## RESULTS

### *Nutrient Dynamics and Quality Issues*

### Water Quality

*Salinity*. Mean salinity levels within monitoring units followed patterns that might be expected (Figure 10). Mean salinity levels appeared to be lowest in the units receiving reclaimed water (Reclaimed Water, Reclaimed Water + Muted Tidal) and the Groundwater Pond, with means typically less than 5 ppt (Figure 10). Although the Reclaimed Water and Groundwater Pond monitoring units do not receive tidal inflow, a marine-derived saline influence may be present ($\bar{x}$=1.50-1.75 ppt) -- possibly a high, saline groundwater table and/or, for certain diked units, lateral transmission or subsurface flux of saline water from adjacent tidal sloughs. Salinity levels within Reclaimed Water and Groundwater Pond monitoring units remained fairly consistent over time (Figure 11). Seasonal variations in salinity were observed in the Reclaimed Water + Muted Tidal, Muted Tidal, Passive Hydrologic Management, and Undiked Marsh monitoring units (Figure 11). Generally, salinities were highest in these monitoring units during the August and November sampling events. With the exception of the Reclaimed Water + Muted Tidal units, there was no or minimal freshwater influence during these months, and the Muted Tidal monitoring unit was being actively flooded with tidal flow. For units that are not tidal or open to tidal flushing, increases in salinity during these months was probably driven by evaporation and subsequent concentration of salts within waters already present.

*pH*. Mean pH in undiked and passively managed diked areas was close to neutral (6.77-7.42) (Figure 10). Mean pH levels in monitoring units receiving reclaimed water (Reclaimed Water, Reclaimed Water + Muted Tidal) or groundwater (Groundwater Pond) appeared to be slightly more basic (~ ≥7.79), while those in the Muted Tidal monitoring unit appeared to be more acidic (<5.5). The slightly more basic pH levels recorded in units receiving reclaimed water or groundwater appeared to result from seasonal increases in pH that were probably associated with elevated phytoplankton productivity (Figure 11). Periodic variations in pH also played a role in the low mean pH recorded in Muted Tidal monitoring units, with acidic conditions observed in August 1999 ($\bar{x}$=4.53±1.3), November 1999 ($\bar{x}$=3.14±0.12), March 2000 ($\bar{x}$=4.21±0.47), November 2000 ($\bar{x}$=6.00±0.71), and January 2001 ($\bar{x}$=5.33±0.91) (Figure 11).

*D.O. and Chlorophyll a.* With the exception of the Passive Hydrologic Management monitoring unit, D.O. and chlorophyll a levels were highest in the diked and managed monitoring units where residence time of waters can be expected to be long (Figure 10). While representing only snapshots in time, the D.O., pH, and chlorophyll a levels recorded suggest that the diked and managed units are typically highly productive and probably eutrophic, at least during the day (Figure 10). Mean daytime D.O. ranged from a high of 11.75±1.81 mg/L in the Reclaimed Water + Muted Tidal monitoring unit to a low of 5.91±1.05 mg/L in the Passive Hydrologic Management monitoring unit (Figure 10). The Basin Plan (RWQCB 1995) sets 5.0 mg/L as the

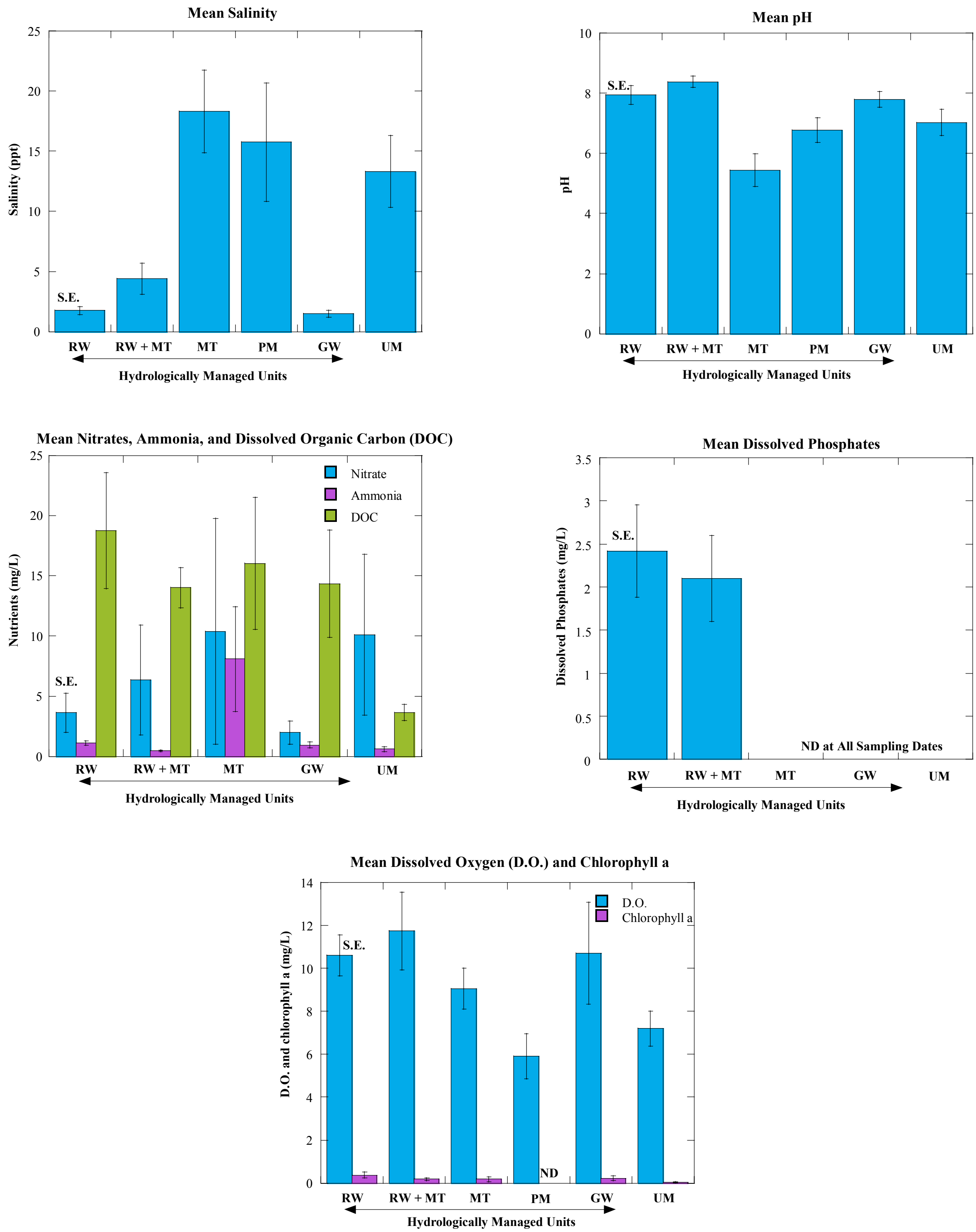


**Figure 10**. Mean water quality parameters within Hudeman Slough Case Study monitoring units. Bars indicate standard error of the mean. (RW-reclaimed water; RW+MT-reclaimed water plus muted tidal; MT-muted tidal; PM-passive management; GW-groundwater pond; UM-undiked marsh)

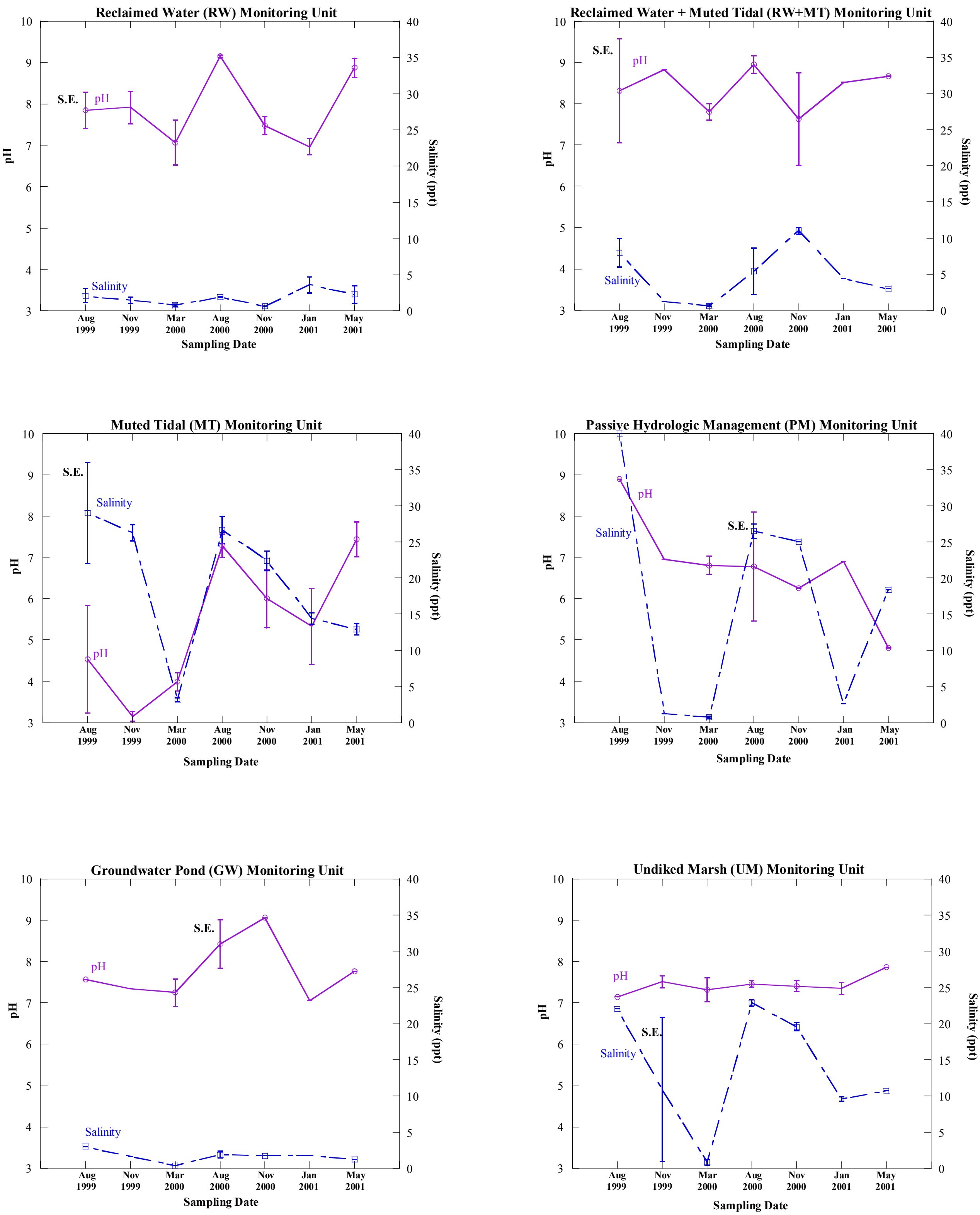


**Figure 11**. Mean salinity and pH in Hudeman Slough Case Study monitoring units over two hydrologic seasons. Bars indicate standard error of the mean for that sampling period.

minimum D.O. for warm water non-tidal areas and tidal areas downstream of the Carquinez Bridge. Levels below 5.0 mg/L were recorded in the Reclaimed Water + Muted Tidal monitoring unit in August and November 2000 (Figure 12). Sampling was not conducted at night, but low to moderate D.O. values (<10.0 mg/L) recorded in the early morning or late afternoon sampling events suggest that some monitoring units may become hypoxic or even anoxic during the night. During the study period, several "fish kill" events did occur, in which carp were occasionally found dead on mud banks. Most of the fish kill events observed took place in the Passive Hydrologic Management monitoring unit. While this unit is not tidal, carp appear to enter through the "one-way" tide gates during periods when waters are discharged (L. Parsons and J. Martini-Lamb, *pers obs*.). At least two fish kill events occurred in Reclaimed Water monitoring units (L. Parsons and J. Martini-Lamb, *pers. obs*.). One of these events appeared to be associated with mowing of one of the units shortly before it was flooded: flooding was almost immediately accompanied by a fish kill event.

