Elkhorn Slough National Estuarine Research Reserve Technical Report: Long-term Water Quality Trends

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Executive Summary

The Elkhorn Slough is a highly eutrophic estuary in Monterey County in central California. The ecosystem of the Elkhorn Slough estuary has been altered by human activities, including diking, harbor construction, and agriculture. Now, much of the Elkhorn Slough is protected. Three entities are active in management of the estuary: the California Department of Fish and Wildlife, the Elkhorn Slough Foundation (ESF), and the Elkhorn Slough National Estuarine Research Reserve (ESNERR), a research program funded by NOAA. ESNERR is one of 29 coastal Research Reserves in the United States. ESNERR has been implementing monthly water quality monitoring throughout the estuary since 1988 at 25 sites. In order to analyze the long-term trends in this data, both graphical and statistical analyses were performed on nutrient and dissolved oxygen concentrations.

Sites were grouped into similar geographic regions for analyses. All regions had 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 Hudson Landing East had high levels of nitrate as N (15 mg/L). The Middle Slough had relatively good water quality except for Strawberry (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 Central Azevedo Pond) 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 Skippers (3 mg/L). Various sites in Moro Cojo appeared among the high concentrations of all three parameters (1.5 mg/L at Moss Landing South for ammonia as N, 7 mg/L of nitrate as N for Moss Landing 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 outstandingly high levels of nitrate as N at all sites, even as high as 50 mg/L at Tembladero Slough.

Graphical analyses 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 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.

Seasonal Kendall Tests show 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. After testing the results with a chi-squared test, it was found that there was not significant correlation by wetland type ($p = 0.36$). However, there was significant correlation by region ($p = 0.02$). The Upper Slough, Azevedo Ponds, Middle Slough, and Bennett Slough regions had the highest proportions of significant improvements in nutrient concentrations.

The results of this analysis offer encouragement, since improvements can be seen in areas where the Elkhorn Slough Foundation land management activities have taken place, along with improved practices by farmers supported by numerous regional agencies and organizations. Furthermore, improvement in water quality can be achieved and documented, even in areas of relatively high nutrient concentrations. Further 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 ESNERR, the Elkhorn Slough Foundation and other groups

working in these areas. We hope that these results may inform decision-making of the Central Coast Regional Water Quality Control Board. More scientific collaboration is still needed in order to research other drivers of the changes in nutrients in the Elkhorn Slough.

Project Objectives

Under the primary supervision of Rikke Jeppesen, estuarine ecologist, and also water quality monitoring scientist John Haskins and research coordinator Kerstin Wasson at the Elkhorn Slough NERR, I had the unique opportunity to conduct an analysis of approximately 30 years of monthly water quality data collected by ESNERR. Since nitrate as N, ammonia as N, orthophosphate as P, and dissolved oxygen are good indicators of estuary health (Gee et al. 2010 and Hughes et al. 2011), the first part of our goal was to identify any long-term trends over the period of data collection. I was to perform exploratory data processing to see which water quality parameters are changing in correlation with a variety of indicators. The second part of my internship goal was to effectively communicate this information with visitors, stakeholders, and other scientists.

To contextualize the data, one performance objective was that I assist with calibration and deployment of the sondes used for collecting water quality data. I would be available to attend monthly water sample collection and filtration to gain experience in nutrient sampling. Continued monitoring of these parameters provides data for future analysis of trends in the estuary.

As a result of this analysis, I intended to complete a number of deliverables for ESNERR, along with the final USDA requirements. First, I will expand on the USDA report to complete a technical report of the first long-term analysis of this index of water quality parameters in the Slough. The report will be posted on the Elkhorn Slough Technical Report webpage, and may subsequently be refined, in collaboration with ESNERR scientists, into a scientific publication. I will prepare a one page summary pamphlet for distribution to the public. I may have the opportunity to present the findings to other employees working at the Elkhorn Slough (including ESNERR, the Elkhorn Slough Foundation, and California Department of Fish and Wildlife) and to the Central Coast Regional Water Quality Control Board.

Project Approach

Sites and years included

Of the sites that have historically been studied by ESNERR's 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 site were added later as a part of other monitoring. The exact years available for each site are shown in Table 1.

Data collection

Monthly water quality sampling was performed according to protocol set out by the CDMO and ESNERR system. Grab samples were collected for analyzing chlorophyll and

nutrients, and sonde measurements took place to record the temperature, salinity, dissolved oxygen, pH, and turbidity of the water at each site. Sondes were calibrated according to the protocol in Mensinger (2017). After collection, samples are kept in a cooler and brought to Moss Landing Marine Labs. Samples are filtered, separating the chlorophyll from the nutrients in the sample, and analyzed for nutrient concentrations according to CDMO protocol (NOAA/NERRS Nutrient Monitoring Committee 2017).

Analysis of temporal patterns

The graphical and statistical analysis of these data followed analysis is similar to the approach of Boyer et. al (1999) in a ten-year study of the Florida Bay. The moving average for these data was plotted and a Seasonal Kendall test was used to confirm if there was a significant increase or decrease over the period of the study. Monthly data were analyzed 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. The "decompose" function in the "stats" package was used on the time series data for obtaining these deseasonalized moving average series, which were plotted 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 are 0.1 mg/L, 1 mg/L, and 0.13 mg/L, respectively. For dissolved oxygen, the measured values were plotted as the difference from 100% saturation. These moving averages were then visually compared 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.

The Seasonal Kendall Test (SKT) for non-parametric data was used 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. I was able to tally these data by type of wetland – restricted or nonrestricted – and perform a chi-squared test to see if there was significant correlation between wetland type and change in status.

Project Outcomes

The temporal patterns for sites within each of the seven regions are provided below, with graphs and text summarizing findings. Next, the results of the statistical analyses are presented. Finally, the significance of the results is discussed in a concluding text section.

