

ELKHORN SLOUGH

TECHNICAL REPORT SERIES 2019: 1

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Long-term trends and spatial patterns of water quality in estuarine wetlands of central California

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March 2019



HOW TO CITE THIS DOCUMENT

The appropriate citation for this document is:

Hicks K, Jeppesen R, Haskins J, Wasson K. 2019. Long-term trends and spatial patterns of water quality in estuarine wetlands of central California. Elkhorn Slough Technical Report Series 2019:1. Available at <http://www.elkhornslough.org/research-program/technical-report-series/>

AUTHOR AFFILIATION

Kathleen Hicks conducted this analysis as a part of the Applied Marine and Watershed Science professional Masters program at California State University Monterey Bay. The analysis was funded through a grant from the Water Resources Policy Initiative's Watershed Management Experiential Learning for USDA Careers Internship Program, enabling Hicks to serve as a Water Resources Intern at the Elkhorn Slough National Estuarine Research Reserve (ESNERR). Rikke Jeppesen, John Haskins, and Kerstin Wasson were employed by ESNERR during the preparation of this report.

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The mission of the Elkhorn Slough Foundation and the Elkhorn Slough National Estuarine Research Reserve is conservation of estuarine ecosystems and watersheds, with particular emphasis on Elkhorn Slough, a small estuary in central California. Both organizations practice science-based management, and strongly support applied conservation research as a tool for improving coastal decision-making and management. The Elkhorn Slough Technical Report Series is a means for archiving and disseminating data sets, curricula, research findings or other information that would be useful to coastal managers, educators, and researchers, yet are unlikely to be published in the primary literature.

Executive Summary

Elkhorn Slough and the surrounding wetlands comprise a highly eutrophic estuarine ecosystem in Monterey County in central California. These wetlands have been altered by human activities, including diking, harbor construction, and agriculture. The Elkhorn Slough Reserve has been conducting monthly water quality monitoring at 25 sites throughout the estuary since 1988. In order to analyze the long-term trends in these data, we performed both graphical and statistical analyses on nutrient and dissolved oxygen concentrations.

The graphical time series analysis of selected water quality parameters allowed us to compare the ranges of average nutrient levels in the 25 sites to see what regions had notably high concentrations. We grouped sites into similar geographic regions for analyses. Water quality was typically better for sites in the Lower and Middle Slough, and worse in regions with longer water retention times like the South Estuary and Moro Cojo Slough.

All regions had individual sites that reached high average levels (using a moving average window of 12 for monthly samples) relative to all sites for at least one parameter. In the Upper Slough, Carneros Creek had high levels of ammonia as N (1.5 mg/L) and orthophosphate as P (1.5 mg/L) and Blohm Porter Marsh had high levels of nitrate as N (15 mg/L). The Middle Slough had relatively good water quality except for Strawberry Road (4 mg/L for ammonia as N, 3 mg/L for nitrate as N, 1.5 mg/L for orthophosphate as P). Azevedo Pond sites had some of the higher levels of ammonia as N (1.5 mg/L in South and 1 mg/L in Azevedo Pond, Central) and orthophosphate as P (1.5 mg/L in South). In the Lower Estuary, the only relatively high value was for nitrate as N at Skipper's Landing (3 mg/L). Various sites in Moro Cojo appeared among the high concentrations of all three parameters (1.5 mg/L for ammonia as N, at Moss Landing Road, South, 7 mg/L of nitrate as N for Moss Landing Road, North and Moro Cojo Slough, and 2 mg/L of orthophosphate as P for the Moss Landing Sites). In Bennett Slough, Struve Pond had high levels of ammonia as N and orthophosphate as P (1 mg/L for both). The South Estuary had exceedingly high levels of nitrate as N at all sites, even as high as 50 mg/L at Tembladero Slough. These levels are high compared to other levels reported in literature for estuarine ecosystems at a global scale (Caffrey et al. 1997).

Graphical analysis of time series for each region and site revealed marked interannual variability in concentrations over time. In most cases, the temporal patterns of nutrient and dissolved oxygen concentrations did not closely follow precipitation or upwelling patterns, suggesting interannual differences in local tide gate management or surrounding land use management play a bigger role than broader scale weather or oceanographic drivers. These analyses also revealed some stark contrasts in temporal patterns among nearby sites, again highlighting the importance of local factors.

Seasonal Kendall tests showed that of three parameters (ammonia as N, nitrate as N, and orthophosphate as P) at 25 sites, 35 parameters had improved, 16 had worsened, and 24 had not significantly changed in either direction. Thus, patterns of improvement outnumbered patterns of deterioration of water quality conditions. After testing the results with a chi-squared test, we found a significant correlation by region ($p = 0.02$). The Middle and Upper regions of Elkhorn Slough, Bennett Slough, and Azevedo Ponds had the highest frequency of statistically significant water quality improvements, while the Lower region of Elkhorn Slough, Moro Cojo Slough, and the South Estuary had the highest frequency of water quality deterioration.

The results of these analyses offer encouragement, since improvements can be seen in areas where land management has improved due to improved farming practices as well as

restoration by the Elkhorn Slough Foundation, Elkhorn Slough Reserve, and partners. It is heartening that improvement in water quality can be achieved and documented, even in areas of relatively high nutrient concentrations. Despite the potential for slow response times due to legacy effects from nutrient enrichment, we documented significant improvement over relatively short time-scales. Future efforts will be necessary to continue these improvements and to reach water quality goals. Areas of concern can be pinpointed for conservation efforts undertaken by resource management agencies, conservation groups, and regulatory processes in these areas. More collaboration is still needed between agricultural stakeholders and estuarine scientists to identify linkages between specific land use practices and changes in nutrients in the Elkhorn Slough area.

Highlights

- Sites showed strongly contrasting patterns over time, with high variation among years that was not generally correlated to weather or oceanography, suggesting that local factors, such as land use activities and tide gate management, have strong and rapid effects on wetland water quality
- Overall water quality is improving with significant improvements in water quality over time outnumbering significant deterioration in water quality, for 25 sites and three nutrient water quality parameters
- The Middle and Upper regions of Elkhorn Slough, Bennett Slough, and Azevedo Ponds had the highest frequency of statistically significant water quality improvements, while the Lower region of Elkhorn Slough, Moro Cojo Slough, and the South Estuary had the highest frequency of water quality deterioration
- Water quality remains highly impaired at many sites, especially those with artificial tidal restriction resulting in increased residence times
- The significant improvements documented in regions with high conservation and restoration investments provide hope for the future, and illustrate that, despite the potential for slow response times due to legacy effects from nutrient enrichment, water quality can be improved relatively quickly when resources are appropriately directed

Background

Wetlands in and around Elkhorn Slough in Monterey County, Central California, have been highly altered by human activities, including extensive diking of wetland and construction of the Moss Landing harbor (Van Dyke and Wasson 2005). The amount of watershed under agricultural cultivation has been estimated between 7 and 26% (Gee et al. 2010, Saiz and Keeling 2016, Wankel et al. 2011). Eutrophication indicators such as algal mats, subtidal algal cover, and high levels of chlorophyll *a* are present, suggesting excessive nutrient inputs into the estuary (Hughes et al. 2011, Hughes et al. 2013; Jeppesen et al. 2018). Eutrophication is a threat to the ecological function of the estuary. The process of eutrophication can fuel high algal abundance, which in turn can lead to extreme fluctuations in levels of dissolved oxygen. Dissolved oxygen levels peak during the day while algae photosynthesize, and hypoxia (low oxygen) becomes more extreme overnight while algae respire in the absence of light (Hughes

2011). Strong swings in dissolved oxygen concentrations (hyperventilation) are apparent in the upper areas of the Slough, particularly in areas with restrictions on tidal flow and high concentrations of nutrients (Chapin et al. 2004; Beck and Bruland 2000). Hypoxia has been shown to attribute to stress and lower survival in fish and oysters in the Elkhorn Slough (Jeppesen et al. 2018).

Numerous conservation and restoration initiatives have attempted to improve water quality and restore ecological functions to wetlands in the Elkhorn Slough area. Many of the wetlands and adjacent uplands are owned by the Elkhorn Slough Foundation and the California Department of Fish and Wildlife (CDFW), as a part of the Moss Landing Wildlife Area and the Elkhorn Slough National Estuarine Research Reserve. The Elkhorn Slough Reserve is managed in partnership with NOAA and monitors estuarine wetlands in this region. Beneficial uses for the Elkhorn Slough have been identified and the Central California Regional Water Quality Control Board is in the process of setting Total Maximum Daily Load (TMDL) targets for the region (Saiz and Keeling 2016).

Problematic nutrient concentrations can be linked to large-scale climate drivers such as precipitation as well as local-scale land uses and may be an increasing concern over time. An early multi-year study of water quality by Caffrey et al. (1997) conducted for the Elkhorn Slough took place from 1988-1996. Caffrey et al. (1997) obtained data from the 1970s and observed that in all stations where they had overlapping data, the nitrate concentrations increased from the 1970s to the 1990s. High nitrate concentrations were linked to high rainfall. Wasson et al. (2017) correlated increases in nutrients with increased fertilizer use, and to increased algal mat cover. Nutrient input from rivers like the Salinas River and from agricultural drainages are significant freshwater inputs into the Elkhorn Slough, as identified by a draft report submitted to the Central California Regional Water Quality Control Board (Saiz and Keeling 2016). Over 52,000 acre-feet of discharge from the Old Salinas River and Tembladero Slough flows into the Elkhorn Slough.

Tidal exchange has been found to be an important factor in the estuary's response to high nutrient levels. Caffrey et al (1997) found that restrictions to tidal flow affected oxygen levels, with restricted areas becoming hypoxic or anoxic in late summer or early fall, which was not observed in tidally flushed marshes. Research conducted by Chapin et al. (2004) on nutrient sources and sinks observed high correlations of tidal cycling with water quality parameters. Hughes et al. (2011) studied how variables like tidal range, turbidity, salinity, temperature, depth, and distance to estuary mouth affected the estuary's response to the eutrophication driver of dissolved inorganic nutrients from the surrounding agricultural area. They found that tidal range correlated with primary and secondary indicators of eutrophication (chlorophyll *a*, and presence of floating and intertidal algal mats, hypoxia, daytime DO variation, hypoxia, sediment quality, pH, and free ammonia), with higher eutrophication more commonly in areas with anthropogenic restrictions on tidal exchange.

The estuary's response to high nutrient concentrations may be influenced by biotic factors. Chapin et al. (2004) suggested that denitrification in sediments and nutrient demand from macroalgae, benthic algae, and phytoplankton may play a significant role in the Elkhorn Slough nutrient cycle. Wise (2017) observed significant nutrient uptake by the prominent macroalgae *Ulva* and found that nutrients were both removed by and released from the sediments at different levels varying by site and time of year. Other studies have found differing distributions of ammonia-oxidizing bacteria in sites in the estuary that were impacted by agricultural runoff compared to unimpacted sites (Wankel et al. 2011). It is uncertain how much

the rates of sediment nutrient fluxes and biotic uptake of nutrients affects water quality at the Elkhorn Slough.

