

**Statewide and Regional Changes in
Nutrient Concentrations in Florida's Groundwater
(1991–2022)**

Rick Copeland

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Florida Department of Environmental Protection
Division of Assessment and Restoration
Water Quality Assessment Program
Watershed Monitoring Section



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Executive Summary and Recommendations

The Florida Department of Environmental Protection (FDEP) has declared several of Florida's springsheds to be impaired for nitrate plus nitrite as N; abbreviated NO₃. The damage is caused because of an increase in nitrogen loading from the land surface. Once in an aquifer, if enough nitrification occurs, the excess nitrate is transported in groundwater and, if springs are present, is discharged from the aquifer into spring runs. Once in the spring run, the high levels of nitrate can contribute to an abundance of nuisance algae and other biota. To address these concerns, the FDEP Division of Environmental Assessment and Restoration (DEAR) has established Basin Management Action Plans (BMAPs) to restore the spring water. Since the nitrate concentrations are elevated in groundwater throughout most of the BMAP areas, evaluations of groundwater quality within entire springsheds, and upgradient of impaired springs, is critical.

DEAR has been systematically monitoring groundwater quality since 1991. Through 1999, a fixed station monitoring design was employed. In 2000, a probabilistic monitoring design was implemented utilizing a random site selection process. The revised monitoring network is referred to as the Status Network. It monitors unconfined and confined aquifers. In addition, it monitors the following fresh surface-water resources: small lakes, large lakes, small streams, large rivers, and canals. The Status Network sampling design ensures sampling sites are spread over the actual geographical distributions of each water resource.

Although NO₃ has caused the most degradation to groundwater quality in springsheds, other nutrients are of concern to the Department. For these reasons, it was decided to conduct trend analyses of Florida's groundwater resources for a suite of nutrients and several ancillary indicators for the period 1991 through 2022. Analyses were conducted for unconfined and confined aquifers at the statewide scale and within regions. The six regions are referred to as zones. The four northernmost zones correspond to four of Florida's water management districts. For the south, since the South Florida Water Management District is much larger in area than the other districts, it was split into a western and an eastern half; each representing a separate zone. On the statewide scale, analyses revealed no nutrient trends for unconfined aquifers. For confined aquifers, total phosphorus significantly decreased. Total phosphorus and NO₃ increased in some zones and decreased in others. Regarding NO₃, when upward trends were observed, they were often found in confined aquifers in the northern and central portions of the state, where protective, confining sediments are either thin or missing. The reasons for the decrease in total phosphorus are not fully understood. The most likely driver of increasing nitrate concentrations is nitrogen loading. During the latter years of the investigation, decreasing concentrations of NO₃ were found in some of the zones. Evidence suggests the decreases were due to the dilution, caused by an increase in rainfall.

Regarding ancillary indicators, water temperature and dissolved oxygen had the highest frequency of trends. At the statewide scale, temperature trended upwards, while dissolved oxygen trended downward. At the zonal scale, when trends were observed, dissolved oxygen trended downward. On both the statewide and the regional scales, groundwater temperature increases were likely due to an increase in air temperature. Dissolved oxygen was found to be negatively correlated with increases in air and water temperature. One possibility is that increased temperature possibly provided sufficient energy to break the molecular bonds between hydrogen and oxygen, allowing dissolved oxygen to escape from the groundwater resulting in a negative correlation with temperature.

Recommendation

It is recommended that DEAR improves its ability to obtain more accurate nutrient loading data and to do so at higher frequencies than it currently obtains. In this study, the most plausible explanations for the observed decreases in nitrate concentrations are: (1) a reduction in nitrogen-loading, or (2) in unconfined aquifers, by an influx of low nitrogen concentration recharge water, which resulted in the dilution of nitrate concentrations, or (3) a combination of the two. Unfortunately, there are insufficient data to make conclusive inferences regarding a reduction in loading and therefore the recommendation listed above.

Caveats

Regional and local characteristics, such as differences in groundwater basins, topography, geology, aquifer confinement, climate, precipitation patterns, land-use patterns, and groundwater extraction each can affect the statistical results of this investigation. While this study investigated potential relationships of these variables, incorporating each of them into the analyses was beyond the scope of this investigation.

Upon inspection of the data, Color, Total Organic Carbon (TOC), and Turbidity (Turb), during early sampling cycles often had many missing values. For this reason, trend analyses for Color and TOC were only conducted during the latter period (2013-2022).

Total nitrogen (TN) is a calculated value. It represents the sum of laboratory values of nitrate + nitrite plus total Kjeldahl nitrogen (TKN). Also, if the reported value of NO₃ was below the method detection limit, the NO₃ values were raised to the limit value. This was done to assist in the statistical evaluation for trends. This issue will be discussed in detail in the Methods section of this report.

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Introduction and Purpose of Study

DEAR has been systematically monitoring Florida's groundwater quality for the FDEP since 1991. The primary purpose of this investigation is to determine if changes in concentrations of nutrients and related indicators in Florida's groundwater have occurred for the period 1991-2022 (32 years) and to discuss plausible drivers of changes if they are observed. Nutrient indicators include ammonia (NH₃), nitrate (NO₃), total Kjeldahl nitrogen (TKN), total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC). Ancillary indicators are true color (Color), dissolved oxygen (DO), turbidity (Turb), pH, specific conductance (SC), and water temperature

(Temp). For each analyte, Table 1 lists its indicator group, the indicator name, its abbreviation, and its unit of measure.

Although DEAR has analyzed and reported on groundwater quality conditions for various periods, no statewide and regional report has, until now, been prepared for nutrients in groundwater covering several decades. In addition to the period 1991 – 2022, trend analyses were also conducted for 2000 – 2022 (Period B) and 2013 – 2022 (Period C). As explained shortly, FDEP redesigned the network and began monitoring, using the new strategy in 2000. The revised network is called the Status Network (SN). Hence, Period B represents the years 2000 – 2022. The decision to use Period C is strictly arbitrary. It represents the most recent decade of operating the SN.

Table 1. Indicators.

Indicator Group	Indicator	Abbreviation used in this report	Unit of Measure
Nutrient	Ammonia	NH3	milligrams per liter (mg/L)
Nutrient	Kjeldahl Nitrogen (Total)	TKN	mg/L
Nutrient	Nitrate (NO3 + NO2 as N)	NO3	mg/L
Nutrient	Nitrogen (Total)	TN	mg/L
Nutrient	Organic Carbon (Total)	TOC	mg/L
Nutrient	Phosphorus as P (Total)	TP	mg/L
Laboratory/ Field	Color (true)	Color	Platinum Cobalt Units (PCU)
Field	Oxygen (Dissolved)	DO	mg/L
Field	pH	pH	pH units
Field	Specific Conductance	SC	µS/cm
Field	Turbidity	Turb	Nephelometric Turbidity Units (NTU)
Field	Water Temperature	Temp	Degrees C or °C

DEAR Groundwater Monitoring Networks

The Background Network (BN) was the predecessor of the SN. It used a fixed-station design (the same wells were used for each sampling cycle). The purposes of monitoring were to:(1) document changes in groundwater quality in areas minimally impacted by human land use activities and (2) compare BN data to those obtained in areas of the state suspected of being contaminated. The BN began monitoring the state in a series of statewide sampling cycles beginning in 1991. Sampling cycles represent periods of statewide sampling events. One third of the state was sampled annually and after three years the sampling cycle was completed. The statewide sampling cycles were: 1991 – 1993 (BN1), 1994 – 1996 (BN2), and 1997 – 1999 (BN3). Each cycle included several hundred sampled wells.

The Status Network (SN) was developed by DEAR to monitor five fresh surface water and two fresh groundwater resources for statewide and regionwide reporting. The five surface water resources are large lakes, small lakes, large rivers, small streams, and canals. The two groundwater resources are unconfined aquifers (UA) and confined aquifers (CA). The Status Network began

operation in 2000. In the SN, sites are randomly selected for sampling for each sampling cycle. There were several alterations to the SN's reporting units for regionwide reporting. During 2000 – 2003 the reporting units were 20 aggregations of eight -digit USGS Hydrologic Unit basins (four within each water management district), with five reporting units sampled annually resulting in a four-year cycle to complete statewide sampling. During 2004 – 2008, the reporting units were the current 29 Total Maximum Daily Load (TMDL) basins, with six reporting units sampled annually resulting in a five-year cycle to complete statewide sampling.

The current SN sampling methodology was initiated in 2009. Reporting units are effectively the five water management districts (WMDs) with the South Florida Water Management District split into an east and west region (Figure 1). These six regions, from here on in referred to as Zones, are Zone 1 the Northwest Florida Water Management District (NFWWMD), Zone 2 the Suwannee River Water Management District (SRWMD), Zone 3 the St. Johns River Water Management District (SJRWMD), and Zone 4 the Southwest Florida Water Management District (SWFWMD), and Zone 5 and Zone 6 is the South Florida Water Management District (SFWMD). Figure 1 depicts the state (study area), plus the six zones.

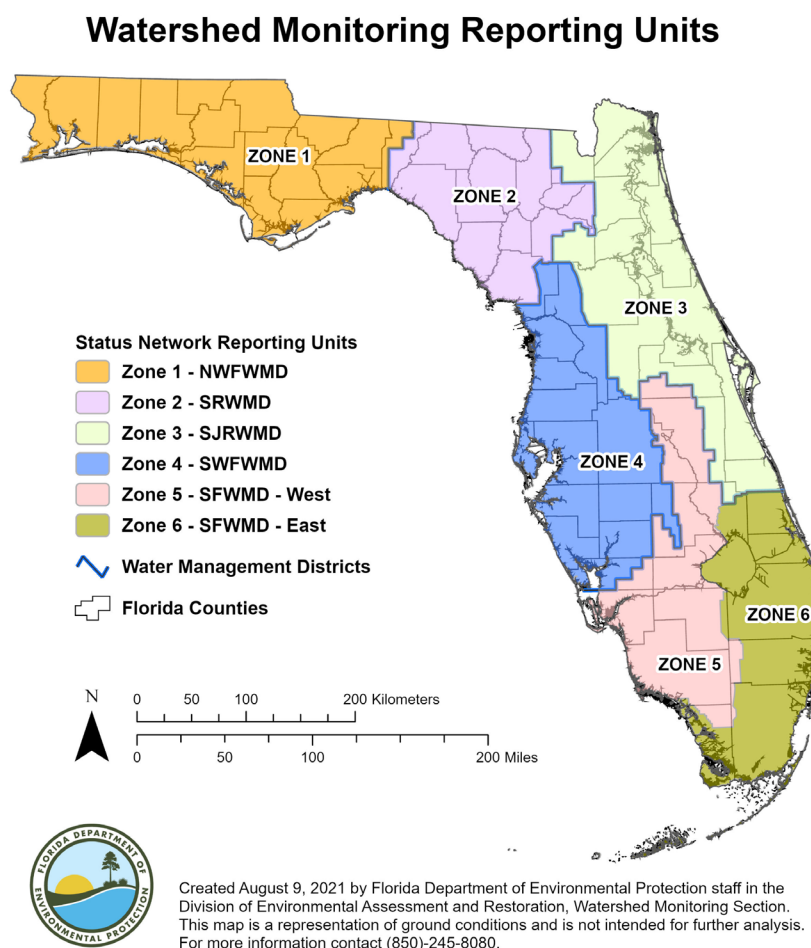


Figure 1. Study Area and Status Network Reporting Units Zones.

The purpose of the SN is to be able to characterize the overall environmental conditions of

the state for its groundwater (and surface water) resources. Regarding groundwater, with a lack of confinement, the UA is more susceptible to contamination from land surface than is the CA. Pollutants originating from land surface are less likely to move downward and find their way to CA because the overlying confining units of the CA can retard the movement of pollutants.

In addition to the old BN wells, wells in the SN include existing public supply, private supply, industrial, agricultural, and newly installed wells. Annually, FDEP requests well construction and location information from the WMDs, the USGS, and other monitoring agencies for wells that can potentially be incorporated into the SN. Some wells are excluded from being incorporated into the network. Excluded wells include those that (1) extract groundwater directly within or beneath a permitted facility's (FDEP, 2019) zone of discharge (F.A.C. Chapter 62-522.300(2)(c)), (2) those that tap groundwater influenced by well injection (Class I and II wells) (FDEP, 2019), and (3) draw water from multiple aquifers. As of 2022, the SN has more than 38,000 wells in a well frame which is used to make annual random selections.