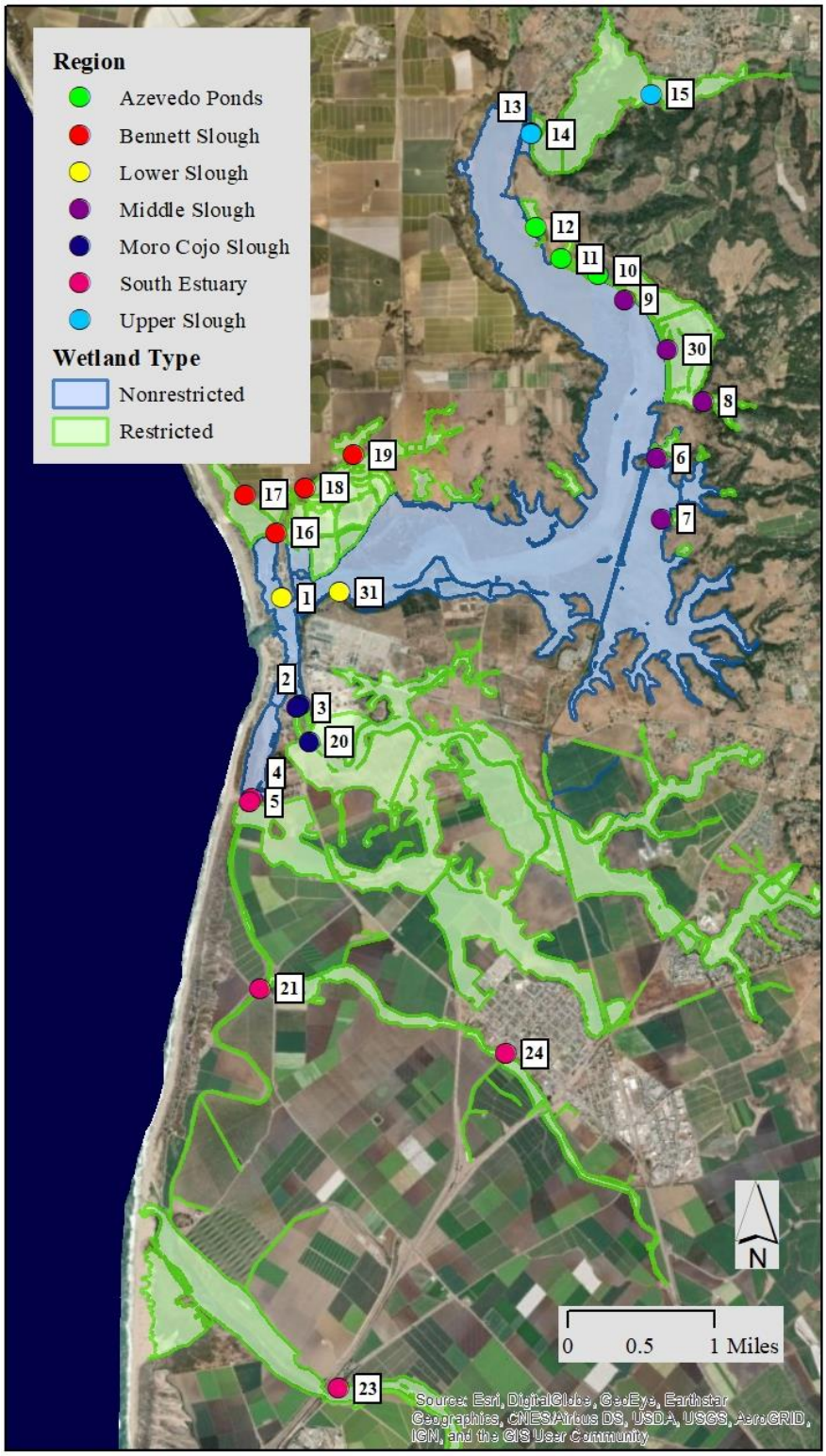


Figure 1: Map of the Slough's location and significant landscape features. Elkhorn Slough National Estuarine Reserve monitoring sites are labeled.

Table 1: Site codes and corresponding names of locations

ID	Site Name
1	Skippers
2	Moss Landing Rd. North
3	Moss Landing Rd. South
4	Potrero Rd. North
5	Potrero Rd. South
6	Whistlestop
7	South Marsh Sonde
8	Strawberry
9	Kirby Park
10	South Azevedo Pond
11	Central Azevedo Pond
12	North Azevedo Pond
13	Hudson Landing West
14	Hudson Landing East
15	Carneros Creek
16	Jetty Rd.
17	Bennett Slough West
18	Bennett Slough East
19	Struve Pond
20	Moro Cojo Slough
21	Monterey Dunes Way
23	Salinas River Bridge
24	Tembladero Slough
30	North Marsh
31	Vierras

Temporal patterns by region

Upper Slough

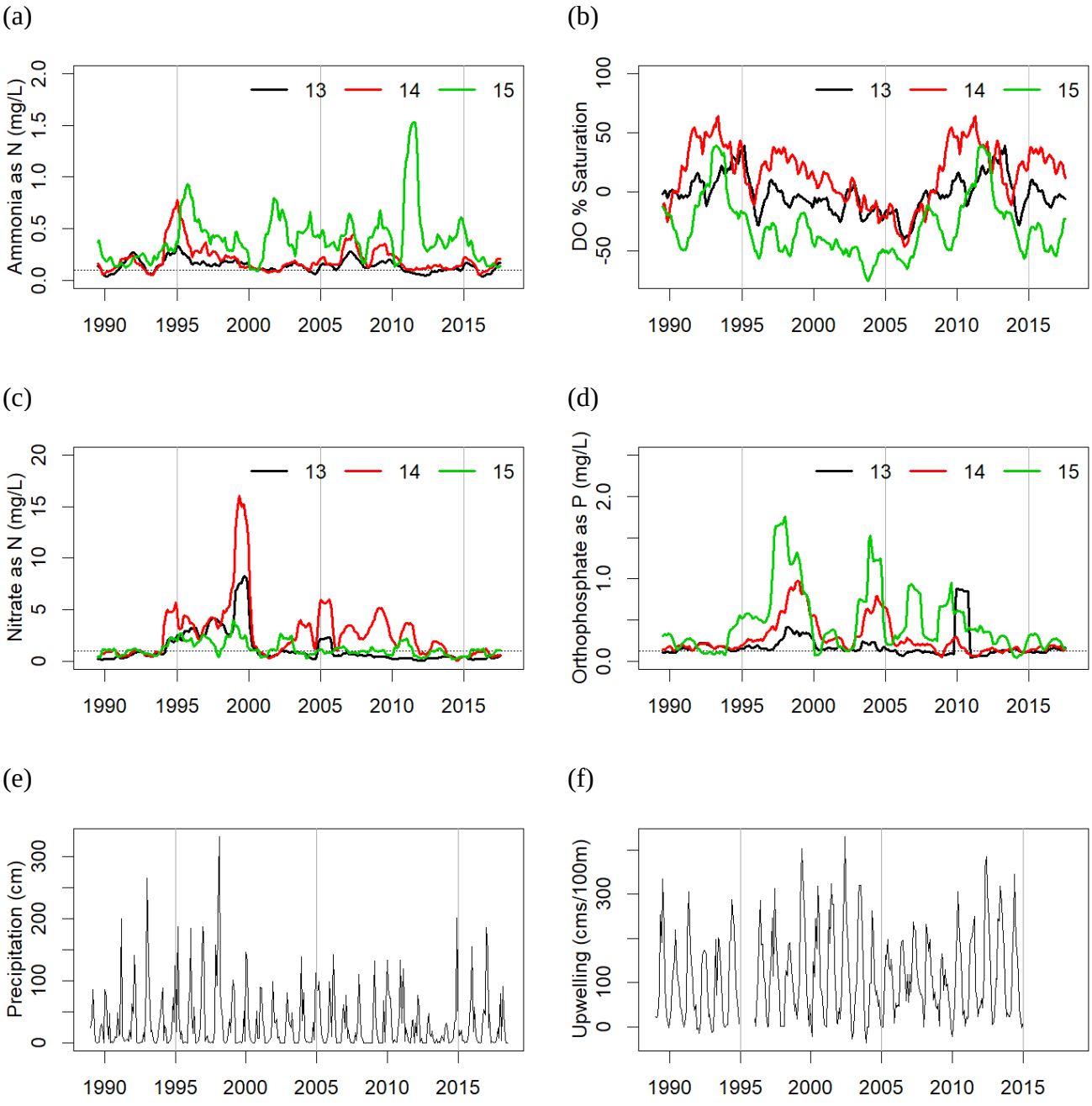


Figure 2 (a-f): Average nutrient and DO concentrations in the Upper Slough region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. Dashed line represents threshold nutrient levels. Sites in this region are: Hudson Landing West (13), Hudson Landing East (14), and Carneros Creek (15).

The Upper Slough is located in the north end of the slough, at the beginning of the estuary. Carneros Creek (15) 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 (15) 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 West (13) and Carneros Creek (15) have tended towards averaging at or below the threshold for the majority of the time since 2001. In this case, Hudson Landing East (14) 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 Hudson Landing East, and lowest Hudson Landing West. 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. Hudson Landing East'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. Hudson Landing East tends towards the opposite, with frequently high averages around 150% saturation. Hudson Landing West 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

