). The Sunnyvale WPCP effluent data show a carbonaceous BOD of 2.2 mg/L and a DO concentration of 7.38 mg/L on the same day that our BOD samples were collected (September 13; Dave Grabiec, Sunnyvale WPCP, written commun., November 27, 2007).

- The water-surface elevation (NGVD29) in pond A3W was about -1.65 ft for September 11–13, -1.55 ft for September 14–17, -1.40 ft for September 18–20, and -1.50 ft for September 21–24 (Eric Mruz, FWS, written commun., September 18, 2007).

- DO increased to the north (toward the Golden Gate) in South Bay. In the bay, DO was 6.4–6.6 mg/L (83-85 percent saturation) on September 21 off Calaveras Point and generally increased northward (USGS *Polaris* cruise data, http://sfbay.wr.usgs.gov/access/wqdata/query/index.html). DO in the Sunnyvale WPCP effluent on the same day was 6.55 mg/L (74 percent saturation, Dave Grabiec, Sunnyvale WPCP, written commun., November 27, 2007).

Discussion – Second Deployment

- DO concentrations in pond A3W were not uniform in time or space.

- DO concentrations throughout the pond were lowest in the early morning (pre-dawn) when photosynthetic rates were minimal and highest in the late afternoon or earlier evening after the phytoplankton had been photosynthetically active all day.

- Spatially, the lowest DO concentrations occurred near the algal mats (Hansen, 2004; Takekawa and others, unpublished data, 2004–07) that collect around the discharge structure (the down-wind corner of the pond). Other regions of the pond away from the algal mats tended to have higher DO concentrations (Hansen, 2004; Takekawa and others, unpublished data, 2004–07). The spatial and temporal variability led to dramatic changes in the DO concentrations of the water discharging from the pond into the slough. Water that discharged initially from the pond as the tide fell in the slough came from the region of the pond near the algal mats (around the discharge structure). This water had relatively low DO concentrations. As the tide continued to fall and the discharge rates from the pond increased, water was pulled from regions of the pond that are further from the discharge structure and algal mats. This water had higher DO concentrations than the water that was near the algal mats. The water discharging from the pond during the low tide later in the day had higher DO concentrations than the water that discharged earlier in the day because of the oxygenation of the shallow pond water by photosynthetic organisms.

- Combined, the factors led to a generally mixed semidiurnal DO signal in the discharge as measured in A3W at the discharge structure, with discharges earlier in the day having lower DO concentrations than afternoon discharges and the discharge water increasing in DO concentration with increasing discharge period (fig. 8).

- DO concentrations in pond A3W were lower than in Guadalupe Slough, with the 10th percentile over the September study of 0.11 mg/L in the pond and 1.76 mg/L, 1.73 mg/L, and 1.99 mg/L for landward, middle, and seaward sites, respectively, in the slough.

- The slough BOD samples were near the BOD concentrations of the WPCP effluent (that is, low). The samples from the pond were variable. Water from the BOD 1 site was collected directly adjacent to a dying, anoxic algal mass and would be expected to have an increased BOD (although a value of about 19 mg/L is not dramatically high; John Johnston, CSUS, written commun., 2007). The BOD for site BOD 3 was roughly the same as the BOD in the slough, while the sample from the discharge location in the pond showed extremely low BOD. This suggests that the pond discharge was not contributing significant BOD to the slough.

- Sediment oxygen demand (SOD) in pond A3W and Guadalupe Slough was not quantified.

Question 3: Does Changing the Volume of Discharge from Pond A3W (One Versus Three Culverts) Substantially Affect Dissolved Oxygen Concentrations in Guadalupe Slough?

Technical Considerations

- This question was only addressed during the second deployment.

- If pond discharge were responsible for substantially affecting DO concentrations in the slough, then altering the pond discharge from one to three culverts (and back) should show a distinct change in slough DO concentrations (and other constituents) that correspond to the changes in volume of pond discharge.

Results

- Daily pond A3W discharge estimates are as follows (estimates from PONDCALC, Shellenbarger and others, 2007): September 11–13, 27.6 MGD (million gallons per day, three culverts discharging); September 14–17, 6.6 MGD (one culvert discharging); September 18–20, 5.4 MGD (one culvert discharging); September 21–24, 26.5 MGD (three culverts discharging). When all three culverts were discharging, the daily discharge from pond A3W during this study was about three times that of the Sunnyvale WPCP discharge estimate of 8.7 MGD (range 6.9–10.4 MGD; Dave Grabiec, Sunnyvale WPCP, written commun., November 27, 2007).
- Typically during spring low tides, water with DO higher than the DO in the slough discharged from the pond, while during neap tides, the DO concentrations were almost always higher in the slough than the pond (fig. 9). The higher DO values at the discharge structure in the pond, particularly around spring low tides, likely resulted from the transport of higher DO pond water toward the discharge location because of the longer discharge period during the lower tides (see above explanation for higher DO water near the discharge structure).

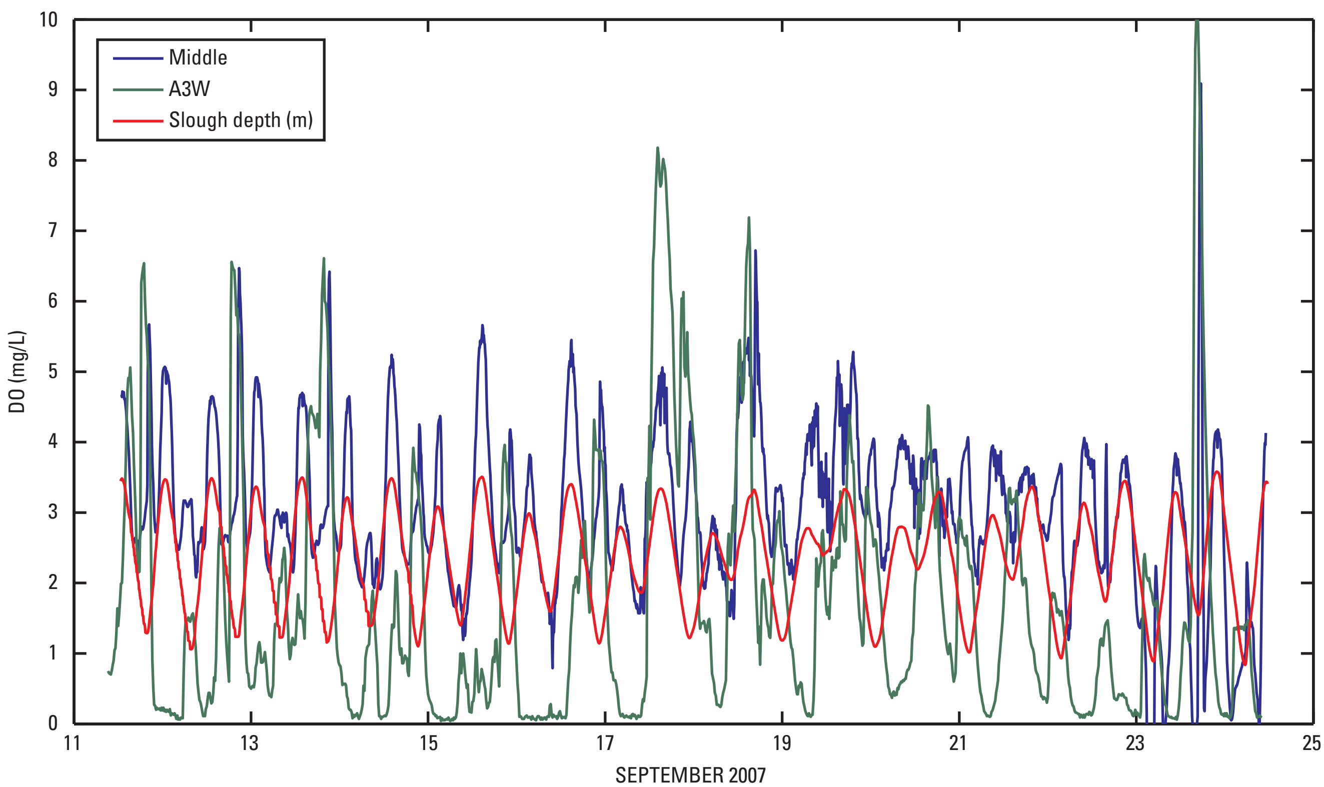

Figure 9. Dissolved oxygen (DO) concentrations in the pond and Guadalupe Slough (middle site) over the period of study. Discharge from the pond was changed on September 13 (from three to one culvert) and on September 20 (one to three culverts).

- Specific conductivity is a conservative tracer of pond water (specifically, the slough conductivity changes only due to mixing with water of different conductivities, such as bay or pond water; we assume that evaporation in the slough has a negligible effect in this case). Figure 10 shows the running mean (24-hour window) of specific conductance for the three slough sonde locations (Seaward, Middle, and Landward). Slough conductivities began to decrease coincident with the A3W discharge change from three to one culvert. However, slough conductivities increased to pre-change levels prior to the change back from one culvert to three discharge culverts.
- There was no clear change in slough DO concentrations when discharge from A3W was changed from three culverts to one or the reverse (fig. 11). DO concentration variability appeared to be controlled more by tide (spring versus neap) than by culvert management.