During the early years of the BN, multiple agencies and multiple laboratories were used. Due to less than perfect quality assurance (QA) and quality control (QC) measures, early data were not as good for use in trend analyses as later data. To correct these imperfections, since the mid-1990s the Florida Department of Environmental Protection (FDEP) Central laboratory has analyzed almost all water samples from the SN. With several exceptions, groundwater samples are now being collected mostly by FDEP staff but staff from WMDs and counties are used as needed.

The first complete statewide sampling cycle of the SN was 2000 – 2003 (C01). The second sample cycle was 2004 – 2008 (C02). Beginning in 2009, the SN has been sampled, statewide, in one-year cycles. From 2009 – 2022 the sample cycles are referred to as C03 – C16. Annually, approximately 240 randomly selected SN wells, split equally between the UA and CA resources, are sampled. Thus, in each Zone 20 wells are scheduled to be sampled per year. However, for a multitude of reasons, occasionally less than 20 wells can be sampled per cycle. The actual number is typically between 17 – 20. Table 2 lists the network, cycle name, sample cycle number, the years of each cycle, number of samples per cycle. Figure 2 displays the locations of UA and CA wells sampled from 2000 through 2022. Since 2000, over 9,000 individual wells have been randomly sampled from the SN frame (list) of potential wells to be sampled. Detailed information regarding each SN well is available by contacting the database manager of the Watershed Monitoring Section of DEAR.

Data regarding the total depths and casing depths of UA and CA wells are found in Table 3. Data are based on wells sampled at least once during the 32-year period (1991-2022). The table displays the 25th, 50th, and 75th percentile percentiles (P_{25} , P_{50} , and P_{75} respectively). Percentiles are referred to as the 1st, 2nd, and 3rd quartiles (Q1, Q2, and Q3). Q2 is the median. Two references that give excellent presentations of descriptive statistics are Triola (1998) and Triola (2021). The median total depth of those UA wells is 52 ft while the median total depth of CA wells is 200 ft.

Table 2. Background and Status Network Statewide Sampling Cycles.

Network	Name of Cycle	Sample Cycle Number	Year(s)	n Samples CA	n Samples UA
Background (BN)	BN1	1	1991 – 1993	346	286
Background (BN)	BN2	2	1994 – 1996	383	431
Background (BN)	BN3	3	1997 – 1999	250	269
Status (SN)	C01	4	2000 – 2003	366	440
Status (SN)	C02	5	2004 – 2008	379	455
Status (SN)	C03	6	2009	99	111
Status (SN)	C04	7	2010	107	117
Status (SN)	C05	8	2011	99	109
Status (SN)	C06	9	2012	98	116
Status (SN)	C07	10	2013	110	107
Status (SN)	C08	11	2014	111	108
Status (SN)	C09	12	2015	110	107
Status (SN)	C10	13	2016	109	114
Status (SN)	C11	14	2017	106	103
Status (SN)	C12	15	2018	106	111
Status (SN)	C13	16	2019	106	112
Status (SN)	C14	17	2020	106	106
Status (SN)	C15	18	2021	103	109
Status (SN)	C16	19	2022	102	104

Miscellaneous Information

Since 1991, sampling collection methods for some indicators changed from being collected to provide a total fraction of the water sample to providing a dissolved fraction of the water sample, Table 1. The dissolved fraction is obtained after the water sample passes through a 0.45-micron filter. Of the two fractions, total was the fraction most frequently obtained. For this reason, the total fraction was used whenever possible. However, to make the time series as complete as possible, the dissolved fraction was used whenever the total fraction was missing. Although the differences between the two species can be significant, it is believed that using an estimate of the total species (the dissolved species) is better than having a missing value.

Since 1991, laboratory method detection limits (MDLs) have varied over time. If trend analyses are conducted using the variable MDLs as concentration values, the trend analyses tests could be deceiving. For example, suppose for a given indicator, a site was monitored for 15 years. Suppose a laboratory's MDL for the first 10 years was 10.0 mg/L, but for the last five years it was lowered to 5.0 mg/L. Finally, suppose that during this 15-year period, the true concentrations

ranged from 1.0 to 4.9 mg/L. Conducting a trend analysis test on this observed time series data, using these detection levels, would suggest that the indicator concentration decreased from 10.0 to 5.0 mg/L. Clearly the trend analysis would be incorrect. To adjust for variable MDLs, during this investigation, for each indicator, all values reported as the corresponding MDL were adjusted to the maximum MDL value for the entire period of record. This process was one method recommended by Helsel (2005) for conducting trend analyses using censored data.

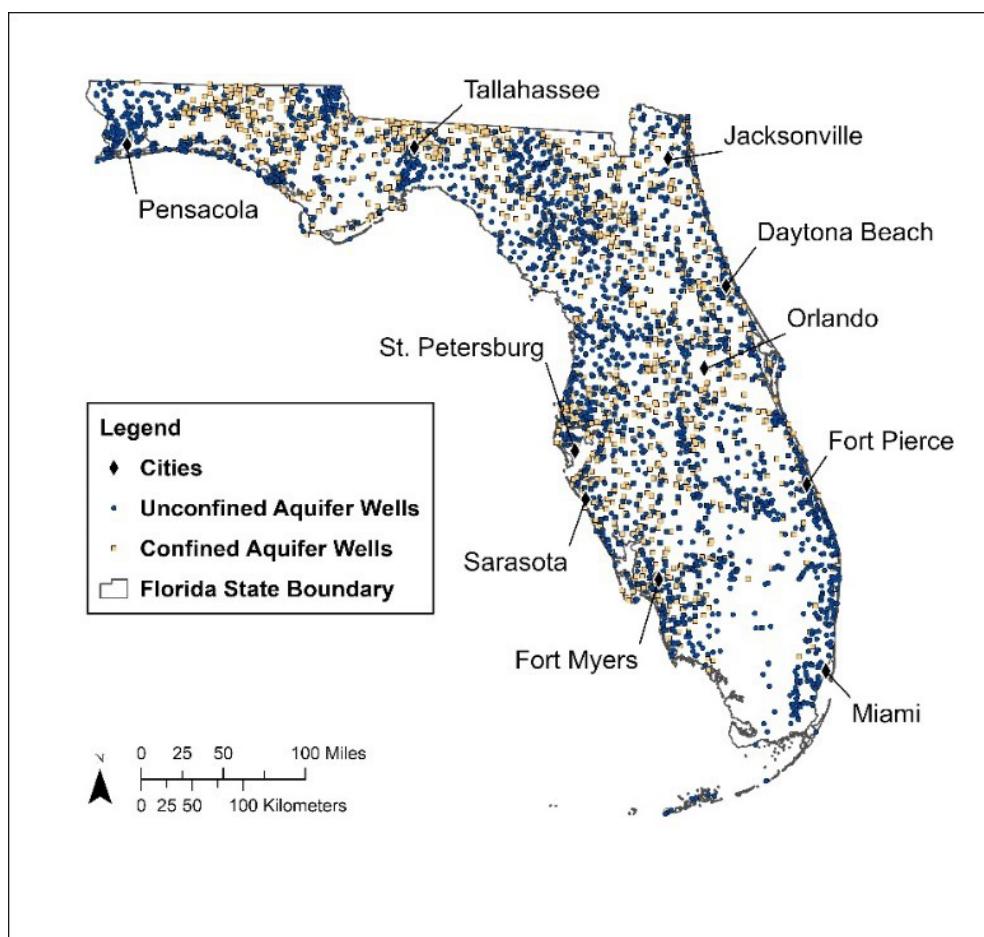


Figure 2. Status Network Sampled Wells (2000 – 2022).

Table 3. Descriptive statistics of the depths of sampled Unconfined and Confined Aquifer wells.

	¹ n	² Q1	³ Q2	⁴ Q3
UA Total Depth (ft)	2557	27	52	100
UA Casing depth (ft)	2557	18	39	77
CA Total depth (ft)	2365	127	200	308
CA Casing depth (ft)	2365	80	130	232

¹n = sample size ²Q1 = data distribution first quartile ³Q2 = median value ⁴Q3 = third quartile ⁵one ft = 0.3048 m

Florida's Aquifer Systems

Florida is underlain by several freshwater aquifer systems (Southeastern Geological

Society (SEGS) 1986). To fully understand the statewide UA and CA monitoring efforts, one needs to be familiar with these aquifer systems. Only a synopsis is presented here. If more details are needed, see Miller (1984), Sprinkle (1987), Scott (1989), Berndt et al. (1998), Williams and Kuniansky (2015), and Upchurch et al. (2019).

The three systems are: (1) the Floridan aquifer system (FAS), (2) the intermediate aquifer system (IAS) or intermediate confining unit (ICU), and (3) the surficial aquifer system (SAS). In most places, the IAS/ICU behaves as an upper confining unit to the FAS. Thus, depending on location, the FAS can be under unconfined or confined conditions. Where present, aquifers within the IAS are generally confined below and above by relatively impermeable sediments (the ICU). In northwestern Florida, the major aquifer within the SAS is the sand and gravel aquifer. In southeastern Florida, the major aquifer of the SAS is the Biscayne aquifer. The aquifers within the SAS are almost always under unconfined conditions.

Materials and Methods

Groundwater Monitoring Network Designs

A companion document, “The Hexagon Design - A Flexible Sampling Design for Groundwater Monitoring” by DEAR and other entities (Copeland, 2025), discusses DEAR’s groundwater monitoring network designs. DEAR is currently utilizing a Generalized Random Tessellation Stratified (GRTS) design for statewide and regional scale assessments. GRTS was developed by the U.S. Environmental Protection Agency (EPA). The GRTS design assures that samples are spatially balanced. That is, sampling distributions of sites reflects the actual spatial distribution of the resources. DEAR has used the GRTS design since 2000, not only for monitoring groundwater but also Florida’s fresh surface water resources.

Regarding groundwater, the GRTS design works well at the state and regional scales, but for several reasons it is not often used at scales when the area is smaller than a water management district (WMD). For this reason, DEAR established an alternate sampling design, the “hexagon method”. It is flexible and can be easily adopted for groundwater monitoring by DEAR and other entities at various scales. Hexagons are used to address spatial autocorrelation and will be discussed later.

Using the hexagon method (discussed in the companion document mentioned above), a map of equal-area hexagons is overlain on a map of the region of interest (e.g. the state of Florida). For each sampling cycle, hexagons are randomly selected and then a well is randomly selected from the selected hexagon for sampling. This results in a simple random sample design of equally weighted hexagons.

However, for this post hoc investigation, a modification to the hexagon method was made. Within each zone, wells instead of hexagons, were randomly selected. The geographic coordinates of each well were assigned to its corresponding hexagon. For each sampling cycle, some hexagons contained multiple sampled wells, some contained only one well, and many hexagons contained no wells. For the hexagons with multiple sampled wells, the mean and the median values for the sampling cycle were used to represent the corresponding hexagon. In this manner no hexagon is represented more than once. Each sampled hexagon is represented by a single value for each sampling cycle. Since hexagons are of equal size, for each sampling cycle, for each zone, the

design provides an approximation of a simple random sample of equal area hexagons. To obtain a statewide estimate, each zone is treated as a separate stratum weighted by its zonal area. Thus, a statewide estimate is obtained using a stratified random sample design.

Returning to the GRTS design, no well is sampled more than once per sampling cycle. Also, as mentioned previously, the GTRS design assures that the sampled wells simulate the distribution of existing wells across Florida. Unfortunately, there are portions of Florida where wells do not exist. Nevertheless, with more than 38,000 wells in the SN well frame, based on professional judgement, it is assumed that the distribution of sampled wells sufficiently represents all wells within the state.

Since 1991, several thousand wells, and hexagons, have been sampled for both Confined Aquifers and Unconfined Aquifers. Figure 3 (left) displays the distribution of hexagons with at least one CA well in the SN sampling frame (listframe). Figure 3 (right) shows the distribution with at least one UA well in the SN listframe. Figure 4 (left) depicts the hexagons with at least one sampled CA well obtained during the study. Figure 4 (right) does the same for the UA. By comparing Figures 2, 3 and 4, one can see that sampled hexagons approximate the distribution of existing wells.