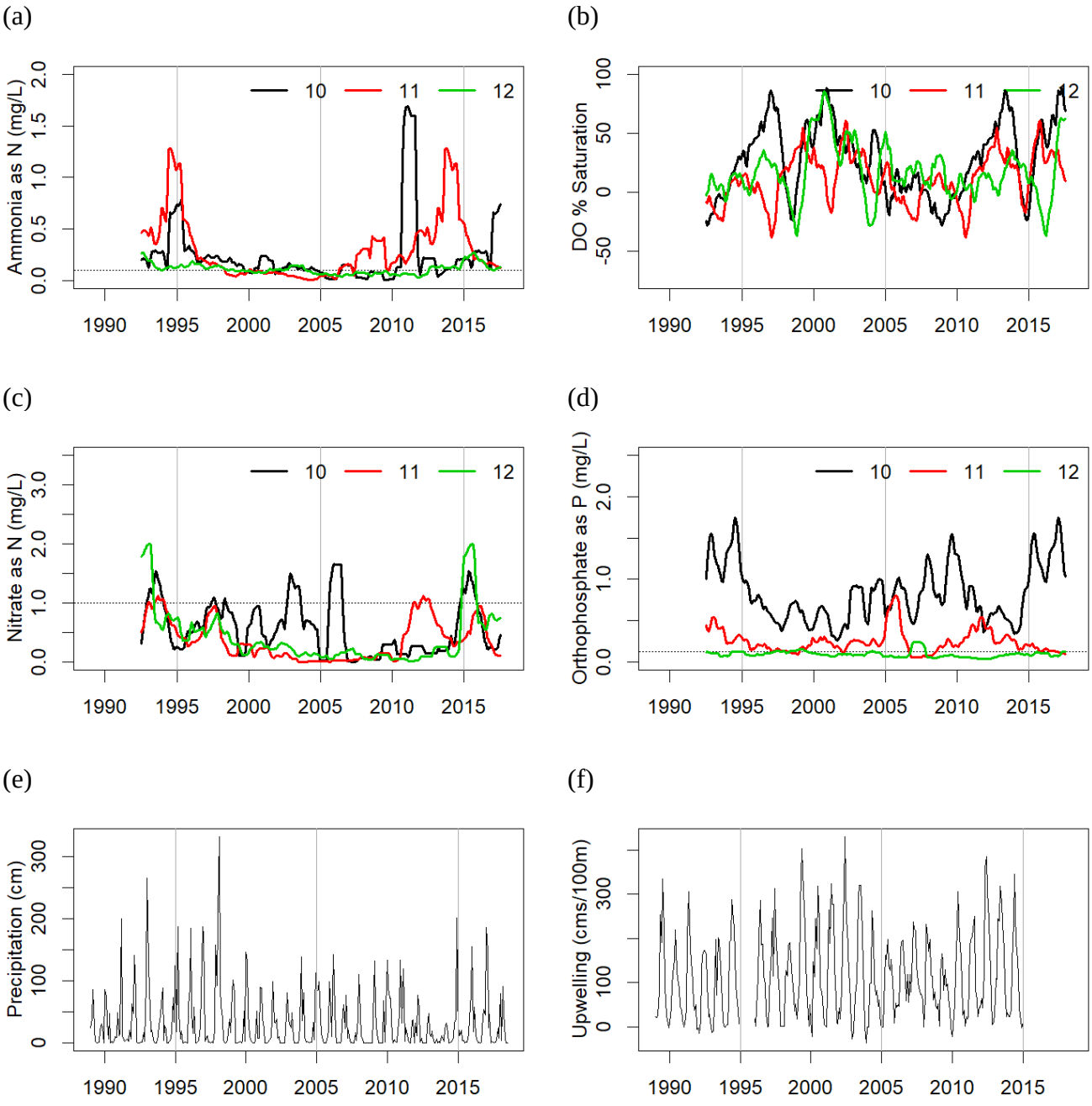


Figure 3 (a-f): Average nutrient and DO concentrations in the Azevedo Pond Region. Dashed line represents threshold nutrient levels. Sites in this region are: South Azevedo Pond (10), Central Azevedo Pond (11), and North Azevedo Pond (12).

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 tidal gates, Gee et al. identified significant improvements in nutrient levels.

Ammonia as N has decreased to close to threshold levels at South and Central Azevedo Pond (10 and 11) since a peak in 1995 (Figure 3(a)). All three sites spend significant time with average levels below the threshold until Central Azevedo Pond 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 North Azevedo Pond (12) site does not show such an extreme departure from the low levels of the early 2000s but appears to be increasing slightly since 2012. South Azevedo Pond's maximum average of approximately 1.5 mg/L and Central Azevedo Pond'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 show decreasing levels after high averages early in the study period (Figure 3(c)). South Azevedo Pond is the slowest to reach consistent low levels, not obtaining steady low levels until 2007. Central Azevedo Pond 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 South Azevedo Pond 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 South Azevedo Pond frequently maintain averages double the levels of orthophosphate as P in the other sites in this region (Figure 3(d)). South Azevedo Pond'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. North Azevedo Pond 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%. At times the ponds track each other in DO trends, but other times the sites correlate negatively with each other.

Middle Slough

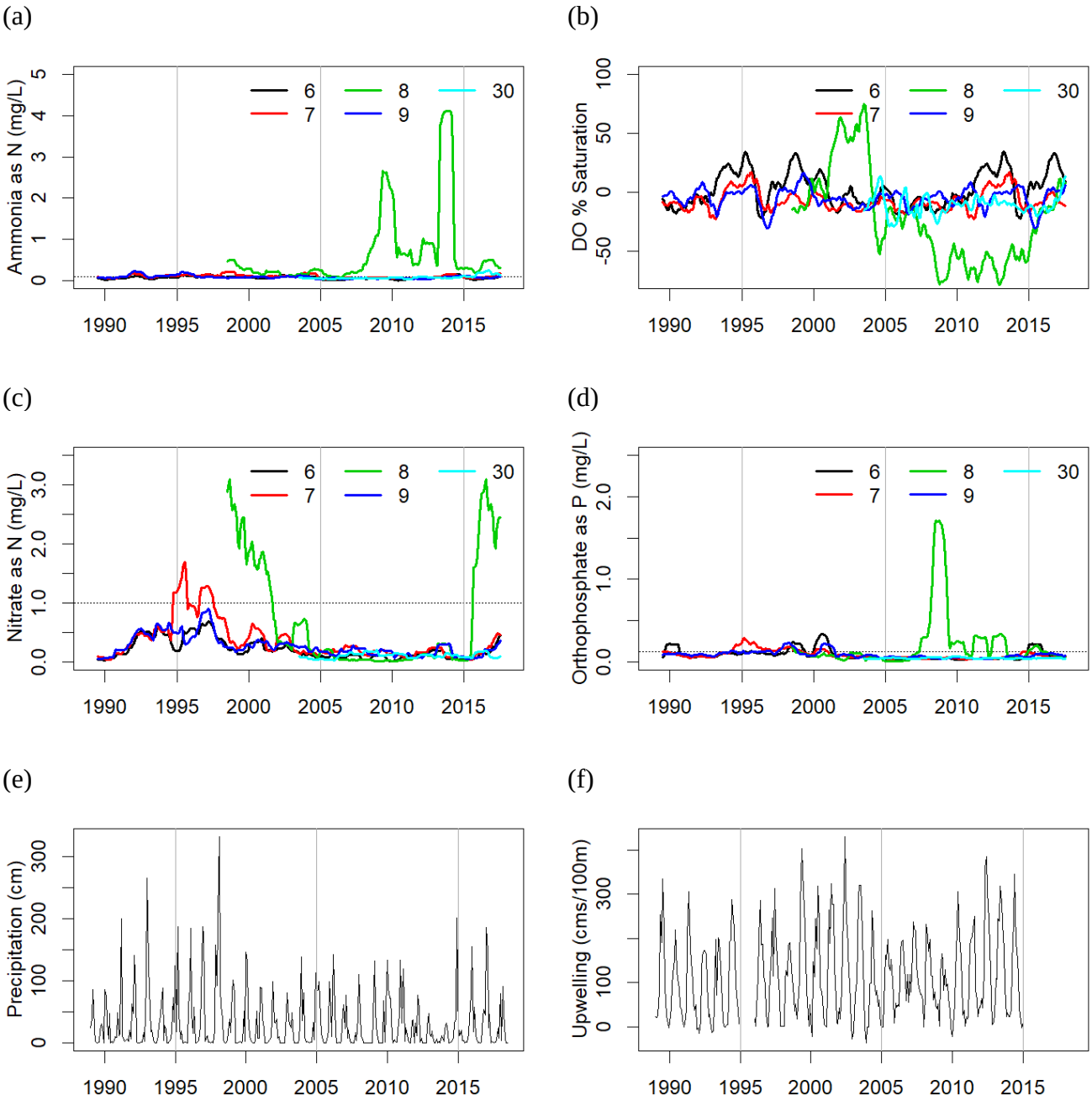


Figure 4 (a-f): Average nutrient and DO concentrations in the Middle Slough Region. The Nitrate as N and Ammonia as N axes have a larger range in y-values in order to contain the higher average parameter values for these sites. Dashed line represents threshold nutrient levels. Sites in this region are: Whistlestop (6), South Marsh Sonde (7), Strawberry (8), Kirby Park (9), and North Marsh (30).

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 and 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 (8) (Figure 4(a)). While the Middle Slough ammonia as N trends at most of the remainder of the sites are indistinguishable, North Marsh (30) has a small increase in 2016. During low rainfall from 2007 to 2015 Strawberry shows the highest averages of ammonia as N for the region. The maximum average concentration of approximately 4.0 mg/L at Strawberry 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 follow an inverse pattern to that of ammonia as N. Strawberry's nitrate as N is lowest when its ammonia as N levels are highest, 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 and the South Marsh Sonde site (7) had an average over the threshold. Whistlestop (6), South Marsh Sonde, and Kirby Park (9) all appear to indicate a slightly increasing average in the most recent years of the study period.