*Nitrates/Nitrites*. Mean levels of nitrates appeared highest in either fully or muted tidal monitoring units (>10.0 mg/L; Figure 10). Lowest mean levels were recorded in the Groundwater Pond (1.98±0.97 mg/L) and Reclaimed Water (3.62±1.62 mg/L) monitoring units, respectively (Figure 10). Elevated means in monitoring units open to tidal flushing appeared to be largely driven by pulses of nitrates recorded after the season's first rainfall events (fall 2000), with nitrate levels often exceeding 25 mg/L (Figure 13). The fall 2000 sampling and observed nitrate pulse just preceded the beginning of "discharge" season for the treatment plant: the SVTP is allowed to discharge directly to San Pablo Bay waters from November 1 through April 30. High nitrate levels in fully tidal areas persisted into late spring (May 2001; Figure 13). Nitrate concentrations in all monitoring units exceeded those considered characteristic of natural waters (0.05-1.0 mg/L; A. Horne, unpub. data). However, levels in Reclaimed Water monitoring units remained lower than those considered characteristic of recycled waters (5-25 mg/L; Horne, unpub. data). During the study period, nitrate concentration in treatment plant effluent averaged 14.4±0.8 mg/L (SVCSD, unpub. data). Nitrites were not detected in monitoring units during any of the sampling events, but the detection limit was relatively high (2.0 mg/L). Nitrite toxicity can occur at concentrations of 0.5 mg/L (A. Horne, unpub. data).

*Total Ammonia*. Mean total ammonia levels appeared to be substantially higher in the Muted Tidal monitoring unit than in any of the other managed and unmanaged areas (Figure 10). Mean total ammonia levels in the Muted Tidal monitoring unit (8.08±4.34 mg/L) were three times higher than those in other monitoring units, which ranged from 0.46±0.07 mg/L in the Reclaimed Water + Muted Tidal monitoring unit to 1.11±0.19 mg/L in the Reclaimed Water unit (Figure 10). With the exception of the Muted Tidal monitoring unit, mean total ammonia concentrations generally fell within levels considered characteristic of natural waters (0.005-1.0 mg/L; A. Horne, unpub. data). Notably, mean total ammonia concentrations in the Reclaimed Water monitoring units were substantially higher than those in treatment plant effluent (0.36±0.02 mg/L) during the study period. The effluent levels were below the range considered characteristic of recycled water (1-25 mg/L; A. Horne, unpub. data). Elevated means in the Muted Tidal monitoring unit appeared to be driven by pulses of ammonia during the

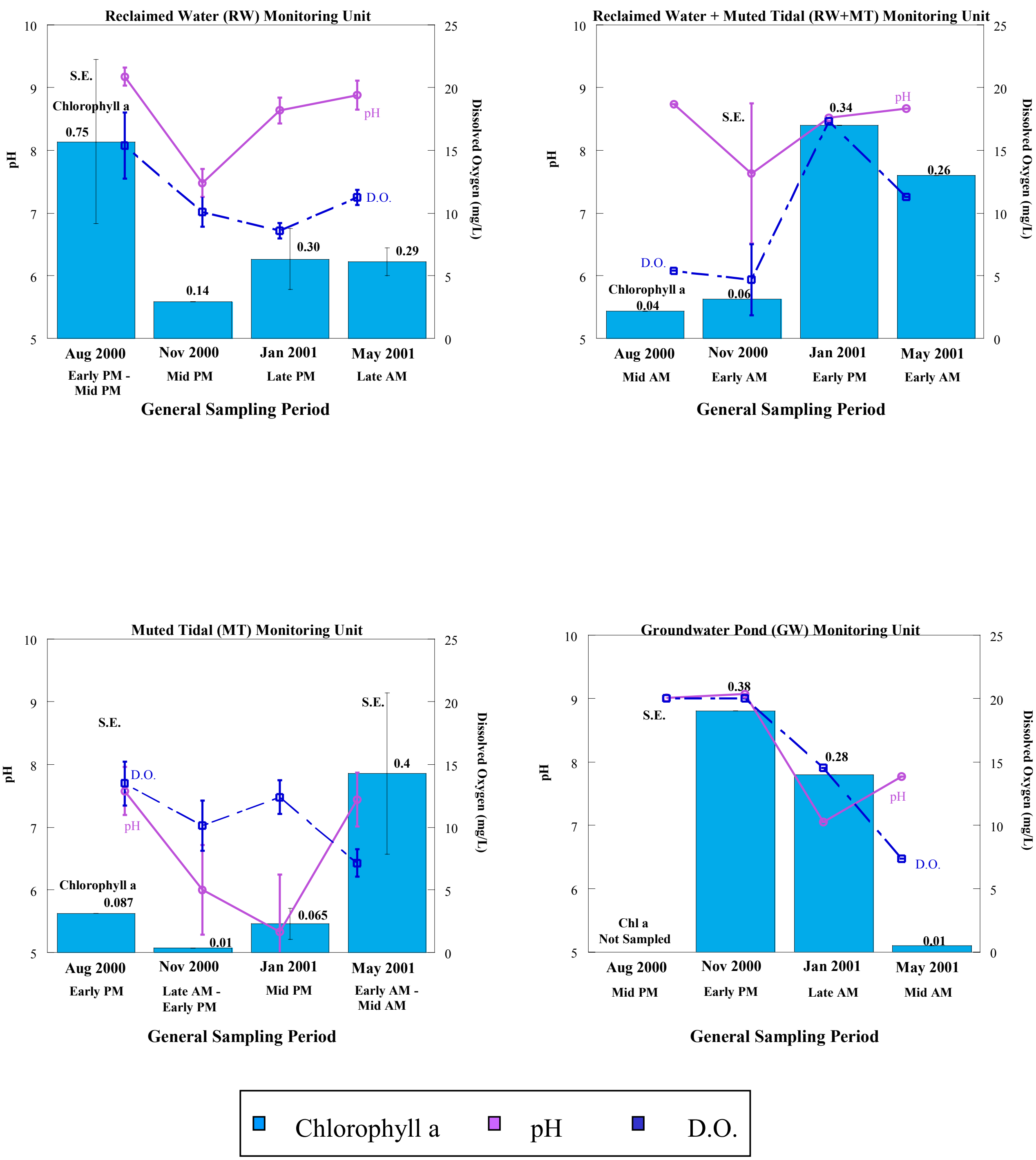


**Figure 12**. Dissolved oxygen (D.O.), pH, and chlorophyll a in waters of the Hudeman Slough Case Study monitoring units over period sampled. Bars indicate standard error of the mean for that sampling period.

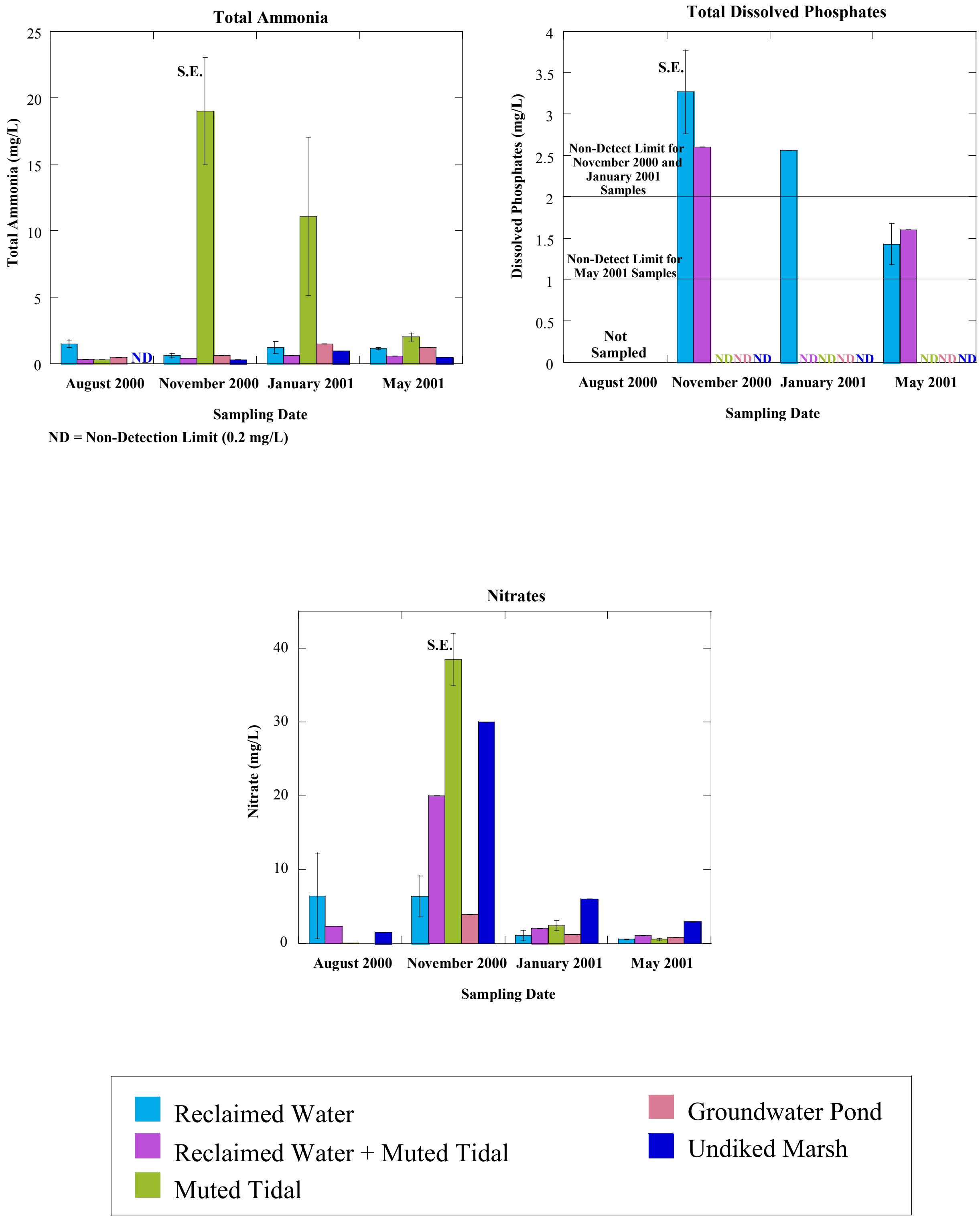


**Figure 13**. Concentrations of nutrients in waters of the Hudeman Slough Case Study monitoring units over one hydrologic season (August 2000 - May 2001). Bars indicate standard error of the mean during that sampling period.