One methodology for studying the spatial distribution of water quality at the Elkhorn Slough and surrounding wetlands was developed in 2014 by Laura Mercado in collaboration with ESNERR scientists. This consists of a water quality index summarizing magnitude and frequency of threshold exceedance of different parameters (Mercado et al. 2014). The water quality index visually summarizes the results of monthly water sampling and a map for every year of the water quality record has been created in the form of a water quality report card. An interactive online report card is available at <http://elkhornslough.org/water/>. While Mercado et al.'s study does give a view of historical water quality level, it did not test for trends over time, which we focused on for this report.

Monitoring of restoration efforts has indicated successful improvements in water quality over short time scales. Gee et al. (2010) performed a study that focused on the effects of coincident restoration and tide gate management changes. Restoration at Azevedo Pond consisted of moving row crops 100 feet back from the high tide mark and replanting with native species. From the changes in agricultural practice, highly affected sites decreased in ammonia, nitrate, and phosphate. Sites closer to the restoration showed larger nutrient decreases even when the area restored was small compared to the watershed (averaging a 50% reduction).

The goal of our investigation was to examine long-term trends in water quality, with emphasis on nutrients and dissolved oxygen, at all 25 sites sampled monthly for the past 20-30 years. We were interested generally in whether water quality has gotten better or worse over time, and in comparing patterns in different geographic areas that have received varying levels of conservation investment. Time-series analysis of deseasonalized, average nutrient and dissolved oxygen concentrations were performed for each site. This would allow for close examination of average levels over time, comparing patterns between sites within each region, and comparison with environmental drivers. The seasonal Kendall test was used to determine if nutrient parameters had overall significantly increased or decreased over time, and if there was a regional pattern in changes in water quality.

Methods

Sites and years included

Of the sites that have historically been studied by the Elkhorn Slough National Estuarine Research Reserve (ESNERR) water quality monitoring program in the Elkhorn Slough and adjacent waterways, 25 sites had at least 20 years of acquired nutrient data (Figure 1 and Table 1). Other stations had less data and were omitted. Of the included sites, the time series were not exactly the same for all, because sampling ended at some due to landowner access issues or landscape changes, and new sites were added later as a part of other monitoring. The exact years available for each site are shown in Table 2. The most wide-ranging nutrient data span the period from September 1989 to February 2018.

Data collection

Monthly water quality sampling methods were kept as uniform as possible over the 30 years of data collection. As with any long-term monitoring program, consistency in sampling, personnel, and analytical methods was a challenge and a priority. Grab samples were collected for analyzing chlorophyll *a* and nutrients, and sonde measurements took place to record the

temperature, salinity, dissolved oxygen, pH, and turbidity of the water at each site. During the early 2000s, there was a transition in sampling times to align with ebbing tides. ESNERR employees and volunteers followed the protocol set out by the National Estuarine Research Reserve System's Central Data Management Office (CDMO) and ESNERR system. Sondes were calibrated according to the protocol in Mensinger (2017). Early sampling took place using a Solomat sonde for multiparameter measurements. Sampling shifted to a YSI instrument in the early 2000s with a period of overlap to quantify any differences from the different models.

After collection, samples were kept in a cooler and brought to an external laboratory for analysis. Samples were filtered, separating the chlorophyll *a* from the nutrients in the sample, and analyzed for nutrient concentrations according to CDMO protocol (NOAA/NERRS Nutrient Monitoring Committee 2017). Initially Monterey County Consolidated Chemistry Lab conducted the nutrient analysis, but due to unavoidable circumstances, ESNERR transitioned to Moss Landing Marine Labs during the years before and after 2010. The extended transition was performed to quantify any differences between the two labs.

Analysis of temporal patterns

For the graphical and statistical analyses of these data, we plotted the moving average for these data and used a seasonal Kendall test to determine if there was a significant increase or decrease over the period of the study, similar to the approach of Boyer et. al (1999) in a ten-year study of the Florida Bay. We analyzed monthly data in R (R Core Team, 2018) to represent a moving average of the time series to remove the seasonal component of these data and to be able to more easily visually identify increasing or decreasing trends in the parameters over time. We used the “decompose” function in the “stats” R package on the time series data for obtaining these deseasonalized moving average series. We plotted the average series in comparison to thresholds for nutrient concentrations previously used in Mercado et al. (2014). The limits for ammonia as N, nitrate as N, and orthophosphate as P were 0.1 mg/L, 1 mg/L, and 0.13 mg/L, respectively. For dissolved oxygen, we plotted the measured values as the difference from 100% saturation. We then visually compared these moving averages against precipitation data collected from University of California Agriculture & Natural Resources Integrated Pest Management Program and upwelling data compiled by Brent Hughes from www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling.

We used the seasonal Kendall test (SKT) for non-parametric data to determine for each site and parameter if there had been overall change in the nutrient levels (ammonia as N, nitrate as N, and orthophosphate as P) over the length of the study period. Each year was divided into 12 seasons (months) using the “kendallSeasonalTrendTest” function in the “EnvStats” package. We were able to tally these data by region and perform a chi-squared test to see if there was significant correlation between region and change in status.

Project Outcomes

Below we illustrate the temporal patterns for sites within each of the seven regions, with graphs and text summarizing findings. Next, we present the results of the statistical analyses. Finally, we review how the results can inform future directions in a discussion section. The raw data plots for each parameter at each site can be found in the Appendix.

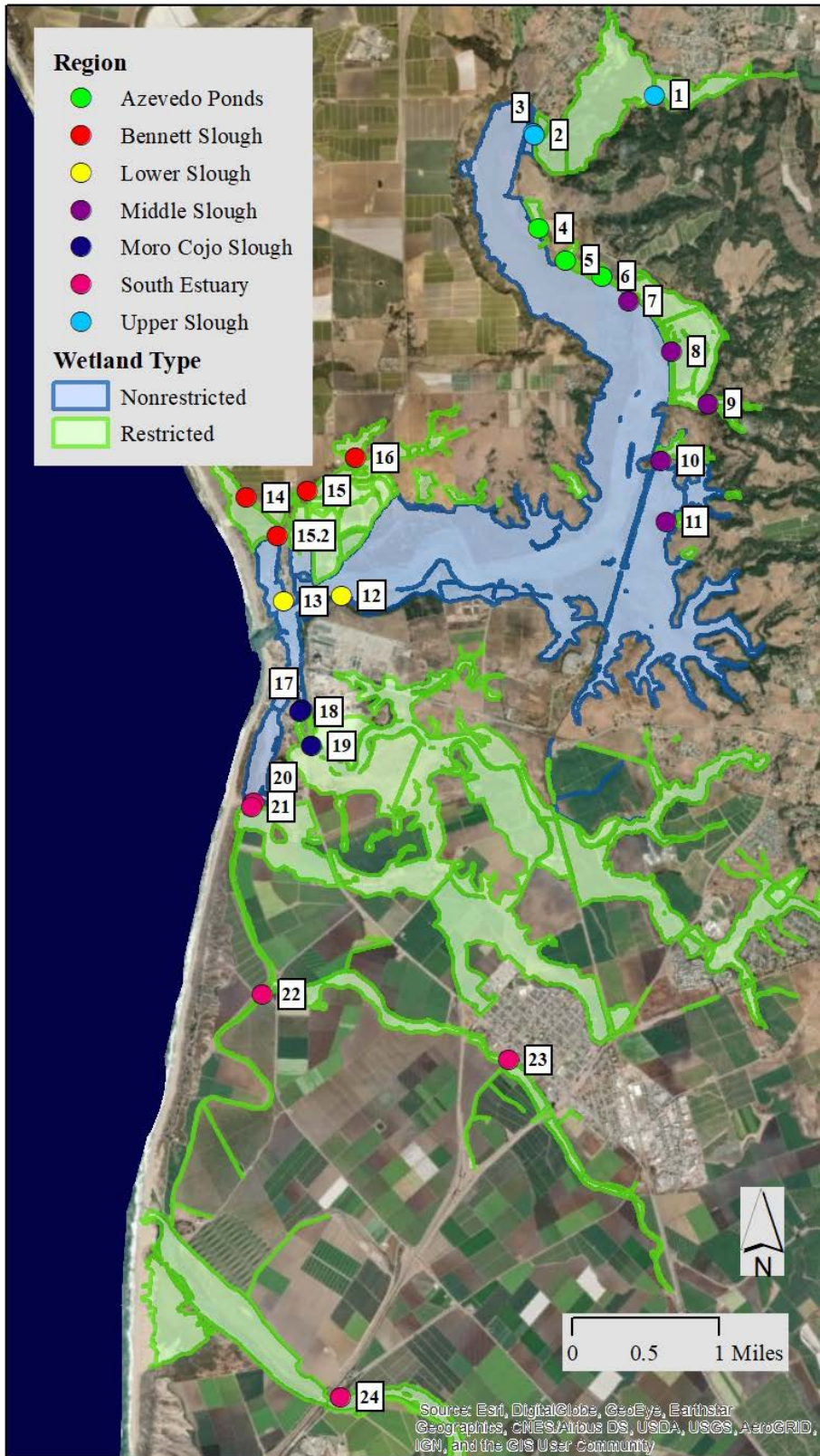


Table 1: Site codes and corresponding names of locations

ID	Site Name
1	Carneros Creek
2	Blohm Porter Marsh
3	Hudson Landing
4	Azevedo Pond, North
5	Azevedo Pond, Central
6	Azevedo Pond, South
7	Kirby Park
8	Reserve North Marsh
9	Strawberry Road
10	Whistlestop Lagoon
11	South Marsh
12	Vierra
13	Skipper's Landing
14	Bennett Slough, West
15	Bennett Slough, East
15.2	Jetty Road
16	Struve Pond
17	Moss Landing Road, North
18	Moss Landing Road, South
19	Moro Cojo Slough
20	Potrero Road, North
21	Potrero Road, South
22	Monterey Dunes Way
23	Tembladero Slough
24	Salinas River Bridge

Figure 1: Map of estuarine wetlands and significant landscape features. Elkhorn Slough National Estuarine Reserve monitoring sites are labeled.