Strawberry orthophosphate as P levels (Figure 4(d)) peak at the same time as ammonia as N levels at the site. The other sites, Whistlestop, South Marsh Sonde, and Kirby Park, make a notable decrease after 2001. For most of the next 15 years, these sites and the newer North Marsh site maintain averages notably below the threshold. Whistlestop has a small peak in 2016. Strawberry'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 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 is most consistently close to 100% between 2000 and 2010.

Lower Slough

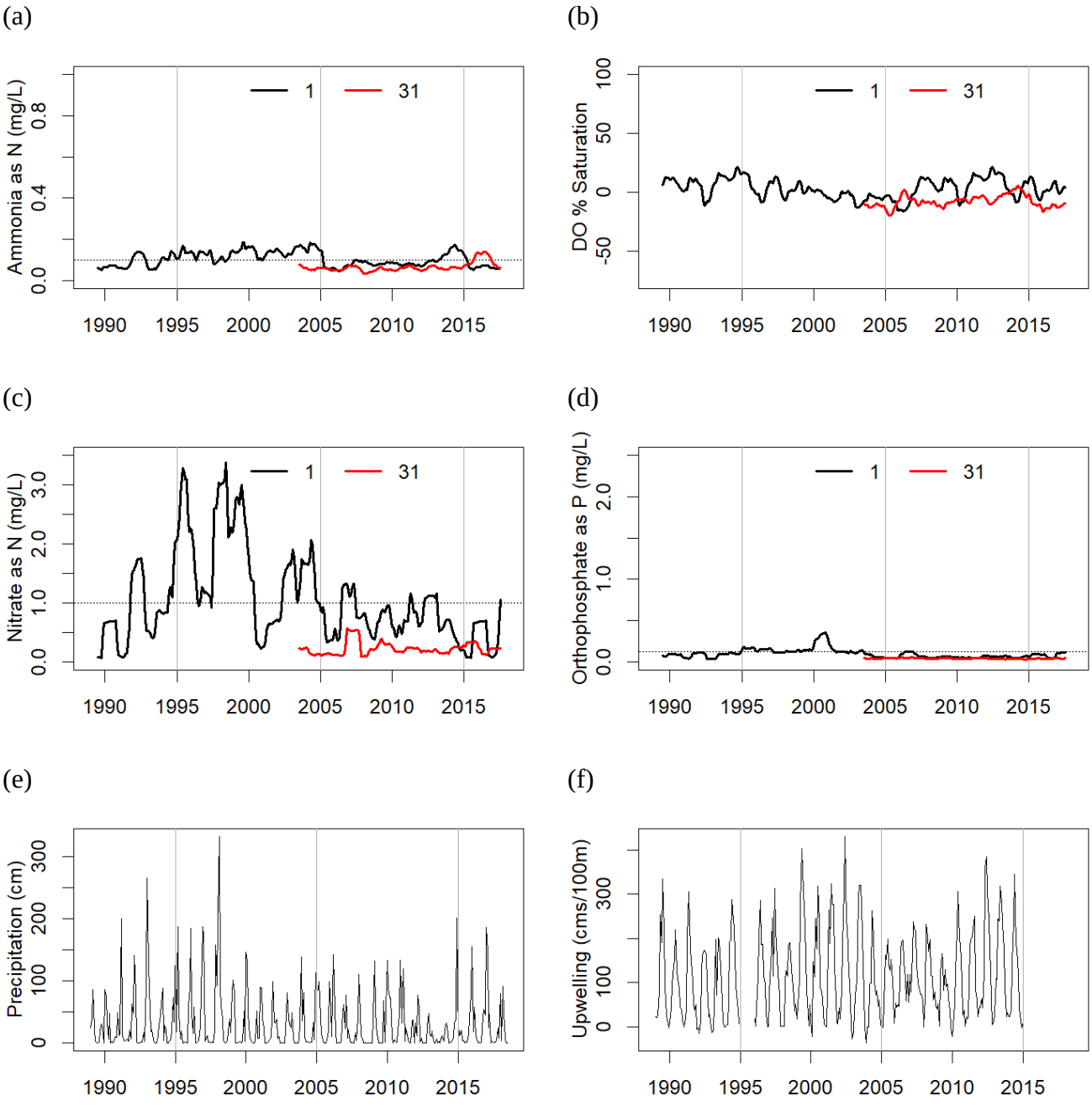


Figure 5 (a-f): Average nutrient and DO concentrations in the Lower Slough Region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. The Ammonia as N axis has a lower range in order to show the variation in values for these sites. Dashed line represents threshold nutrient levels. Sites in this region are: Skippers (1), Vierras (31).

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 Skippers (1) 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. This small period of increase was delayed at Vierras (31) until 2016.

Nitrate as N levels at Skippers show some similarities with patterns in precipitation (Figures 5(a), (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 Skippers 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 Skippers had a peak in the average over the threshold in 2000. After 2004, Skippers has maintained a lower average level compared to before the peak in 2000, and a lower level than the threshold. Vierras has consistently averaged below the threshold for the duration of the study period.

Dissolved oxygen levels in the Lower Slough, especially for Vierras, have had low variation from 100% saturation (Figure 5(b)). Skippers 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

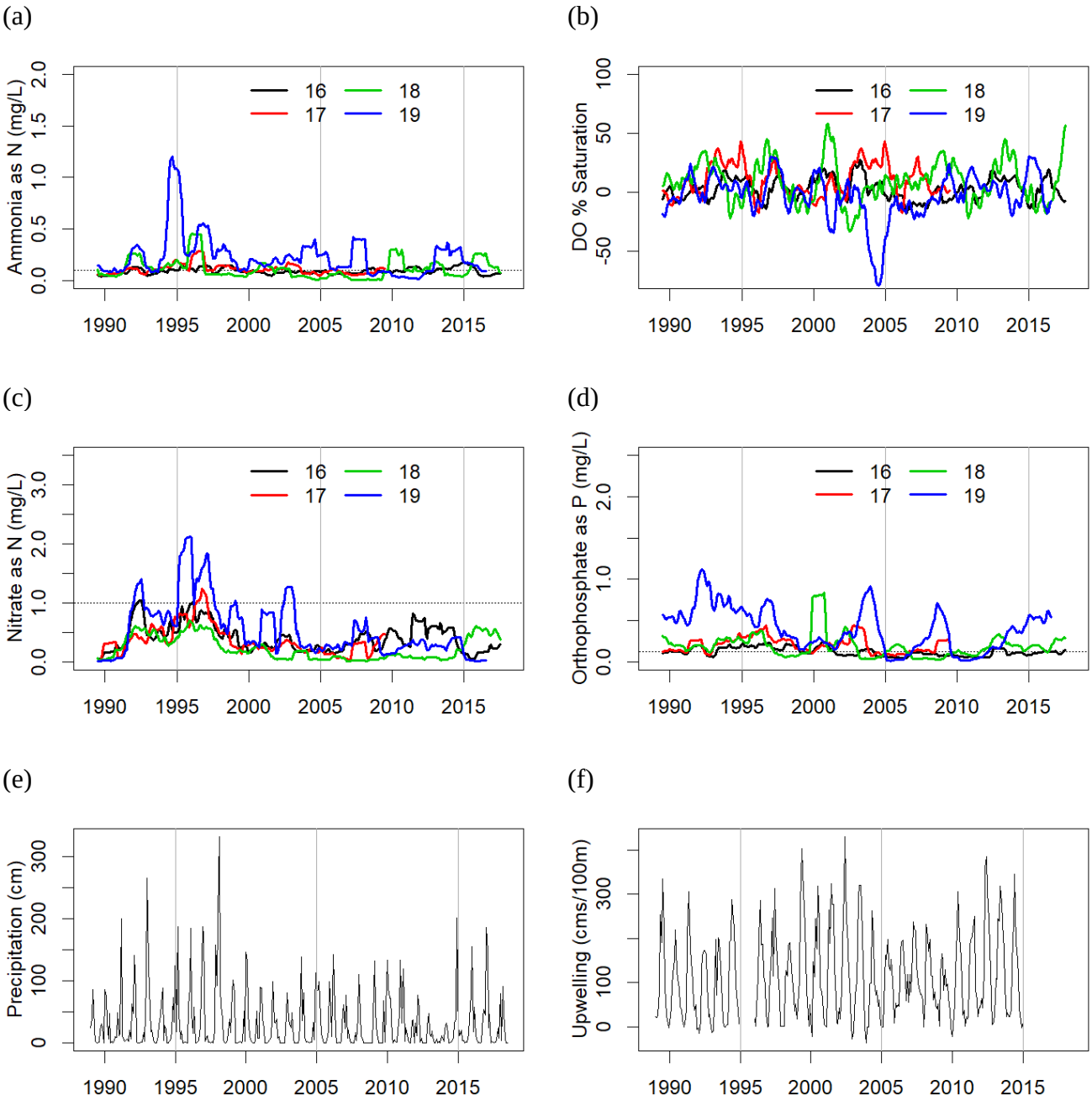


Figure 6 (a-f): Average nutrient and DO concentrations in the Bennett Slough Region. Dashed line represents threshold nutrient levels. Sites in this region are: Jetty Road (16), Bennet Slough West (17), Bennett Slough East (18), and Struve Pond (19).