November 2000 and January 2001 sampling events, with concentrations ranging from 17 to 23 mg/L (Figure 13). It should be noted that during these periods the Muted Tidal monitoring unit was generally flooded and water pHs were very acidic (pH <4).

*Unionized Ammonia*. Unionized ammonia concentrations varied between monitoring units and seasons (Figure 14). The highest mean unionized ammonia levels (0.25±0.14 mg/L) were recorded in the Reclaimed Water monitoring unit in August 2000, a month before these units are typically flooded with reclaimed water (Figure 14). During the period when units were flooded with reclaimed water (September-October/early November 2000), unionized ammonia was generally not detected (<0.02 mg/L) or, in one subunit, detected only at low concentrations (0.04 mg/L; Figure 14). Unionized ammonia concentrations increased again to a mean of 0.11±0.08 mg/L in January 2001, when the Reclaimed Water monitoring unit receives only precipitation and run-off from adjacent uplands (Figure 14). In the Reclaimed Water + Muted Tidal and Groundwater Pond monitoring units, unionized ammonia was present only in the summer (August 2000) and fall (November 2000) sampling dates, and concentrations ranged from 0.15 mg/L (Groundwater Pond; August 2000) to 0.03 mg/L (Reclaimed Water + Muted Tidal; November 2000). Unionized ammonia was never detected in the Muted Tidal or Undiked Marsh monitoring units (data from the Undiked Marsh are not presented in Figure 14). The Basin Plan (RWQCB 1995) sets a maximum of 0.4 mg/L for lower San Francisco Bay and 0.16 mg/L for central San Francisco Bay, which includes San Pablo Bay. The only exceedance of this criteria occurred in the Reclaimed Water monitoring unit in August 2000.

*Dissolved Phosphates*. Mean dissolved phosphates were only detected in monitoring units receiving reclaimed water (Figure 10). Dissolved phosphates averaged 2.41±0.53 mg/L in the Reclaimed Water monitoring unit and 2.1±0.5 mg/L in the Reclaimed Water + Muted Tidal unit (Figure 10). Detection limit for this analyte was 2.0 mg/L, which was above the concentrations considered characteristic of natural waters (0.005-0.10 mg/L; A. Horne, unpub. data). Concentrations in recycled water often range between 3 and 8 mg/L (A. Horne unpub. data), slightly above that detected in the units receiving reclaimed water and slightly below that found in the SVTP effluent ($\bar{x}$=11.3±0.5 mg/L; SVCSD, unpub. data) during the study period. Dissolved phosphates were detected in Reclaimed Water monitoring units during not only the November 2000 sampling event when units were actively flooded with reclaimed water, but in the January and May 2001 events, when reclaimed water was either not present (Reclaimed Water + Muted Tidal) or being actively pumped into units (Reclaimed Water; Figure 13).

*DOC*. With the exception of undiked marshes, mean levels of dissolved organic carbon (DOC) appear to be similar between monitoring units and relatively high (Figure 10). Mean DOC ranged from a high of 18.76±4.82 mg/L in the Reclaimed Water monitoring unit to a low of 3.65±0.68 in the Undiked Marsh, with most of the other units ranging from 14.02±1.67 (Reclaimed Water + Muted Tidal) to 16.03±5.49 (Muted Tidal; Figure 10). In comparison, the highest DOC ever recorded in the history of the RMP occurred at the Petaluma River station in 1999 (10.76 mg/L; SFEI 2001).

*Metals*. Metals were sampled selectively in locations with low, moderate, and high water pHs to determine whether acidification episodes referenced above under pH were associated with pulses in metals and decreased water alkalinity. As acidification episodes were typically detected

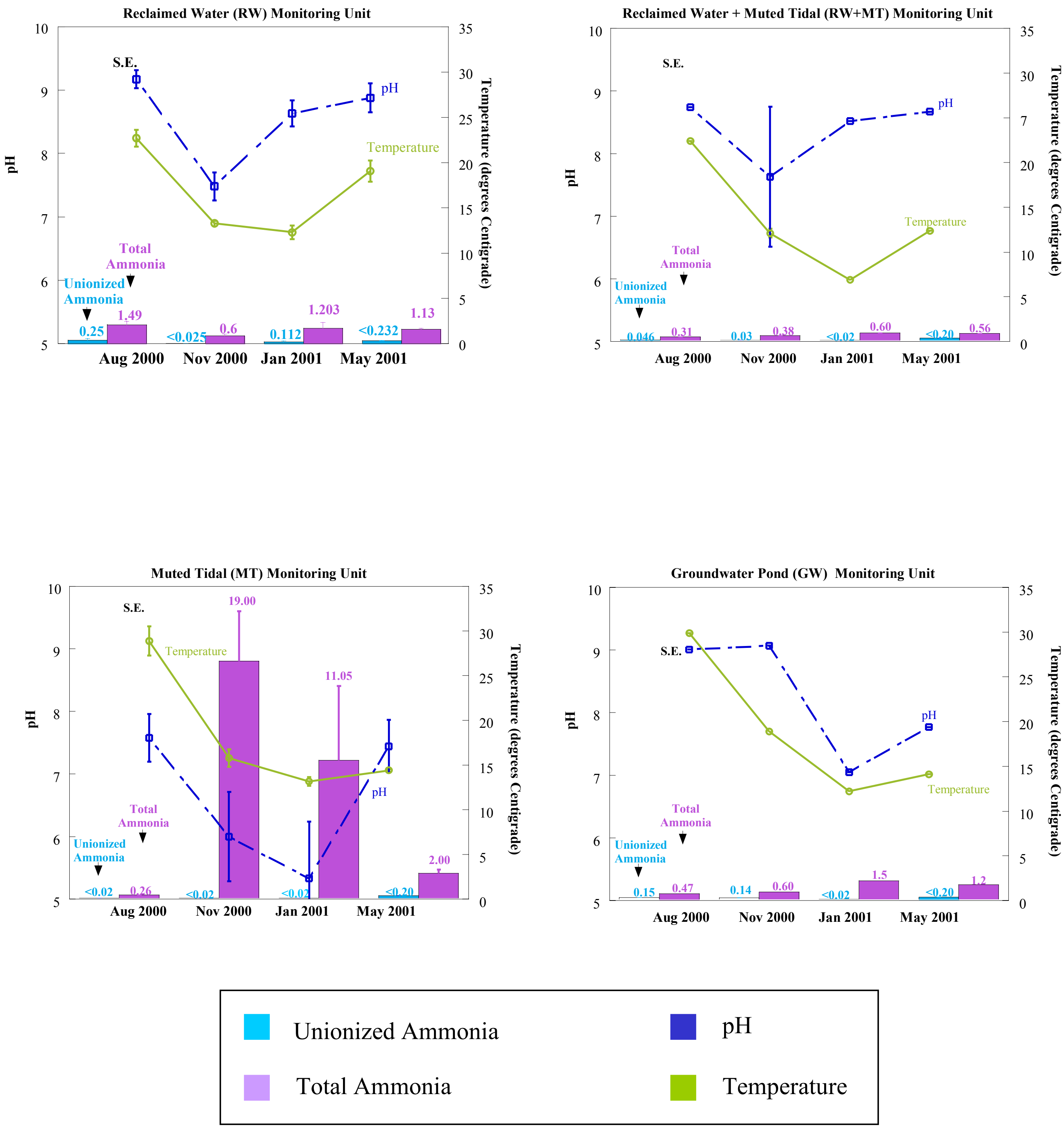


**Figure 14**. Temperature, pH, and concentrations of unionized ammonia and total ammonia in waters of the Hudeman Slough Case Study monitoring units. Bars indicate standard error of the mean during that sampling period.

in monitoring units where reclaimed water was not used, almost all of these sampling locations are in Muted Tidal (BS, TOH) or Passive Hydrologic Management (MU2) monitoring units. Relative to sampling locations with moderate to moderate-high pH, the areas with acidification (pH <5-6) and low alkalinity (<1 ppm) had pulses of aluminum, cadmium, chromium, copper, dissolved and total iron, manganese, nickel, lead, and zinc (Figure 15). Concentration of metals in sampling locations with very low pH (<3.5) exceeded that of other sampling locations anywhere from a factor of three (cadmium, chromium, manganese) to a factor of 15 (dissolved iron; Figure 15). Pulses of metals such as cadmium, chromium, copper, and lead were detected only in sampling locations where pH was very low (3.5), with concentrations generally minimal to non-detect in other sampling locations (Figure 15). Conversely, concentrations of metals such as aluminum, manganese, nickel, and zinc appeared to decrease somewhat linearly as the pH and alkalinity increased, with the lowest levels of these metals occurring in sampling locations with moderate-high pH (8.0) and alkalinity (110.3 ppm; Figure 15).

Results for some of these metals exceeded California Toxics Rule water quality criteria (U.S. EPA 2000), specifically copper, nickel, and zinc. As almost all of the sampling locations occurred in areas where salinity exceeded 5 ppt for more than 75 percent of the time (RWQCB 1995), the saltwater criteria was applied. Copper concentrations in all four sampling locations (4.4-36 ppb) were above the 4-day saltwater criteria of 3.1 ppb, with most of the sampling locations ranging between 4.4 and 7 parts per billion (ppb, Figure 15). Similarly, concentrations of nickel (40-800 ppb) greatly exceeded the 4-day saltwater criteria of 8 ppb in all four sampling locations. Zinc concentrations were above the 4-day saltwater criteria of 81 ppb only in the sampling with very low (3.5) to low (5) pHs, with levels of 95 and 410 ppb, respectively. One of the moderate-high pH (8.0) sampling locations was in a Reclaimed Water monitoring sub-unit. A one-time sample yielded concentrations of metals that were either among the lowest observed (aluminum, chromium, dissolved iron, manganese, and zinc) or non-detect (cadmium, copper, and lead). Only nickel concentrations (32 ppb) exceeded the 4-day saltwater criteria (8 ppb). Nickel concentrations in the treatment plant effluent during the study period averaged 3.1±0.2 ppb.

Silver, arsenic, mercury, and selenium were not detected in any of the sampling locations on any of the sampling dates. It should be noted, however, that the detection limit for mercury (1 ppb) exceeded the 4-day saltwater criteria of 0.025 ppb.