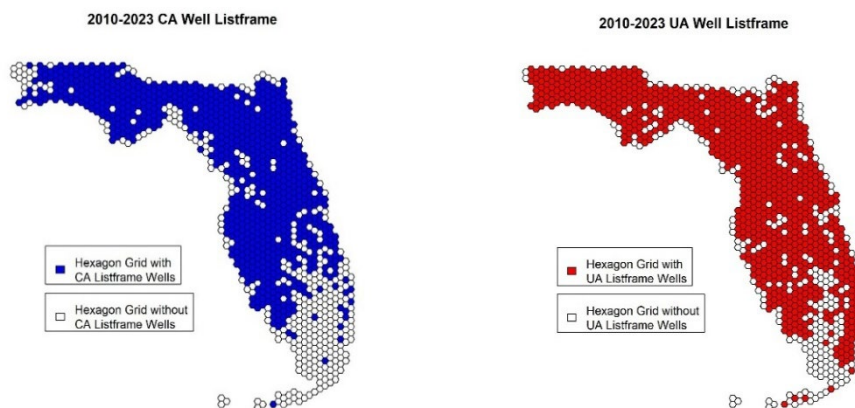


Figure 3. 2023 Hexagon sample listframe containing at least one well (CA (left) and UA (right)).

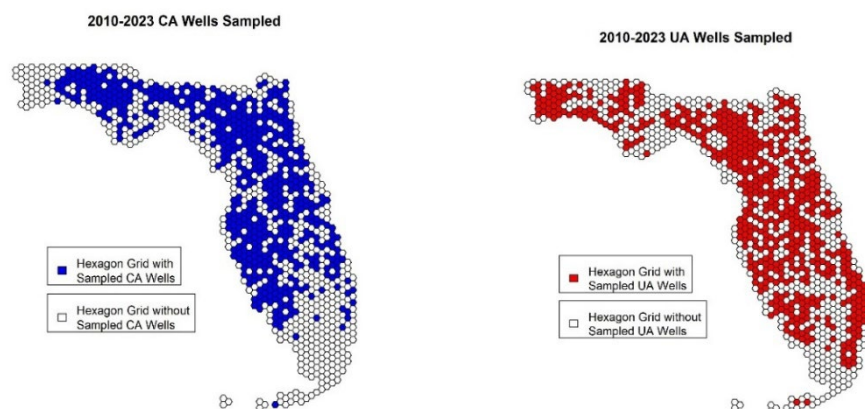


Figure 4. Hexagons sampled at least once 2010 through 2022 (CA (left) and UA (right)).

The size of the hexagons was based on the concept that if sampled wells are located too close to one another in terms of distance (or time), sampling results tend to be autocorrelated with each other. It is analogous to obtaining a partial replicate sample. Spatial and serial autocorrelation (AC) can adversely affect the results of trend analyses tests by incorrectly lowering the resulting p-value of the test. Thus, the distance at which AC becomes insignificant (the range) must be determined. Wells spaced at a distance greater than the range are considered independent of each other and do not affect the resulting p-value of the test. Although, in two-dimensions, several polygon shapes can be used, Olea (1984) indicated that hexagons are efficient shapes for minimizing the effects of spatial AC. For this study, the range (hexagon diameter) was determined to be 50,000 feet (9.5 miles). The companion report discusses the process for determining the range used in this study. From a random starting point, 1173 hexagons were used to cover the state of Florida.

Time, as well as distance, can adversely influence trend tests results. Addressing AC with respect to time is accomplished during analyses of the data. The process will be addressed later.

Regarding the GRTS design, it currently uses the number of wells (points) in each region as statistical weights to estimate statewide means and medians. However, GRTS can easily be modified to use the area of a region as weights. The hexagon method uses area as a weighting factor. It should be noted that the use of weights by either points or area can be beneficial. For example, someone might be interested in determining the proportion of all wells that have concentrations of an analyte (e.g. nitrate) exceeding a primary drinking water health standard (e.g. 10.0 mg/L) (Florida Administrative Code (F.A.C), Chapter 62-500.310). Alternately someone might want to be interested in determining the proportion of area of a water resource that exceeds a threshold.

In the companion report, a series of tests were conducted to determine if the results produced by the hexagon method were comparable to those produced by the GRTS. It was discovered that if weighting is based on area, the two methods produce comparable results. For this investigation the hexagon method was used at both statewide and zonal scales. Thus, results are based on area, not the number of points.

Data Sources, Quality Assurance, and R Statistical Platform

Data were obtained from FDEP's Oracle-based Generalized Water Information System (GWIS). All sample collection, field, and laboratory analyses were conducted in accordance with F.A.C. Chapter 62-160. Data preparation and analyses procedures, along with associated data qualifiers are available in Appendix A. Data analyses were conducted with statistical packages in the R programming language (R Core Team, 2023). The major R scripts and packages used for data retrieval and statistical analyses are found in Appendix B. Occasionally, the mean, median, and proportion of values exceeding a pre-selected value were calculated using Microsoft Excel® spreadsheets.

Statistical Methods

Nonparametric statistical methods were used for trend analyses for the following reasons. Most indicators' data distributions were positively skewed. For several indicators, it was not unusual for their concentrations to be below the corresponding method detection limit. Sporadically, there were missing data values.

For non-trend analyses, occasionally, parametric methods were desired. These latter procedures generally offer more flexibility in terms of the number of different techniques available for analyses. However, they have more assumptions that need to be met, relative to nonparametric methods. As needed, diagnostic procedures were performed to determine if parametric procedures were the most appropriate.

Over the years, scientists have developed statistical methods for detecting increasing or decreasing trends in water-quality indicators. For this study, R software packages utilizing these statistical methods were used. The minimum number of values needed for trend analysis was dependent on the R package used. In most situations the minimum number was eight or 10. Trend analysis was based on hypothesis testing, and the results of the tests were based on a probability value (p-value). A p-value is the probability of the sample test statistic being at least as extreme as the observed sample test statistic, assuming the null hypothesis is true (Triola, 2021). Each test statistic is converted into a probability of it occurring if the null hypothesis is true. As the p-value gets smaller, it provides stronger evidence that the null hypothesis should be rejected. In this investigation, the p-value was used as a decision tool. For each trend analysis, the null hypothesis is no change in the slope or central tendency (mean or median). The alternate hypothesis is that of change. If the p-value is less than alpha (a pre-set threshold), it is inferred that a change occurred, and if the p-value is greater or equal to alpha then it is inferred that either no trend is present or there is insufficient evidence. For this study, all tests are two-sided. The p-value of each test is compared to a pre-set alpha level. For this investigation, it was set to 0.10. Note, for many investigations, alpha is set to 0.05. However, using any pre-set values has problems and this topic is discussed below.

Wasserstein et al. (2019) discussed several problems facing investigators when they use a pre-set alpha level as the sole source decision-making criterion for a hypothesis test. The authors mentioned that caution is needed when using a 0.05 alpha level, or any other values. One argument against a pre-set 0.05 alpha level is that the difference, for example, between 0.051 and 0.049, is immaterial. The authors presented many alternatives to using one pre-set value but pointed out, that at the current time, none have been adopted by the American Statistical Association. Despite

the criticism and with no definitive alternative, the use of p-values as a tool for detecting trends continues (Helsel et al. 2020). From a practical perspective, threshold values can be useful. However, p-values should be used with caution. For this investigation, a gradational set of p-values is used. For each trend analyses hypothesis test, if the resulting p-value is < 0.01 , the result is considered a strong trend. If the p-value is ≥ 0.01 but < 0.05 , a moderate trend (or moderate evidence of a trend) is inferred. If the p-value is ≥ 0.05 but < 0.10 , a weak trend (or weak evidence of a trend) is considered to have occurred. Finally, if the p-value is ≥ 0.10 , no trend, or insufficient evidence of a trend, is inferred. It is the author's opinion that the use of a gradational scale is an attempt to address the p-value issue. However, any resulting p-value in this investigation should be used with caution.

Another statistical issue needs to be addressed. Kutner et al. (2005) indicated that multiple tests can adversely affect hypothesis testing results by potentially lowering the resulting p-value. The authors indicated that multiple comparisons arise when a statistical analysis involves multiple simultaneous statistical tests, each of which has a potential to produce a 'discovery'. A stated confidence level generally applies only to each test considered individually, but often it is desirable to have a confidence level for the whole family of simultaneous tests. Under this scenario, addressing negative effects of multiple comparisons should be employed. However, addressing negative effects of multiple comparisons is not always needed (Rothman (1990) and Saville (1990)) when simultaneous tests are conducted. For example, if one only wants to draw one conclusion for the variable of interest, and if an overall confidence level based on a family of simultaneous tests is not the goal, then multiple comparison adjustments are not needed. This investigation fits into the latter category. The goal is to draw one conclusion for each variable in each zone. Statewide inferences are not based on a family of tests. Rather, for each variable, data are aggregated and then one statewide test is conducted based on the aggregated data. However, one aspect of this study does pertain to multiple comparisons, where the resulting test p-values need to be adjusted. The issue will be discussed later.

During analyses, it was discovered that median hexagon values for NO₃ were often below the MDL for most sampling cycles in each zone. This was not the situation for any other indicator. As such, conducting trend analysis using NO₃ medians provided limited information for detecting potential changes in concentrations. For this reason, for NO₃, an alternative statistic was developed for trend analyses. Initially, one statistic considered was the geometric mean. Since the geometric mean can be considered an estimate of the median (Vogel, 2020), no advantage could be obtained by using the geometric mean. The statistic selected was the proportion of hexagon median NO₃ concentrations that were greater than a threshold of 0.35 mg/L. This statistic is abbreviated as GT0.35. The major reason for using the statistic is that the threshold is used in BMAPs by DEAR as the level to which NO₃ concentrations must be lowered to restore the water quality in spring runs (FDEP, 2008). Two additional justifications are: (1) Zones 1- 4 have the highest NO₃ concentrations in the state and (2) most springs in the state are located Zones 1- 4 (Scott et al., 2004).

By using the GT0.35 statistic, one creates two classes of observations: (1) GT0.35 and (2) less than or equal (LE) to the threshold. The major restriction to using the GT0.35 statistic is that for some analyses' procedures, the number of observations in each of the two classes must be at least five (Triola, 2022), and some believe a minimum of ten should be used (Agresti and Franklin, 2009). During investigation, it was discovered that, occasionally, the number of observations (n)

was less than 10 in the GT0.35 class. However, in all situations, n was 10 or greater in the LE class. To account for an adequate n size, NO₃ trend analyses were occasionally conducted on the LE class of data and then reported on the GT0.35 class. This is justified since the number of observations in the LE class for each sampling cycle is equal to 1.0 minus the number in the GT class. Also, the resulting trend test p -value using the GT0.35 class of data is equal to the p -value for the LE class. However, to obtain the Sen Slope of the GT0.35 data, the Sen Slope of the LE class is multiplied by -1.0.

Note that other thresholds could be used. For example, 0.05 mg/L could have been used as a threshold. It was discussed earlier. It represents the largest method detection level (MDL) used by the FDEP analytical laboratory for NO₃ in the early 1990s. The log of the mean was another statistic considered. However, occasionally even after taking the log of highly skewed distributions, normality is not obtained. For this reason, it was not selected.

Mann-Kendall Test. The primary trend analysis test used in this study for time-series data is the Mann-Kendall (MK) test. It is a nonparametric test for monotonic trends. The test was developed by Mann (1945) and Kendall (1975). Gilbert (1987) mentioned that the procedure is useful since missing values are allowed. In addition, the test can be used when data are reported as trace or less than the detection limit. The “Kendall”, “rkt” and “modifiedmk” packages in R were used for analyses. Mann (1945) discussed the test assumptions. Observations need to be representative of the population and unbiased. These assumptions are addressed by using the random well selection process of the target population. Mann mentioned a third assumption; observations need to be (serially) independent. If not, the resulting p -value can be adversely lowered. For this study, sample cycle medians and means were used for analyses. If no serial correlation was present, then serial independence can be assumed. For each indicator, the cycle medians and means were tested for serial correlation using the autocorrelation function and the partial autocorrelation function (Pankratz, 1983; and Helsel and Hirsch, 2020). The functions are available in the standard statistical package in R. If serial AC was observed, the modified Mann-Kendall test in the “modifiedmk” package in R was used for analysis. See Hamed and Rao (1989) for details. The modified test adjusts the sample variance to account for the potential adverse effects of serial AC.

Gilbert mentioned the MK test is used to test for sufficiently strong statistical, decreasing or increasing, trends in temporal data. As used in this investigation for each indicator, both the sample cycle median and mean are used in time series tests. The R programs conducting the analyses check for all possible differences between the relative magnitude of one value on a (time) line to all other successive values. If sufficient differences increase (or decrease), a trend in the slope of the data is inferred. The null hypothesis is there is no difference in the slope of the time series. The alternate hypothesis is there is a change.