Bennet 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 (19) occur from 1994 to 1995, and for Bennett Slough East (18) in 1996. Jetty Road (16) 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. 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

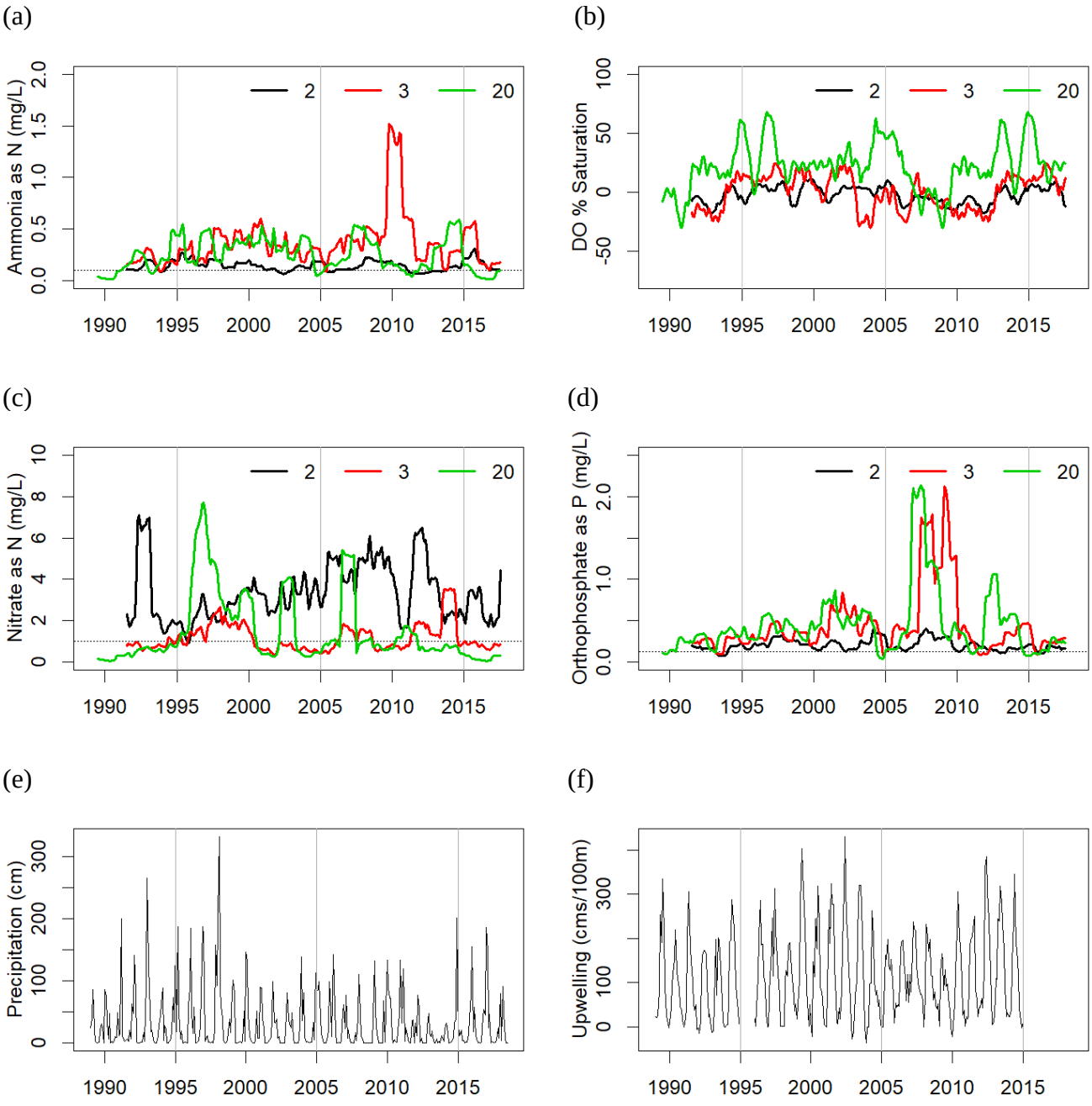


Figure 7 (a-f): Average nutrient and DO concentrations in the Moro Cojo Slough Region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. Dashed line represents threshold nutrient levels. Sites in this region are: Moss Landing North (2), Moss Landing South (3), and Moro Cojo Slough (20).

Moro Cojo Slough has been observed as one of the most extremely eutrophic regions, frequently with extensive algal mats present. Moss Landing Road North (2) 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 North (2) consistently has the lowest average ammonia as N levels. Moro Cojo Slough (20) and Moss Landing South (3) have similar patterns until Moss Landing 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 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 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 South and Moro Cojo Slough. The opposite was observed for Moss Landing North, which had an increasing trend since 1996. The high average nitrate as N concentrations in Moss landing 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 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 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 North has levels most consistently around 100% compared to the rest of the region. Moss Landing 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