**Sediment Nutrients**

*Salinity*. Soil salinity patterns showed a strong response to both tidal and freshwater hydrologic regimes present in the monitoring units. As would be expected, mean soil salinities were lowest (2-6 ppt) in monitoring units with either no exposure to tidal flooding (Seasonal Pond, Groundwater Pond, Reclaimed Water, Passive Hydrologic Management) or an elevated degree of freshwater flooding relative to tidal flooding (Reclaimed Water + Muted Tidal; Figure 16). As discussed under the Water Quality results, marine salts present in areas that are currently flooded only by freshwater (e.g., run-off, precipitation) or reclaimed water may result from an elevated saline groundwater table, or, in diked areas near tidal sloughs, lateral transmission or subsurface flux of saline waters through levees. It may also represent a relic of historic tidal

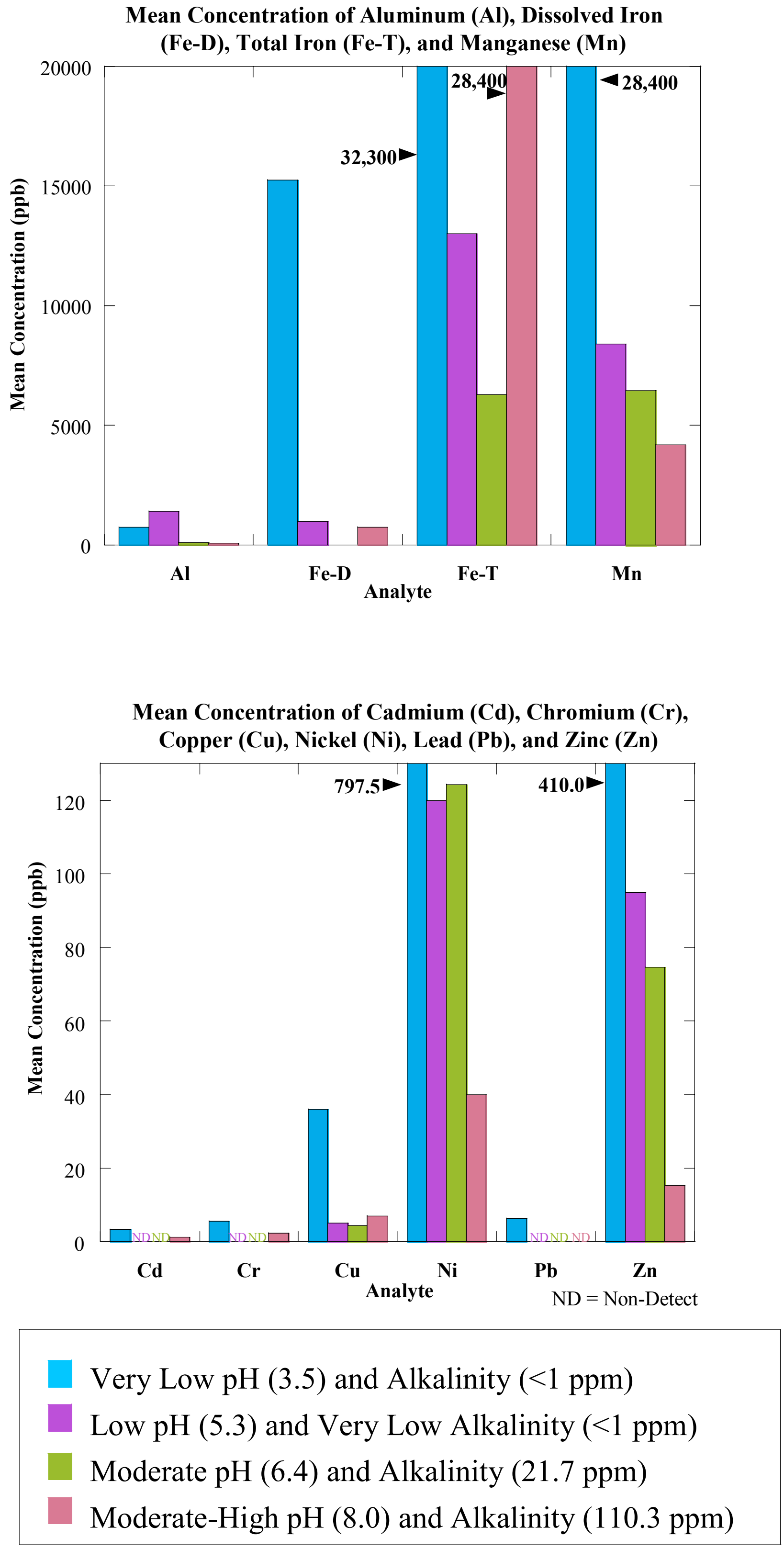


**Figure 15**. Mean concentrations of metals in water of the Hudeman Slough Case Study sampling areas with varying levels of pH and alkalinity.

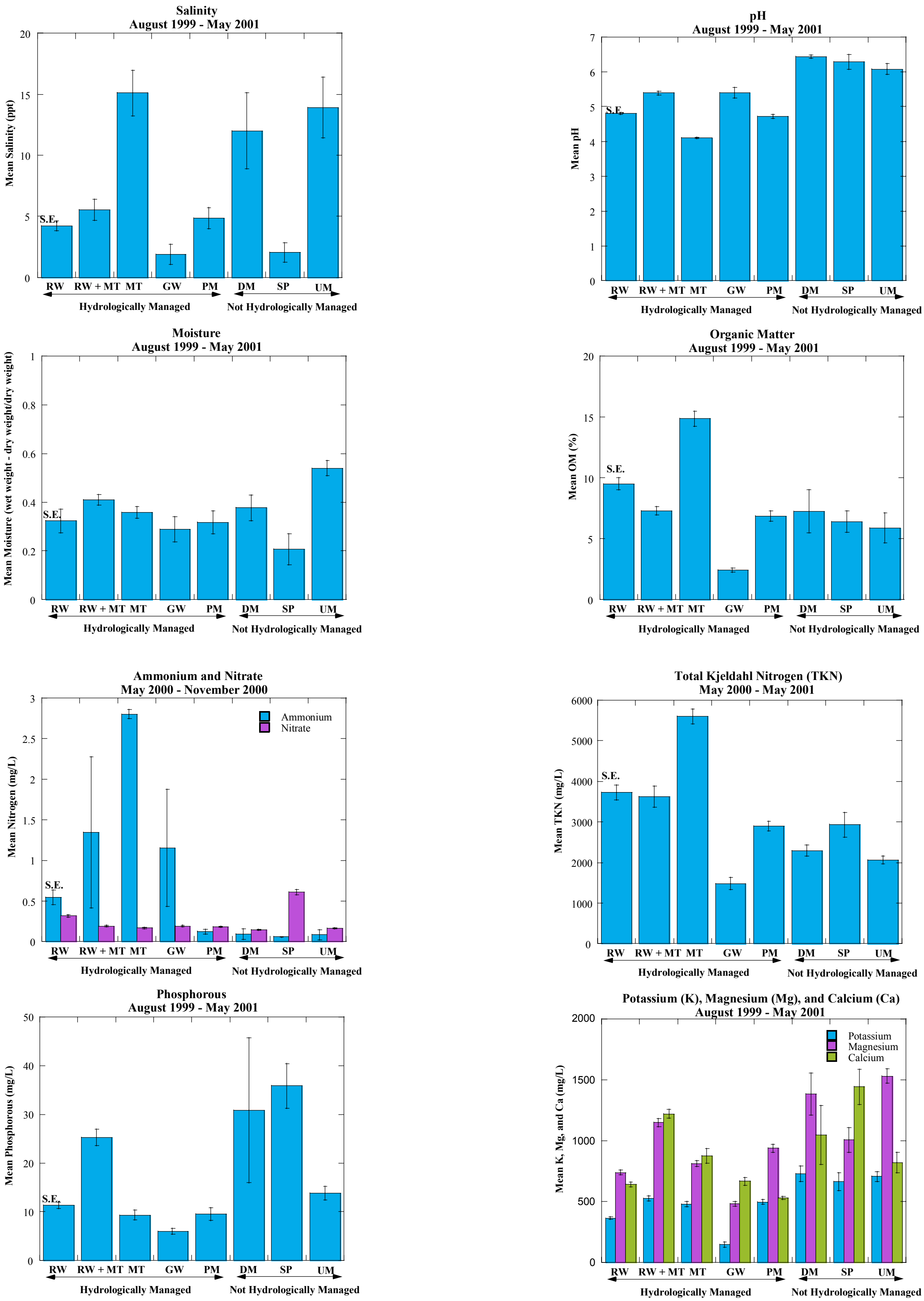


**Figure 16**. Mean sediment quality parameters and nutrient concentrations in sediment of monitoring units. Bars indicate standard error of the mean. (RW-reclaimed water; RW+MT-reclaimed water plus muted tidal; MT-muted tidal; PM-passive management; GW-groundwater pond; PM-passive management; DM-diked marsh; SP-seasonal pond; UM-undiked marsh)

flooding. The highest mean soil salinities occurred in the Muted Tidal, unmanaged Diked Marsh, and Undiked Marsh, with mean salinities ranging from 12.0±3.1 (unmanaged Diked Marsh) to 15.1±1.9 ppt (Muted Tidal; Figure 16). Mean soil salinity for the Muted Tidal monitoring unit appeared to be slightly higher than that of the Undiked Marsh (13.9±2.5 ppt), probably due to concentration of salts in the sediment after tidal waters within diked units evaporate. Salinity levels seemed to vary minimally between seasons and sampling locations in the Reclaimed Water monitoring units, whereas the other monitoring units displayed varying degrees of seasonal and sampling location variation, with the highest variability occurring in the Muted Tidal, Diked Marsh, and Undiked Marsh units. Typically, the highest salinities for all monitoring units were recorded during the summer and fall months, when evaporative potential was at its peak.

*pH*. In general, mean soil pH of monitoring units that were not hydrologically managed appeared to exceed that of units that were hydrologically managed. Mean pH for hydrologically managed monitoring units ranged from 4.11±0.02 (Muted Tidal) to 5.44±0.15 (Groundwater Pond; Figure 16). Mean soil pH for the unmanaged monitoring units produced an even tighter range, from 6.08±0.16 (Undiked Marsh) to 6.44±0.04 (unmanaged Diked Marsh; Figure 16). pH values reflect the fact that soils were dried prior to determining pH: when pH could be assessed in the field, pH values were generally 1 to 2 pH units higher, with the exception of two Reclaimed Water monitoring sub-units in November 1999, when interstitial soil water pHs ranged as low as 4.21-4.71. Soil pH showed little variation within monitoring units between seasons and between sampling locations.

*Moisture*. Despite disparate hydrologic regimes, mean levels of soil moisture appeared to be remarkably similar between monitoring units. Mean moisture levels for Reclaimed Water, Reclaimed Water + Muted Tidal, Muted Tidal, Groundwater Pond, Passive Hydrologic Management, and Diked Marsh displayed a moderately tight range (0.29-0.41; Figure 16). Mean moisture levels appeared to be slightly lower for the unmanaged Seasonal Pond, but probably not enough to characterize it as different from the others (0.21±0.06; Figure 16). However, the difference between these means and that of the Undiked Marsh (0.54±0.03) did appear to be large enough to allow us to conclude that mean moisture levels in the Undiked Marsh were probably higher than in other managed and unmanaged units. As might be expected, soil moisture levels peaked during the wet season (November and May sampling periods) and bottomed out during the dry season (August sampling period) for most of the monitoring units. Exceptions were the Reclaimed Water monitoring unit, which typically had high soil moisture levels only in November sampling periods, and Reclaimed Water + Muted Tidal, which had consistent moisture levels throughout all sampling periods. The degree of inundation or saturation during the fall, particularly the early fall months, differed between managed and unmanaged monitoring units, because some of the managed units were flooded early through either muted tidal flow or pumped groundwater or reclaimed water to attract waterbirds.