For each trend analysis test, for NO₃, the MK test was used on the proportion of hexagon median values GT0.35 for each sampling cycle. For all other indicators, the median value of hexagon medians was used. Trend tests were conducted, both at the statewide and at zonal scales.

Mann-Whitney Test. Kincaid and Olsen (2012) mentioned that trend detection can often be conducted by estimating changes in summary measures, such as medians and means, between two time periods. Helsel and Hirsch (2002) stated if a sufficiently long time exists in the data series, but not necessarily on a regular sampling frequency, trend analysis can also be conducted with the two-sample step-trend test. One such test is the Mann-Whitney (MW) test. It is sometimes referred

to as the Wilcoxon Rank Sum test. For this investigation, MW terminology is used. The MW test is discussed by Conover (1999) and Triola (2022). As used, the test is a two-sided, two-sample, step-trend test. It is used to determine if the distribution of concentrations changes between two time periods. The test was conducted with the “Wilcox” function in the R standard statistical package.

The MW test assumes that the individual samples are independent, both between and within the two time periods. For groundwater, independence between the two interludes is assumed if there is a minimum gap of three years between the two periods (Lindsey and Rupert, 2012). The null hypothesis is there is no difference in the distributions, including the mean or the median concentrations, between two separate periods. The alternate hypothesis is there is a change.

Correlation and Correlation Tests. Correlation exists between two variables when one of them is related to the other in some way (Triola, 2021). Regarding the correlation between two different variables, the “cor.test” function in the “Stats” basic package in R was used to gauge its strength, via the p-value. Since most distributions were nonparametric, the Spearman correlation (Hollender and Wolfe, 1973) version of the test (method = c(“spearman”)) in R was used.

Estimating Autocorrelation and Partial Autocorrelation. Recall, autocorrelation (AC) is the correlation of one variable to itself over a lag of distance or time, and that spatial or serial autocorrelation can adversely affect the results of a trend analysis test. As a simple test for the presence of serial AC, Pankratz (1983) suggested using the autocorrelation function (ACF) and the partial autocorrelation function (PACF). Serial AC is the correlation between the elements of a time series and others from the same series separated from each other by a given interval (lag). The ACF is a diagram. Figure 5 is an example of statewide dissolved oxygen means in CA (1991-2022). The ACF in the figure displays 12 sampling cycles. The y-axis displays autocorrelation. Note, they can be either positive or negative. The x-axis displays the lags. The horizontal dashed lines (both positive and negative) represent the 95% confidence bounds. At each lag, including zero, the vertical lines (spikes) represent the AC values. If a spike crosses either the positive or negative confidence bound, it indicates autocorrelation is significant at the corresponding lag. AC at lag zero is always 1.00. Pankratz mentioned that autocorrelation at lags greater than $n/4$ is not considered significant. In the example in Figure 5, ACF, $n/4 = 19/4 = 4.75$. Therefore, AC spikes after 4.75 are not considered significant. AC spikes at lags 5 through 12 need not be considered, even though the spike at lag 7 suggests significant AC. AC is only significant at lag 0 and lag 1. Since AC is significant at lag 1, the modified MK test, not the MK test, should be used.

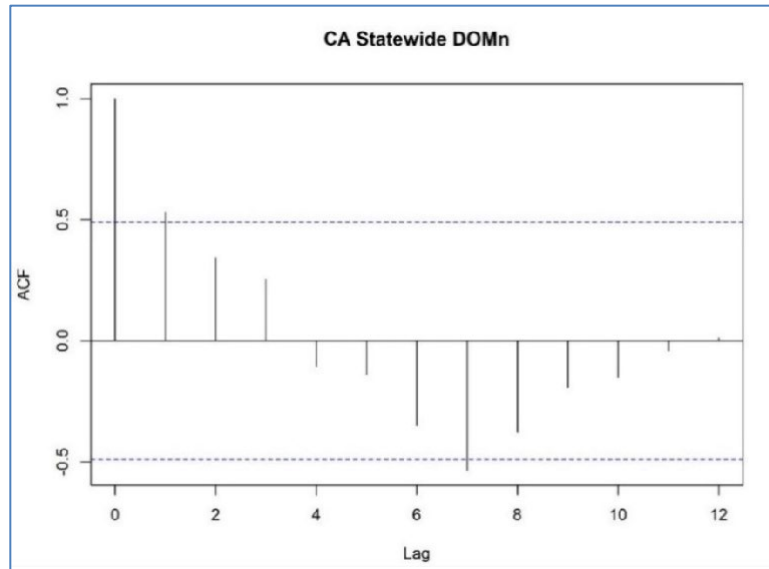


Figure 5. ACF of Dissolved Oxygen Means for the CA (1991-2022).

Partial autocorrelation is essentially the same as autocorrelation, except, for a given lag, the relationships of intervening observations are removed. Reading a PACF is like reading the ACF. For this investigation if either the ACF or the PACF reveal significant correlation, the MK test was used for trend analysis. The ACF and PACF diagrams are displayed in Appendix C.

ACF and PACF tests for serial AC were performed using the “stats” package in R. Again, if serial AC was present, the modified MK test was used. For each sampling cycle, overall hexagon median was determined and used for monotonic trend analysis. Occasionally, for each sampling cycle, the proportion of hexagon medians, exceeding a pre-set threshold value, was used for analysis. This issue will be discussed in more detail later.

Two-Sample Proportion Test. A proportions test is a method of comparing the proportions of two populations Agresti and Franklin (2009). Tests were conducted in the “stats” package in R.

Statewide Time-Series Plots and Trend Analysis Results

Before addressing the results of trend analyses, a few issues need to be revisited. Time-series plots were constructed for each indicator using annual medians. Although means were not used for trend analyses, visually inspecting changes in the means in the time-series plots of NO₃ proved to be beneficial. As it turns out, the sampling cycle means of NO₃ were almost always below the MDL. For this reason, NO₃ means, as well as medians were included in their time series plots. However, plots of means for the other indicators proved to not be successful. For this reason, plots of means were only constructed for NO₃. In addition, since NO₃ is in some of Florida's spring basins' groundwater must be lowered to 0.35 mg/L to meet water quality standards, plots regarding the proportion of samples > 0.35 mg/L were generated. The plots are presented separately.

Statewide Time-Series Plots.

With a few exceptions, only plots of indicators for which trends were observed are displayed below. However, all plots are found in Appendix D. Recall the three periods are: (A) 1991 – 2022, (B) 2000 – 2022, and (C) 2013 – 2022. Previously, the reasons for the periods and sampling cycles were discussed in the description of DEAR's groundwater monitoring networks. Table 4 displays cycle numbers and the year(s) corresponding to each cycle. Cycle numbers are in Columns 1,3, and 5. Years are found in columns 2, 4, and 6.

Table 4. Background and Status Network Sampling Cycles.

Sample Cycle Number	Years	Sample Cycle Number (Continued)	Year	Sample Cycle Number (continued)	Year (Continued)
1	1991 – 1993	6	2009	13	2016
2	1994 – 1996	7	2010	14	2017
3	1997 – 1999	8	2011	15	2018
4	2000 – 2003	9	2012	16	2019
5	2004 – 2008	10	2013	17	2020
		11	2014	18	2021
		12	2015	19	2022

The nutrients NO₃ and TP have adversely affected Florida's water resources more than the other nutrients assessed in this study. For these reasons, emphasis is given NO₃ and TP.

Figures 6a and 6b display the sampling cycle mean and median values for NO₃ (1991- 2022). Figures 6c and d display cycle proportions GT0.35 for the UA and CA, respectively. Figure 7a and b only display annual medians for TP.

DO and Temp displayed the greatest frequency of trends for the ancillary indicators. For this reason, most emphasis for the latter group of analytes is placed on them. Figures 8a and b display time series plots for DO. Figures 9a-b do the same for Temp.

Regarding Color, pH, SC, NH₃, TKN, TN, TOC and Turb, each one that has a corresponding trend in any of the periods will be discussed shortly. Trend information regarding the analyses for all indicators is found in Appendix E. Time-series plots for all indicators are found in Appendix D.

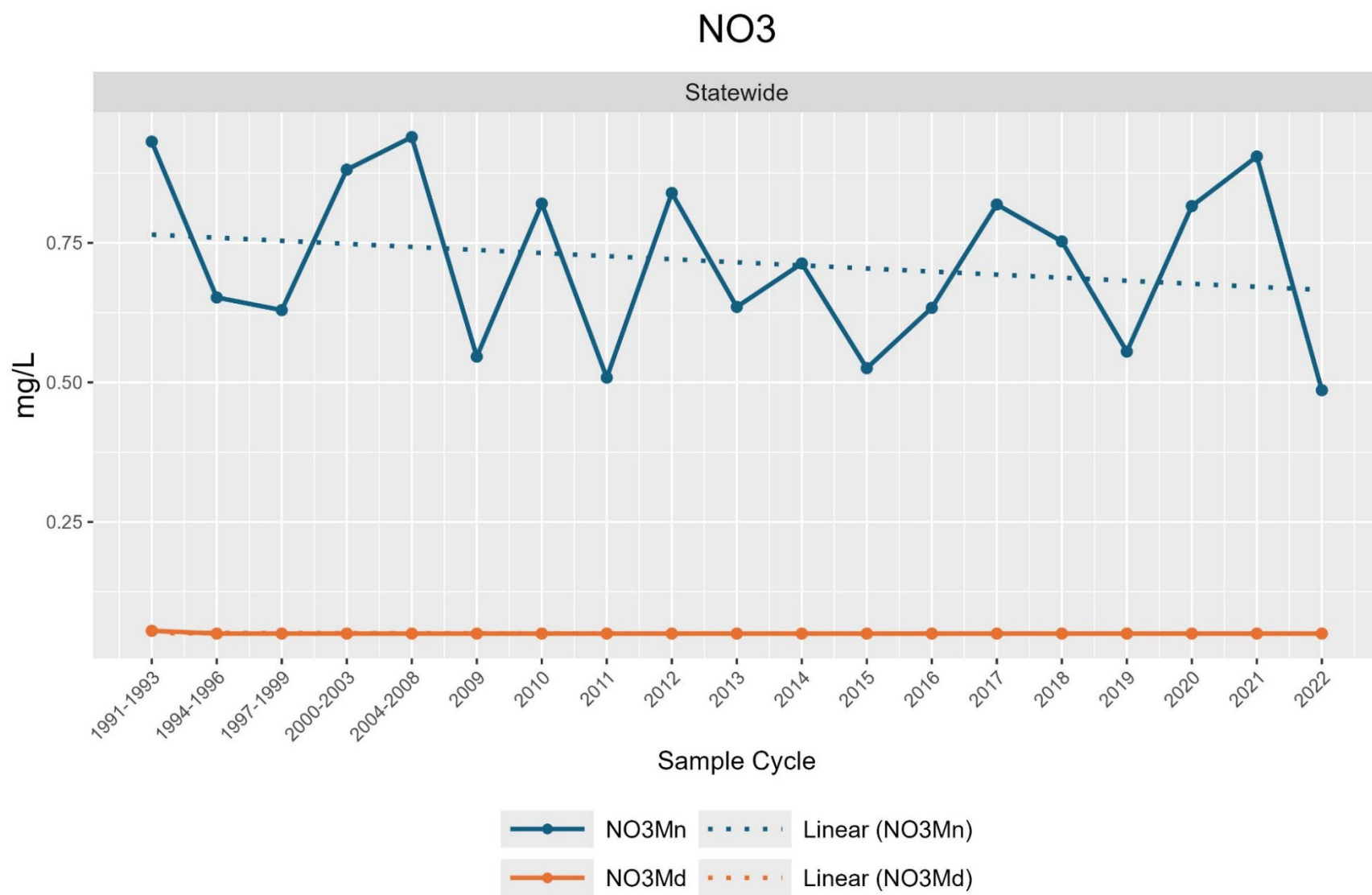


Figure 6a. Median (Md) and Mean (Mn) Concentrations of NO3 for the 19 Sampling Cycles for the UA (1991-2022).