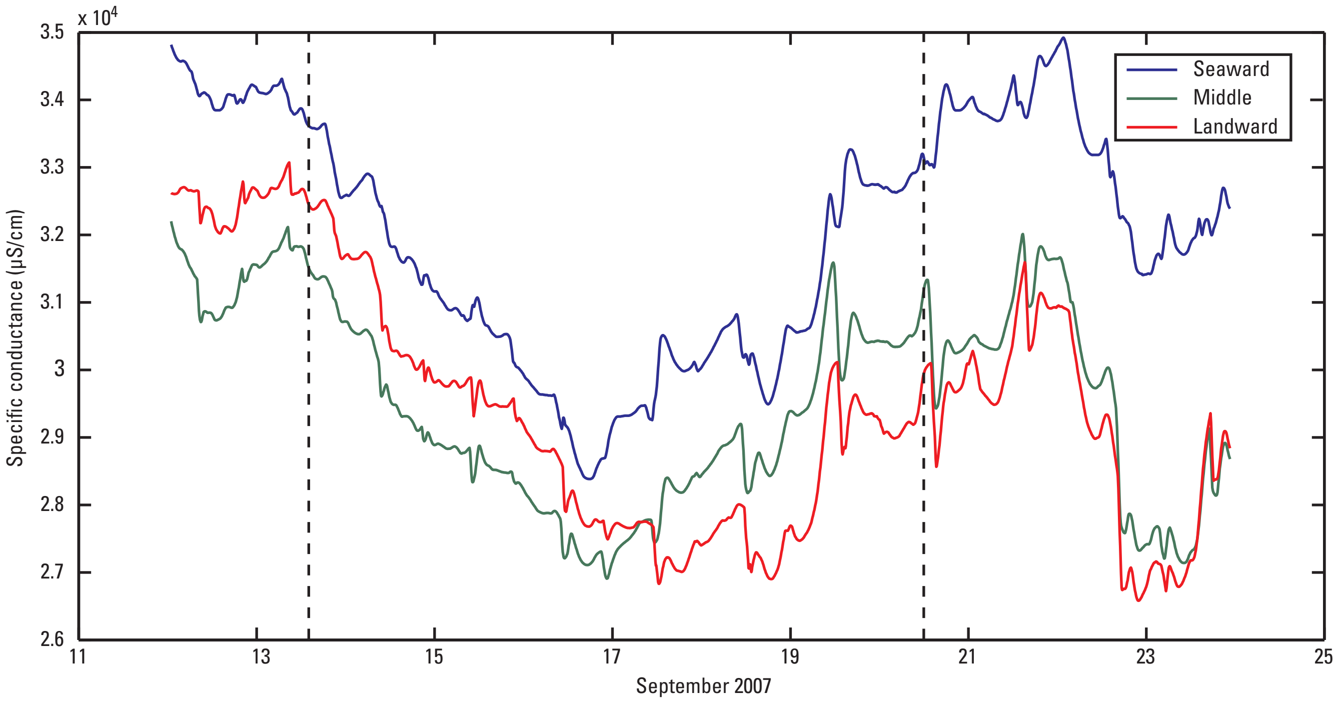

Figure 10. Running mean of specific conductance at the three sonde locations in Guadalupe Slough. The window for the running mean is 24 hours. Dotted vertical lines represent roughly when the A3W discharge operations were changed: on the afternoon of September 13 (reduced from three to one culvert) and on the afternoon of September 20 (increased from one to three culverts).

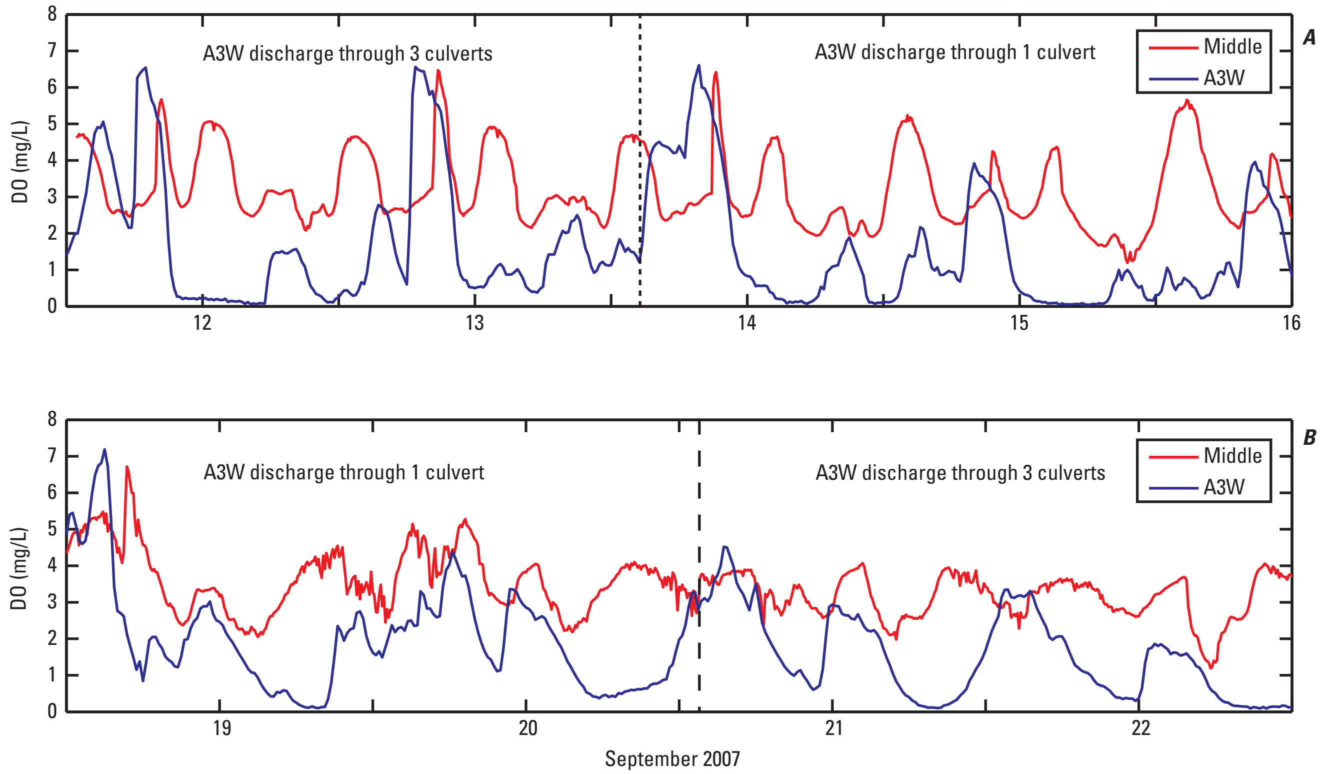

Figure 11. Dissolved oxygen (DO) in pond A3W and Guadalupe Slough (middle site). The dotted line (*A*) shows the approximate time of change from three to one discharge culvert, while the dashed line (*B*) shows the approximate time of change from one to three discharge culverts.

Discussion

- Pond discharge affected the slough DO concentrations the most during lower tides when pond discharge was greatest and dilution by slough water was smallest.
- Spring-neap tidal changes and potential precipitation effects appeared to have a larger impact on slough DO concentrations than the change from one to three discharging culverts (fig. 7*E*).
- In spite of the large difference in volume discharge from A3W between one or three culverts, there was no clear DO signal change associated with changing management of A3W discharge during this study (figs. 9 and 11). The variability of the data due to the spring-neap tidal cycle, and perhaps a change in the weather, overwhelmed the ability to see changes in slough DO concentrations that may have occurred because of changing pond-volume discharge.
- In addition, the changing conductivities in the slough appeared to be more related to the spring-neap tidal cycle than changing the volume discharge of higher conductivity pond water (fig. 10). Tidal energy began to increase by September 18 and so did conductivity, despite no change in the number of open culverts. Increased tidal energy can increase salinity intrusion up the slough. Another possible explanation was that pond discharge (high-conductivity water) increased as low tide got lower, but most of the conductivity increase in the slough happened before the two additional culverts were opened (the opening of which quadruples the pond discharge during this period; fig. 10). Even though the decrease in slough conductivities was coincident with the 75-percent decrease in discharge volume of high conductivity pond water, the subsequent rebound of conductivity in the slough began to happen 3 days before the pond discharge volume was increased back to over 25 MGD. If a distinct effect on slough conductivities from the pond discharge could not be seen with a conservative tracer like salt, it likely would be more difficult to identify effects with non-conservative dissolved oxygen.

- Whether the co-occurrence of minimum slough DO and low water was caused by pond discharge, upstream Sunnyvale WPCP, and/or sediment oxygen demand is unknown.
- Scope of findings: The second deployment period included a single spring-neap tidal cycle, a significant drop in air temperature, and a precipitation event. This deployment helped to understand the effects of changing pond A3W discharge, and it served to inform designing a comprehensive monitoring program for DO in the sloughs. A comprehensive DO monitoring and analysis program would include different seasons, tides, pond operations, and additional ponds.

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Appendix

In the following plots, all of the collected sonde data for both the first deployment and the second deployment are presented. The data include temperature, specific conductance, pH, DO, DO percent saturation, water height above the Sontek ADV, and velocity. Data labeled "Landward", "Middle", and "Seaward" refer to the Guadalupe Slough sites. Data from the Sontek ADV (water height and velocity) are also from Guadalupe Slough. No dissolved oxygen percentage data were obtained from pond A3W. Please refer to the full report for additional details.

First Deployment (August 13–17, 2007)