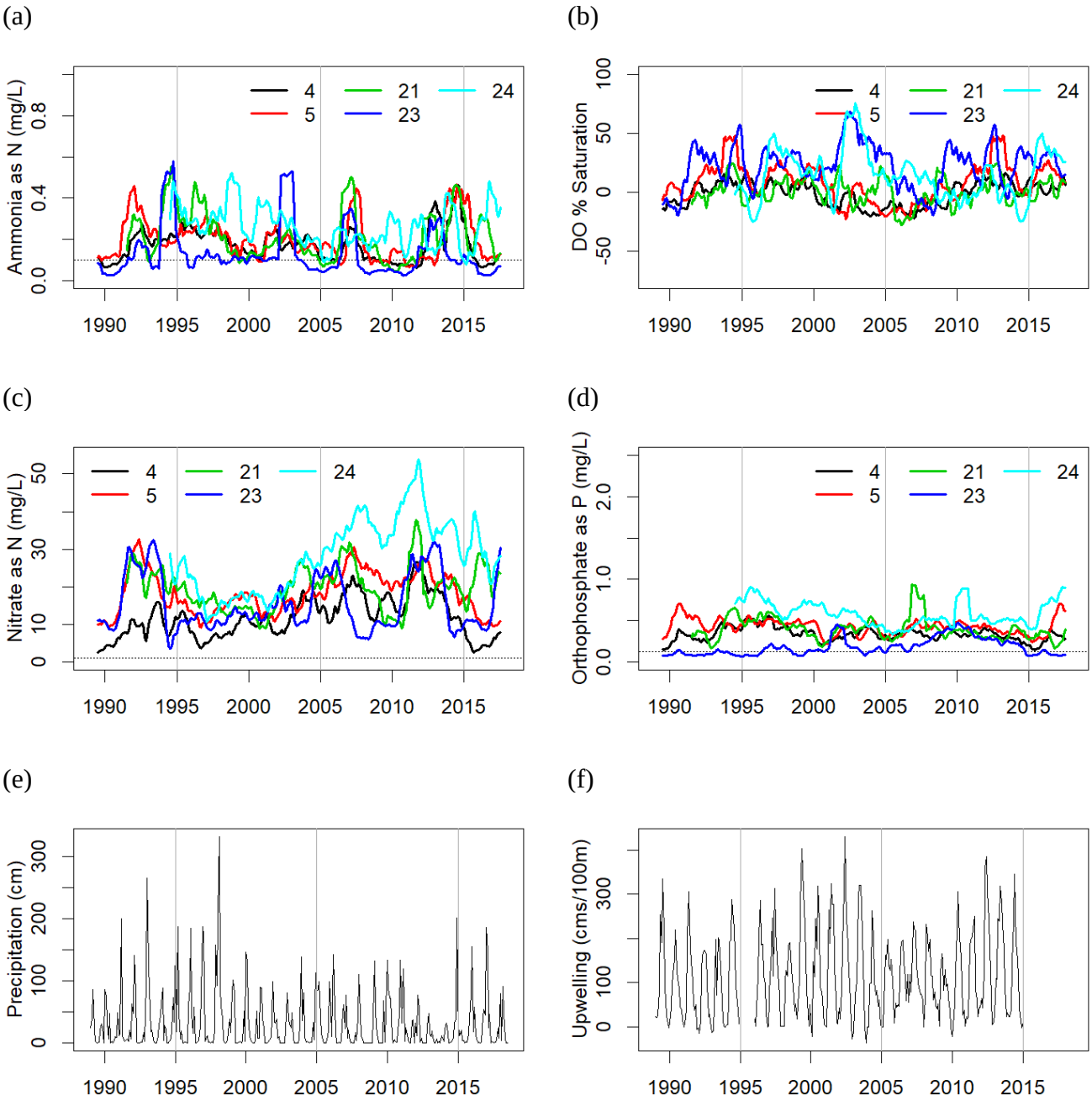


Figure 8 (a-f): Average nutrient and DO concentrations in the South Estuary Region. The Nitrate as N axis has a larger range in y-values in order to contain the higher average parameter values for these sites. Dashed line represents threshold nutrient levels. Sites in this region are: Potrero Road North (4), Potrero Road South (5), Monterey Dunes Way (21), Salinas River Bridge (23), and Tembladero Slough (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 (4) are categorized as restricted wetlands. 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.

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 (4 and 5, 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 (24) 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 (23) 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 (21) 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 against each other, 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.

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.

Nitrate as N concentrations (Figure 10) are the exception to the higher than threshold average trends, with all regions except the South Estuary falling below threshold levels after 2015. It is evident in Figure 10 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.

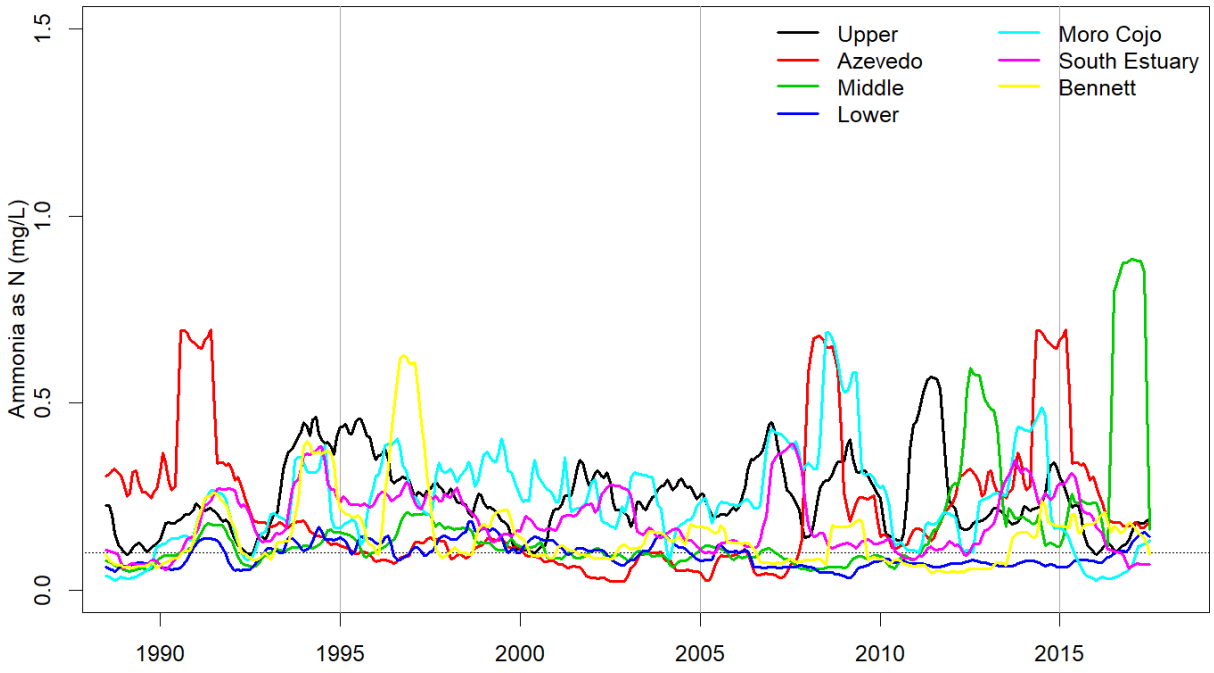


Figure 9: Deseasonalized moving averages of the average ammonia as N concentrations of all sites for each month. Dashed line at 0.1 mg/L represents threshold concentration for Ammonia as N.

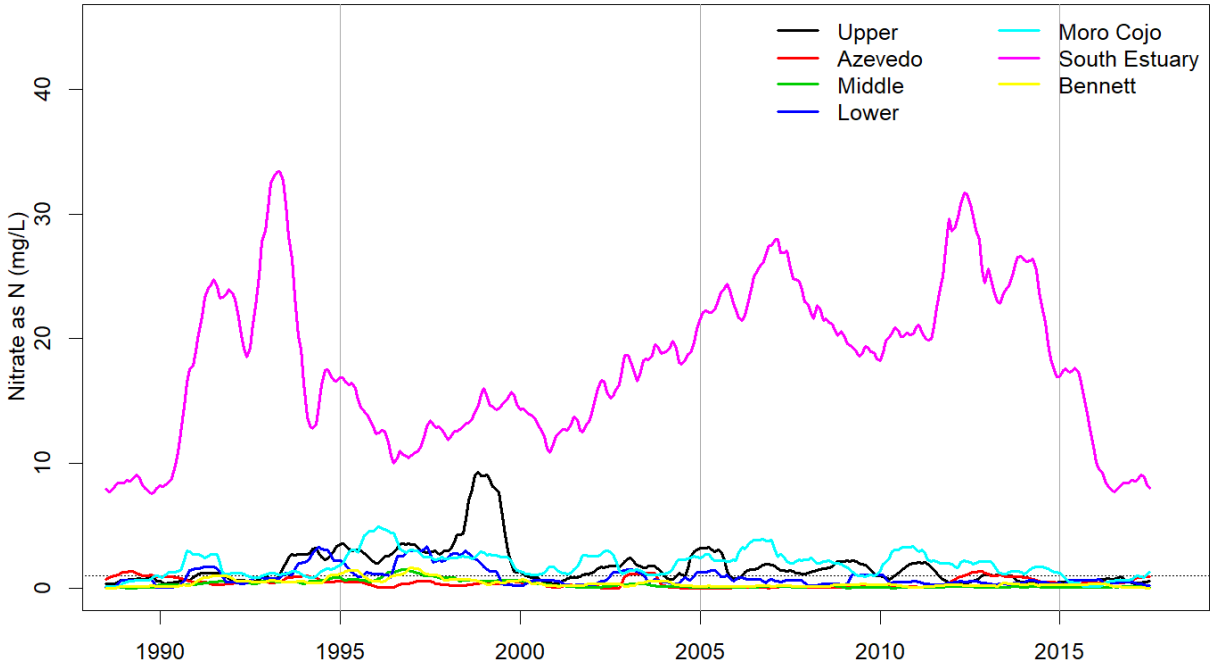


Figure 10: Deseasonalized moving averages of the average nitrate as N concentrations of all sites for each month. Dashed line at 1.0 mg/L represents threshold concentration for nitrate as N.