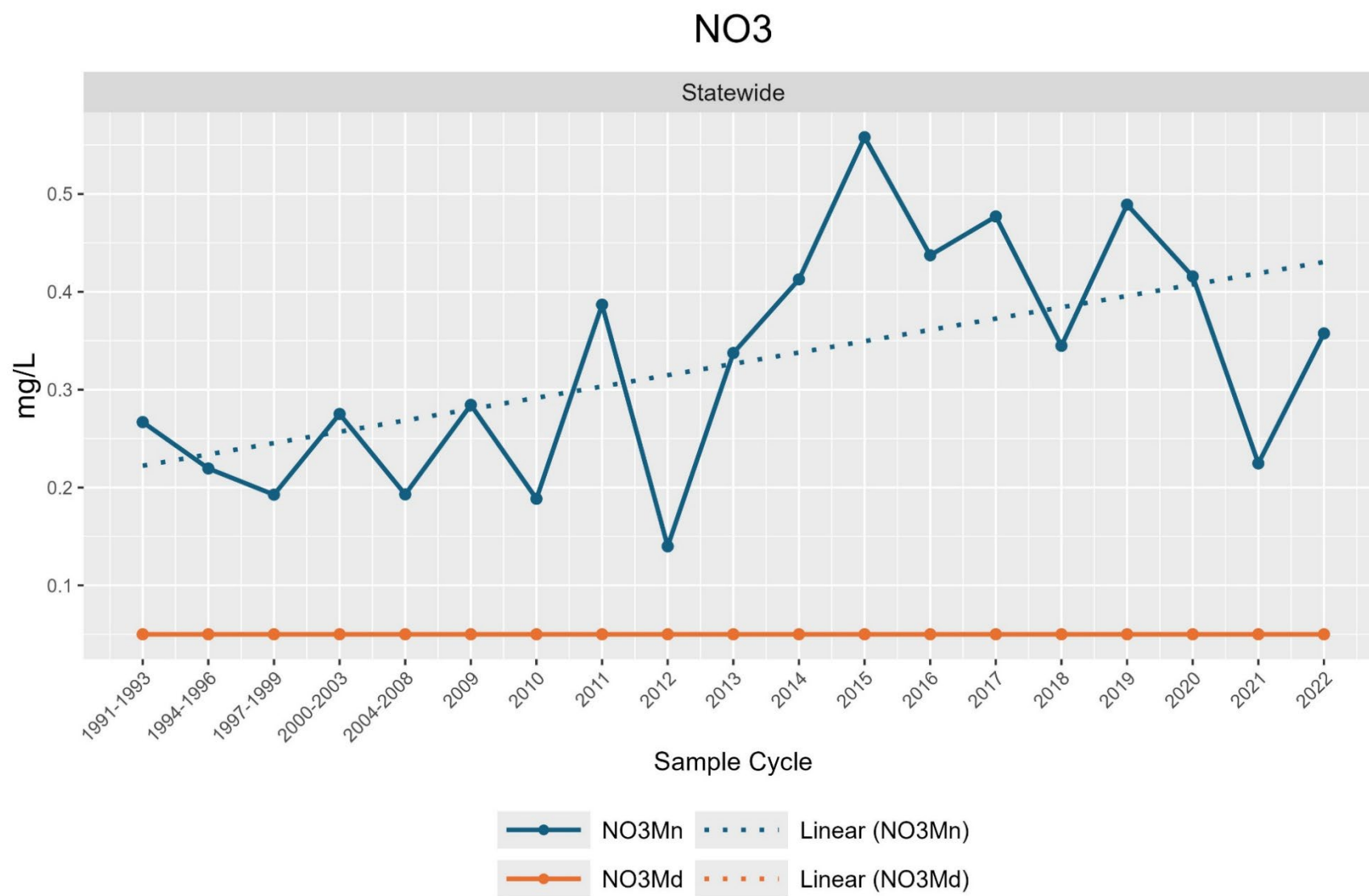


Figure 6b. Median (Md) and Mean (Mn) Concentrations of NO3 for the 19 Sampling Cycles for the CA (1991-2022).

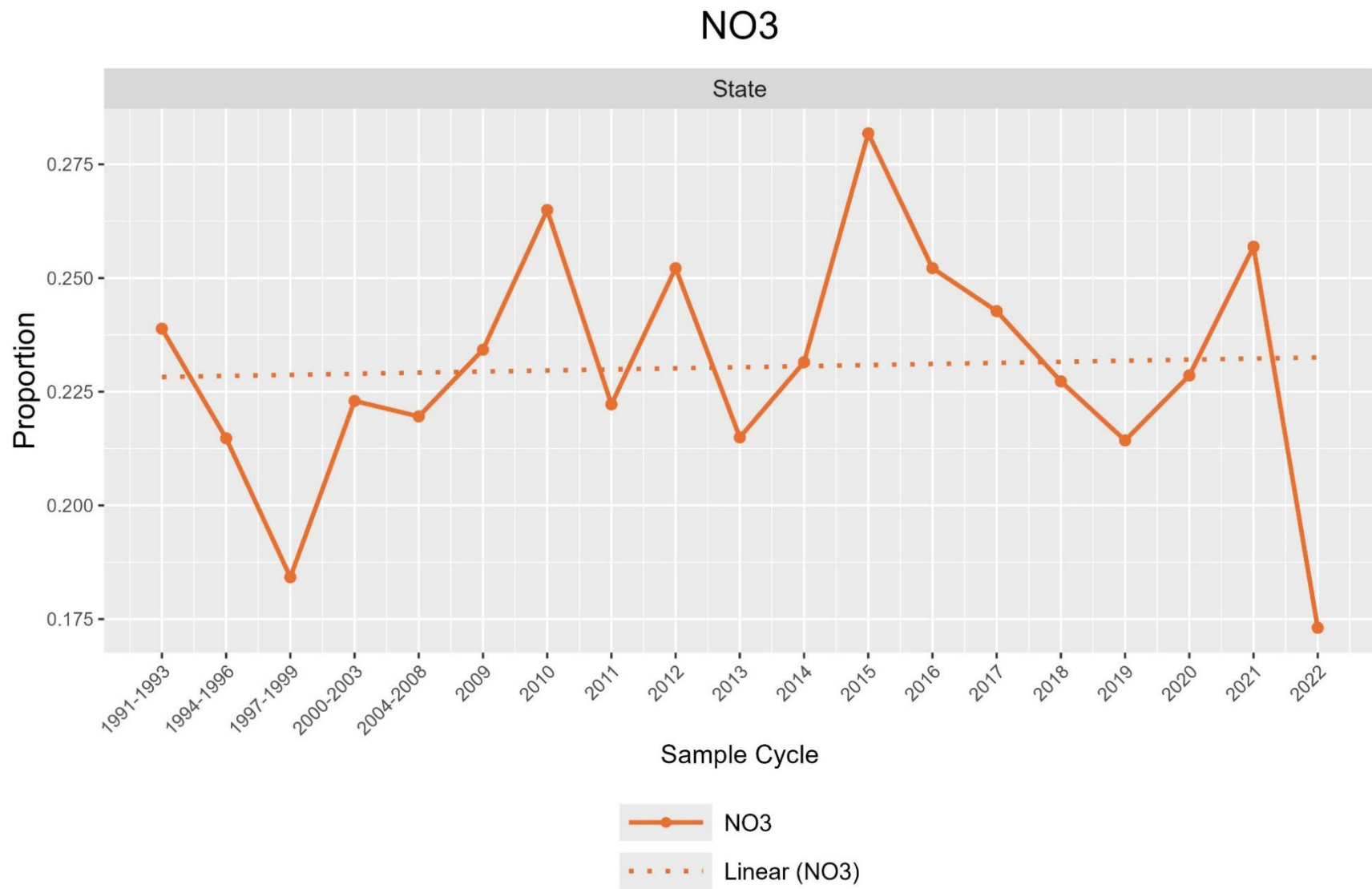


Figure 6c. Proportions of Wells Having NO3 Concentrations Greater Than 0.35 mg/L for the 19 Sampling Cycles for the UA (1991-2022).

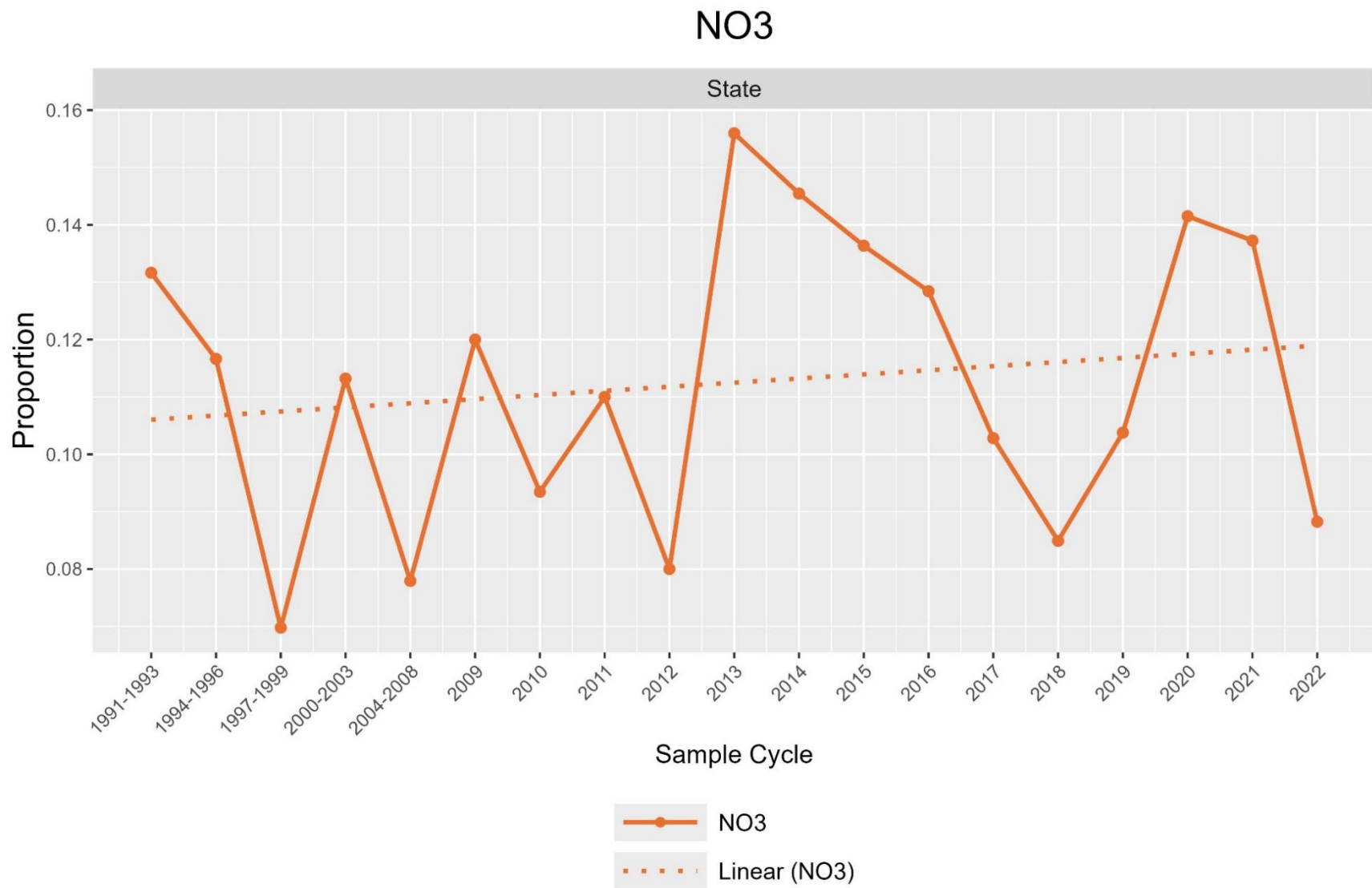


Figure 6d. Proportions of Wells Having Nitrate Concentrations Greater Than 0.35 mg/L for the 19 Sampling Cycles for the CA (1991-2022).