Guadalupe Slough and Control Sloughs Newark and Mowry

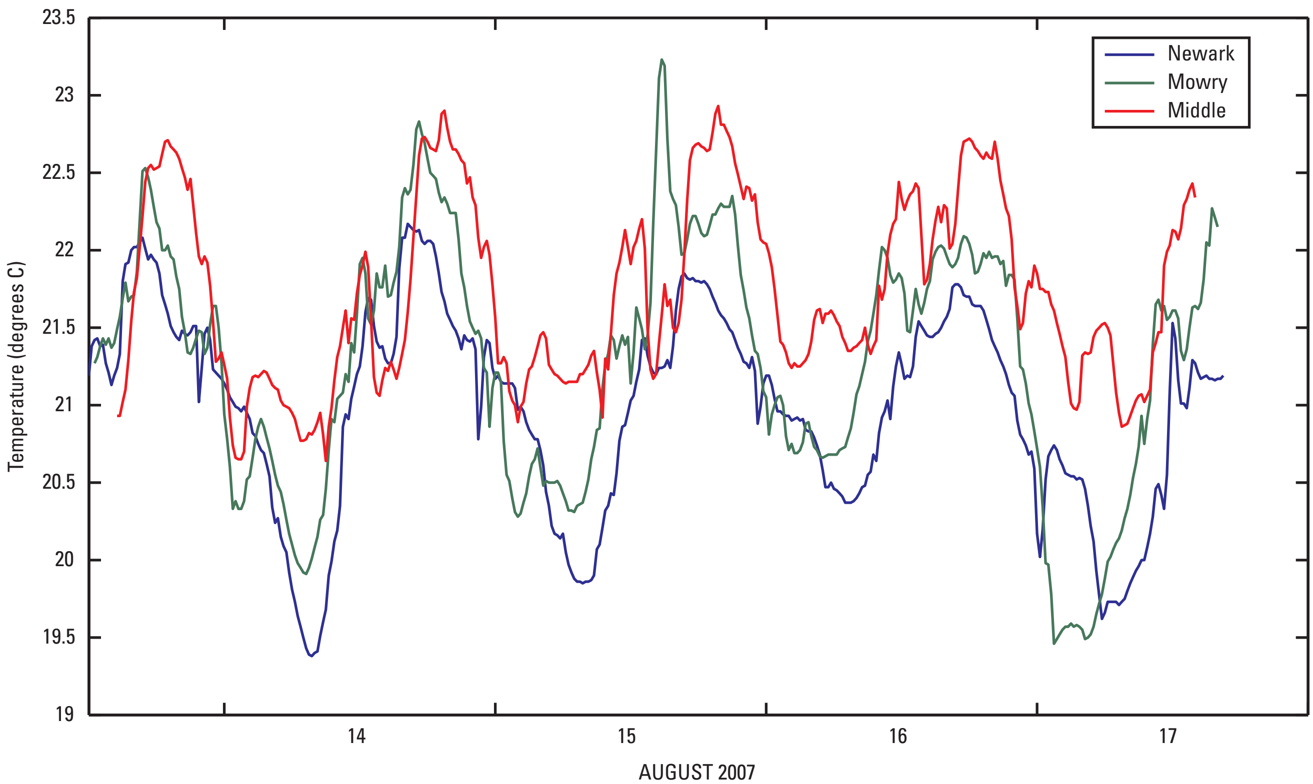

Figure A1. Temperature in Guadalupe Slough and control sloughs during the first deployment.

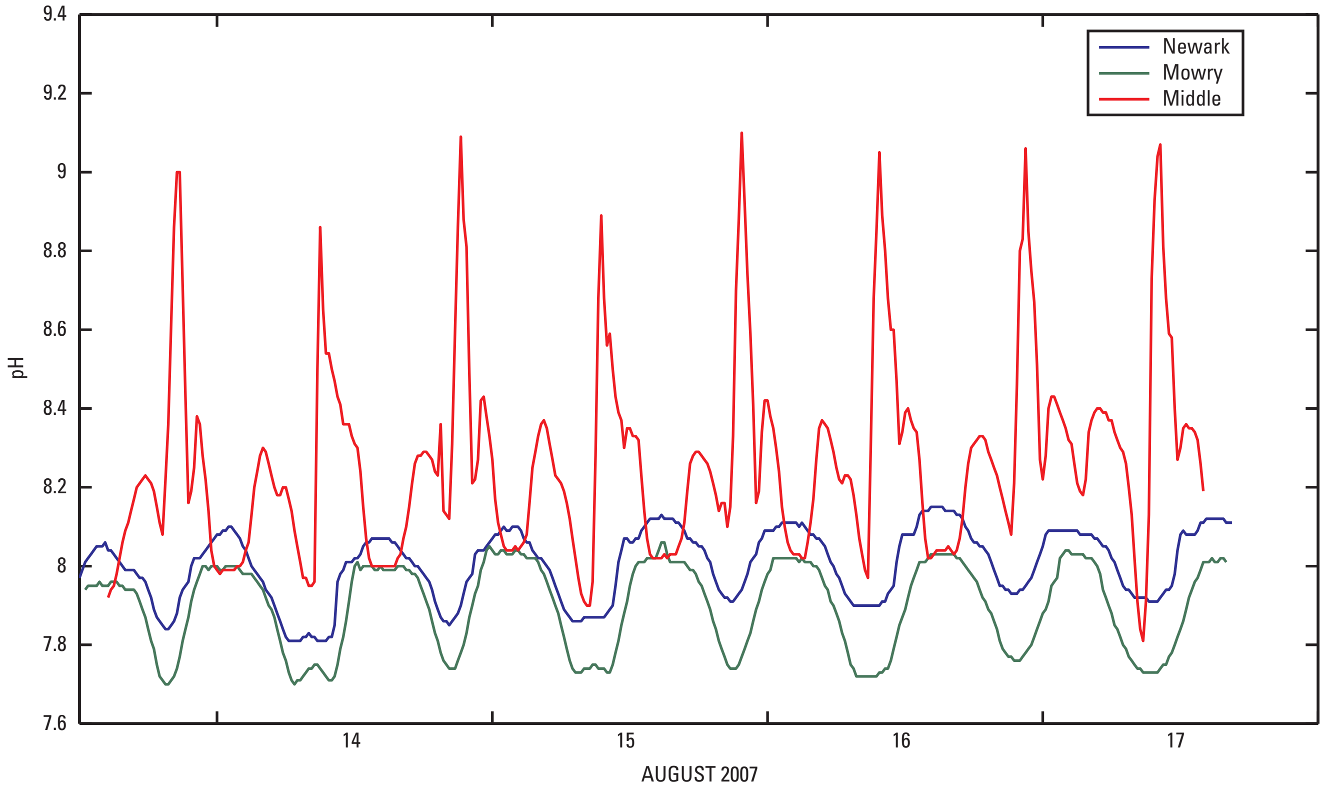

Figure A2. Specific conductance in Guadalupe Slough and control sloughs during the first deployment.

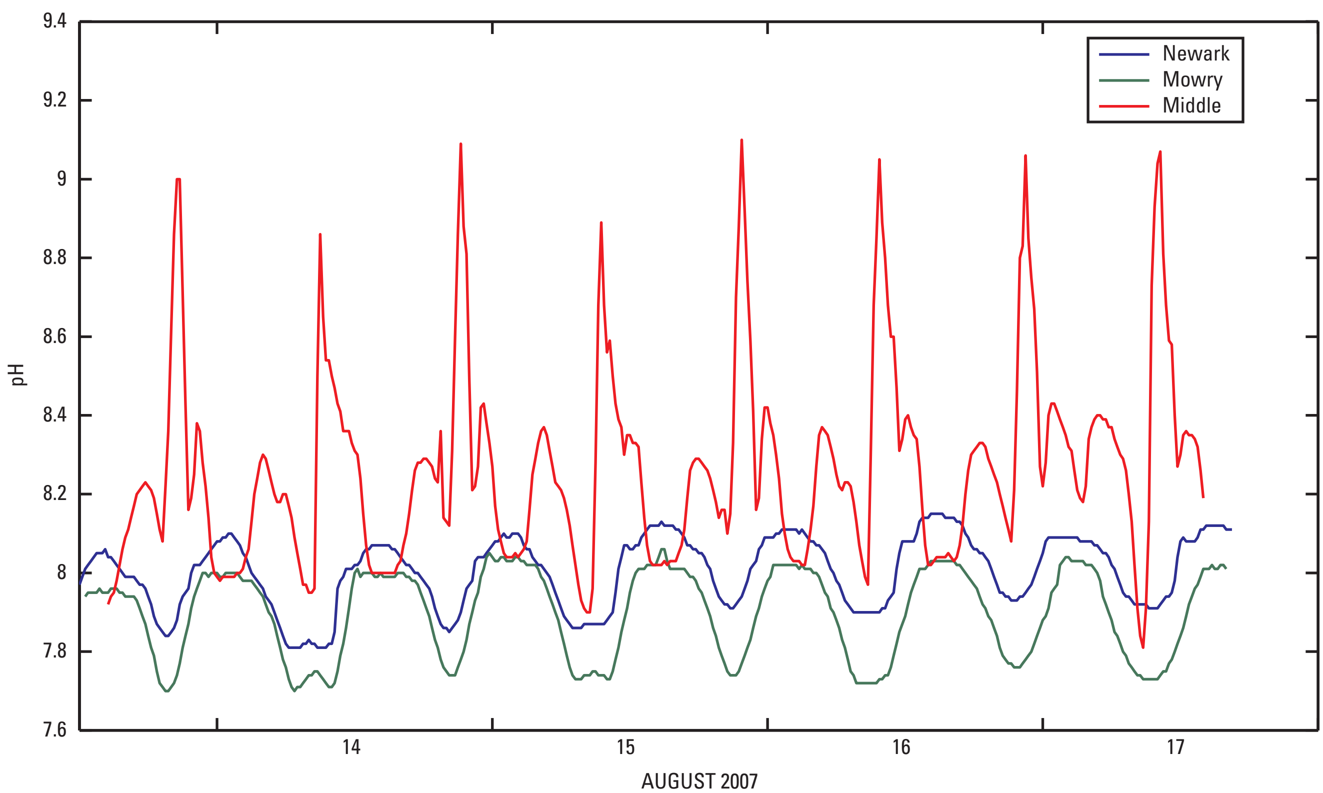

Figure A3. pH in Guadalupe Slough and control sloughs during the first deployment.