*Organic Matter (OM)*. On the basis of organic matter content, monitoring units appeared to fall into four groups. Mean OM levels of the Muted Tidal monitoring unit (14.9±0.6 percent) exceeded that of other monitoring units by at least five (5) percentage points (Figure 16). The second highest levels of OM appeared to occur in the Reclaimed Water monitoring unit (9.5±0.5 percent; Figure 16). Organic matter content of soils in the Reclaimed Water + Muted Tidal, Passive Hydrologic Management, Diked Marsh, Seasonal Ponds, and Undiked Marsh monitoring units were extremely similar, ranging narrowly between 5.9±1.2 percent (Undiked Marsh) to 7.3±1.8 percent (unmanaged Diked Marsh; Figure 16). The lowest OM levels were recorded in the Groundwater Pond (2.4±0.2 percent; Figure 16). In general, OM content showed moderate variation between seasons and sampling locations within monitoring units, although the managed monitoring units generally displayed more variability than the unmanaged ones.

*Total Kjeldahl Nitrogen (TKN).* Total Kjeldahl Nitrogen (TKN) results corresponded closely to those shown by monitoring units for OM, as might be expected, as TKN comprises both organic and inorganic nitrogen. The highest mean TKN was reported in the Muted Tidal monitoring unit (5,598.0±183.6 mg/L), followed by Reclaimed Water (3,725.8±182.2 mg/L), and Reclaimed Water + Muted Tidal (3,617.0±255.9 mg/L). Groundwater Pond also displayed the lowest TKN levels (1,479.3±148.3 mg/L; Figure 16). As with OM, TKN levels showed moderate variation between seasons and sampling locations within monitoring units (Figure 17).

*Ammonium/Nitrate.* Mean ammonium levels in the sediment were generally highest in hydrologically managed monitoring units. Highest levels were recorded in the Muted Tidal monitoring unit (2.80±0.06 mg/L), followed distantly by the Reclaimed Water + Muted Tidal (1.34±0.93 mg/L), Groundwater Pond (1.15±0.72 mg/L), and Reclaimed Water (0.55±0.09 mg/L; Figure 16). Mean ammonium levels of the remaining monitoring units (Passive Hydrologic Management, Diked Marsh, Seasonal Ponds, and Undiked Marsh) were lower and roughly similar (0.06-0.12 mg/L) between units (Figure 16). With some exceptions, monitoring units demonstrated little variability in ammonium levels either between seasons or sampling locations within monitoring units (Figure 17). The Reclaimed Water + Muted Tidal and Groundwater Pond monitoring units showed both the greatest seasonal variability and the greatest variability between sampling locations (Figure 17). Ammonium levels peaked in May 2000 in the Reclaimed Water + Muted Tidal monitoring units and in November 2000 in the Groundwater Pond (Figure 17).

The Seasonal Pond and Reclaimed Water monitoring units had the highest mean nitrate levels, 0.61±0.39 and 0.32±0.12 mg/L, respectively (Figure 16). Mean nitrate levels in the remaining monitoring units were roughly similar, ranging narrowly from 0.15±0.01 mg/L (unmanaged Diked Marsh) to 0.19±0.07 mg/L (Reclaimed Water + Muted Tidal; Figure 16). Variation in nitrate levels between seasons and sampling locations within monitoring units also appeared minimal (Figure 17). The Reclaimed Water and Reclaimed Water + Muted Tidal monitoring units displayed slight increases in nitrates during the summer (August 2000), whereas some of the other units appeared to have the highest levels in the fall (November 2000; Figure 17). In fact, high nitrate levels in November 2000 appeared to drive the high mean generated by the Seasonal Pond monitoring unit (Figure 16). With the exception of the Passive Hydrologic Management unit, mean ammonium levels exceeded mean nitrate levels in the managed monitoring units, while the converse was generally true for the unmanaged ones.

*Phosphorous*. The pattern for phosphorous differed to some degree from that of nitrogen. While Seasonal Pond (35.8±4.5 mg/L) appeared to have the highest mean phosphorous levels, as well as the highest mean nitrate levels, the second and third highest concentrations were observed in the unmanaged Diked Marsh (30.8±14.8 mg/L) and Reclaimed Water + Muted Tidal (25.3±1.7

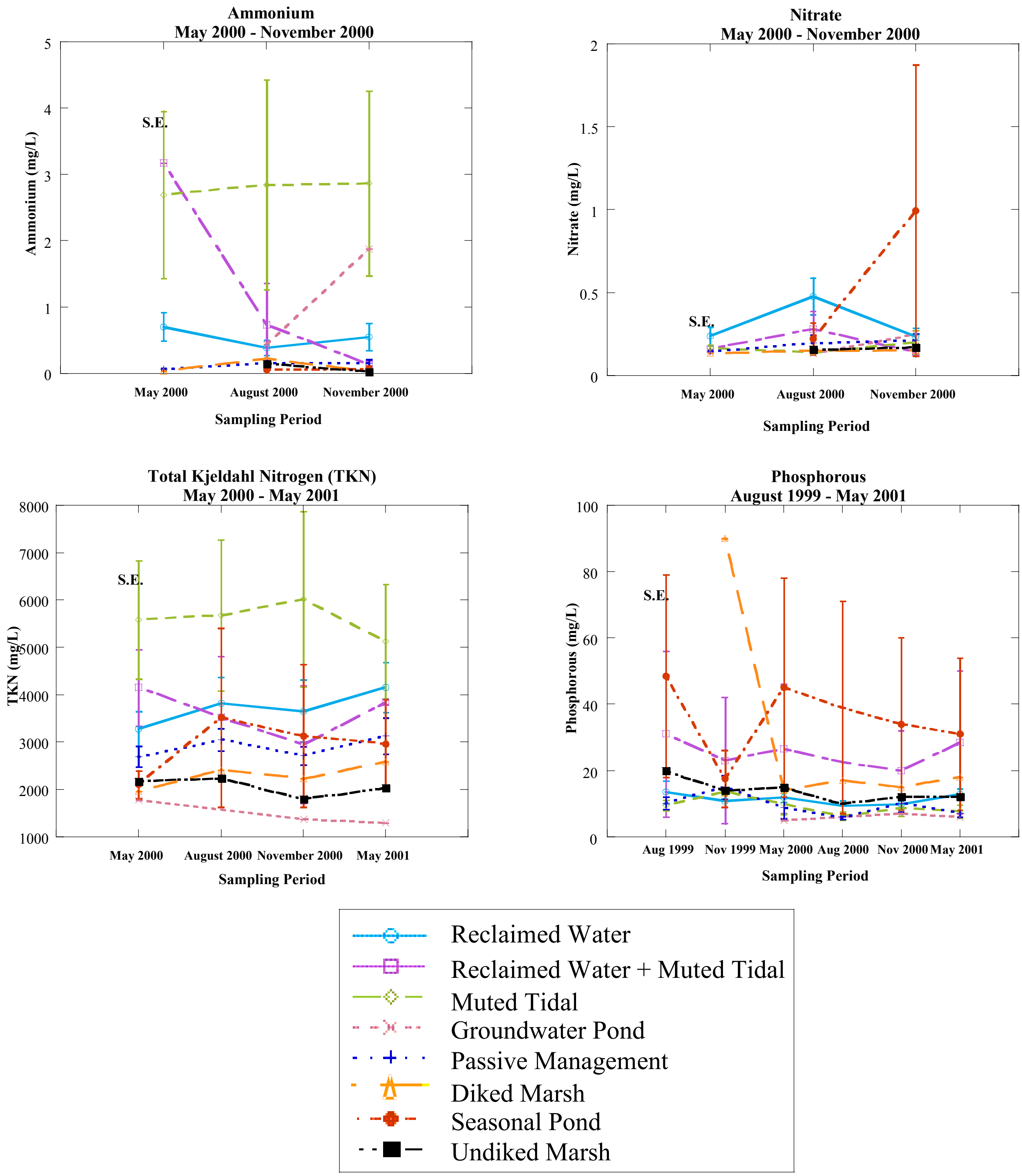


**Figure 17**. Nutrient concentrations in sediment of Hudeman Slough Case Study monitoring units during sampling period. Nitrate and ammonium were only sampled from May 2000 - November 2000; TKN, May 2000 - May 2001, while phosphorous was sampled during the entire study period. Bars indicate standard error for that sampling period.

mg/L) monitoring units (Figure 16). Mean phosphorous levels for the Undiked Marsh (13.8±1.4 mg/L), Reclaimed Water (11.3±0.7 mg/L), Passive Hydrologic Management (9.5±1.3 mg/L), and Muted Tidal (9.3 ± 1.0 mg/L) monitoring units appeared to be relatively similar (Figure 16). Lowest mean phosphorous levels were recorded in the Groundwater Pond monitoring unit (6.0 ± 0.6 mg/L; Figure 16). The greatest variation in phosphorous levels between sampling locations appeared to occur in the Seasonal Pond and Diked Marsh monitoring units. Similarly, these two units also showed the greatest variation in phosphorous concentrations between seasons (Figure 17). In fact, elevated phosphorous levels in November 1999 appeared to artificially inflate the mean for the unmanaged Diked Marsh monitoring unit, as phosphorous levels throughout the other sampling periods were generally similar to the other units and consistent between seasons. Certainly, no spike in phosphorous concentrations was detected during the same time of year (November) in 2000 (Figure 17). Conversely, phosphorous levels in the Seasonal Pond monitoring unit remained elevated throughout all sampling periods, except November 1999, when it dropped as much as 20 mg/L (Figure 17). Phosphorous concentrations in other monitoring units were generally stable between sampling periods (Figure 17).

*Potassium, Magnesium, and Calcium*. In general, mean concentrations of micronutrients or common metals such as potassium, magnesium, and calcium appeared to be higher in monitoring units that were not hydrologically managed, with the possible exception of Reclaimed Water + Muted Tidal (Figure 16). Mean potassium levels generally ranged between 363.5±11.0 mg/L (Reclaimed Water) and 731.0±64.6 mg/L (unmanaged Diked Marsh), except for Groundwater Pond, which had lower levels (146.3±21.4 mg/L; Figure 16). In general, the highest potassium levels occurred in unmanaged monitoring units (e.g., unmanaged Diked Marsh, Seasonal Ponds, and Undiked Marsh; Figure 16). Similarly, magnesium levels were highest in the Undiked Marsh (1,531.8±56.9 mg/L) and unmanaged Diked Marsh (1,382.8±173.5 mg/L) monitoring units, while calcium levels were highest in the Seasonal Pond (1,441.4±144.8 mg/L), Reclaimed Water + Muted Tidal (1,221.0±35.7 mg/L), and unmanaged Diked Marsh (1,048.6±240.9 mg/L) monitoring units (Figure 16). Lowest mean magnesium concentrations were recorded in the Groundwater Pond (482.0±21.0 mg/L) monitoring unit, with lowest mean calcium concentrations in the Passive Hydrologic Management (530.7±11.8 mg/L) unit (Figure 16). Potassium, magnesium, and calcium levels remained strongly consistent between sampling seasons and moderately similar between sampling locations within monitoring units.

*Cation Exchange Capacity*. Mean CEC of most of the diked and undiked units dominated by salt marsh vegetation (i.e., pickleweed) was roughly similar, regardless of whether the area was fully tidal, muted tidal, or not tidal at all. CEC within these five monitoring units (Reclaimed Water + Muted Tidal, Muted Tidal, Passive Hydrologic Management, Diked Marsh, and Undiked Marsh) averaged approximately 36.0±2.6 to 41.0±1.9 meq/g. Means for the other monitoring units were 30.5±1.2 meq/g for the Reclaimed Water monitoring unit; 24.0±1.2 meq/g for Seasonal Ponds, and 13.5±0.5 meq/g for Groundwater Pond.