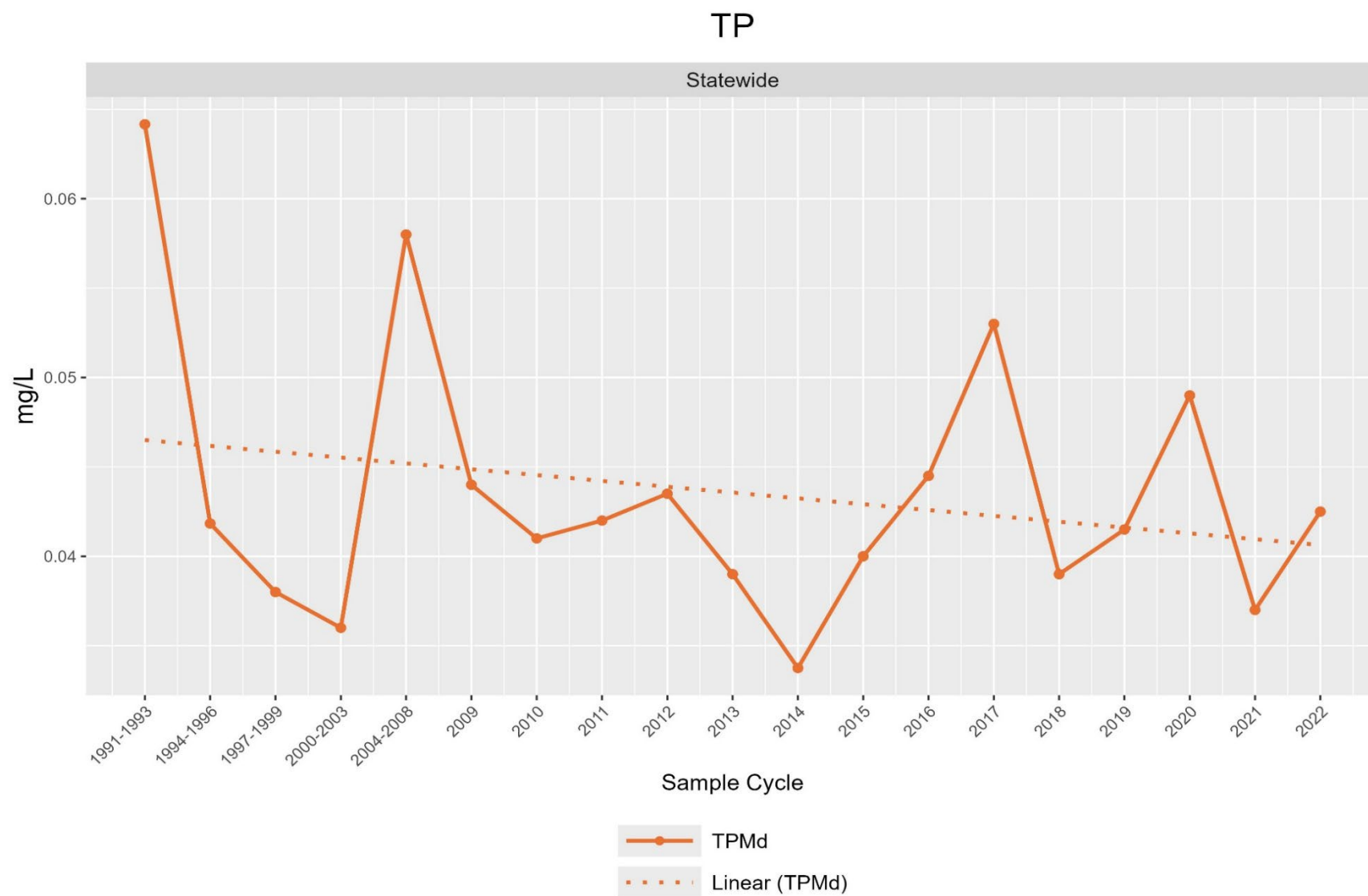


Figure 7a. Median Concentrations of Total Phosphorus (TP) for the 19 Sampling Cycles for the UA (1991-2022).

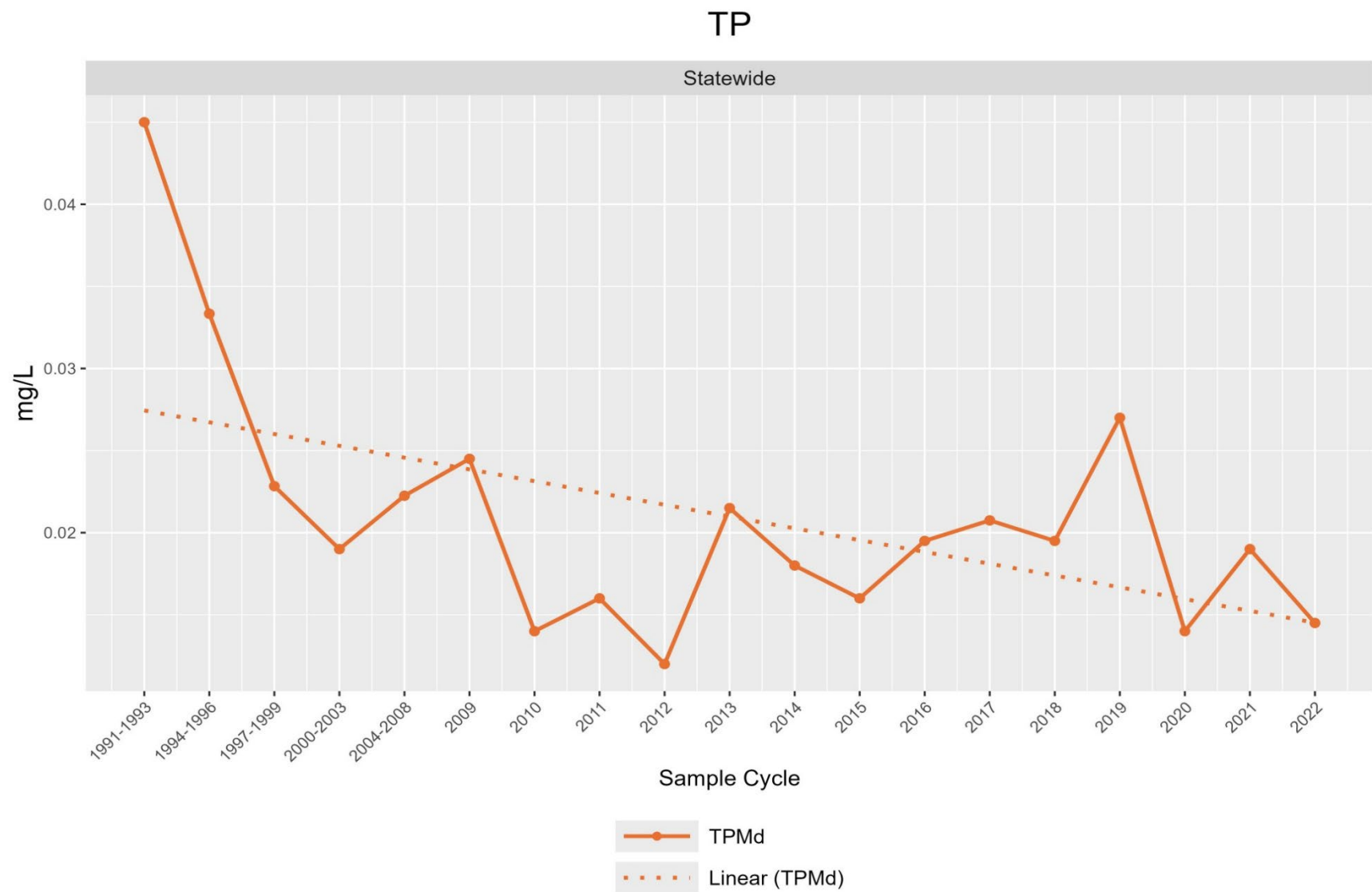


Figure 7b. Median Concentrations of Total Phosphorus (TP) for the CA (1991-2022).

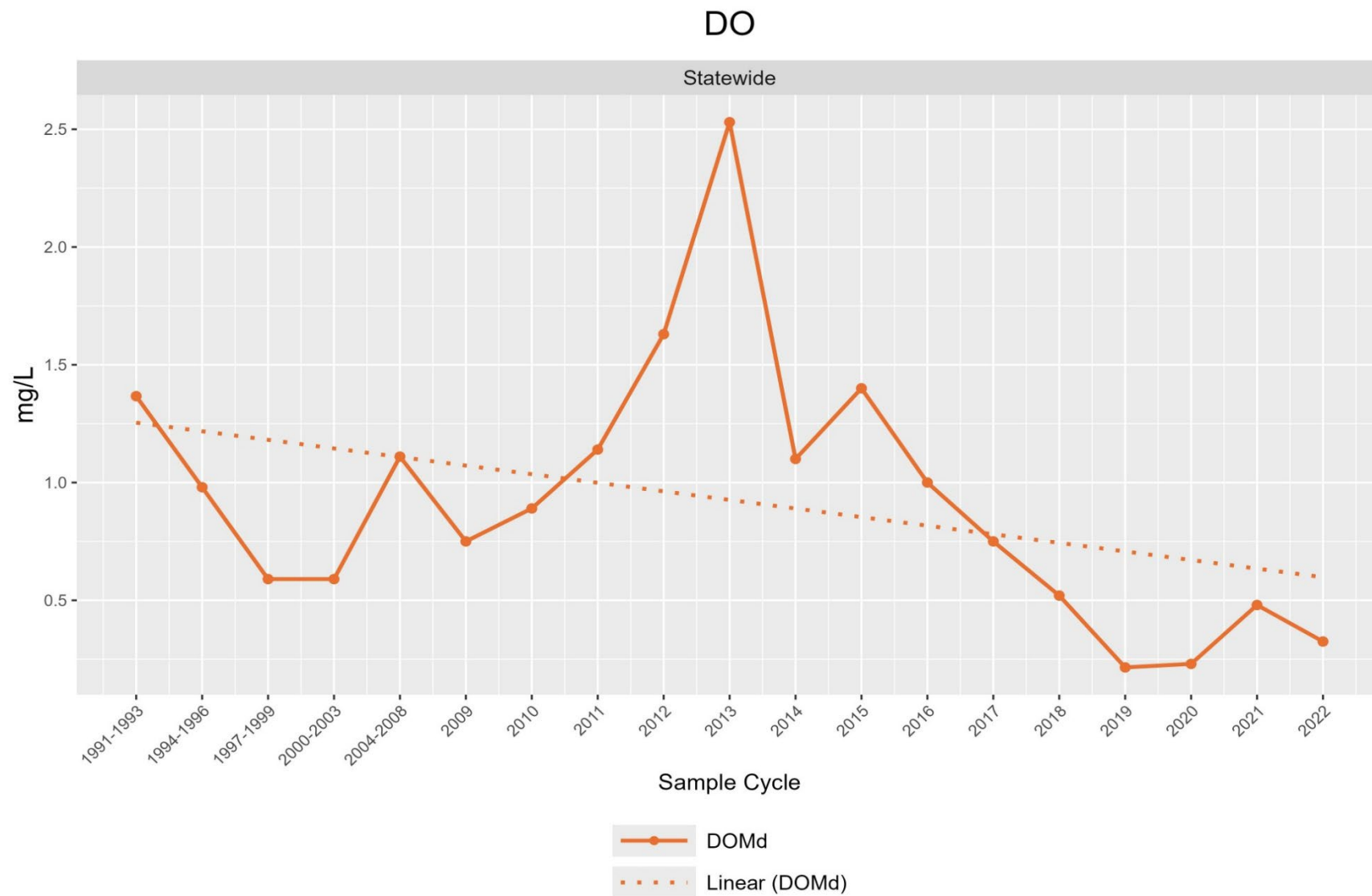


Figure 8a. Median Concentrations of Dissolved Oxygen (DO) for the 19 Sampling Cycles for the UA (1991-2022).