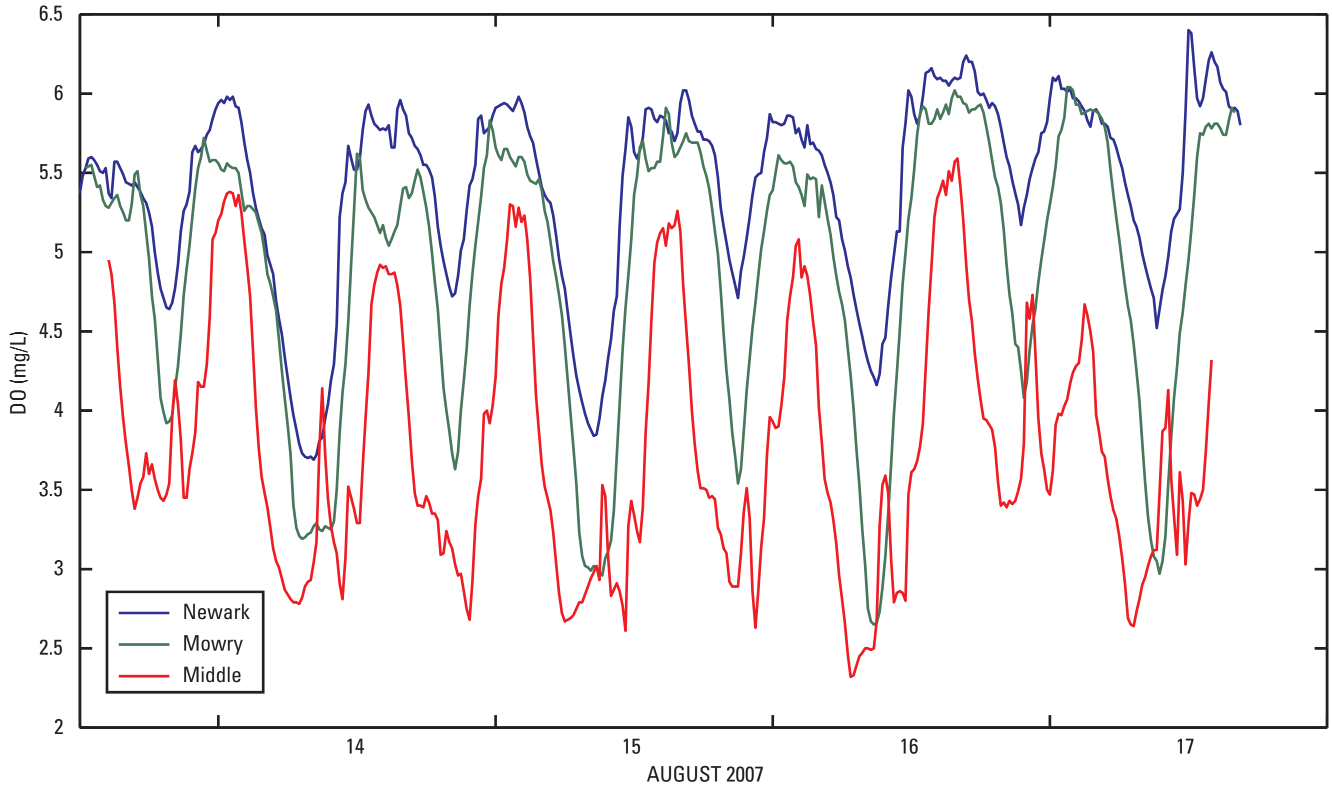

Figure A4. Dissolved oxygen (DO) in Guadalupe Slough and control sloughs during the first deployment.

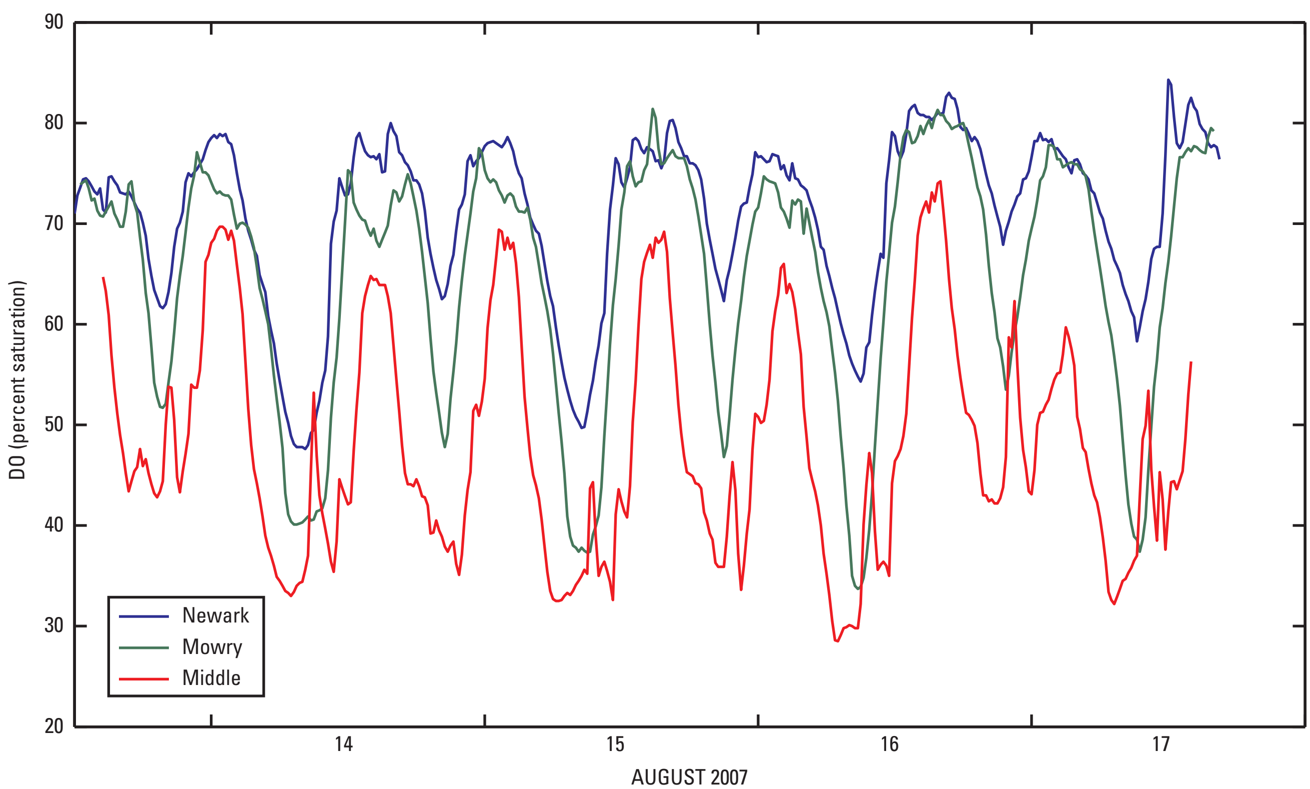

Figure A5. Dissolved oxygen (DO) percent saturation in Guadalupe Slough and control sloughs during the first deployment.

Guadalupe Slough and Discharge Pond A3W

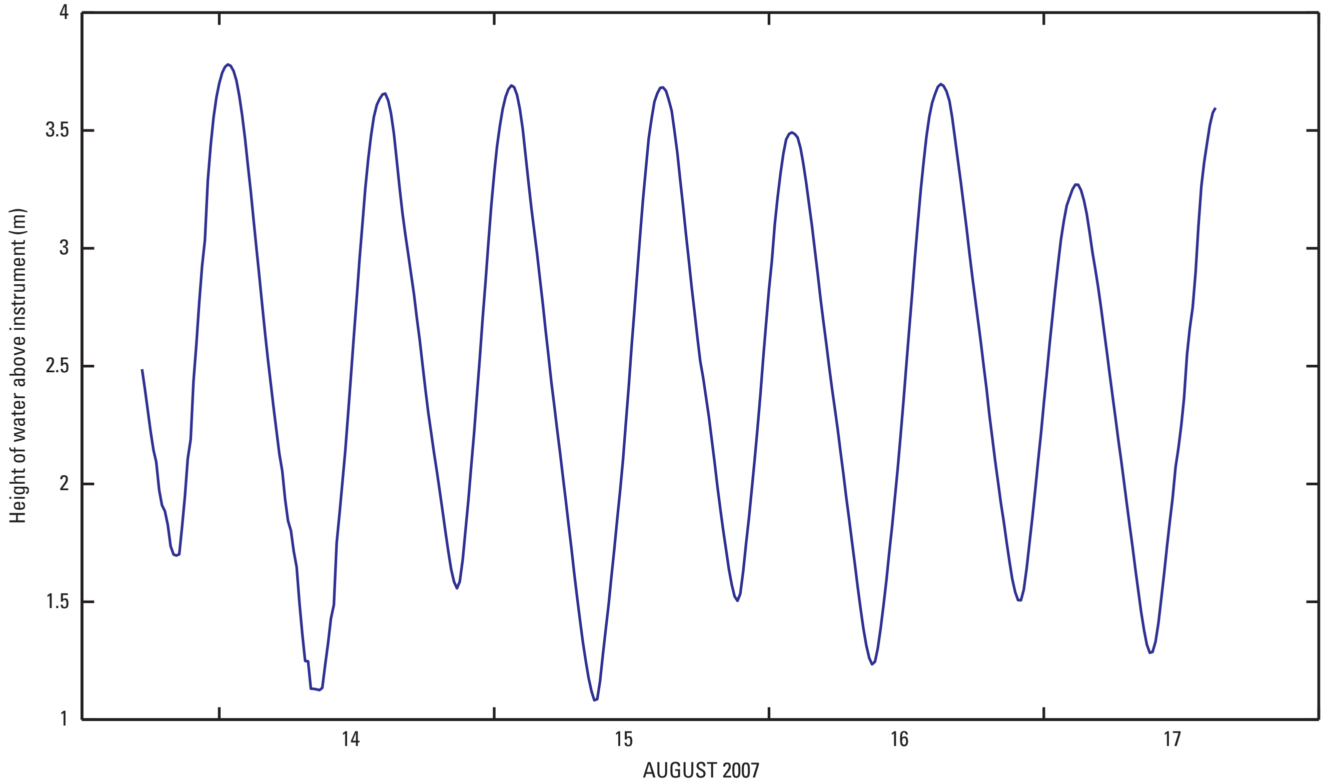

Figure A6. Height of the water above the Sontek acoustic Doppler velocimeter in Guadalupe Slough during the first deployment.