Temporal patterns by region

Upper Slough

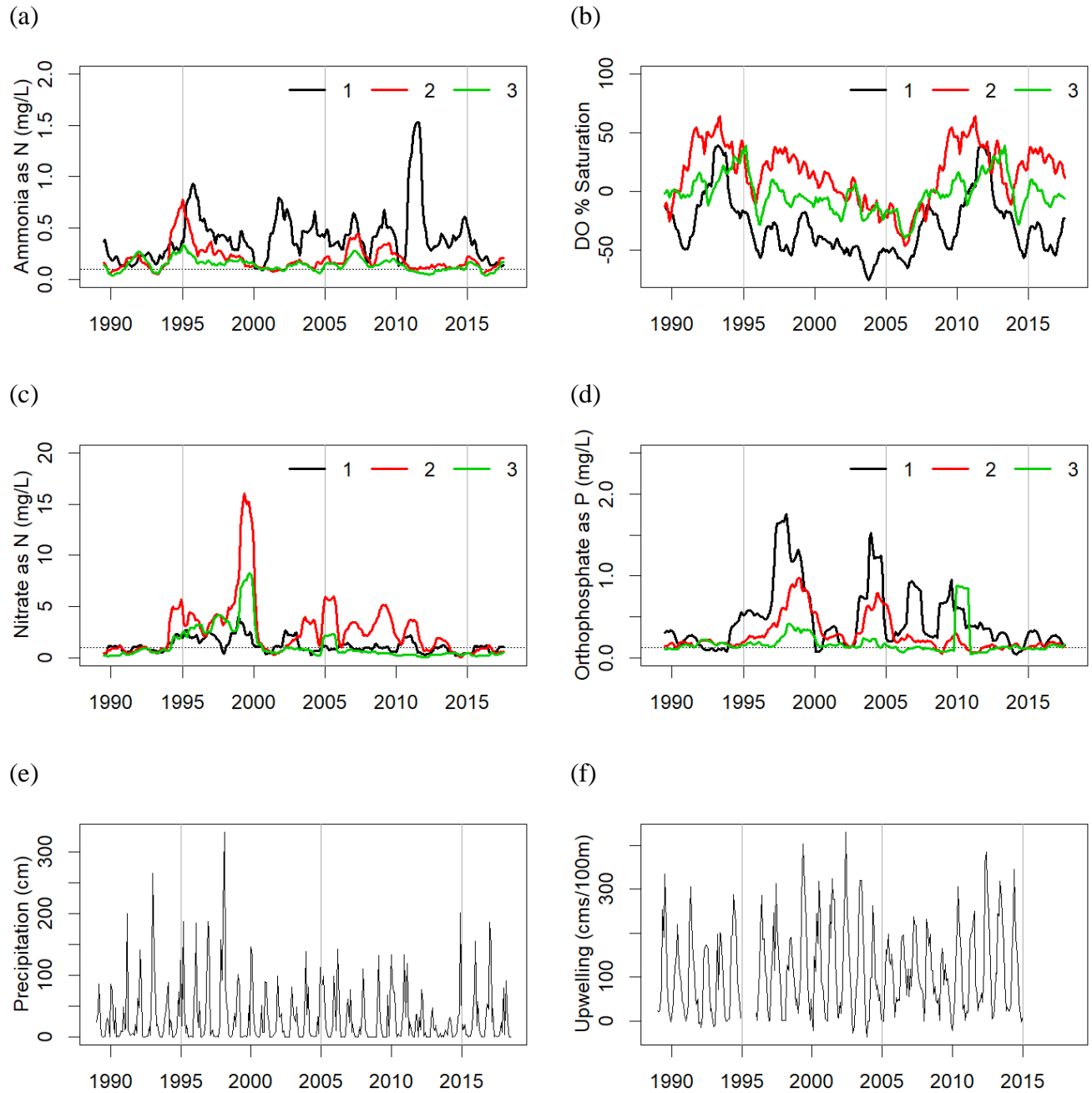


Figure 2 (a-f): Average nutrient and DO concentrations in the Upper Slough region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. The dashed line represents threshold nutrient levels. Sites in this region are: Carneros Creek (1), Blohm Porter Marsh, (2), and Hudson Landing (3).

The Upper Slough is located in the north end of the slough, at the head of the Elkhorn Slough estuary. Carneros Creek (1) is a freshwater source for the estuary but does not flow all year long. Water in this region has longer residence times compared to other parts of the estuary that are along the main channel.

The deseasonalized moving average for the sites in the Upper Slough are regularly above the threshold level for ammonia as N (Figure 2(a)). Carneros Creek (1) regularly peaks at higher levels than the Hudson Landing sites, with 2011 to 2012 averages as high as 1.5 mg/L, or almost 15 times the rest of the region. Average ammonia as N levels in Carneros Creek are high relative to most other sites in other regions as well.

All three sites in the Upper Slough have shown a decreasing trend in nitrate as N after each peaked in 1999 (Figure 2(c)). Hudson Landing (3) and Carneros Creek (1) have tended towards averaging at or below the threshold for the majority of the time since 2001. In this case, Blohm Porter Marsh (2) regularly maintains an above average nitrate as N level with the highest average over 15 mg/L, which is one of the highest averages of all the sites, with the exception of sites in the South Estuary.

Many peaks for all three nutrient parameters show temporal correlation between two or more sites in the region, but the cause of these peaks is unrelated to weather or oceanography: future studies could identify underlying land use activities that were behind these peaks. For orthophosphate as P (Figure 2(d)) and ammonia as N, the sites show the same ranking order of highest to lowest levels of nutrient concentrations. Carneros Creek is higher on average, followed by Blohm Porter Marsh, and lowest Hudson Landing. Orthophosphate as P levels higher than 1.5 mg/L in Carneros Creek are among the second highest averages observed for all sites in all regions. Blohm Porter Marsh's maximum average of approximately 0.75 mg/L also ranked high compared to other regions.

Dissolved oxygen (DO) in Carneros Creek (Figure 2(b)) is the lowest of the region, centering around 50% saturation. Blohm Porter Marsh tends towards the opposite, with frequently high averages around 150% saturation. Hudson Landing most consistently stays close to 100% saturation. From the period of 1997 to 2006 all three sites show decreasing saturation of DO but return to higher levels in 2010 and 2011.

Azevedo Pond Sites

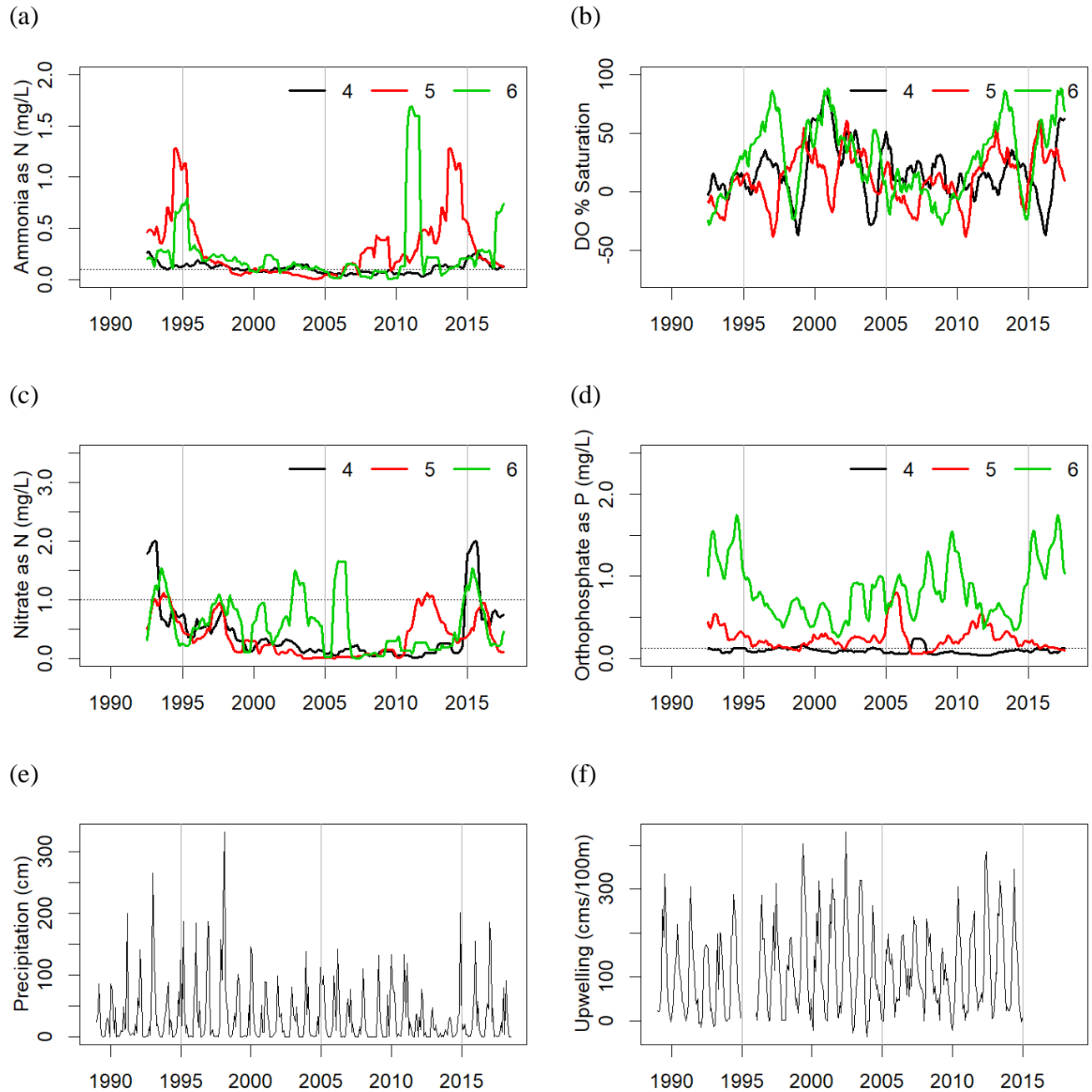


Figure 3 (a-f): Average nutrient and DO concentrations in the Azevedo Pond Region. The dashed line represents threshold nutrient levels. Sites in this region are: Azevedo Pond, South (6), Azevedo Pond, Central (5), and Azevedo Pond, North (4).

The Azevedo Pond sites are three ponds that are restricted from the main estuary behind culverts that run below the railroad. Gee et al. (2010) studied these sites before and after tidal gate repairs and later the modified agricultural practices completed in 1997. After the repair of the tide gates, Gee et al. identified significant improvements in nutrient levels.

Ammonia as N has decreased to close to threshold levels at Azevedo Pond, South and Azevedo Pond, Central (6 and 5) since a peak in 1995 (Figure 3(a)). All three sites spent significant time with average levels below the threshold until Azevedo Pond, Central levels began to increase approximately in 2006, peaking in 2014 and returning to threshold levels by the end of the study period. Azevedo Pond, South has a shorter in duration but more extreme peak in 2011. Both of these peaks occur during an extreme low rainfall period. The Azevedo Pond, North (4) site does not show such an extreme departure from the low levels of the early 2000s but appears to be increasing slightly since 2012. Azevedo Pond, South's maximum average of approximately 1.5 mg/L and Azevedo Pond, Central's maximum average higher than 1.0 mg/L are among the highest levels of ammonia as N observed at all sites. The lack of synchronization of peaks in nutrients at these sites suggests local factors (tide gate management or actions in immediately adjacent farmlands) are responsible.

Nitrate as N levels in this region also decrease after high averages early in the study period (Figure 3(c)). Azevedo Pond, South is the slowest to reach consistent low levels, not obtaining steady low levels until 2007. Azevedo Pond, Central is the first to show an increase after a period of consistent low levels; in 2011-2013 there is a broad peak, followed by another peak in 2016. North and Azevedo Pond, South also peak again after 2015. This happens at the same time as rainfall returns to moderate levels after a drought period.

Orthophosphate as P levels in Azevedo Pond, South frequently maintain averages double the levels of orthophosphate as P in the other sites in this region (Figure 3(d)). Azevedo Pond, South's consistently high average around 1 mg/L and multiple peaks higher than 1.5 mg/L are some of the highest orthophosphate as P levels observed for all sites in all regions. Azevedo Pond, North shows the best water quality of the region with respect to orthophosphate as P, consistently staying below the threshold level.

The Azevedo pond sites seemed to show high variability in dissolved oxygen (Figure 3(b)), and in particular lots of high values even greater than 150%. Oxygen variation to as high as 250% saturation in the Azevedo region has been observed in previous studies and has been linked to anthropogenically-derived nutrient sources (Beck and Bruland 2000). At times the ponds track each other in DO trends, but other times the sites correlate negatively with each other.