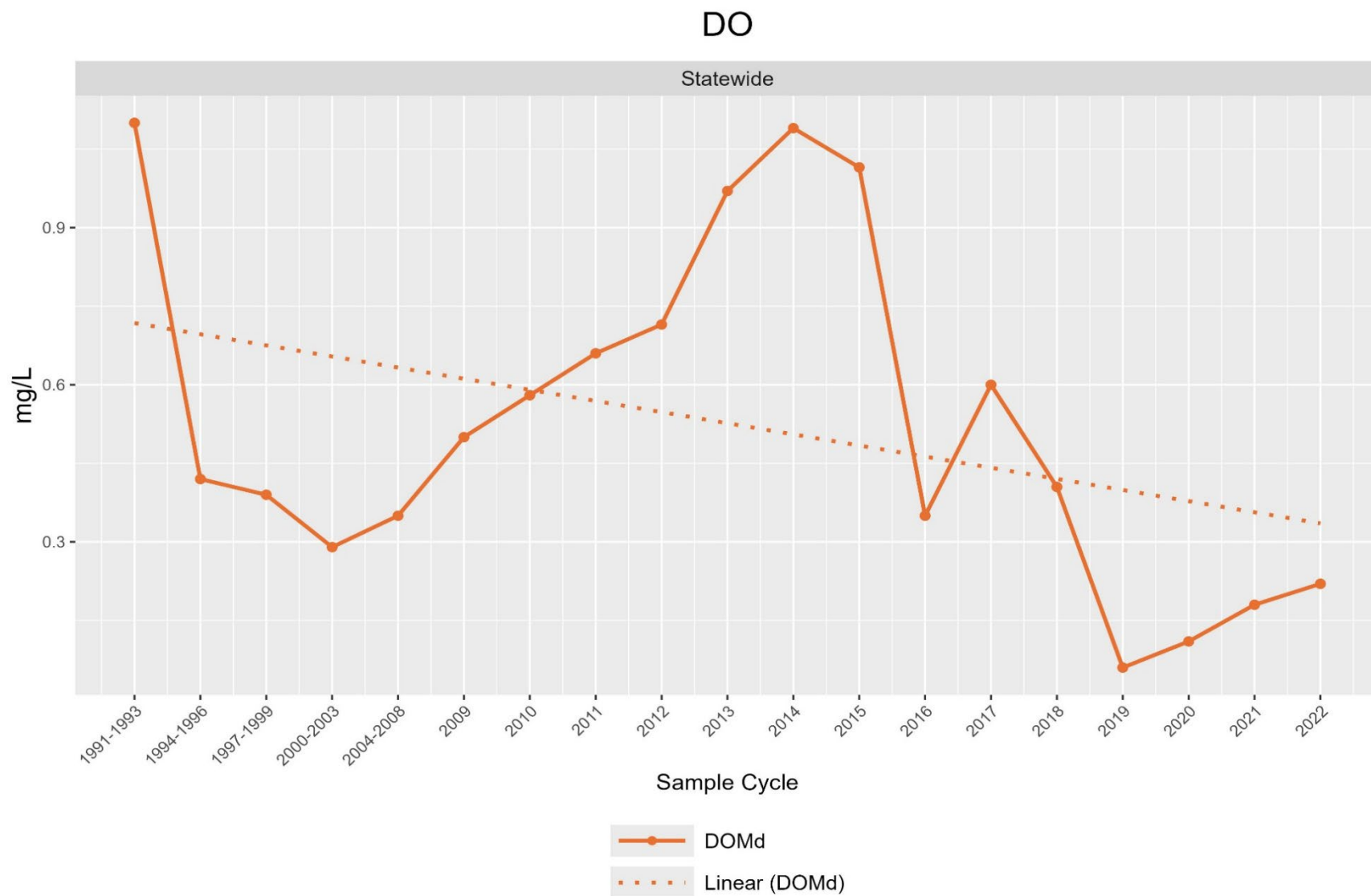


Figure 8b. Median Concentrations of DO for the 19 Sampling Cycles for the CA (1991-2022).

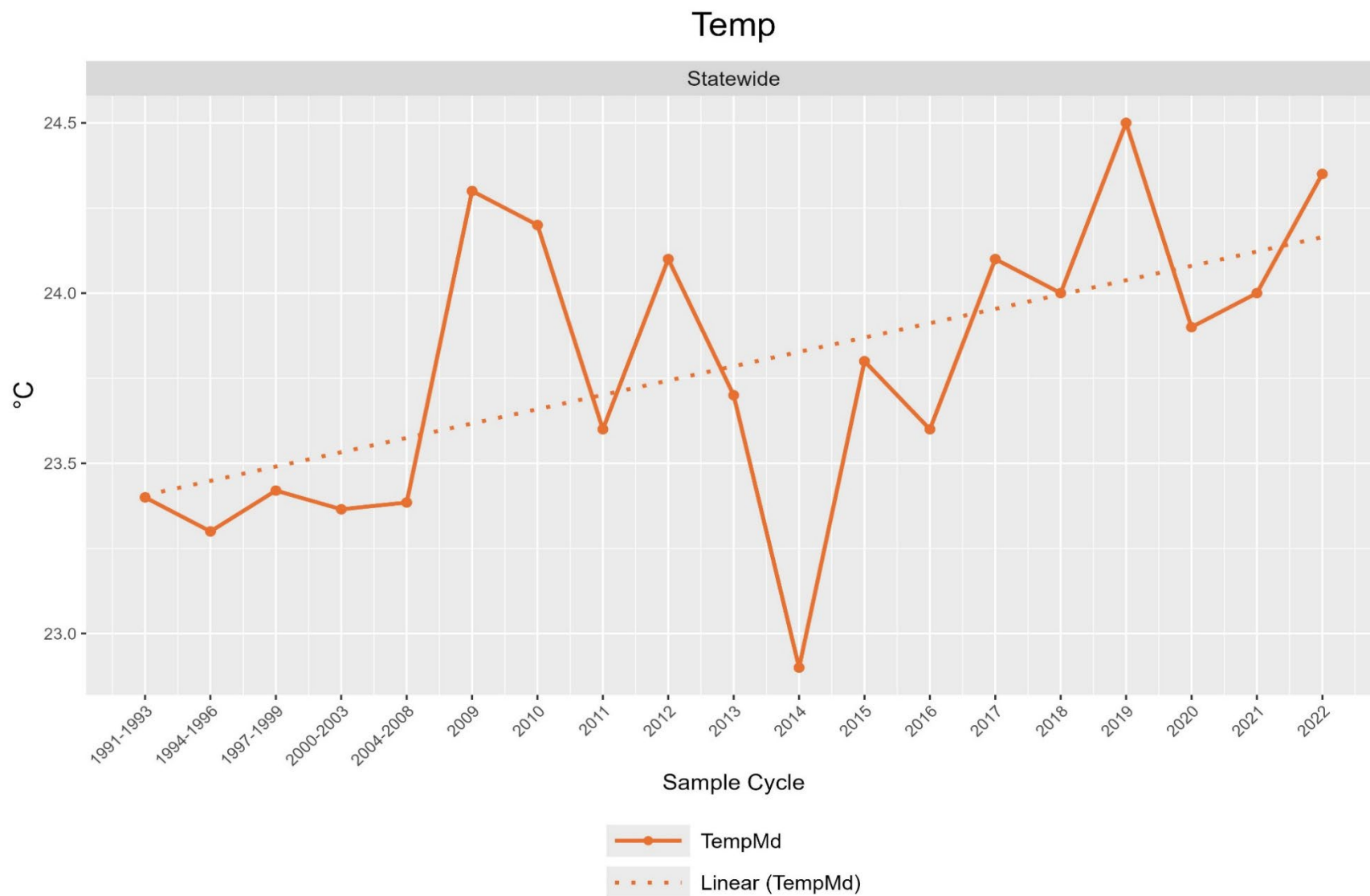


Figure 9a. Medians of Temp (Temp) for the 19 Sampling Cycles for the UA (1991-2022).

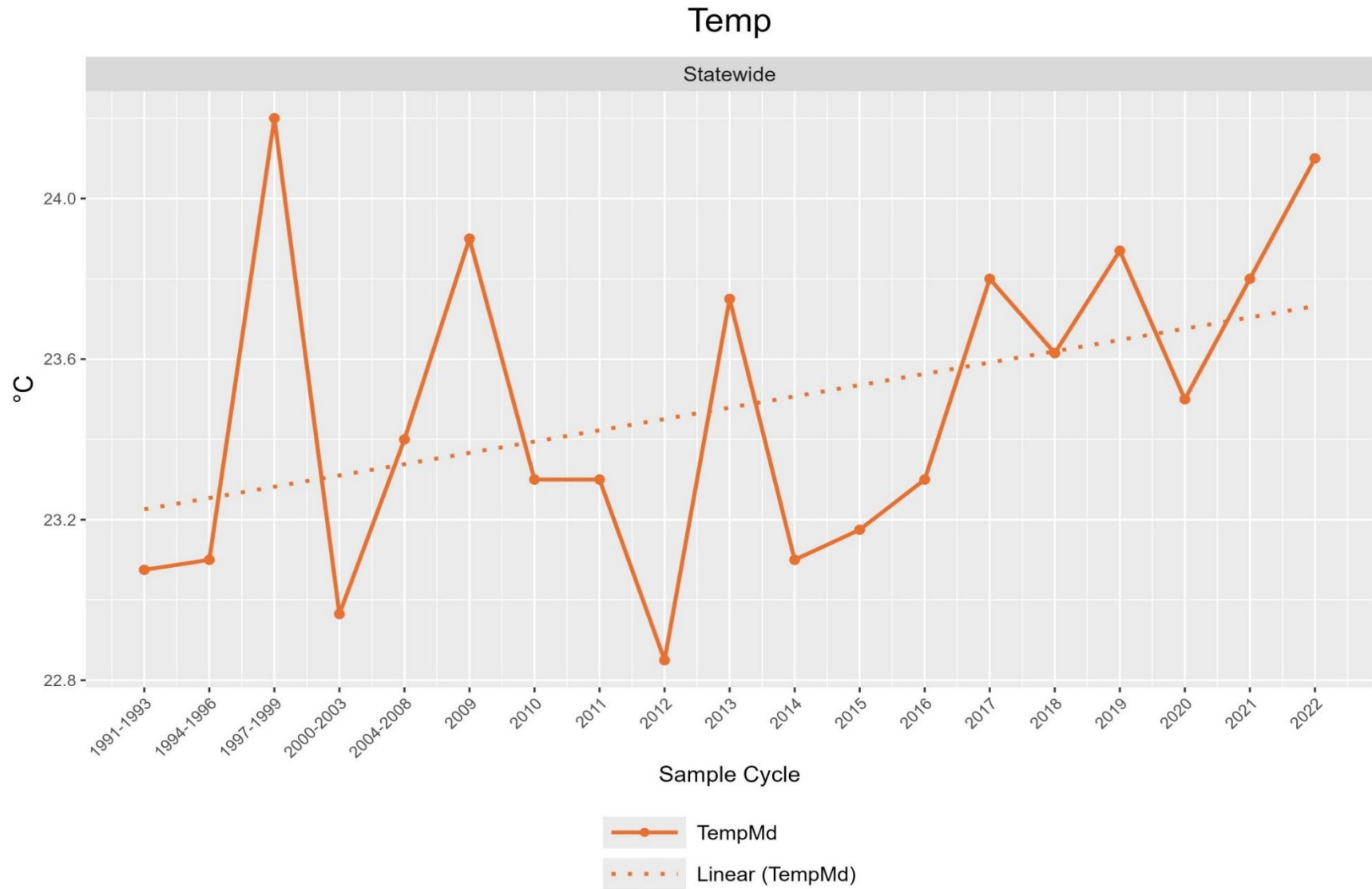


Figure 9b. Medians for Temp for the 19 Sampling Cycles for the CA (1991-2022).

Statewide Trend Analyses.

Trend analyses were performed on the proportion GT0.35 for NO₃ and medians for the other indicators. Results of indicators displaying statewide trends are in Table 5. The table displays the trend analyses results during each period. Period A is presented first, followed by Periods B and C. For each period, the UA results are followed by CA results. Column 1 displays the indicator. Columns 2 and 3 display the period and resource. Column 4 shows which test, Mann-Kendall (MK) or Modified Mann-Kendall (MMK) was used. Note, the MMK test was used instead of the MK test if serial AC was observed in the corresponding estimated ACF or the PACF figures (Appendix C). Column 5 displays the number of sampling cycles in the period. Column 6 displays the resulting trend analysis test p-values. Column 7 displays the adjusted Sen slope and column 8 shows the direction of the change.

Recall, if the p-value < 0.010, a strong trend or change is inferred. If $0.01 \geq \text{p-value} < 0.05$, a trend or change, also referred to as a moderate trend, is inferred. If $0.05 \geq \text{p-value} < 0.10$, a weak trend is inferred. Strong trends are presented in **bold** font. Moderate trend is presented in italicized and underlined font. Weak trends are represented by the regular font. Note, the calculation of the Sen slope assumes each sampling cycle represents one year. However, the first five cycles were each between three and five years. Thus, the reported Sen slopes generated by the “Kendall” and the “modifiedmk” commands in R, were adjusted as needed, from units per sampling cycle, to units per year. For example, since Period A consists of 32 years covering 19 sampling cycles, the annual rate of change is estimated by multiplying corresponding slope by 1.684 (32 years over 19 cycles). For Period B, multiply the slope by 1.438 (23 years over 16 cycles). Since the Sen slopes during Periods A and B have been altered, the Sen slopes represent modified Sen slopes. For Period C, sampling cycles represent years, and no adjustment is needed.

Table 5. Statewide Trends, based on the Mann-Kendall (MK) and the Modified Man-Kendall (MMK) Tests, for Unconfined and Confined Aquifers for three Periods (A: 1991-2022, B: 2000-2022, and C: 2013-2022).