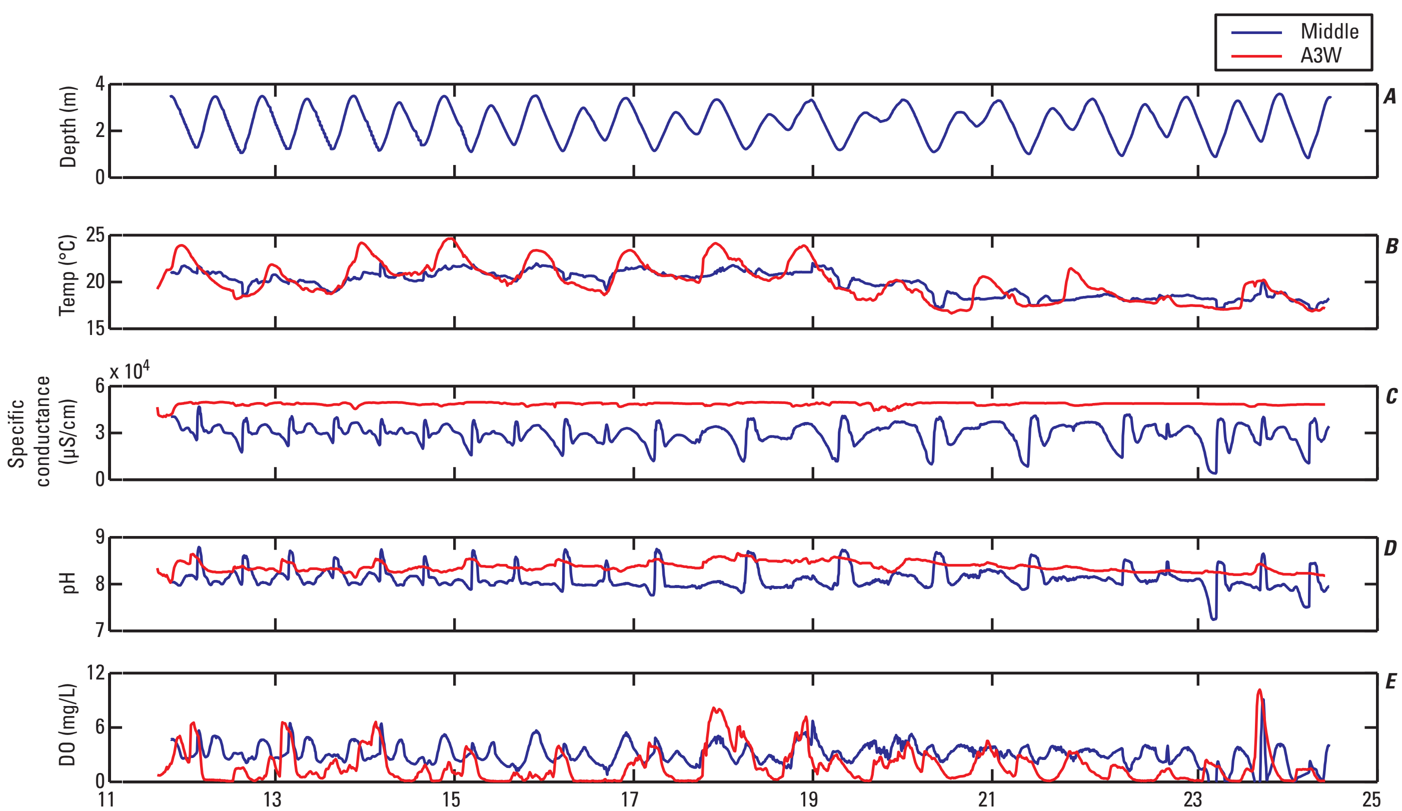

Figure A7. Temperature in Guadalupe Slough and pond A3W during the first deployment.

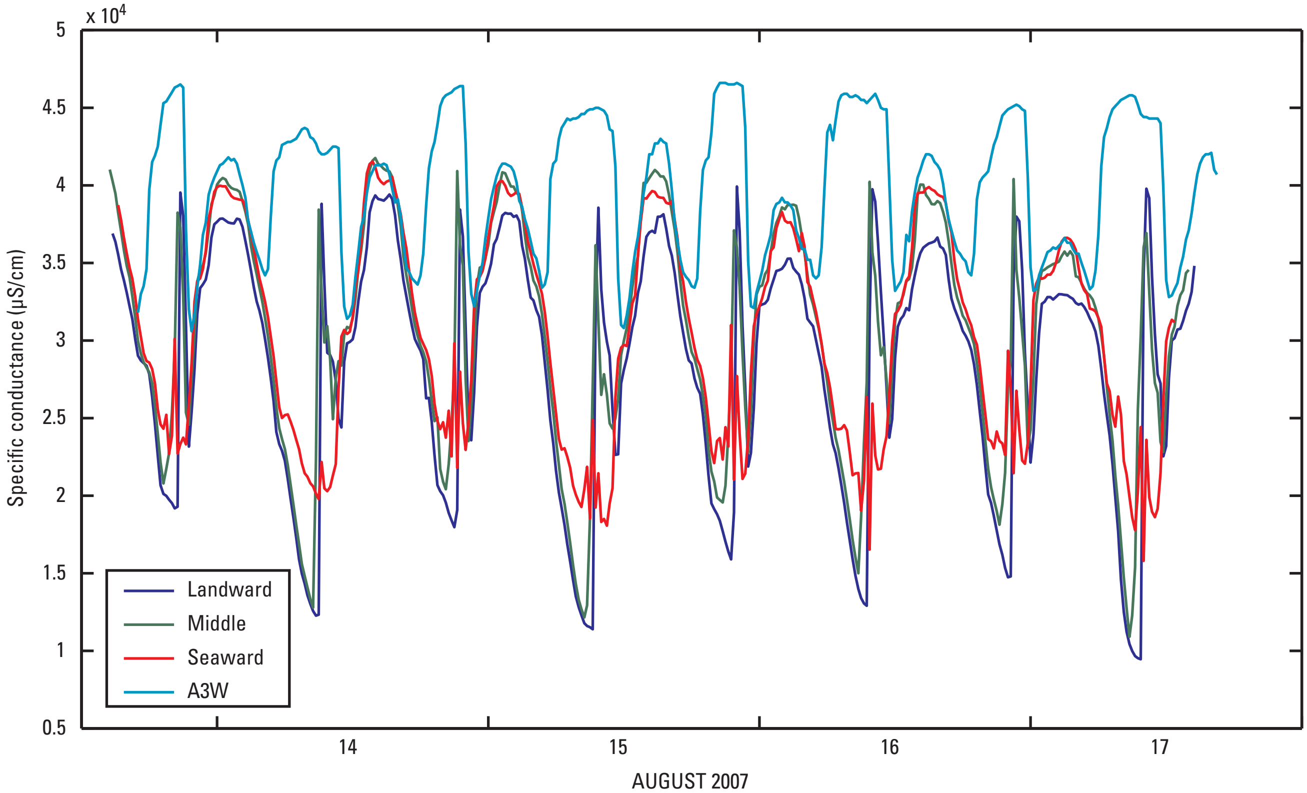

Figure A8. Specific conductance in Guadalupe Slough and pond A3W during the first deployment.

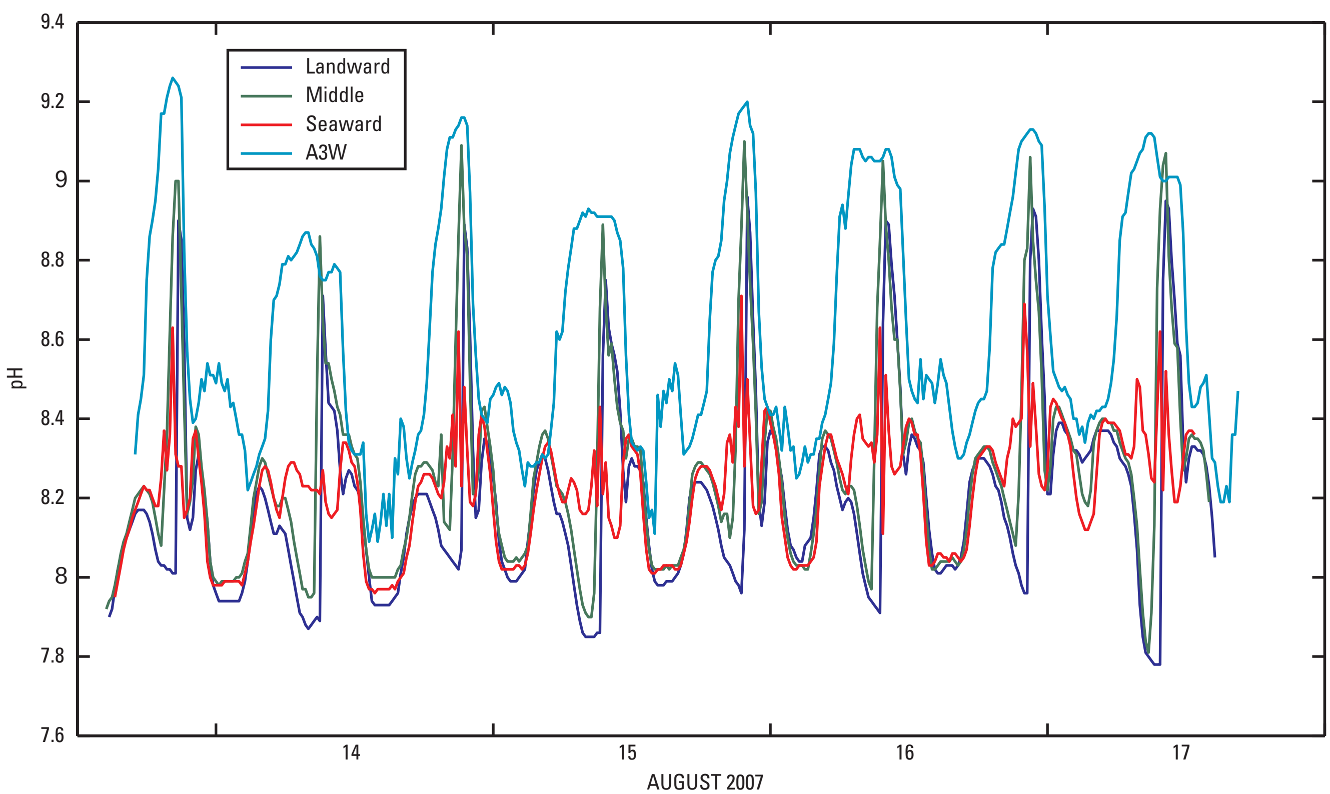

Figure A9. pH in Guadalupe Slough and pond A3W during the first deployment.