Middle Slough

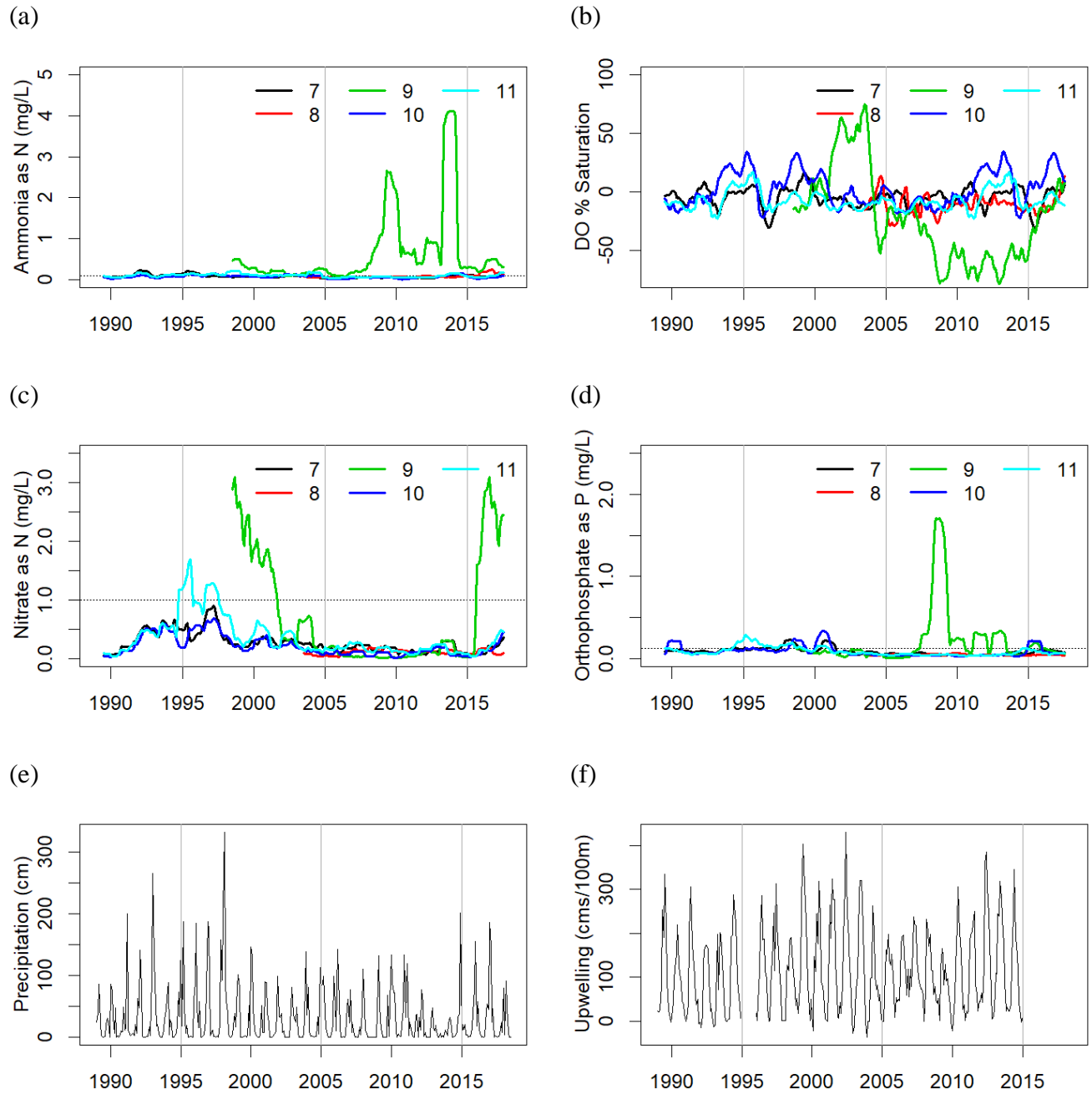


Figure 4 (a-f): Average nutrient and DO concentrations in the Middle Slough Region. The Nitrate as N and Ammonia as N axes have a larger range in y-values in order to contain the higher average parameter values for these sites. The dashed line represents threshold nutrient levels. Sites in this region are: Kirby Park (7), Reserve North Marsh (8), Strawberry Road (9), Whistlestop Lagoon (10), and South Marsh (11).

The Middle Slough is made up of a combination of main channel sites and sites that are behind culverts underneath a railroad. Main channel sites experience a full tidal signature but irregular tidal patterns, while longer residence times occur the tidally restricted sites.

Ammonia as N levels in the Middle Slough are on average close to or below the threshold, with the notable exception of Strawberry Road (8) (Figure 4(a)). While the Middle Slough ammonia as N trends at most of the remainder of the sites are indistinguishable, Reserve North Marsh (30) has a small increase in 2016. During low rainfall from 2007 to 2015 Strawberry Road shows the highest averages of ammonia as N for the region. The maximum average concentration of approximately 4.0 mg/L at Strawberry Road was the highest level observed for ammonia as N for all sites in all regions. These levels returned to just above threshold levels from 2015 through 2018. Future studies should address the source of this high ammonia.

The Middle Slough's nitrate as N trends (Figure 4(c)) for Strawberry Road follow an inverse pattern to that of the site's ammonia as N. Strawberry Road's nitrate as N is highest when its ammonia as N levels are low, and is the highest average level of nitrate as N for the region, at times more than tripling measurements at other sites at 3 mg/L. This concentration was one of the higher average concentrations observed for all sites in all regions, behind Moro Cojo Slough and South Estuary sites. Among the other sites in the Middle Slough, 1995 to 1997 show the highest averages for the period of observation, with levels decreasing throughout most of the rest of the study period. These sites show good water quality with respect to nitrate as N, as only Strawberry Road and the South Marsh site (7) had an average over the threshold. Whistlestop Lagoon (6), South Marsh, and Kirby Park (9) all appear to indicate a slightly increasing average in the most recent years of the study period.

Strawberry Road orthophosphate as P levels (Figure 4(d)) peak at the same time as ammonia as N levels at the site. The other sites, Whistlestop Lagoon, South Marsh, and Kirby Park, make a notable decrease after 2001. For most of the next 15 years, these sites and the newer Reserve North Marsh site maintain averages notably below the threshold. Whistlestop Lagoon has a small peak in 2016. Strawberry Road's maximum average concentration of higher than 1.5 mg/L was one of the highest observed for all sites of all regions.

Dissolved Oxygen at Strawberry Road shows high variability (Figure 4(b)). From 2000 to 2005, the site maintained about 150% saturation. A steep decrease then occurred, and in most years between 2005 and 2015, levels were around 50%. The other middle slough sites have averages closer to 100% saturation. Higher variability is seen in the periods from 1990 to 2000 and then from 2010 to the present. DO saturation at all sites besides Strawberry Road is most consistently close to 100% between 2000 and 2010.

Lower Slough

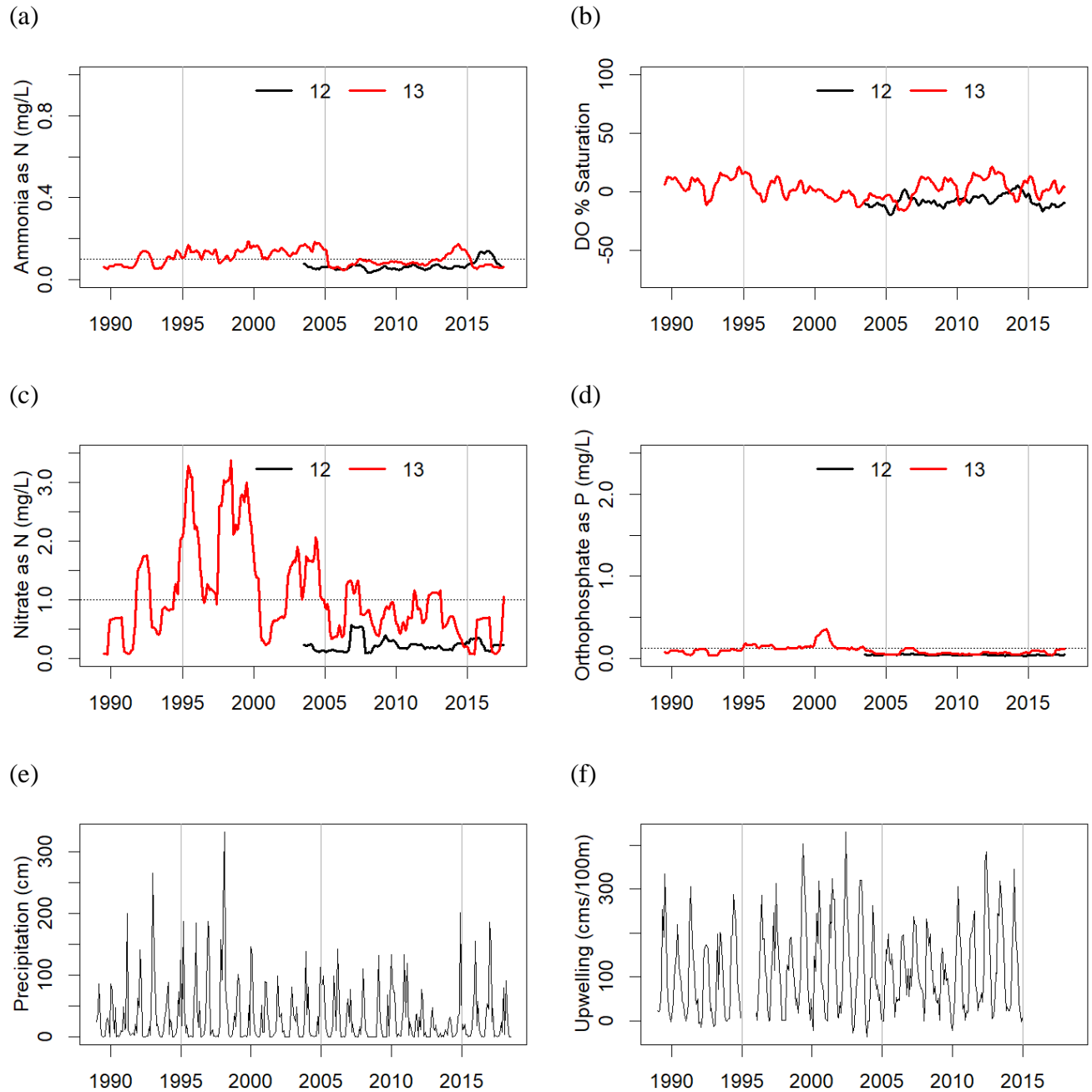


Figure 5 (a-f): Average nutrient and DO concentrations in the Lower Slough Region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. The Ammonia as N axis has a lower range in order to show the variation in values for these sites. The dashed line represents threshold nutrient levels. Sites in this region are: Vierra (12), Skipper's Landing (13).

These two sites are the closest to mouth of the slough. They receive the most marine influence through direct input from the ocean. Water residence times at these sites are short, coordinating with the tidal cycle.

The Lower Slough demonstrates consistent good water quality. Ammonia as N levels (Figure 5(a)) in Skipper's Landing (13) before 2005 were on average slightly over the threshold, but after 2005 this region shows consistently lower than threshold ammonia as N levels, with the exception of one low-magnitude peak in 2014. A similar low-magnitude peak was observed at Vierra (12) in 2016.