*Principal Components Analysis*. Indirect ordination using sediment quality variables in a PCA produced only a moderate amount of separation between sample plots, even after being rotated (Varimax; Figure 18). The first principal component axis (PC1) accounted for approximately 40.2 percent of the variance and seemed related largely to the degree of tidal influence present.

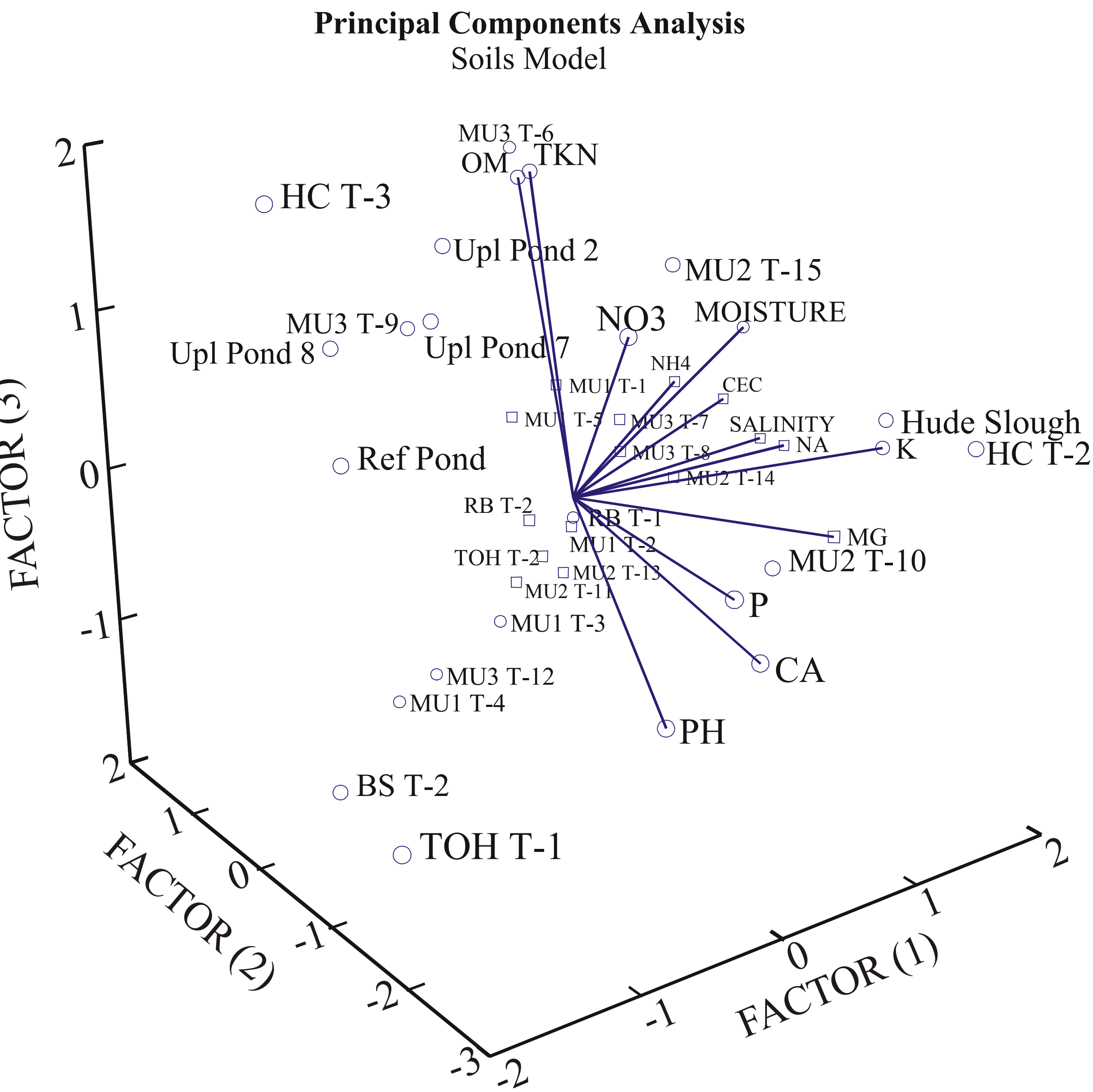


**Figure 18**. Three principal component factors and structure of sampling locations using soils-related variables.

Significant (>0.696) positive loadings on PC1 occurred for salinity, moisture, CEC, and concentrations of ammonium and sodium. Tidal flushing not only increases salinity through elevated concentrations of sodium, but often increases soil moisture content, thereby inhibiting conversion of ammonium to nitrate and breakdown of organic matter within the largely clay soils, and increasing CEC. The second axis (PC2) accounted for 24.8 percent of the variance, with significant negative loadings on PC2 coming from pH, phosphorous, and calcium. Its significance was harder to explain, but it appeared to largely separate diked historic baylands from undiked baylands and historic upland areas. Higher pH would be expected not only in historic upland areas that are low in sulfides and only inundated seasonally, but in sulfide-rich undiked marshes that do not undergo extended periods of oxidation. Similarly, Undiked Marshes often have elevated concentrations of phosphorous (Mitsch and Gosselink 1986), as might areas that receive significant flooding from phosphorous-rich stream and river waters. A third axis (PC3) contributed only minimally to the model (15.9 percent of variance). Significant positive loadings for OM, nitrate, and TKN suggest that PC3 was largely related to a nitrogen gradient. Based on these soil variables, only the unmanaged diked marsh and undiked marsh sample plots could be clearly separated from the other sampling locations (Figure 18). In general, sample plots appeared to cluster into one main group that included all Reclaimed Water, Passive Hydrologic Management, and Groundwater Pond sample plots, as well as some of the Reclaimed Water + Muted Tidal, Muted Tidal, and Seasonal Pond plots.

**Sediment Contaminants**

*Total Metals*. The Passive Hydrologic Management monitoring unit appeared to have the highest mean concentration of total metals (39,071.2±4,668.4 ppm), while the neighboring areas that are flooded with reclaimed water appeared to have among the lowest (18,042.2±1,360.2 ppm; Figure 19). All of the monitoring units appeared to have a lower mean concentration of total metals than that reported for the two San Pablo Bay RMP sampling locations (Napa River, BD22 and Petaluma River, BD15) in 1999, the most recent year of data publicly available (Figure 19). For each of the metals sampled (e.g., arsenic, mercury, etc.), Reclaimed Water monitoring units typically appeared to have either the lowest or second lowest mean concentration (Figure 20). However, mean metal concentrations in all of the monitoring units appeared generally low or moderate (Figure 20). With a few exceptions, mean metal concentrations in the monitoring units were below the ambient level standards (40-100 percent fines) developed by SFEI and the ERL and ERM standards developed by NOAA. The exceptions were silver (exceed ambient: all monitoring units), arsenic (exceed ERL: Passive Hydrologic Management), and nickel (exceed ERM: Passive Hydrologic Management; exceed ERL: Muted Tidal and Undiked Marsh). While selenium was never detected in most of the monitoring units, the Undiked Marsh had one-time levels of selenium (1.67 ppm) that exceeded both ambient level standards (0.64 ppm) and concentrations recorded in the RMP locations in 1999 (0.29-0.31 ppm).

In general, mean concentrations of metals in all of the monitoring units fell below, and seemingly substantially below, those reported for the RMP locations in 1999 and two other San Francisco Bay marshes (China Camp and Petaluma Marsh) in 1995/1996 (Collins and May 1997). The primary exception was silver. Mean concentration of silver in all monitoring units (0.34-0.63 ppm) either equaled or exceeded that reported for the RMP locations (0.08-0.1 ppm) and the China Camp/Petaluma Marsh ones (0.18-0.445 ppm; Figure 20). Interestingly, mercury,

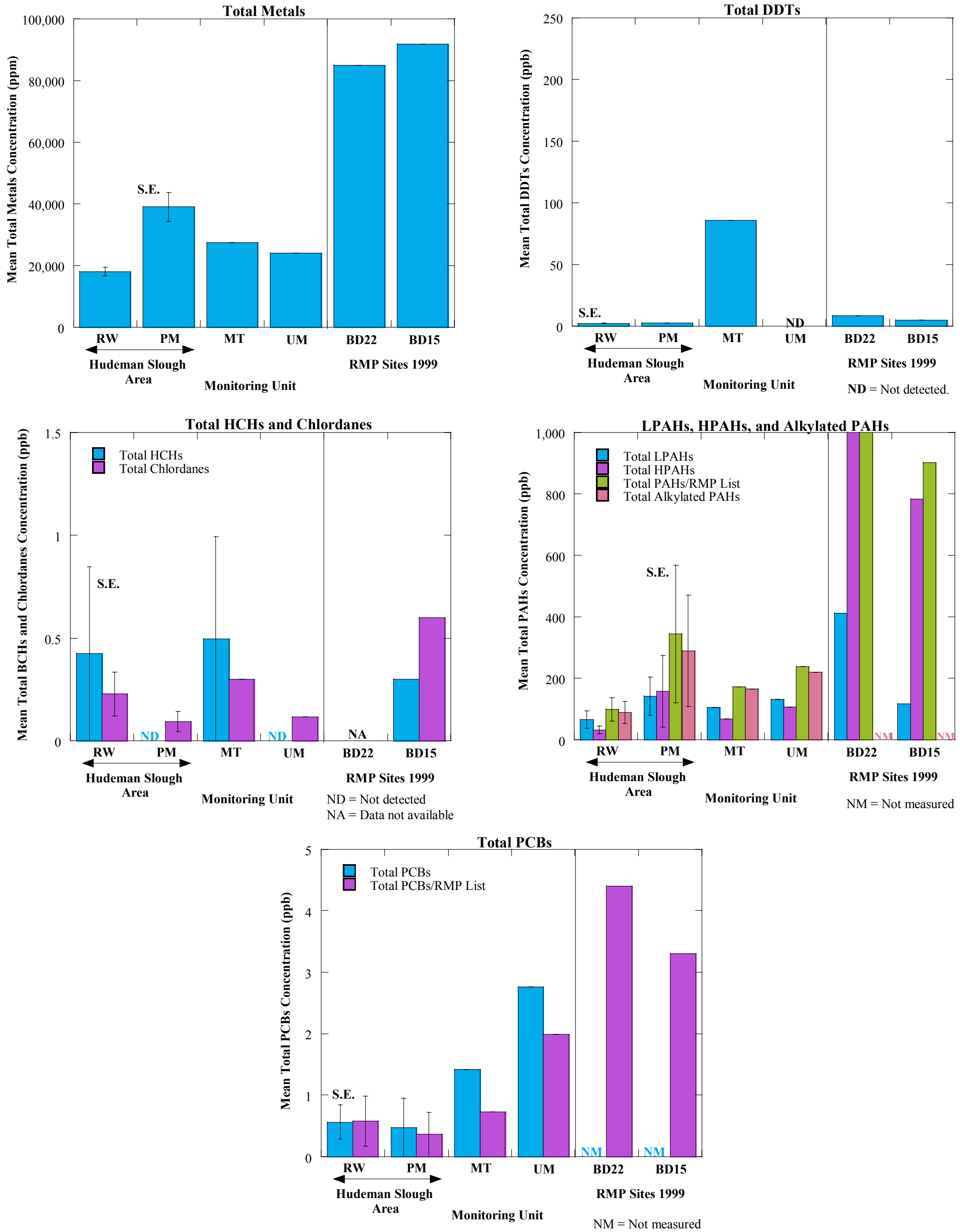


**Figure 19**. Mean concentrations of contaminants in sediment of Hudeman Slough Case Study monitoring units during study period (August 1999 - January 2001). Bars refer to standard error of the means for sampling locations within monitoring units, when multiple sampling locations were present. (RW-reclaimed water; PM-passive management; MT-muted tidal; UM-undiked marsh)