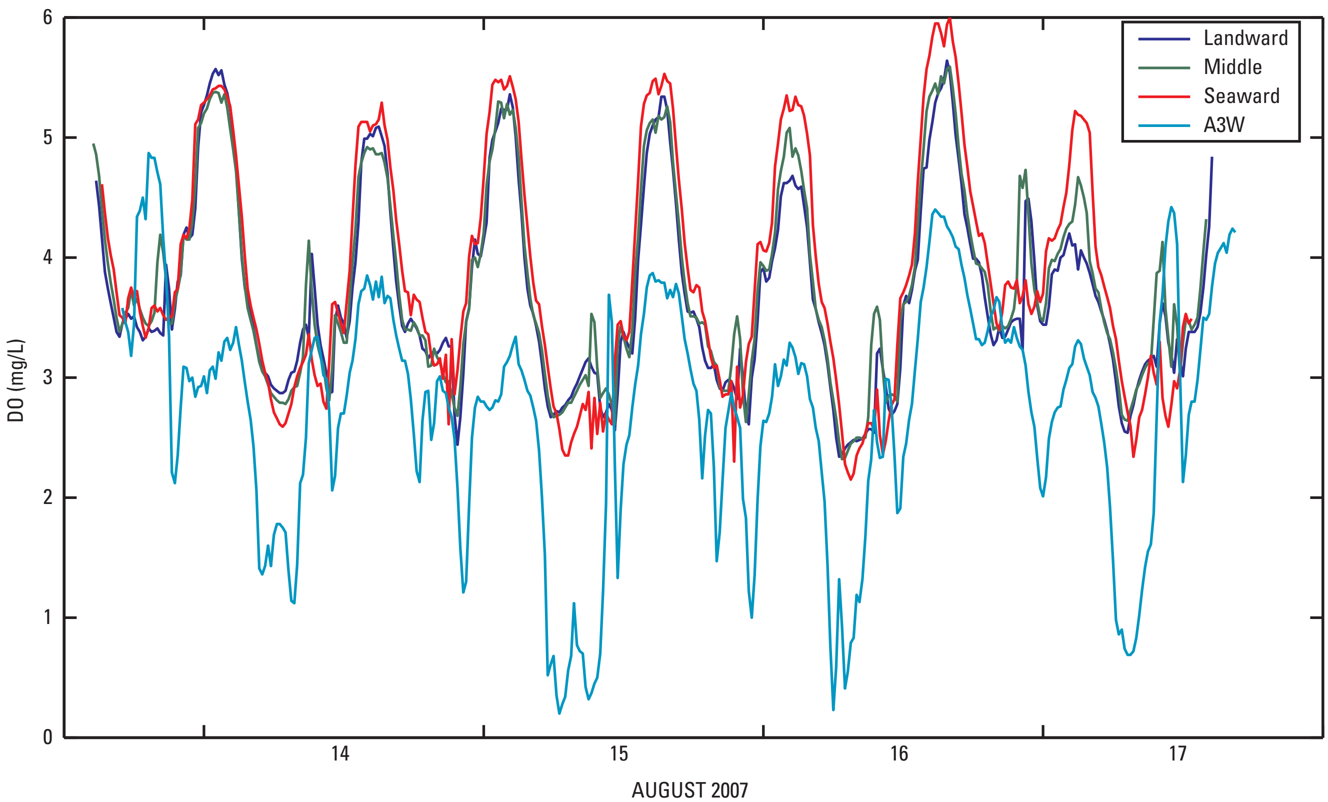

Figure A10. Dissolved oxygen (DO) in Guadalupe Slough and pond A3W during the first deployment.

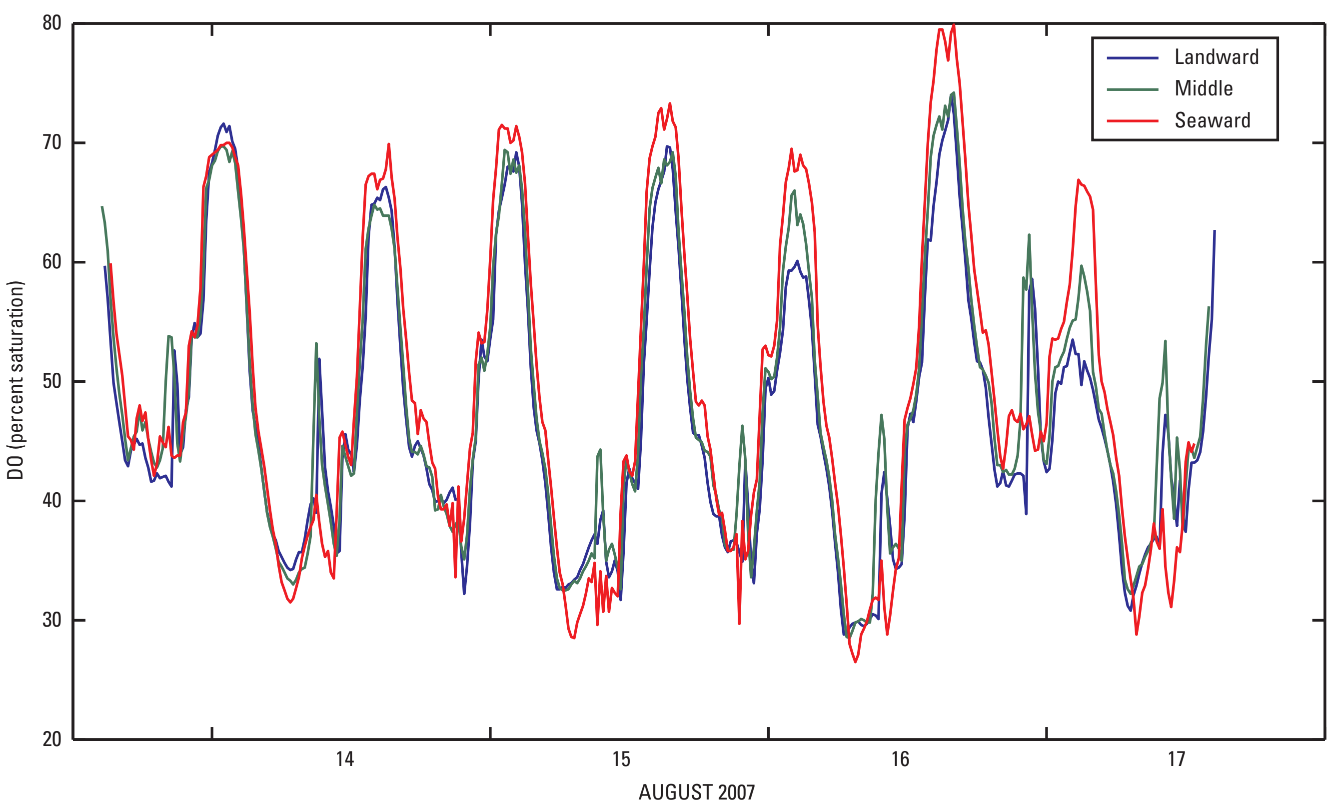

Figure A11. Dissolved oxygen (DO) percent saturation in Guadalupe Slough during the first deployment.

Second Deployment (September 11–24, 2007)

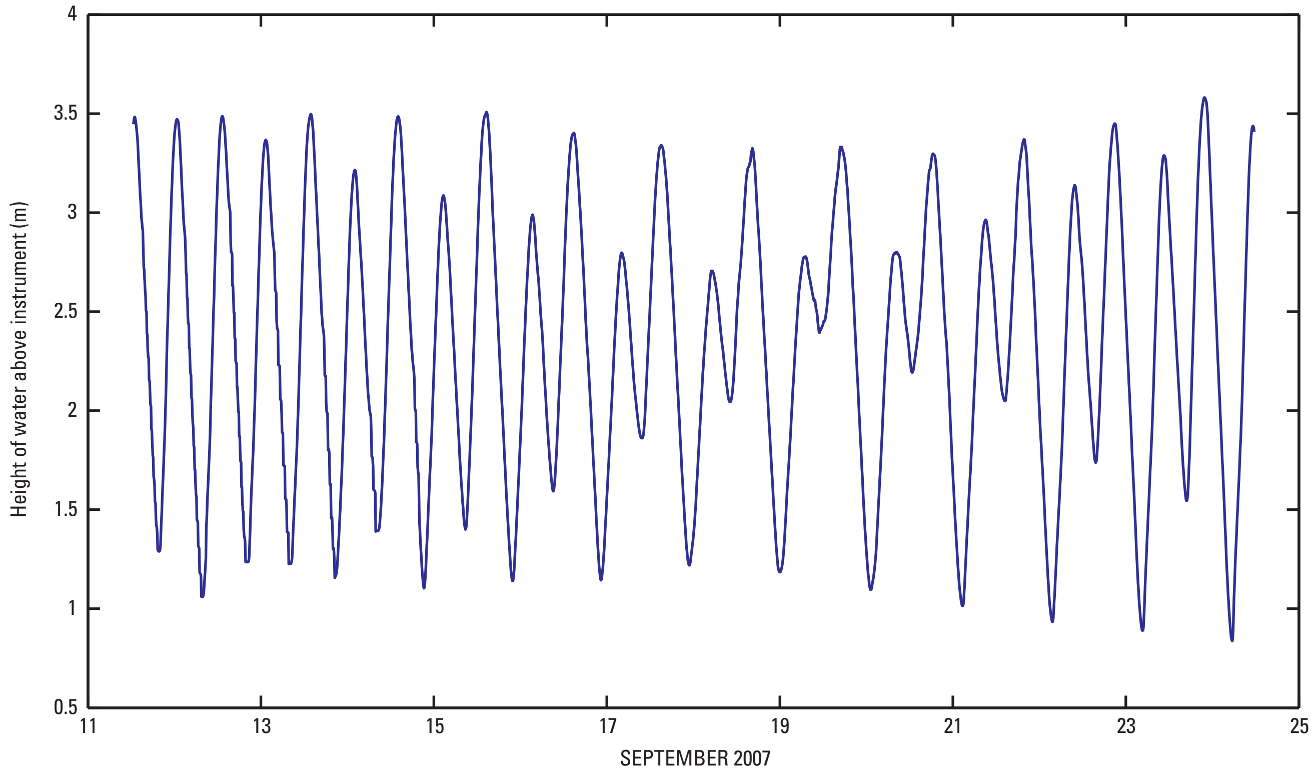

Figure A12. Height of the water above the Sontek acoustic Doppler velocimeter in Guadalupe Slough during the second deployment.