Nitrate as N levels at Skipper's Landing show some similarities with patterns in precipitation (Figures 5(c), (e)), one of the few sites to track precipitation. As with ammonia as N, after 2005 nitrate as N levels drop to lower than threshold concentrations of ammonia as N for the majority of the time. In contrast to the otherwise good water quality observed at the Lower Slough, the maximum average nitrate as N at Skipper's Landing of higher than 3.0 mg/L was among the higher levels of nitrate as N observed for all sites in all regions, but has improved over time.

Orthophosphate as P levels are generally at or below the threshold (Figure 5(d)). Orthophosphate as P at Skipper's Landing had a peak in the average over the threshold in 2000. After 2004, Skipper's Landing has maintained a lower average level compared to before the peak in 2000, and a lower level than the threshold. Vierra has consistently averaged below the threshold for the duration of the study period.

Dissolved oxygen levels in the Lower Slough, especially for Vierra, have had low variation from 100% saturation (Figure 5(b)). Skipper's Landing average saturation has not varied by more than 25% above or below 100% saturation for the duration of the study period. These sites demonstrated the lowest variation in DO for all regions.

Bennett Slough

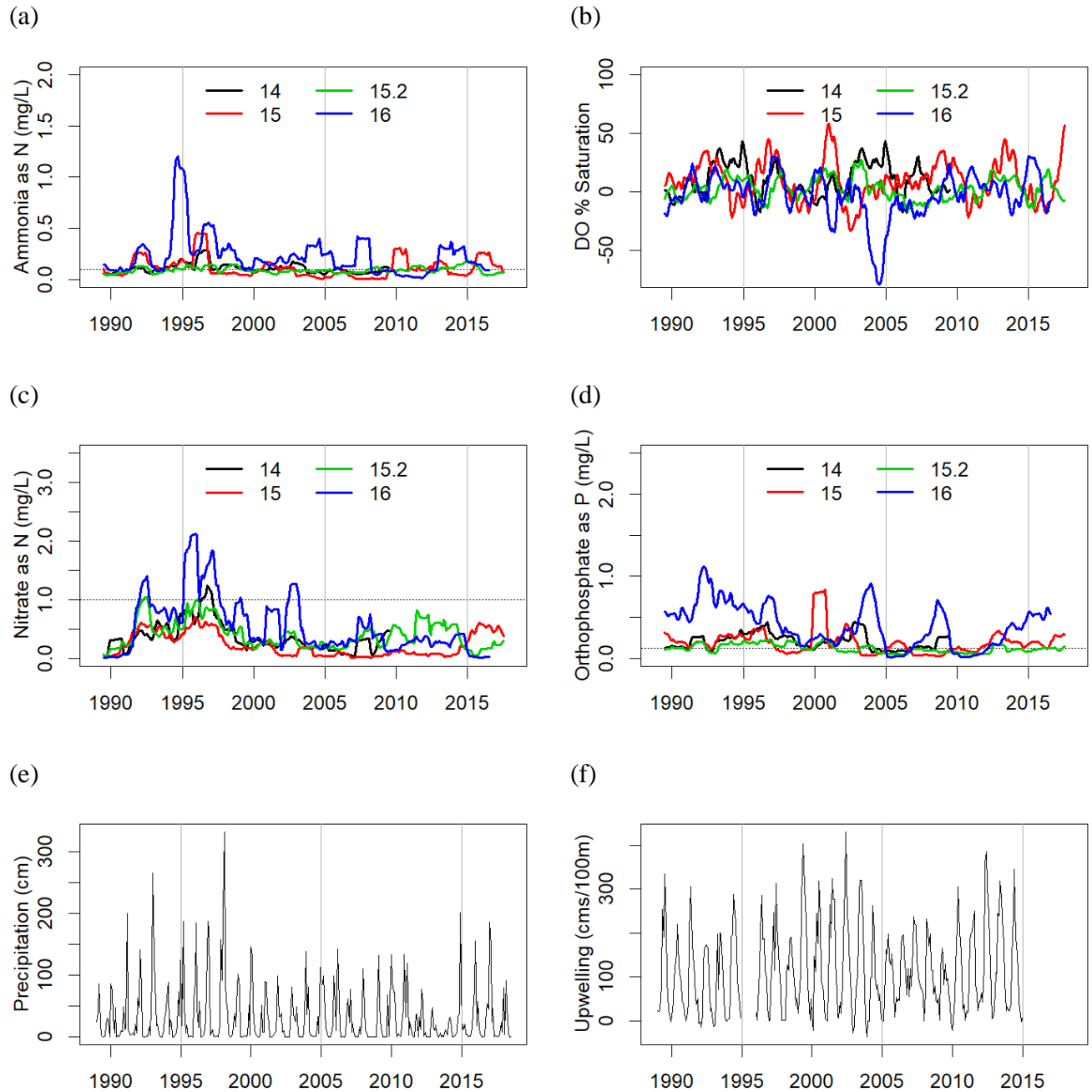


Figure 6 (a-f): Average nutrient and DO concentrations in the Bennett Slough Region. The dashed line represents threshold nutrient levels. Sites in this region are: Bennett Slough, West (14), Bennett Slough, East (15), Struve Pond (16), and Jetty Road (15.2).

Bennett Slough sites are located north of the mouth of the estuary. Culverts from Moss Landing Harbor at the mouth of the slough connect to Jetty Road. The other sites have much more restricted flow and longer residence times.

Bennett Slough ammonia as N shows a decreasing trend across the four sites (Figure 6(a)). Highest average levels for Struve Pond (16) occur from 1994 to 1995, and for Bennett Slough, East (15) in 1996. Jetty Road (15.2) consistently has at or below threshold levels of ammonia as N for the region, without the occasional peaks observed at the other sites in the region. The maximum average higher than 1 mg/L at Struve Pond was among the higher levels of ammonia as N observed for all sites at all regions.

Nitrate as N trends in Bennett Slough (Figure 6(c)) are more similar to the region's ammonia as N trends compared to other regions. Struve pond shows the highest peaks for nitrate as N as well in 1995 This is a good match with the highest average of ammonia as N for the site. For Bennett Slough, nitrate as N levels fall below the threshold for the majority of the time after 1997, maintaining averages as low as half of the nitrate as N threshold. This decrease coincides with a period of low levels of precipitation.

Orthophosphate as P levels for Bennett Slough are commonly over the threshold before 2004 (Figure 6(d)). After this, Jetty Road levels are at or below the threshold. Bennett Slough, West had a small increase in the average during the last year of monitoring in 2009, but from 2004 to 2008 had lower orthophosphate as P levels compared to the previous 15 years. Before 2000, Struve Pond had the highest orthophosphate as P levels and then after 2000 alternates between averaging below the threshold and an average 5 to 10 times the threshold. The site has been increasing in average levels for the last 5 years. Struve Pond's maximum average concentration higher than 1.0 mg/L was among the higher levels of orthophosphate as P observed for all sites in all regions.

Dissolved oxygen levels for these sites are highly variable. Struve Pond has the largest fluctuation in 2004, with the average dropping below 50% saturation.

Moro Cojo Slough

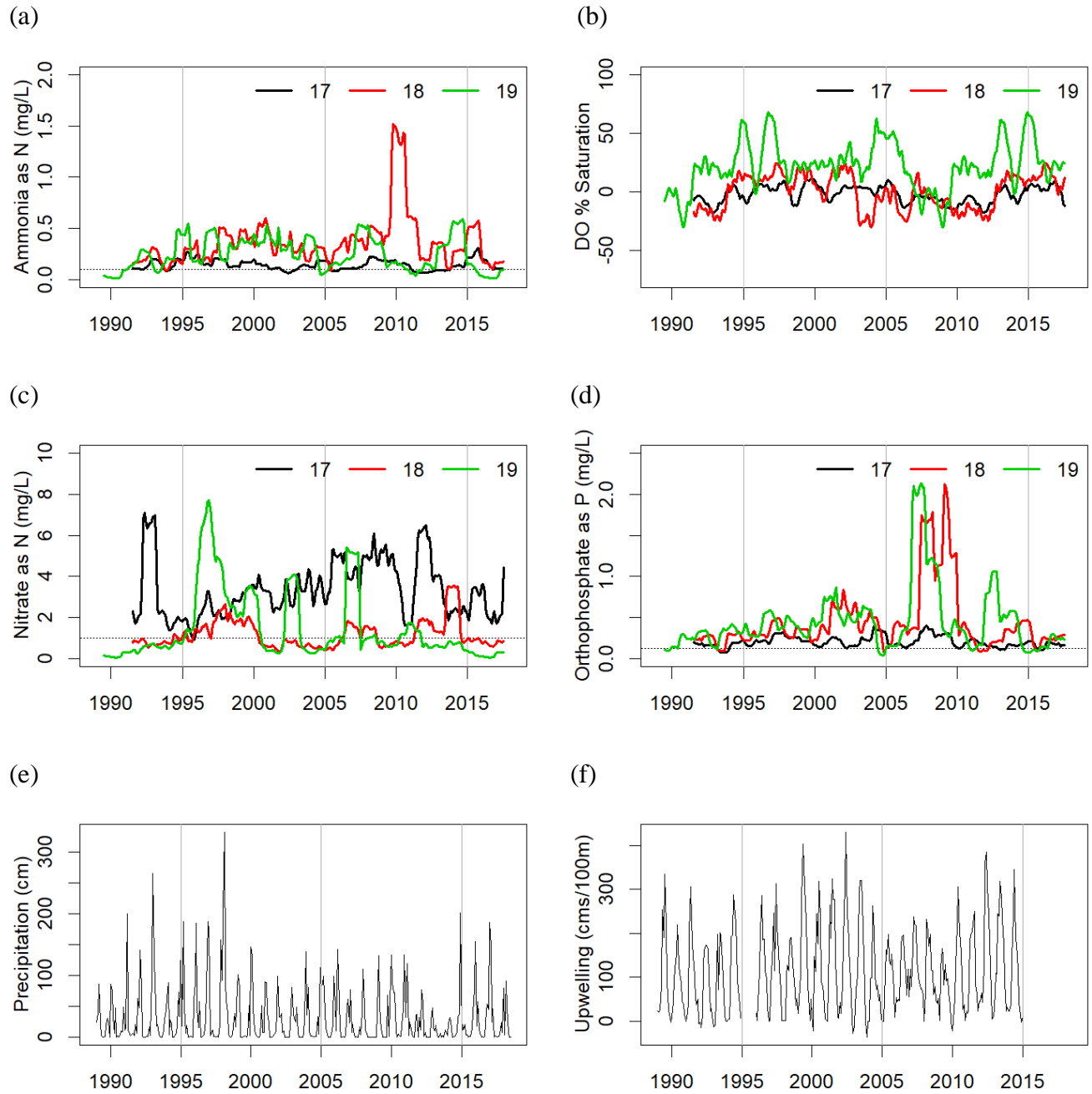


Figure 7 (a-f): Average nutrient and DO concentrations in the Moro Cojo Slough Region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. The dashed line represents threshold nutrient levels. Sites in this region are: Moss Landing Road, North (17), Moss Landing Road, South (18), and Moro Cojo Slough (19).