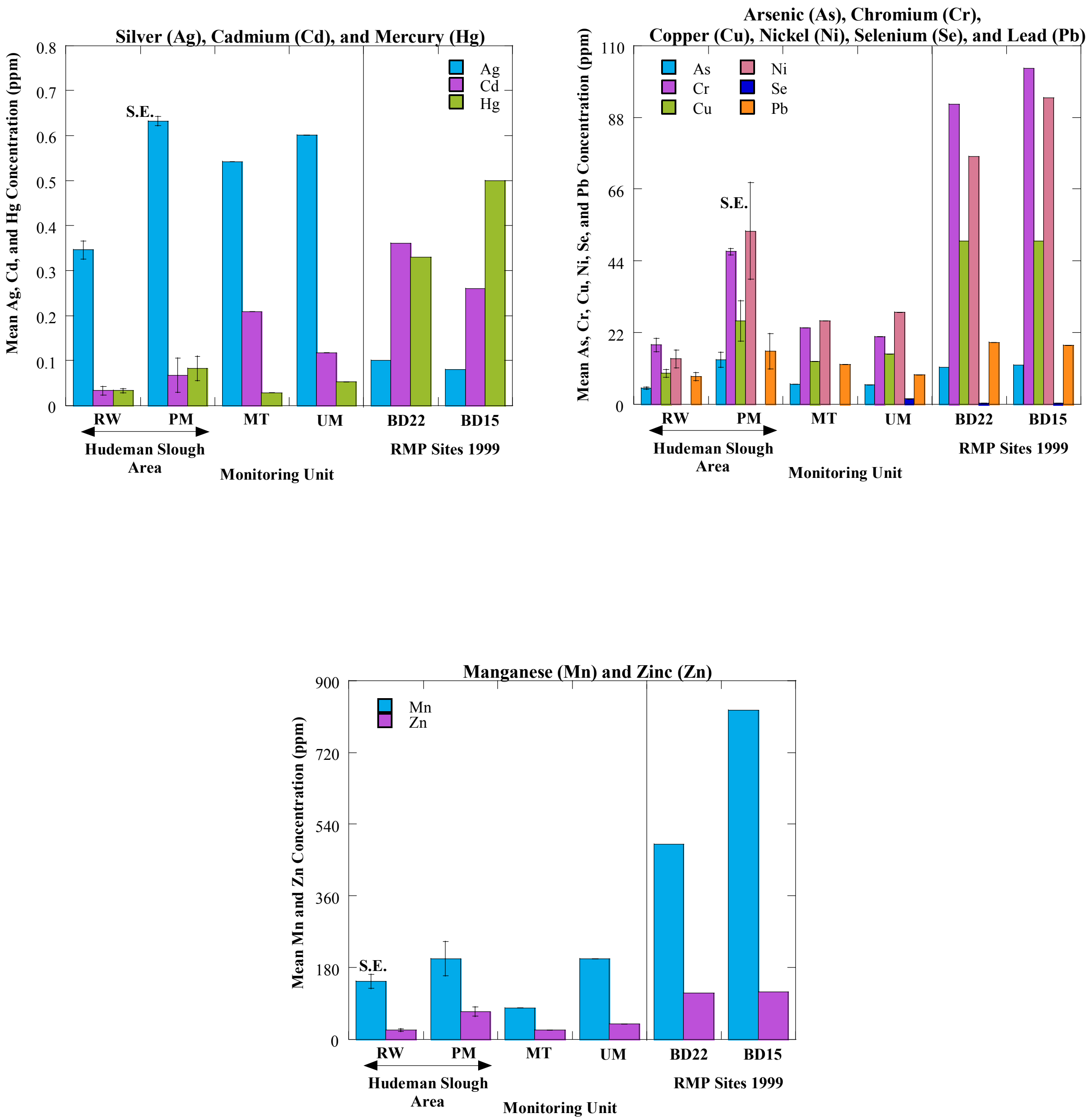


**Figure 20**. Mean concentrations of individual metals in sediments of Hudeman Slough Case Study monitoring units during study period (August 1999 - January 2001). Bars indicate standard error of the mean for sampling locations within monitoring units, when multiple sampling locations were present. (RW-reclaimed water; PM-passive management; MT-muted tidal; UM-undiked marsh)

one of the most problematic contaminants in San Pablo Bay, had mean concentrations (0.03-0.11 ppm; Figure 20) well below that of the RMP locations in 1999 (0.33-0.5 ppm) and the China Camp/Petaluma Marshes in 1995/1996 (0.27-0.42 ppm; Collins and May 1997). Concentrations of metals remained fairly consistent between sampling events (August 1999, February 2000, January 2001; Appendix A). A pulse in cadmium concentrations was observed in August 1999 for the Muted Tidal monitoring unit, while pulses in mercury and nickel concentrations were observed during that same period in the Passive Hydrologic Management monitoring unit (Appendix A, Figure A-1).

Mean concentration of iron within sediments was not included in Figure 20, but it ranged from 9,396.7±597.4 ppm in the Reclaimed Water monitoring unit to 21,933.3±3,533.3 ppm in the Passive Hydrologic Management monitoring unit, with a mean for all units of 15,799.2±2,626.2 ppm.

*Total DDTs*. Mean concentrations of Total DDTs appeared to be highest in the Muted Tidal monitoring unit (85.81±0.00 ppb), well above levels detected in the Reclaimed Water (2.27±0.11 ppb) and Passive Hydrologic Management (2.59±0.00 ppb) monitoring units (Figure 19). (As noted in Methods, standard errors represent variability between sampling locations rather than variability between sampling periods.) DDTs were not detected during any of the sampling events in the Undiked Marsh monitoring unit (Figure 19; Appendix A). Concentrations of Total DDTs in the Muted Tidal monitoring unit were consistently elevated throughout all sampling events (Appendix A). DDT concentrations within the Muted Tidal monitoring unit exceeded all standards (ambient, ERL, and ERM) and appeared to be substantially higher than levels recorded for the RMP locations in 1999 (5-8.2 ppb) and two San Francisco Bay area marshes (China Camp and Petaluma Marsh) in 1995/1996 (2.34-7.96 ppb; Collins and May 1997). However, it should be noted that these elevated concentrations in the Muted Tidal monitoring unit were detected at one sampling site and may not be representative of DDT levels within this monitoring unit as a whole.

*Total HCHs and Chlordanes*. Mean concentration of Total HCHs and Total Chlordanes appeared to be highest in the Muted Tidal and Reclaimed Water monitoring units (Figure 19). HCHs were not detected during any sampling event in the Passive Hydrologic Management and Undiked Marsh monitoring units, and mean Total Chlordane concentrations within these monitoring units appeared to be roughly half that of the Muted Tidal (0.30±0.00 ppb) and Reclaimed Water (0.22±0.11 ppb) units (Figure 19). However, only mean Total HCHs reported in the Muted Tidal monitoring unit actually exceeded any standards, specifically ambient standards developed by SFEI (0.48 ppb). Mean Total HCH levels in the Muted Tidal (0.75±0.00 ppb) monitoring unit also appeared to possibly exceed concentrations reported in the Petaluma River RMP location in 1999 (0.3 ppb) and in the San Francisco Bay area marshes (China Camp/Petaluma Marsh) in 1995/1996 (not detected to 0.37 ppb; Collins and May 1997). Mean concentrations of Total HCHs were driven by elevated levels detected in February 2000. HCHs were not detected at all in the January 2001 sampling event (Appendix A, Figures A-2 and A-4). HCHs and chlordanes were not sampled in the August 1999 sampling event.

A pulse also appeared to largely account for the mean Total Chlordane concentrations recorded in the Reclaimed Water, Muted Tidal, and Undiked Marsh monitoring units, although the pulse in this case occurred in January 2001 (Appendix A, Figure A-4). In general, mean Total Chlordane concentrations of all the monitoring units (0.12-0.30 ppb) fell below or toward the lower end of the range of concentrations reported for the Petaluma River RMP location in 1999 (0.6 ppb) and the two San Francisco Bay area marshes in 1995/1996 (0.1-5.8 ppb; Collins and May 1997).

*Total LPAHs, HPAHs, and Alkylated PAHs*. Mean concentrations of PAHs in the Reclaimed Water monitoring unit appeared to be less than or similar to the Muted Tidal and Undiked Marsh monitoring units (Figure 19). PAH concentrations appeared to be highest in the Passive Hydrologic Management monitoring unit (Figure 19). However, with the exception of Total LPAHs detected in the Petaluma River RMP station, mean concentrations of LPAHs, HPAHs, and Total PAHs in all of the monitoring units fell below those reported for the RMP sampling locations in 1999 and the two San Francisco Bay area marshes in 1995/1996 (490-755 ppb; Collins and May 1997) (Figure 19). Also, none of the monitoring units had concentrations of PAHs that exceeded ambient, ERL, or ERM standards. In terms of variation between sampling events, PAH concentrations detected in the January 2001 sampling event appeared to substantially exceed those detected in the February 2000 event, at least for the Reclaimed Water, Passive Hydrologic Management, and Undiked Marsh monitoring units (Appendix A, Figures A-2 and A-4). PAHs were not sampled during the August 1999 sampling event.

*Total PCBs*. Mean concentrations of Total PCBs appeared to be generally highest in monitoring units currently exposed to tidal flushing, specifically the Undiked Marsh and Muted Tidal monitoring units (Figure 19). Mean PCB concentrations within tidal units (1.42-2.76 ppb) appeared to be generally three to five times higher than non-tidal ones (0.47-0.56 ppb), with the Undiked Marsh area having the highest mean (2.76±0.009 ppb; Figure 19). However, as with some of the other contaminants, mean PCB concentrations within all of the monitoring units were lower than those reported for the RMP sampling locations in 1999 (3.3-4.4 ppb) and the two San Francisco Bay area marshes in 1995/1996 (5-12.6 ppb; Collins and May 1997). Means in the tidal units did appear to be strongly driven by a PCB pulse in the January 2001 sampling event, and PCB concentrations in the Undiked Marsh during this month (4.3±0.00 ppb) were certainly similar to the RMP and Bay area marsh PCB levels referenced above (Appendix A, Figure A-4). PCBs were not sampled during the August 1999 sampling event. None of the monitoring units had PCB concentrations that exceeded ambient, ERL, or ERM standards.