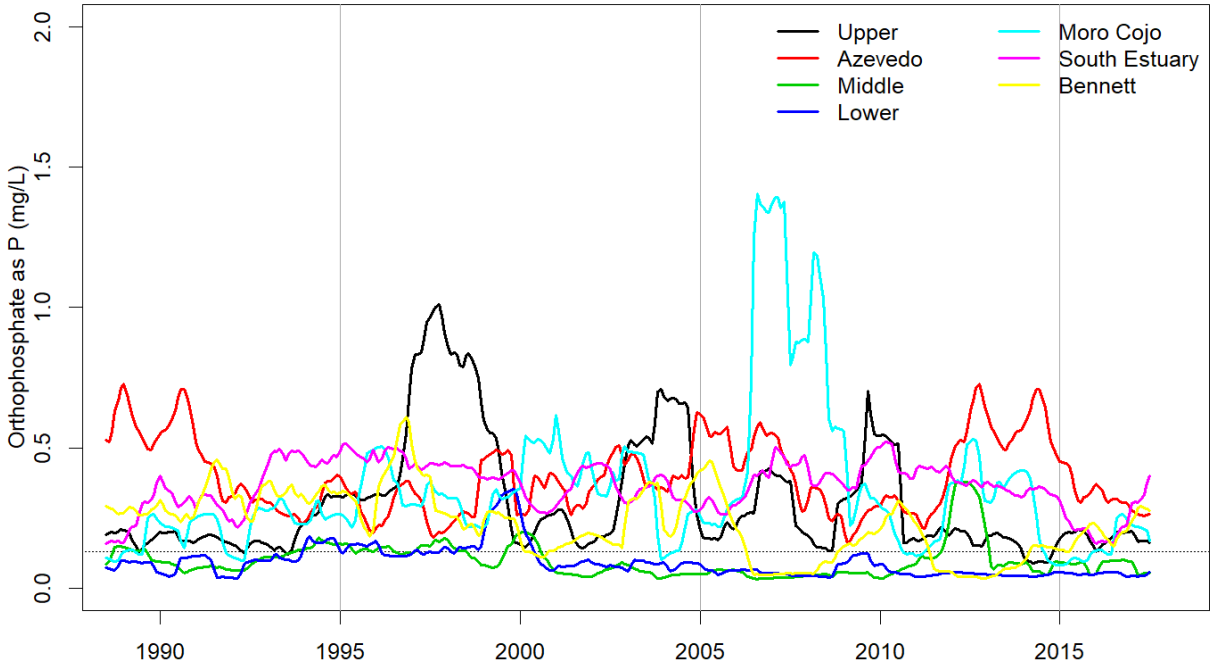


Figure 11: Deseasonalized moving averages of the average orthophosphate as P concentrations of all sites for each month. Dashed line at 0.13 mg/L represents the threshold concentration for orthophosphate as P.

Seasonal Kendall Results

A Seasonal Kendall test performed on the data for each site reveal a regional trend (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). The majority of sites in regions closer to the mouth of the estuary - the Lower Slough and Moro Cojo Slough - show significant increases in nutrient concentrations over time. More results for sites in the South Estuary show significantly increasing nutrient concentrations compared to decreasing nutrient concentrations in the upper estuary regions.

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. Starting years for the monitoring are shown in varying shades of gray, with darker denoting earlier starting years, and thus longer time series. Data were analyzed through the present for all sites except station 17, where data collection stopped in 2010.

		Ammonia	Nitrate	Phosphate	Year Began	Year End
Upper Slough	15^{r}	+	---	ns	1989	
	14^{r}	ns	ns	--	1989	
	13	ns	---	---	1989	
Azevedo	12^{r}	---	---	---	1992	
	11^{r}	---	---	---	1992	
	10^{r}	---	---	ns	1992	
Middle Slough	9	---	---	---	1989	
	30^{r}	+++	++	ns	2003	
	8^{r}	ns	---	ns	1998	
	6	--	---	---	1989	
	7	---	---	---	1989	
Bennett Slough	19^{r}	---	--	---	1989	
	18^{r}	---	---	---	1988	
	17^{r}	ns	ns	ns	1988	2010
	16^{r}	++	ns	---	1988	
Lower Slough	31	+	++	--	2003	
	1	++	ns	-	1988	
Moro Cojo Slough	20^{r}	ns	ns	++	1988	
	3^{r}	++	ns	+	1991	
	2	ns	+++	ns	1991	
South Estuary	23^{r}	ns	ns	+++	1989	
	24^{r}	---	+++	---	1994	
	21^{r}	---	ns	ns	1991	
	5^{r}	-	+++	ns	1989	
	4	ns	+++	+	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 North Marsh (30). The exception to the increased nutrient concentrations in the Lower Slough are the decreased concentrations of orthophosphate as P. The South Estuary, which began with concentrations of nitrate as N many times the levels of other sites, show highly significant increases for the Potrero Road Sites (4 and 5) and Tembladero Slough (24). At the same time, ammonia as N levels for Potrero Road North (4) and Monterey Dunes Way (21) have all decreased over the study period. Both ammonia as N and orthophosphate as P in the Tembladero Slough 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	**Change**		
Type	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 ($p = 0.02$).

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

	Change		
Region	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

Conclusions

The analysis of these data has revealed that there is high regional and spatial 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 affecting average trends for Middle Slough ammonia as N. Furthermore, the chi-squared test on the Seasonal Kendall results indicate that sites of the same wetland type (restricted or unrestricted) are not significantly similar in their trends over time. Thus having multiple sites of the same wetland type will provide important information for further analysis of the drivers of water quality trends.

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 Foundation has 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 restorations 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 for the old Salinas River channel.

Additional scientific collaboration and research is needed to show better understanding of water quality drivers not incorporated in this study that may correlate with such variability of the Elkhorn Slough. Very few regions show trends that suggest good correlation with precipitation levels or upwelling alone. At times, some sites show high concentration spikes. Though the temporal persistence of these high concentrations may be short, for some species concentration levels above a certain level can cause stress, if not acute toxicity. Actual recorded measurements during sampling were even higher than the range of the graphs above due to the process of averaging to identify the trends. Plots of the raw concentrations and saturation can be found in the Appendix.

The process of eutrophication from high concentrations of nutrients can lead to observed high levels of dissolved oxygen during the day, which in turn is associated with hypoxia during the nighttime (Hughes 2011). Hypoxia has been shown to attribute to stress and lower survival in fish and oysters in the Elkhorn Slough (Jeppesen et al. 2015). 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 bacterial makeup has undergone a change, and that bacterial activity could be important factors contributing to the long-term trends. Some of the nutrient peaks that occur only at a very local scale, at single sites within a region, could perhaps be correlated with very local land use changes or irrigation or fertilization regimes, with GIS analyses and farm data. Further investigations into land use practices, fluxes from the sediments and bacterial dynamics, and the patterns of retention time and water movement throughout the estuary are needed.

References

Boyer, J. N., J. W. Fourqurean, R. D. Jones. (1999). Seasonal and Long-Term Trends in the Water Quality of Florida Bay (1989-1997). Estuaries, 22(2): pp. 417-430.

Gee AK, Wasson K, Shaw SL, Haskins J. 2010. Signatures of restoration and management changes in the water quality of a central California estuary. Estuaries and Coasts 33: 1004-1024.

Hughes BB, Haskins JC, Wasson K, Watson E. 2011. Identifying factors that influence expression of eutrophication in a central California estuary. Marine Ecology Progress Series 439: 31-43.

Mensinger, M. (2017). National Estuarine Research Reserve (NERRS) System-Wide Monitoring Program (SWMP): YSI/Xylem Multi-Parameter Water Quality Monitoring Standard Operating Procedure. Version 1.1. M. Lizotte, C. Butler , M. Ide. (eds.). Centralized Data Management Office.