Moro Cojo Slough has been observed as one of the most eutrophic regions, frequently with extensive algal mats present. Moss Landing Road, North (17) is unrestricted while the other two sites are behind a series of culverts. The Moro Cojo Slough's freshwater inputs originate separately from the main Elkhorn Slough.

Moro Cojo Slough's ammonia as N concentration averages higher than threshold for most of the study period (Figure 7(a)), only dipping below for short periods. Moss Landing Road, North (17) consistently has the lowest average ammonia as N levels. Moro Cojo Slough (19) and Moss Landing Road, South (18) have similar patterns until Moss Landing Road, South has a large concentration spike in 2010 to an average of 1.5 mg/L. At this point concentrations in Moro Cojo Slough decreased to almost threshold level. The peak average concentration for Moss Landing Road, South was among the higher levels of ammonia as N for all sites of all regions.

The three Moro Cojo sites have opposite ordered levels of nitrate as N (Figure 7(c)) compared to ammonia as N. Moss Landing Road, North has the highest nitrate as N, where it had the lowest ammonia as N of the region. A decreasing trend in nitrate as N concentrations that can be seen in Moss Landing Road, South and Moro Cojo Slough. The opposite was observed for Moss Landing Road, North, which had an increasing trend since 1996. The high average nitrate as N concentrations in Moss Landing Road, South and Moro Cojo Slough of 7 mg/L were some of the highest levels of nitrate as N observed for all sites of all regions.

Average orthophosphate as P levels at Moro Cojo Slough and Moss Landing Road, South peak in approximately 2007 at higher than 10 times the threshold concentration (Figure 7(d)), earlier than peak observed for ammonia as N in 2010. These high averages of approximately 2 mg/L were the highest orthophosphate as P levels observed for all sites of all regions. Moss Landing Road, North orthophosphate as P levels averages the lowest of the sites in this region, as with ammonia as N, but are still higher than the threshold.

The average dissolved oxygen in Moss Landing Road, North has levels most consistently around 100% compared to the rest of the region. Moss Landing Road, South is more variable, and Moro Cojo Slough is the most variable and reaches the highest average DO of the region. Maximum average DO in the Moro Cojo Slough reaches over 150% saturation. Generally sites are at or above saturation and less frequently below.

South Estuary Sites

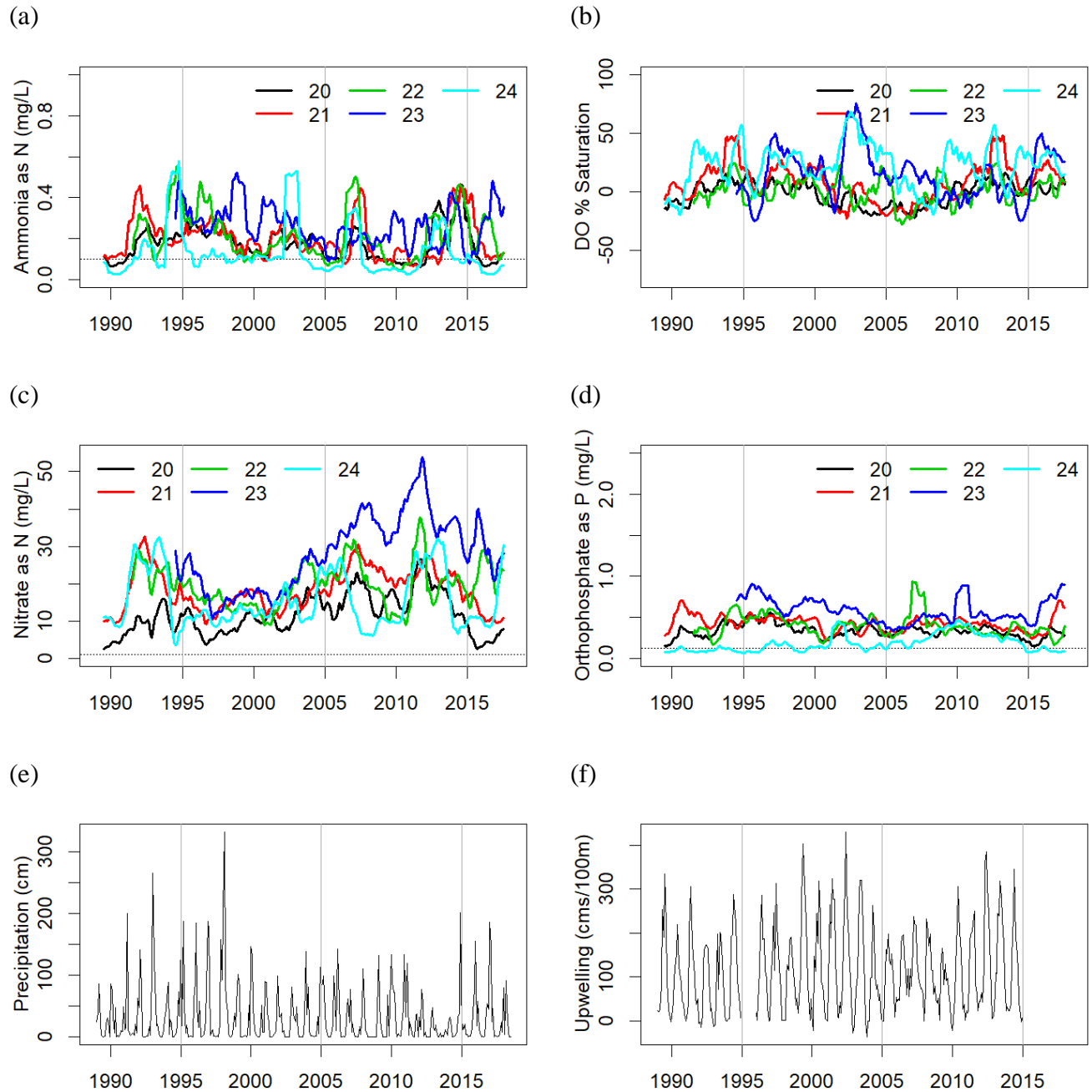


Figure 8 (a-f): Average nutrient and DO concentrations in the South Estuary Region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. The dashed line represents threshold nutrient levels. Sites in this region are: Potrero Road, North (20), Potrero Road, South (21), Monterey Dunes Way (22), Tembladero Slough (23), and Salinas River Bridge (24).

South Estuary sites are located in channels south of Moss Landing Harbor, the mouth of the Elkhorn Slough. All sites except for Potrero Road, North (20) are categorized as having restricted tidal flow. This region does not receive regular tidal flushing. Water exchange is dependent on seasonal flooding and farm runoff. The region receives influence from the Salinas River Channel and agricultural drainages.

Ammonia as N concentrations are variable but frequently higher than the threshold (Figure 8(a)). However, these data suggest no higher averages than 0.6 mg/L. This is on par with some of the other regions. Potrero Roads North and South (20 and 21, respectively) seem to show some improvement but otherwise high variation and higher than threshold levels are the norm. All sites seem to track each other except for Tembladero which has its own unique pattern.

The South Estuary sites have overall much higher magnitudes of nitrate as N and compared to most of the rest of the Elkhorn Slough and have notably increased over the duration of the study period (Figure 8(c)). Nitrate as N averages for these sites have averages as high as 50 mg/L at Tembladero Slough (23) as part of a peak from 2001 to 2011. All sites in this region demonstrate increasing trends from approximately 1997 to 2011. There may be a new decreasing trend since 2011.

Orthophosphate as P levels for all sites are consistently above threshold (Figure 8(d)). Salinas River Bridge (24) started below the threshold but after 2001 has risen to consistently over threshold. Salinas River Bridge also has the lowest values in the region for ammonia as N as it does for orthophosphate as P.

The DO levels for the South Estuary Sites are predominantly at 100% saturation or higher, especially at Salinas River Bridge and Tembladero Slough. The Potrero Road Sites and Monterey Dunes way (22) have levels closer to 100% saturation between 2000 and 2010, but are higher both before and after that decade.

Regional Comparison Summary

In order to compare different regions, the monthly measurements were averaged for all sites within a region and then treated with the same graphical analysis as the individual site time series.

For ammonia as N (Figure 9) the uniqueness of the trend for each region is notable. Few regions spend significant time below the threshold of 0.1 mg/L, with the exception of the Azevedo Pond region between 2000 and 2007, the Lower Slough after 2006, and Bennett Slough between 2006 and 2014. The Middle Slough's high peaks are due to the influence of the high values at Strawberry Road, despite lower values at the rest of the sites in the region.

Nitrate as N concentrations (Figure 10) demonstrate lower averages with respect to the threshold for most regions, with all regions except the South Estuary falling below threshold levels after 2015. It is evident in Figure 11 that the South Estuary nitrate as N levels are both tens of times higher than the threshold of 1 mg/L, and are also increasing until about 2012. The most recent 5 years have seen a decrease in regional nitrate as N in the South Estuary, but levels still average many times higher than the threshold.

For orthophosphate as P (Figure 11), Moro Cojo Slough region has the highest levels between 2005 and 2010 at a regional scale. Only the Middle Slough and the Lower Slough average below the threshold for the majority of the study period. Since 2005, Bennett Slough appears to have improved to be below the threshold for approximately half of the time. Overall average improvement in the Upper Slough can also be noted.

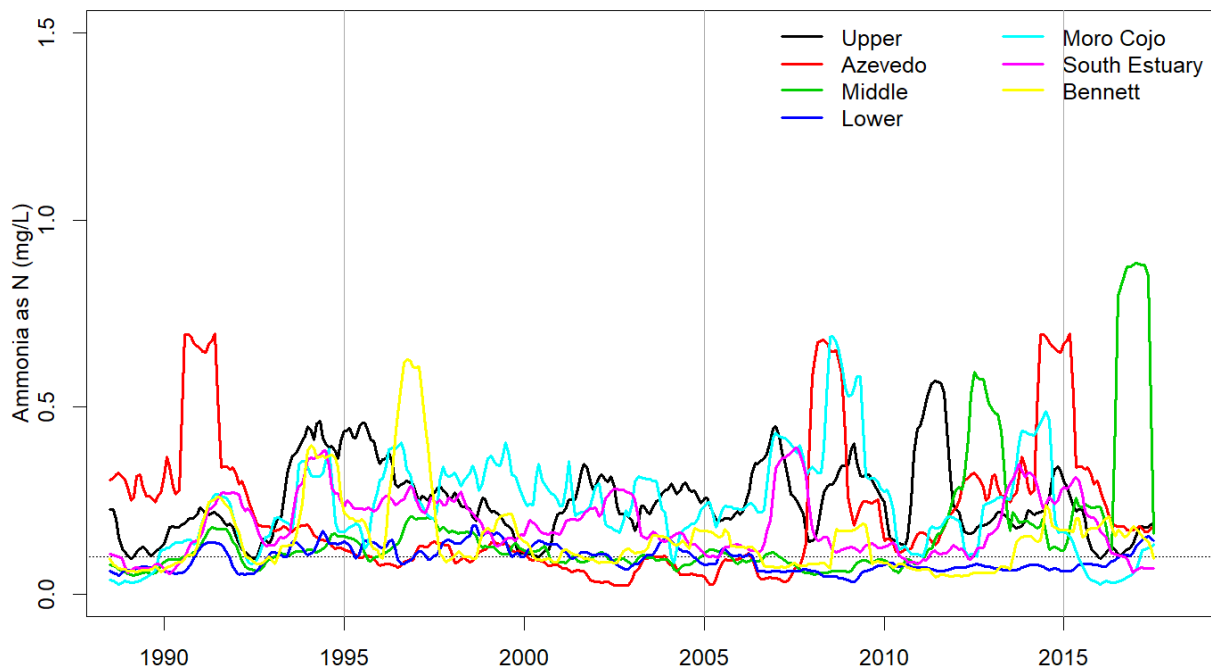


Figure 9: Deseasonalized moving averages of the average ammonia as N concentrations of all sites for each month. Dashed line at 0.1 mg/L represents threshold concentration for Ammonia as N.