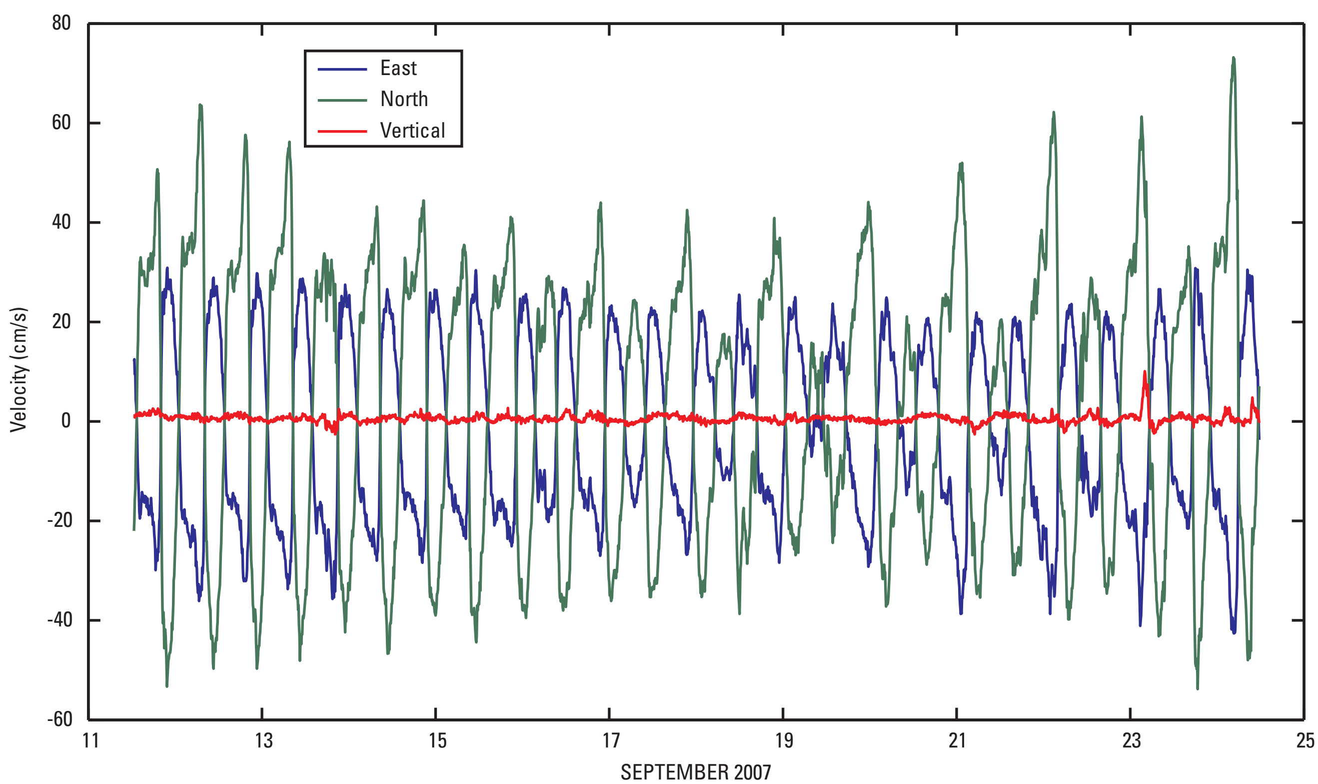

Figure A13. Velocity of the water in Guadalupe Slough during the second deployment.

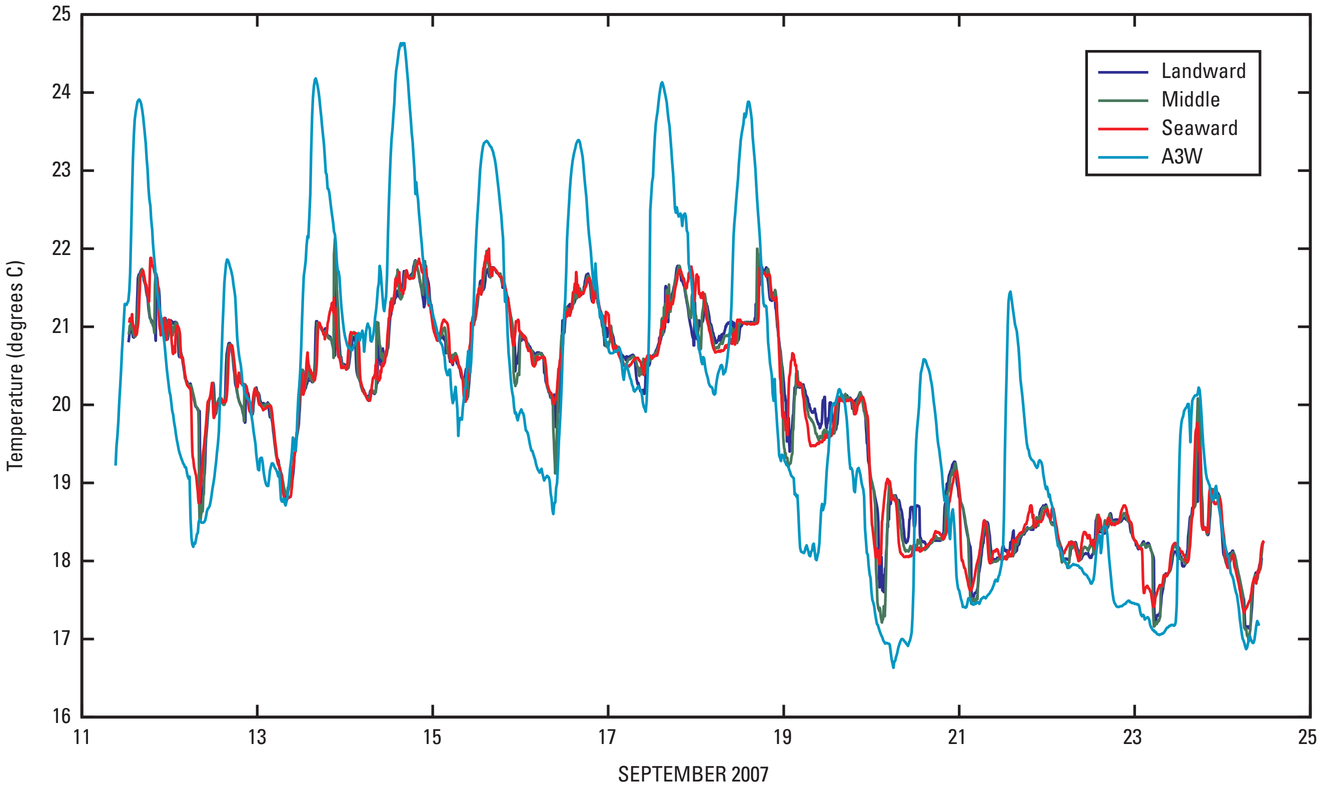

Figure A14. Temperature in Guadalupe Slough and pond A3W during the second deployment.

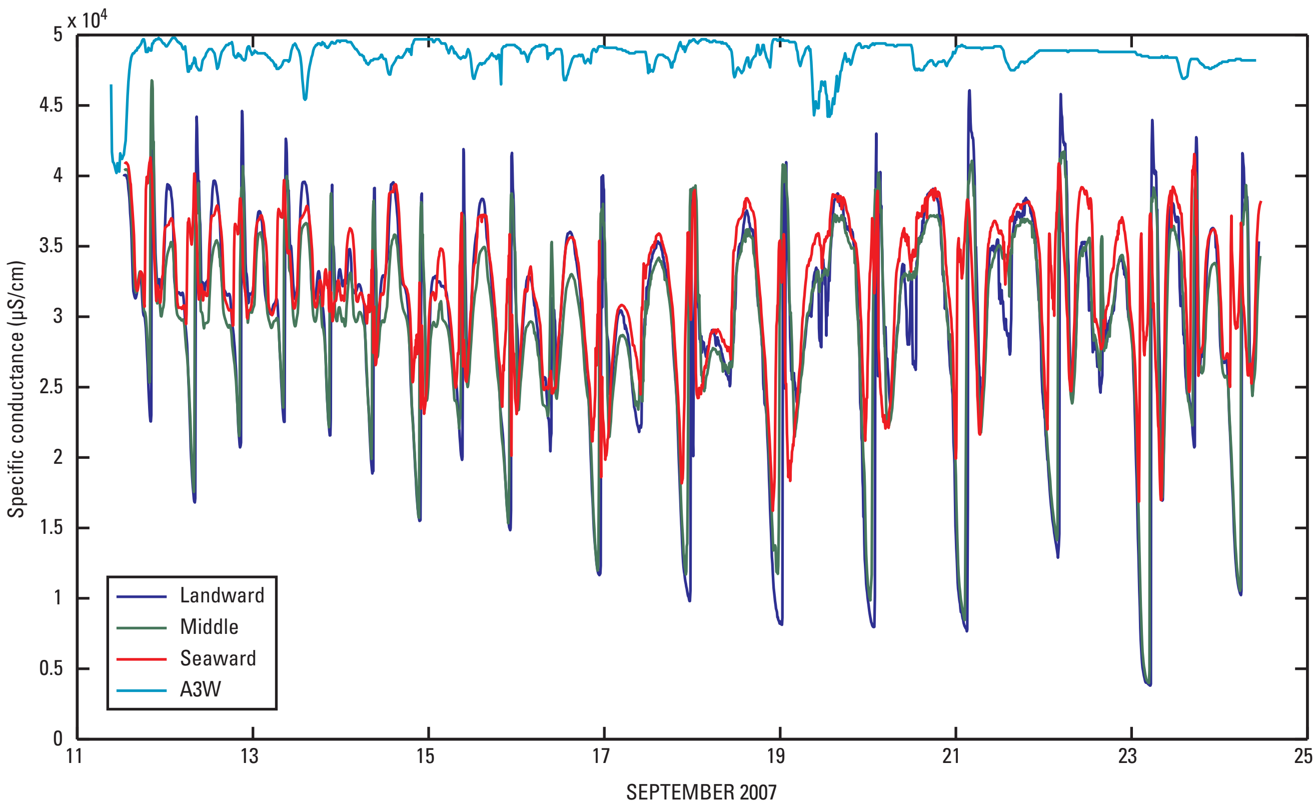

Figure A15. Specific conductance in Guadalupe Slough and pond A3W during the second deployment.