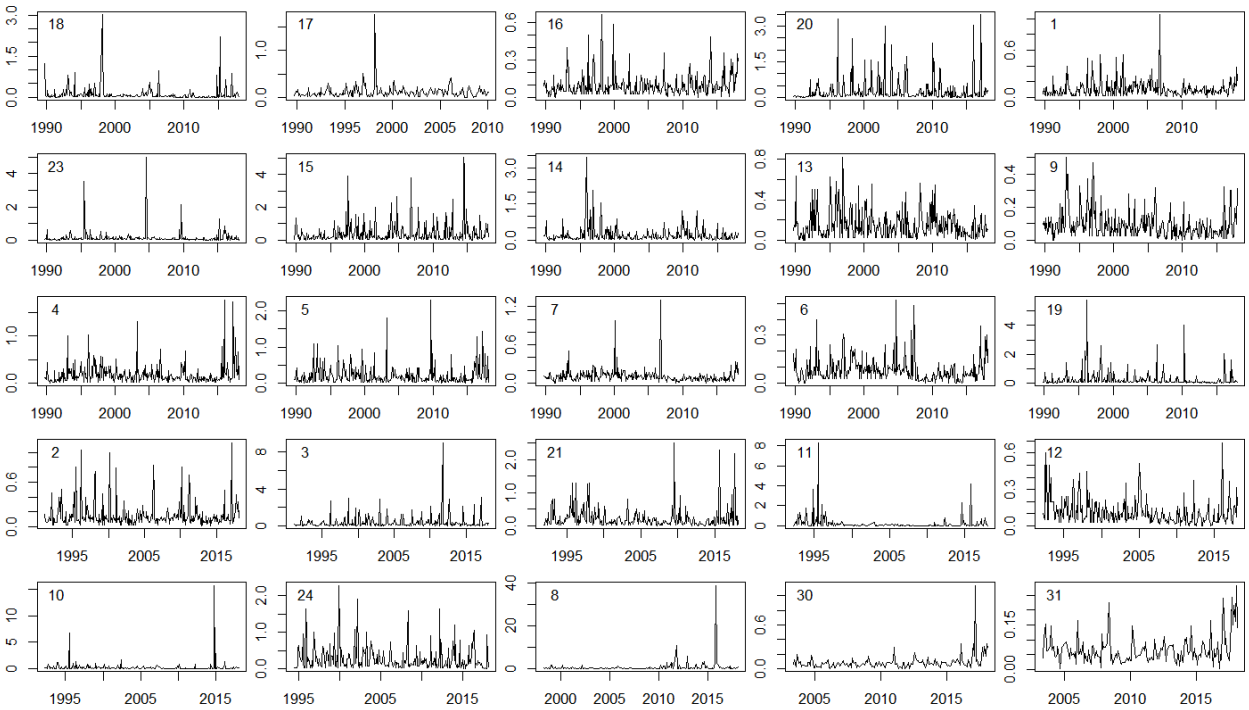
NOAA/NERRS Nutrient Monitoring Committee. (2017). National Estuarine Research Reserve System: Nutrient and Chlorophyll Monitoring Program and Database Design.

R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

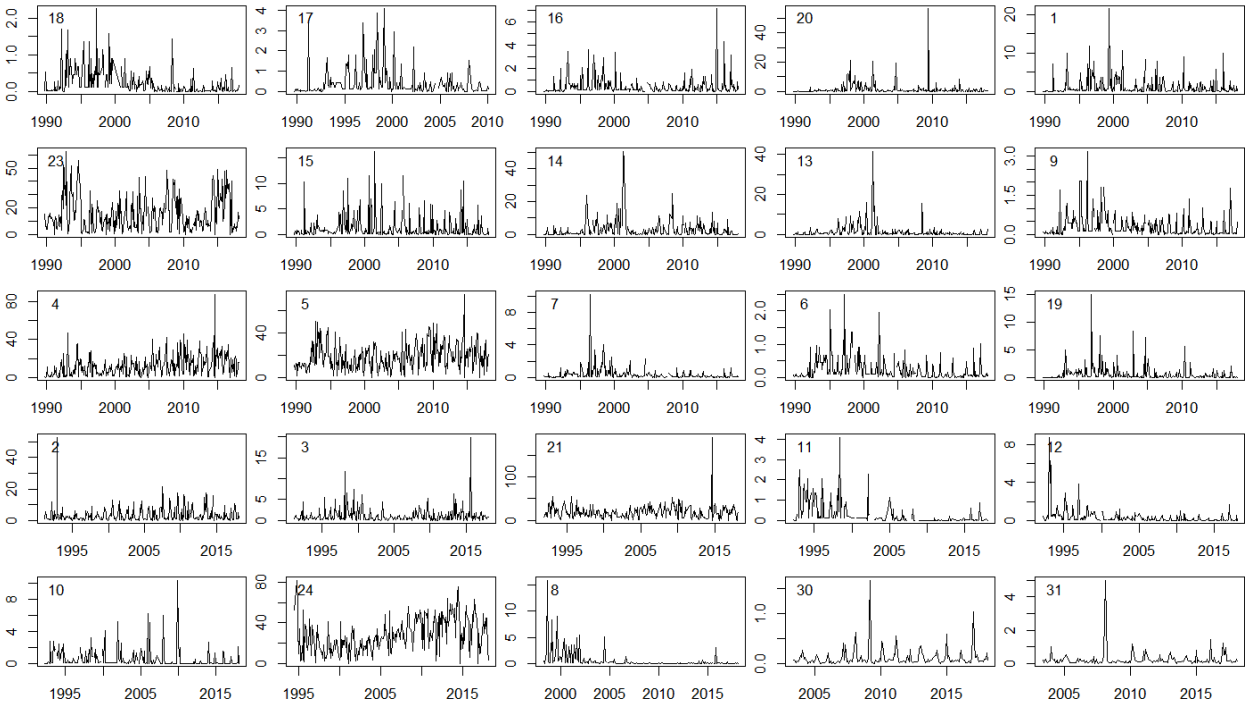
Jeppesen, R., M. Rodriguez, J. Rinde, J. Haskins, B. Hughes, L. Mehner, K. Wasson. (2016). Effects of Hypoxia on Fish Survival and Oyster Growth in a Highly Eutrophic Estuary. Estuaries and Coasts.

Appendix

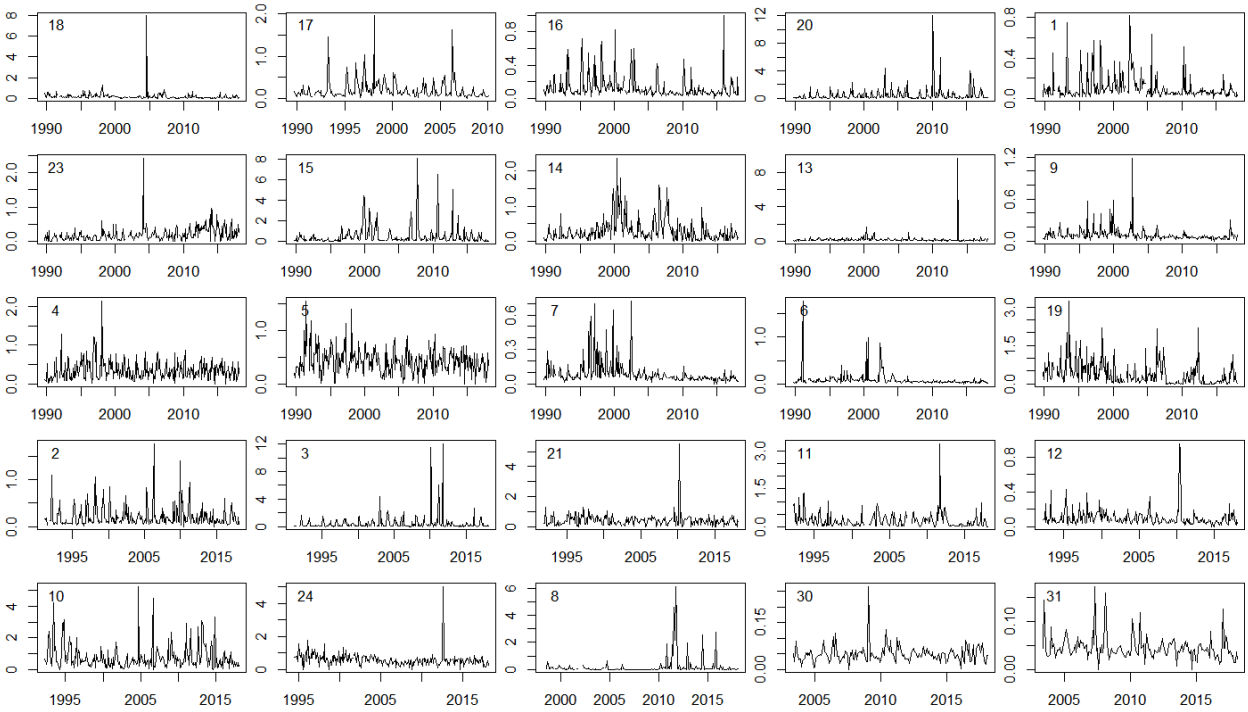
Raw Data Plots for Ammonia as N (mg/L)



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



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



Raw Data Plots for DO % Saturation