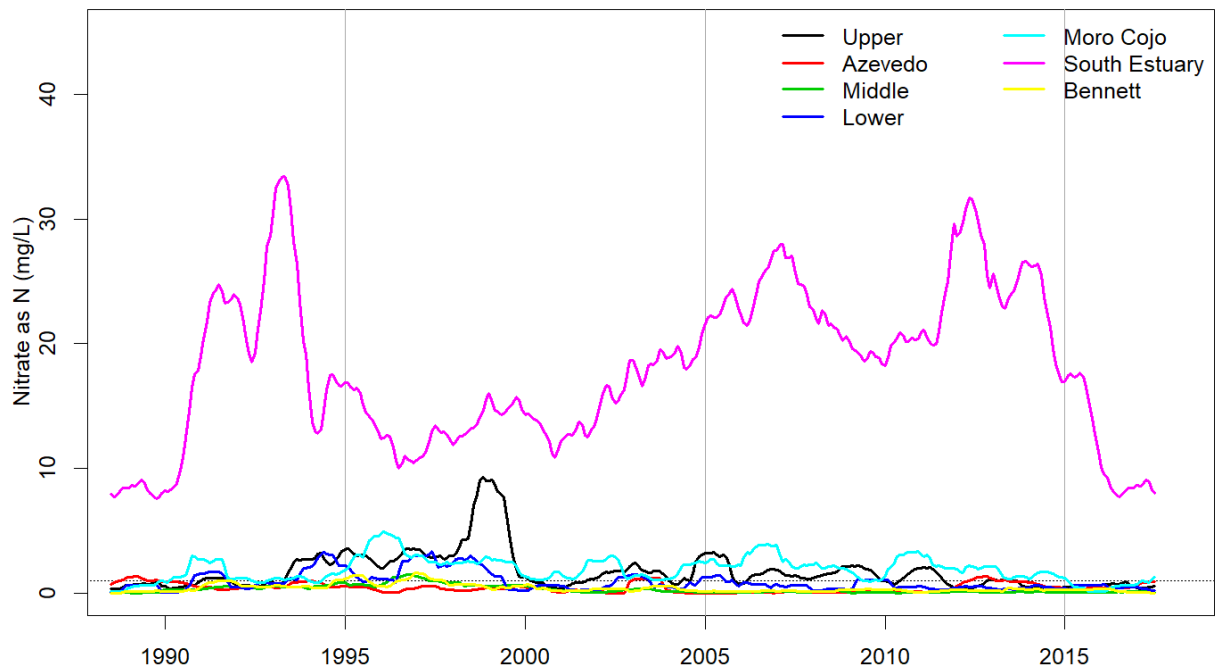


Figure 10: Deseasonalized moving averages of the average nitrate as N concentrations of all sites for each month. Dashed line at 1.0 mg/L represents threshold concentration for nitrate as N.

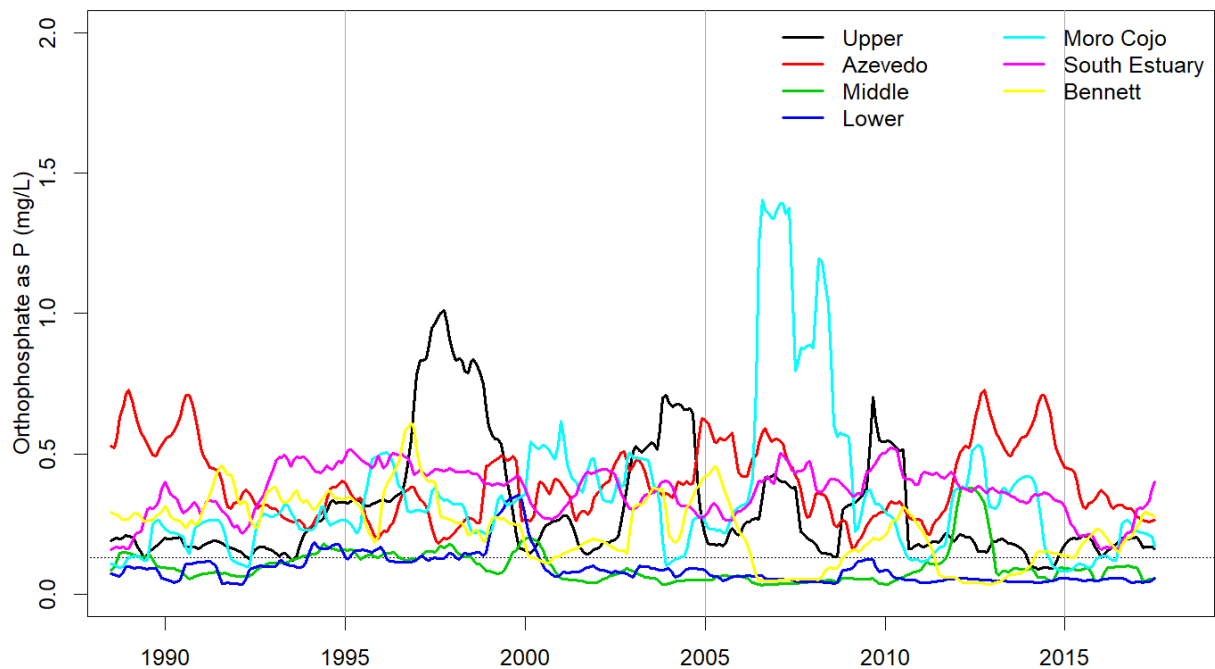


Figure 11: Deseasonalized moving averages of the average orthophosphate as P concentrations of all sites for each month. Dashed line at 0.13 mg/L represents the threshold concentration for orthophosphate as P.

Seasonal Kendall Results

A seasonal Kendall test performed on the data for each site reveal a regional pattern (Table 2). The majority of the sites for the Upper Slough, Azevedo Ponds, Middle Slough, and Bennett Slough show significant improvement across all parameters (decreased nutrient concentrations). For the sites in regions closer to the mouth of the estuary - the Lower Slough, Moro Cojo Slough, and the South Estuary - significant increases in nutrient concentrations over time outnumber decreases in concentration.

Table 2: Results of seasonal Kendall test. Site codes indicated with the “r” superscript are wetlands with restricted flow regimes. Seasonal Kendall results with $p < 0.1$ are indicated with one +/- sign, $p < 0.05$ with two, and $p < 0.01$ with three. Improved water quality is recorded in green, while worsened water quality is recorded in red. The numeric score and letter grades are an average of the last five years of Water Quality Report Card results for each site. Starting years for monitoring are shown in varying shades of gray, with darker gray denoting earlier starting years, and thus longer time series. Data were analyzed through the present for all sites except site 17 (Moss Landing Road, North), where data collection stopped in 2010.

		Ammonia	Nitrate	Phosphate	Numeric Grade	Letter Grade	Year Began	Year End
Upper Slough	1 ^r	+	---	ns	30.1	F	1989	
	2 ^r	ns	ns	--	46	F	1989	
	3	ns	---	---	61	D	1989	
Azevedo	4 ^r	---	---	---	60.4	D	1992	
	5 ^r	---	---	---	41.8	F	1992	
	6 ^r	---	---	ns	30.4	F	1992	
Middle Slough	7	---	---	---	73.1	C	1989	
	8 ^r	+++	++	ns	70	C	2003	
	9 ^r	ns	---	ns	23.4	F	1998	
	10	--	---	---	76.7	C	1989	
	11	---	---	---	76.9	C	1989	
Bennett Slough	16 ^r	---	--	---	39.9	F	1989	
	15 ^r	---	---	---	44.6	D	1989	
	14 ^r	ns	ns	ns			1989	2010
	15.2 ^r	++	ns	---	66	C	1989	
Lower Slough	12	+	++	--	78.6	C	2003	
	13	++	ns	-	73.7	C	1989	
Moro Cojo Slough	19 ^f	ns	ns	++	35	F	1989	
	18 ^f	++	ns	+	37.3	F	1991	
	17	ns	+++	ns	57.5	D	1991	
South Estuary	24 ^f	ns	ns	+++	30.2	F	1989	
	23 ^f	---	+++	---	25.5	F	1994	
	22 ^f	---	ns	ns	27.2	F	1991	
	21 ^f	-	+++	ns	32.1	F	1989	
	20	ns	+++	+	34.9	F	1989	

A few exceptions to the regional pattern can be noted. Overall improvement in the Upper to Middle Estuary is interrupted by increased ammonia as N and nitrate as N in Reserve North Marsh (8). The exception to the increased nutrient concentrations in the Lower Slough are the decreased concentration of orthophosphate as P in the region. At the same time, ammonia as N levels for the Potrero Road, South (21) and Monterey Dunes Way (22) have decreased over the study period. Both ammonia as N and orthophosphate as P in the Tembladero Slough (23) have decreased.

In order to determine if the results showed any pattern with respect to wetland type, the results of the seasonal Kendall test (site improved, worsened, or not significant) were tallied according to wetland type and organized in a table for a chi-squared test (Table 3).

Table 3: Summary of seasonal Kendall test results used in Chi-Squared Test, organized by wetland type.

Wetland Type	Change		
	Improved	Worsened	n.s.
Restricted	22	10	19
Unrestricted	13	6	5

The results of the Pearson’s chi-squared test indicated that there was no significant relationship between the factors ($p = 0.36$). Sites with similar tidal exchange did not show a systematic pattern of improvement or deterioration. However, the same test indicated a significant relationship when organized by region (Table 4) instead of wetland type ($p = 0.02$). In the Upper Slough, Azevedo Slough, Middle Slough, and Bennett Slough, water quality improvements outnumbered water quality deterioration. In the Lower Slough, Moro Cojo Slough, and South Estuary, more parameters worsened compared to improvements in the respective regions. Therefore the results show a statistically significant trend of improvements in the northern regions and worsening water quality in the southern wetland sites.

Table 4: Summary of seasonal Kendall test results used in Chi-Squared Test, organized by wetland type.

Region	Change		
	Improved	Worsened	n.s.
Upper Slough	4	1	4
Azevedo	8	0	1
Middle Slough	10	2	3
Bennett Slough	7	1	4
Lower Slough	2	3	1
Moro Cojo Slough	0	4	5
South Estuary	4	5	6

Discussion

The analysis of these data has revealed that there is high temporal and regional variability in water quality in the Elkhorn Slough. No individual region stands out with low concentrations for all parameters, so no region can be considered a model for overall good water quality. A simplified analysis would obscure some of this variability, and therefore it is still valuable to have such detailed information even if sites seem like they are in similar regions and should behave the same way. For example, data averaged by region allows for high concentrations at individual sites to obscure lower trends in other sites within the region, such as Strawberry Road affecting average trends for Middle Slough ammonia as N. Having multiple sites of the same tidal regime (restricted versus unrestricted) also allows us to determine if sites with substantial changes in management practices experienced improved water quality.