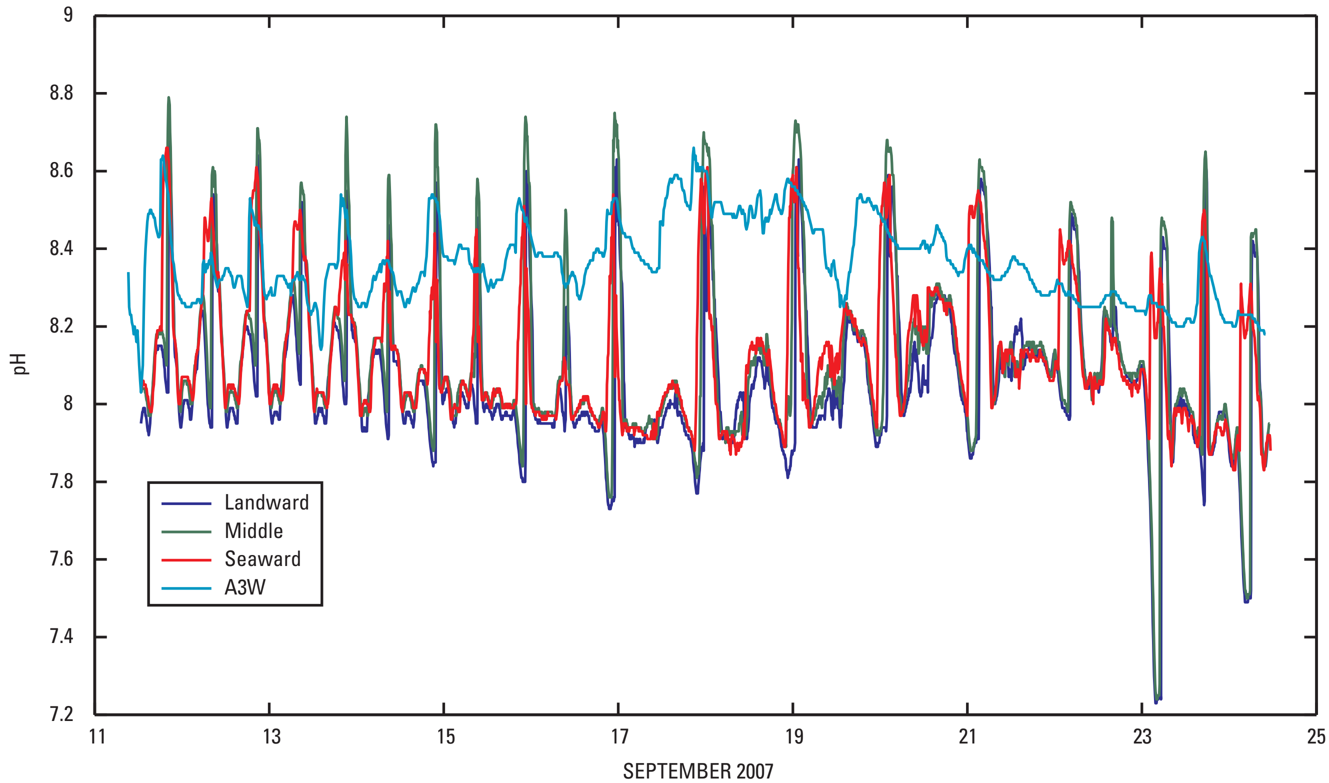

Figure A16. pH in Guadalupe Slough and pond A3W during the second deployment.

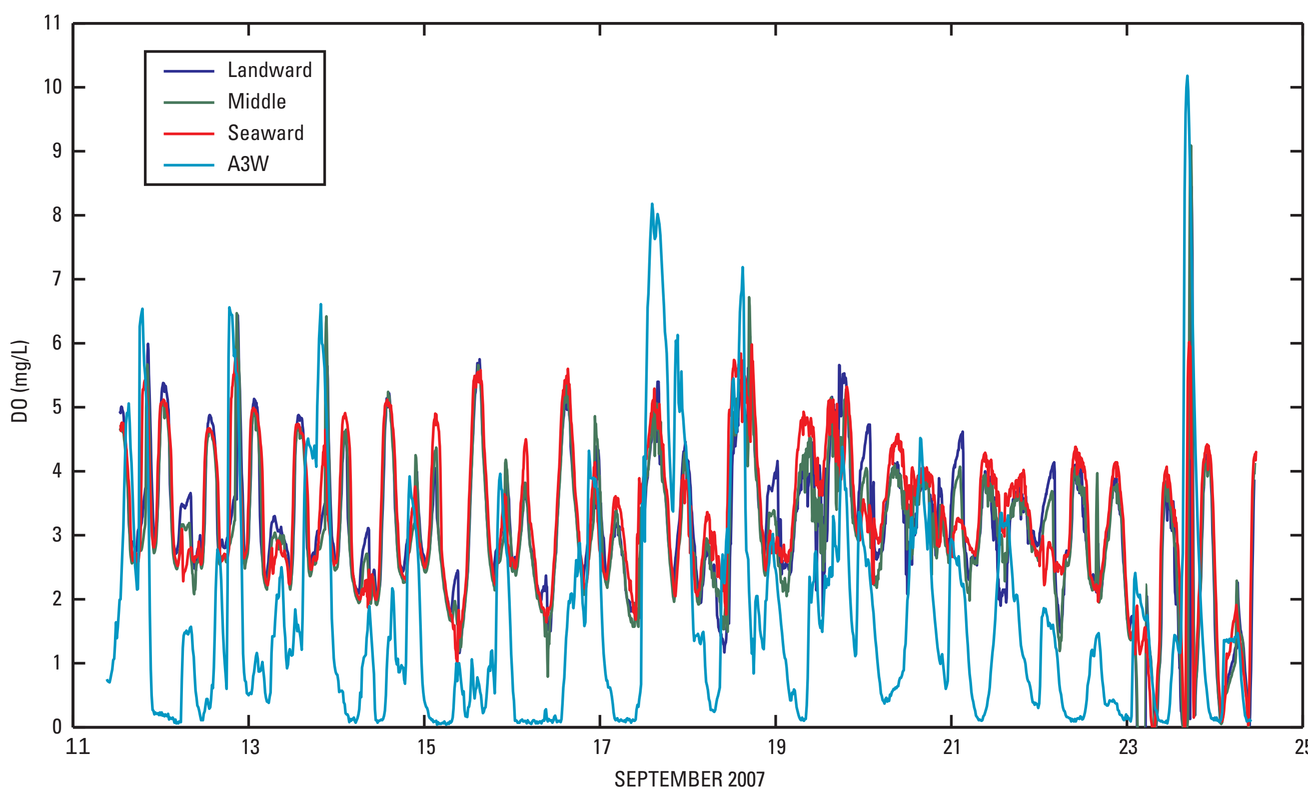

Figure A17. Dissolved oxygen (DO) in Guadalupe Slough and pond A3W during the second deployment.

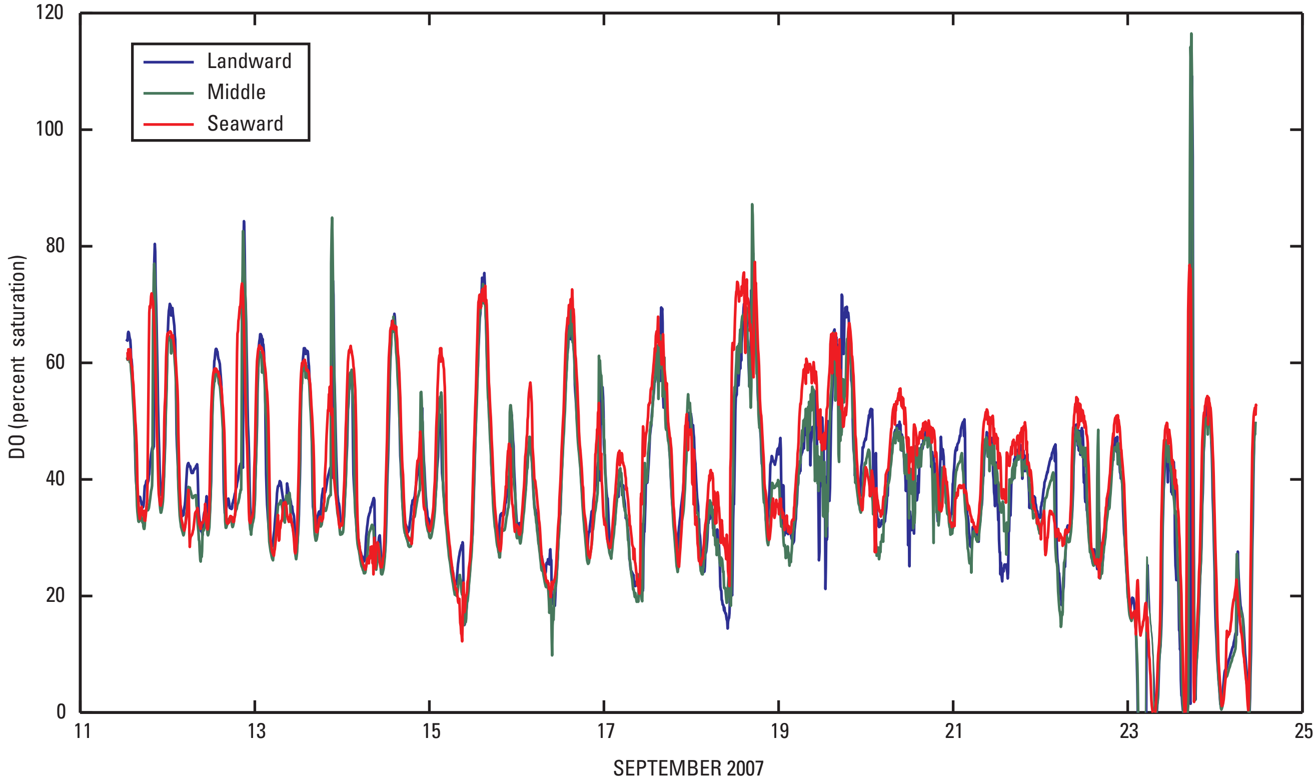

Figure A18. Dissolved oxygen (DO) percent saturation in Guadalupe Slough during the second deployment.

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