*Cluster Analysis*. Sampling locations appeared generally to separate into three (3) groups (Figure 21). The four (4) Reclaimed Water sampling locations clustered with the one-time sampling location on upper Hudeman Creek. Rather than this Hudeman "cluster" then grouping with the two (2) other geographically proximate sampling locations in the Passive Hydrologic Management monitoring unit, it actually grouped with the Muted Tidal and Undiked Marsh monitoring units, both of which are located several miles to the east. This group then combined with one of the two Passive Hydrologic Management monitoring unit sampling locations (MU2 OS), while the other (MU2 BD) remained distinct.

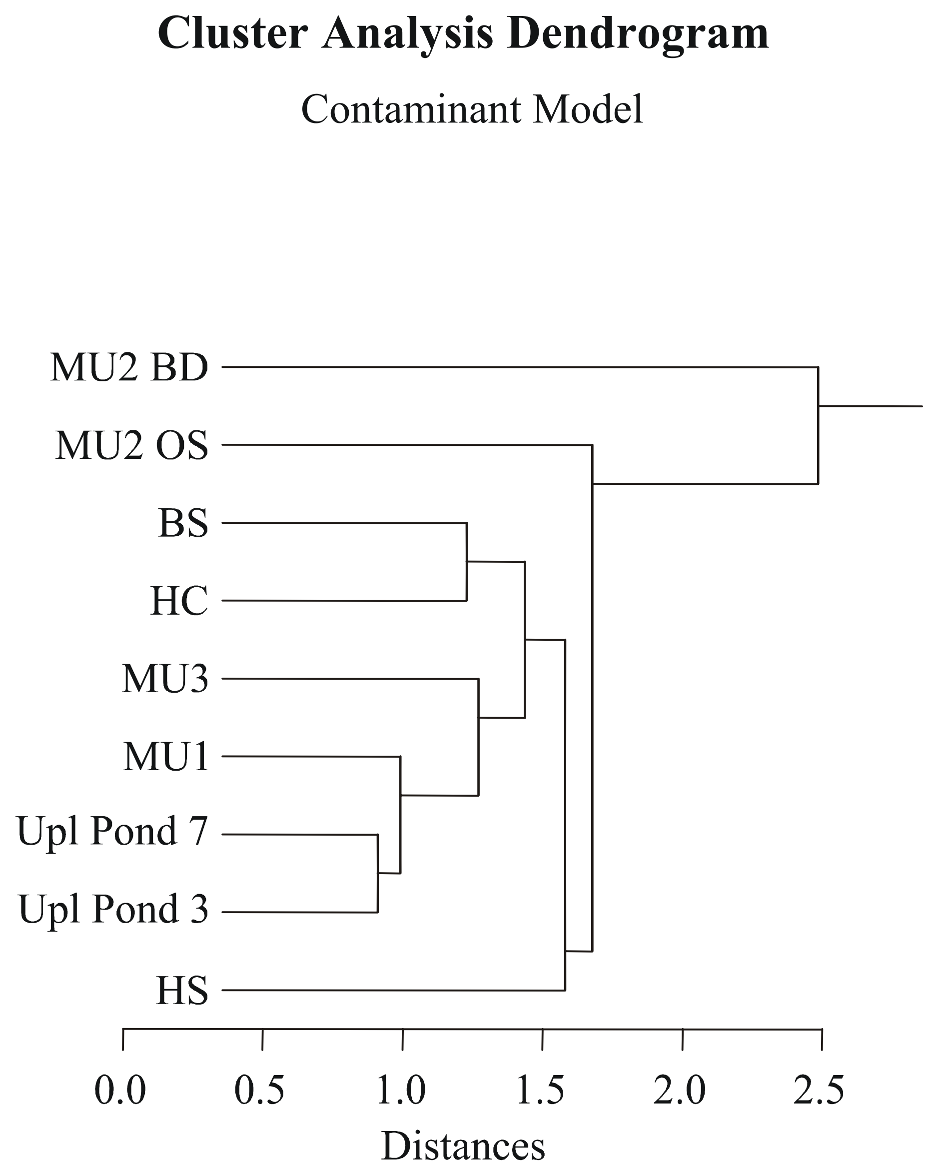


**Figure 21**. Dendrogram depicting results of classification analysis using contaminant variables, including total metals, total DDTs, total BCHs, total Chlordanes, total LPAHs, total HPAHs, alkylated PAHs, and total PCBs.

## Sediment Bioassay

Mean percent survival of *Eohaustorius* amphipods from Reclaimed Water monitoring units either equaled or exceeded that of other monitoring units during all three testing periods (Table 5). The number of organisms surviving in sediment of the Reclaimed Water monitoring unit remained comparatively consistent between sampling periods, ranging from 74.7 ± 9.91 percent (August 1999) to 92.5±2.5 percent (January 2001; Table 5). Survival rates for the other monitoring units displayed a more variable pattern. For example, amphipod survival in the Passive Hydrologic Management and Muted Tidal monitoring units hovered between 30 and 50 percent for the August 1999 and February 2000 testing periods (Table 5). However, in January 2001, the pattern shifted dramatically, with survival rates in the Passive Hydrologic Management monitoring unit jumping to 76±0 percent while those in the Muted Tidal monitoring unit plummeted to 0±0 percent (Table 5). Sediment from the Undiked Marsh monitoring unit typically generated relatively high survival of amphipods (80-87 percent), with the exception of August 1999 (50±0 percent; Table 5).

**Table 5.** *Eohaustorius* sediment bioassay results for the Hudeman Slough Enhancement Wetlands Case Study.

For February 2000 and January 2001 sampling periods, bioassay tests were re-run on selected samples in which acidic conditions developed in overlying waters during initial tests: both sediment and overlying waters were pH adjusted during second run. Boldfaced numbers refer to percent survival rates that exceeded the Bay Protection and Toxic Clean-up Program's "reference envelope" for ambient conditions in San Francisco Bay. A p of 0.10 (69.5 percent survival) was selected for this study, meaning that sampling locations with survival less than 69.5 percent were as toxic or more toxic than the worst 10 percent of sites sampled in San Francisco Bay.

| | August 1999 | February 2000 | | January 2001 | |
|---|---|---|---|---|---|
| | No pH Adj. | No pH Adj. | pH Adj. | No pH Adj. | pH Adj. |
| **Monitoring Unit** | % Survival Mean (SE) | % Survival Mean (SE) | % Survival Mean (SE) | % Survival Mean (SE) | % Survival Mean (SE) |
| Reclaimed Water | **74.7 (9.9)** | **82.3 (11.3)** | | **92.5 (2.5)** | **94.3 (1.4)** |
| Passive Hydrologic Management | 31.0 (0.0) | 26.5 (13.5) | 55.5 (25.5) | **76.0 (0.0)** | 53.0 (0.0) |
| Muted Tidal | 48.0 (0.0) | 36.0 (0.0) | 50.0 (0.0) | 0.0 (0.0) | **84.0 (0.0)** |
| Undiked Marsh | 50.0 (0.0) | **86.0 (0.0)** | | **80.0 (0.0)** | |

In the February 2000 and January 2001 testing periods, survival tests were re-run for selected sampling locations. During all three testing periods, the laboratory observed precipitous drops in pH in sediment from these sampling locations, which were also typically the ones with comparatively low amphipod survival rates. To determine what effect low pH might be having on survival, a second test was performed, using sediment that had been pH adjusted. In general, survival rates improved by 2 percent (Reclaimed Water; January 2001) to 84 percent (84±0 percent; Muted Tidal; January 2001). However, on two separate occasions (February 2000 and January 2001), amphipod mortality actually increased from 10 to 23 percent following pH adjustment at one of the sampling locations in the Passive Hydrologic Management monitoring unit.

Of the individual sampling locations, only sediment of two Reclaimed Water sampling locations produced survival rates with no statistically significant difference from those of the Control sediment, which was collected in Coos Bay, Oregon. One location – a created pond filled perennially with reclaimed water – was similar to the Control on all three testing dates. Comparisons of survival rates from our study are complicated by the high variability exhibited by most of the monitoring units, but rates of at least the Reclaimed Water monitoring unit appeared to compare favorably with those from the RMP, which were also quite variable. In 1999, sediment from the sampling station on the Napa River generated survival rates ranging from as low as 8 percent survival in August to as high as 65 percent in February. In terms of standards set by the Bay Protection and Toxic Clean-up Program, only survival rates of the Reclaimed Water Monitoring Unit fell within the 10 percent "reference envelope" standard on all testing periods (Table 5). The Program allows for user selection of a reference envelope based on standard deviation, with 10 percent being the most commonly used envelope. These standards were also met by the Undiked Marsh monitoring unit in February 2000 and January 2001, as well as the pH-adjusted Muted Tidal monitoring unit in January 2001 (Table 5).

***Food Chain Support and Wildlife Use***

**Vegetation**

*Total Cover, Vascular Plant Cover, and Canopy Complexity*. A list of all plant species observed, including the ones most commonly encountered along vegetation transects, is provided in Appendix B. In general, the Reclaimed Water monitoring unit had similar total cover, vascular plant cover, and canopy complexity as other managed monitoring units. Only the unmanaged monitoring units, Diked Marsh (99±1 percent) and Undiked Marsh (97±0 percent), generated close to 100 percent vegetation cover. The remainder ranged from being sparsely vegetated (30.2±8.2 percent; Seasonal Ponds) to moderately vegetated (89.1±1 percent; Reclaimed Water + Muted Tidal), with unvegetated areas either being comprised of bare ground, including pannes, or open water areas (Figure 22). The Reclaimed Water monitoring unit averaged approximately 80.0±4.4 percent vegetation cover (Figure 22). Means for vascular plant cover, which takes into account "layering" of different plant within herb/forb and shrub strata, were generally from 1 percent (Diked Marsh) to 35 (Seasonal Pond) percent higher (Figure 22), suggesting that there was not much diversity within canopy strata.

Canopy complexity expands upon this layering to include presence of micro- and macro-algae and detritus. Among the macro-algal species or genera observed within monitoring units were *Hydrodictyon reticulatum*, *Spirogyra*, and *Ulothrix* (Table 6). Pennate diatoms (Bacillariophyceae) were the most dominant micro-algae present, typically in canopy breaks or unvegetated pannes, followed by another ochrophyte common to salt marshes, *Vaucheria* (Table 6). Unvegetated areas in the Reclaimed Water and Muted Tidal monitoring units also supported the blue-green algal genera *Oscillatoria* and *Synechocystis*, respectively (Table 6). Most of the algal taxa observed include species that occur in a variety of freshwater, brackish, and estuarine/marine habitats. As with vascular plant cover, all monitoring units displayed a jump in percent cover, but this time, the increase was more substantial. In this case, the highest canopy complexity was reported in the Passive Hydrologic Management monitoring unit (189.8±19.8 percent), and the lowest, in the Muted Tidal monitoring unit (92.8±36.4 percent; Figure 22).

*Vegetation Communities*. The hydrologically unmanaged monitoring units generally had a lower diversity of vegetation communities present than the managed ones. The unmanaged Diked Marsh and Undiked Marsh supported only one community (Brackish Marsh), while Seasonal Ponds supported three (subsaline seasonal wetland, moist grassland, and seasonal marsh), with subsaline seasonal wetland and seasonal marsh accounting for the most cover (Figure 22). Three