Further scientific collaboration using different statistical techniques is needed to better understand water quality drivers not incorporated in this study that may correlate with water quality variability of the Elkhorn Slough. Possible statistical approaches to this could include Random Forest testing of multiple predictors using R. Very few regions show trends that suggest good correlation with precipitation levels or upwelling alone.

Additional sources of data would be useful to incorporate into future analysis. Nitrogen cycle shifts are suggested by the Southern Estuary trends in ammonia as N and nitrate as N. Increase of nitrate as N and decrease in ammonia as N hints that the makeup of photosynthetic and benthic organisms has undergone a change, and that this activity could be an important factor contributing to the long-term trends. Additional information on the fluxes from the sediments and nutrient conversion by microorganisms is needed. Some of the nutrient peaks that occur only at a very local scale, at single sites within a region, could perhaps be correlated with local land use changes or irrigation or fertilization regimes, with GIS analyses and farm data. It would be useful to perform supplementary studies on tide gate management and its impacts on patterns of retention time and water movement throughout the estuary. Further investigations into land use practices could gather data on area farmed, crop type, fertilizer application, and irrigation timing.

The across the board improvements at the Azevedo Pond sites should be celebrated. The Middle Slough and Bennett Slough areas also showed various improvements. Areas where improvement has been most widespread coincide with the areas where the Elkhorn Slough Reserve and Foundation have acquired properties and conducted restoration. Other research has offered support that restoration efforts result in improved water quality, such as Gee et al. (2010) studies of restoration in Azevedo. Regions of worsening water quality tend to be much farther from and less connected to the areas of land conservation work by ESF, ESNERR, and other partnering organizations. Consequently, regions such as the South Estuary that have been identified as having extremely high levels of nitrate can be targeted for more conservation and restoration efforts using data from this study, complementing the Total Maximum Daily Load (TMDL) process underway (Saiz and Keeling 2016). Long-term data such as that provided by ESNERR's monthly sampling provide important references to contextualize future studies of water quality. As management improvements are made, being able to compare results to historical water quality will aid researchers in reaching conclusions about the efficacy of different strategies. The ecological health of the estuary is important to many stakeholders, and protecting and restoring it would benefit many species that take advantage of its unique resources.

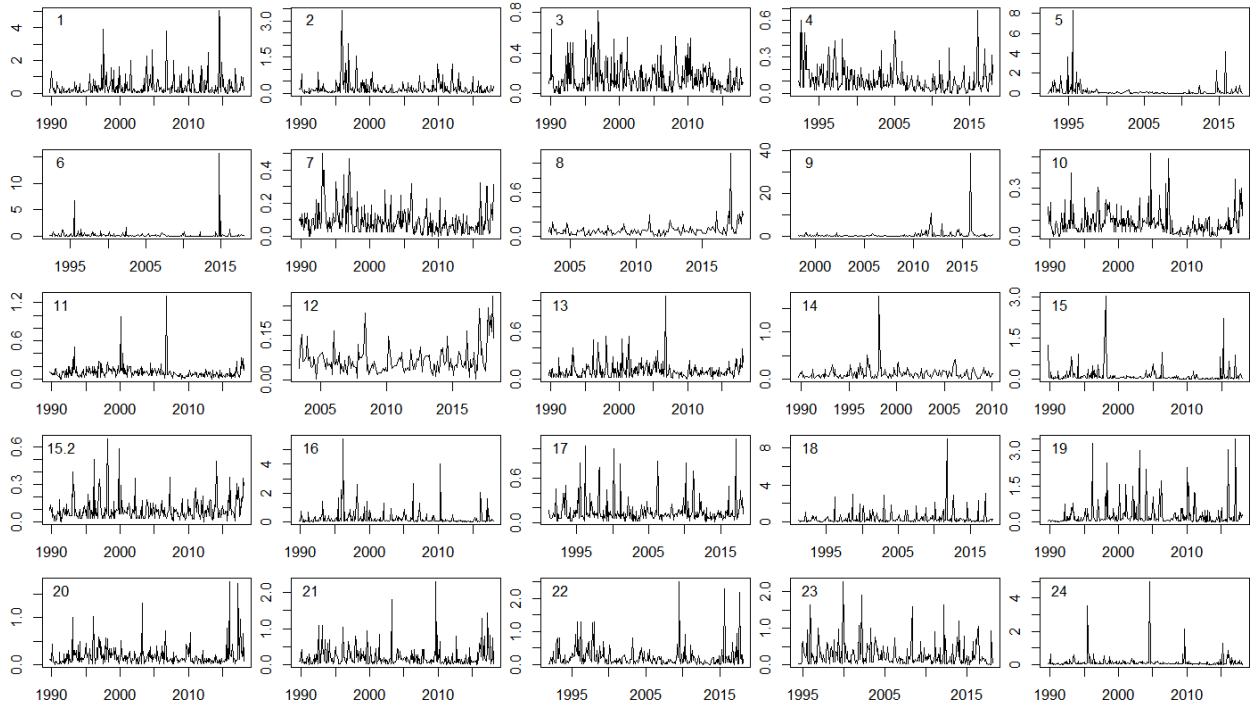
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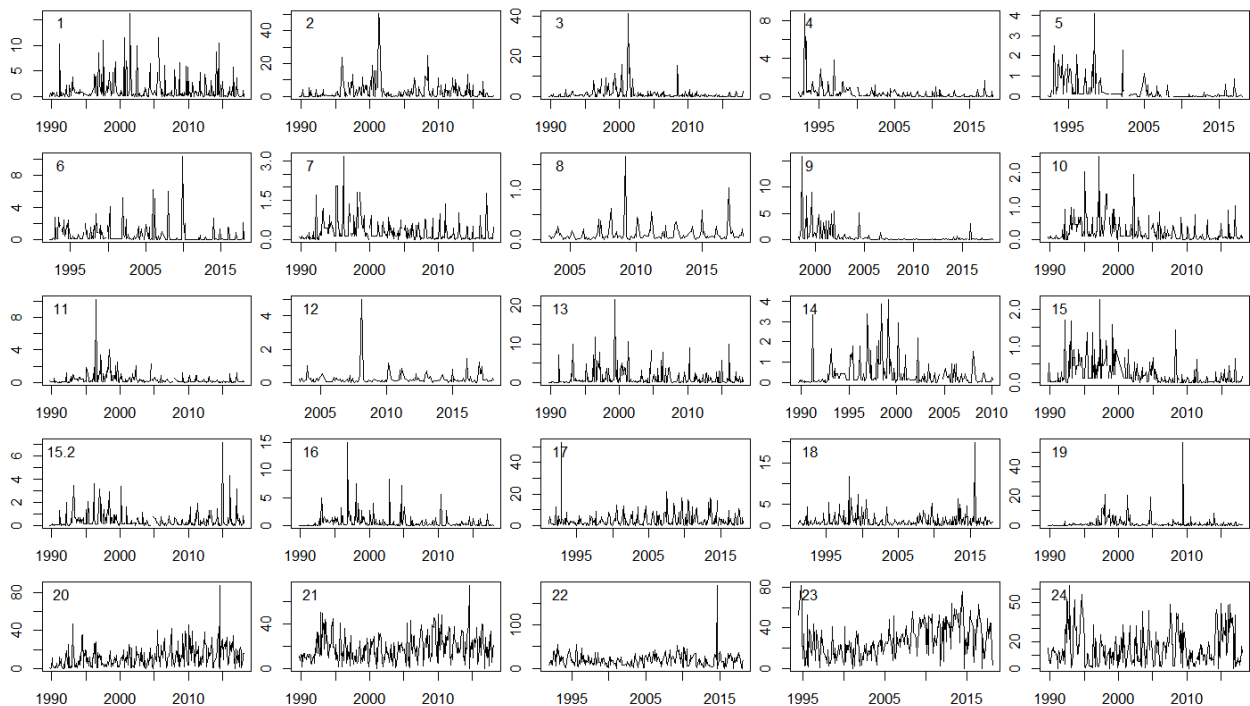
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Appendix

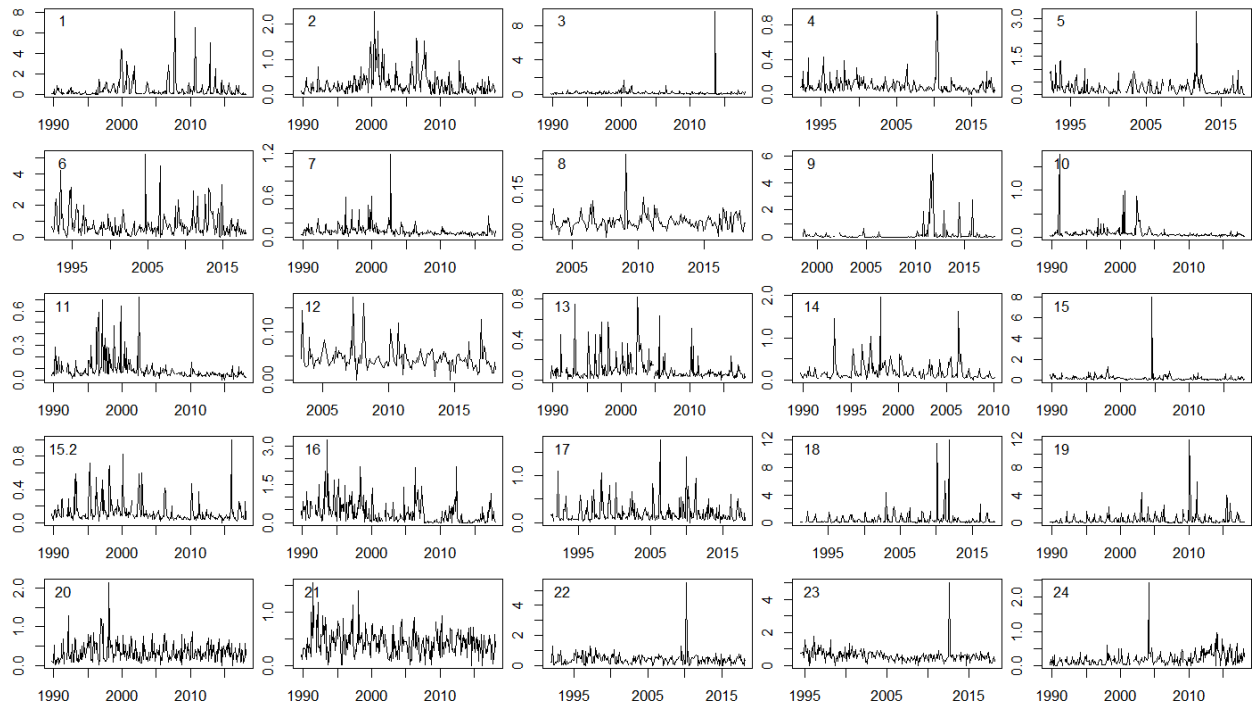
Raw Data Plots for Ammonia as N (mg/L)



Raw Data Plots for Nitrate as N (mg/L)



Raw Data Plots for Orthophosphate as P (mg/L)



Raw Data Plots for DO % Saturation