Indicator	Period	Resource	MK or MMK	Number Cycles	p-value	¹ Sen Slope	Direction
DO	A	UA	MMK	19	² 0.059	-0.090	Down
SC	A	UA	Mk	19	0.093	5.608	Up
TP	A	CA	MK	19	0.058	-0.005	Down
pH	A	CA	MMK	19	³ 0.006	-0.014	Down
SC	A	CA	MMK	19	<u>0.012</u>	8.075	Up
Temp	A	CA	MK	19	<u>0.038</u>	0.066	Up
pH	B	CA	MK	16	<u>0.030</u>	-0.012	Down
SC	B	CA	MK	16	⁴ <u>0.034</u>	4.472	Up
Temp	B	CA	MK	16	<u>0.042</u>	0.072	Up
DO	C	UA	MK	10	0.004	-0.173	Down
Temp	C	UA	MK	10	<u>0.039</u>	0.080	Up
DO	C	CA	MMK	10	<u>0.032</u>	-0.109	Down
pH	C	CA	MK	10	<u>0.031</u>	-0.001	Down
Temp	C	CA	MK	10	<u>0.039</u>	0.077	Up

¹Since Periods A and B have unequal time increments, to obtain the estimated annual slopes, the computed Sen slope was modified. For Period A, the estimated Sen slope was the computed slope multiplied by 1.684 (32 years / 19 cycles). For Period B, the estimated Sen slope was the computed slope multiplied by 1.438 (23 years / 16 cycles). No modification is needed for Period C since cycles represent 1-year increments.

²Weak trend = regular font. ³Strong trends = **bold** font. ⁴Moderate trend = italicized and underlined font.

Regarding nutrients in the UA, during Period A (1991 – 2022), there were no statewide nutrient trends (Table 5). However, for the ancillary indicators, DO (p-value = 0.059) had a weak downward trend, while SC (p-value = 0.093) had weak upward trend.

For the CA, during the same period, there was no NO₃ trend. However, TP trended weakly downward (p-value = 0.058). The ancillary indicators, pH trended strongly downward (p-value = 0.0060), while SC (p-value = 0.012) and Temp (p-value = 0.038) trended upwards.

During Period B (2000 – 2022) the UA had no trends. For the CA, there was no trend for either NO₃ or TP. The ancillary indicator pH (p-value = 0.030) trended downward, while SC (p-value = 0.034) and Temp (p-value = 0.042) had upward trends.

During Period C (2013 – 2022) in the UA, there were no nutrient trends. For the ancillary indicators in the UA, DO had a strong downward trend (p-value = 0.004) and Temp had an upward trend (p-value = 0.039). In CA, no nutrient trends were observed. For the ancillary indicators, DO and pH trended downward (p-values = 0.032 and 0.031, respectively). Temp had an upward trend (p-value = 0.039). Of the 14 statewide trends for the three periods (Table 5), three were for DO and four were for Temp. It is interesting to note that no trend was observed for either NO₃ or TP in the UA in any period. However, TP decreased in CA during Period B. In the UA, DO decreased during Periods A and C. It also decreased in the CA during period C. No trend in the UA was observed for Temp. However, in the CA, it increased during each period. Note, for any trend investigation, determining the reasons, or drivers, of change can be difficult. A list of plausible drivers of change will be presented later.

Zonal Trend Analysis Results

The discussion below presents the zonal scale trend analyses results for those indicators displaying trends during any of the periods. As with the stateside analyses, emphasis is placed on NO₃, TP, DO, and Temp. Zonal results for all indicators are found in Appendix E. Zonal time-series plots are found in Appendix D. For discussions, Zones 1-6 are abbreviated as Z1-Z6. Regarding Color, pH, SC, NH₃, TKN, TN, TOC and Turb, each indicator that has a corresponding trend in any of the periods will be discussed shortly.

Zonal Time-Series Plots

Figures 10a-d display zonal time-series plots for NO₃. Figure 10a shows annual UA mean and median concentrations of NO₃ for each zone (Z). Figure 10b is the same for CA. The two figures demonstrate that using median concentrations for trend analyses is occasionally of limited value. Except for Z1, the median values are mostly below the MDL. In Figure 10b since median NO₃ levels varied significantly among the zones, for better visual comparisons, the vertical axes are presented in variable scales. Figures 8c and d present the proportions of NO₃ GT0.35 for the UA and the CA, respectively. For the UA, the GT0.35 slopes suggest concentrations are possibly increasing in Z3, Z4 and Z6, but possibly decreasing in Z1, Z2, and Z5. Note that for Z1-Z4, and Z6 the proportion of exceedances GT0.35 are in the 0.15 to 0.50 range, but less than 0.05 in Z5. For the CA, Figure 8d suggests the proportions are decreasing in Z1, but increasing in Z2 through Z6.

NO3

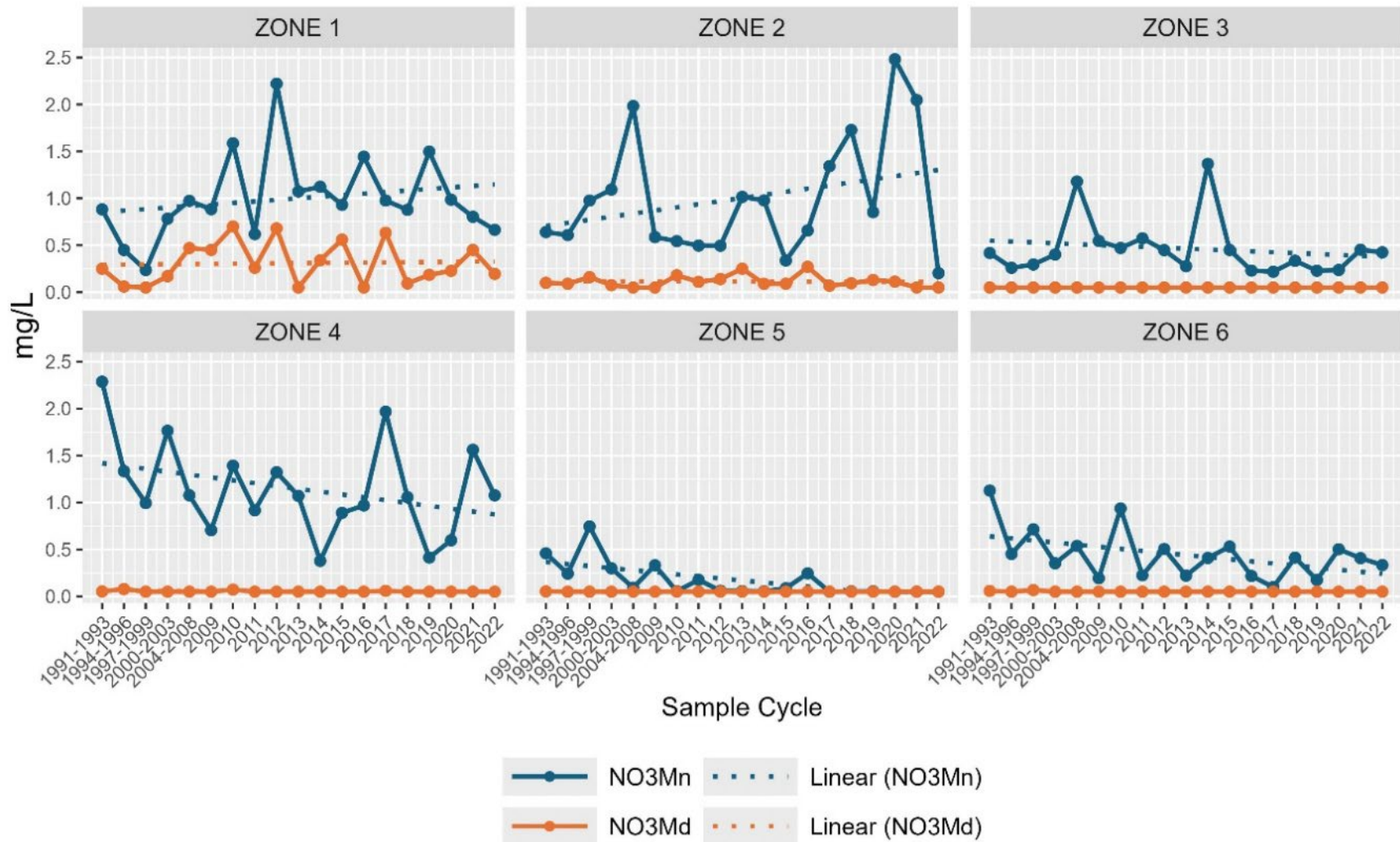


Figure 10a. Time-Series Plots of NO3 Means and Median in the UA for Zones 1-6 (1991-2022).

NO3

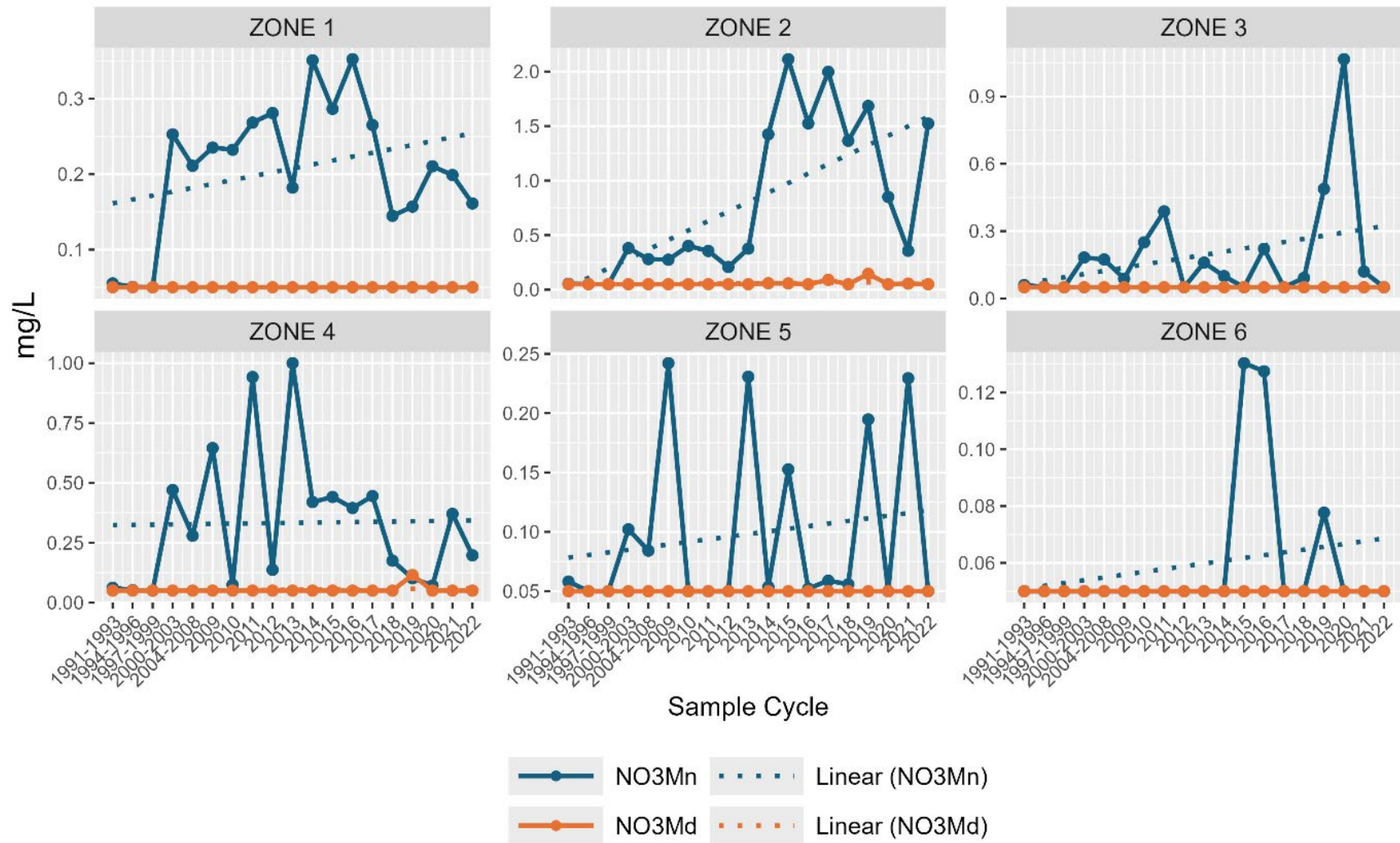


Figure 10b. Time-Series Plots of NO3 Means and Medians in the CA for Zones 1-6 (1991-2022).

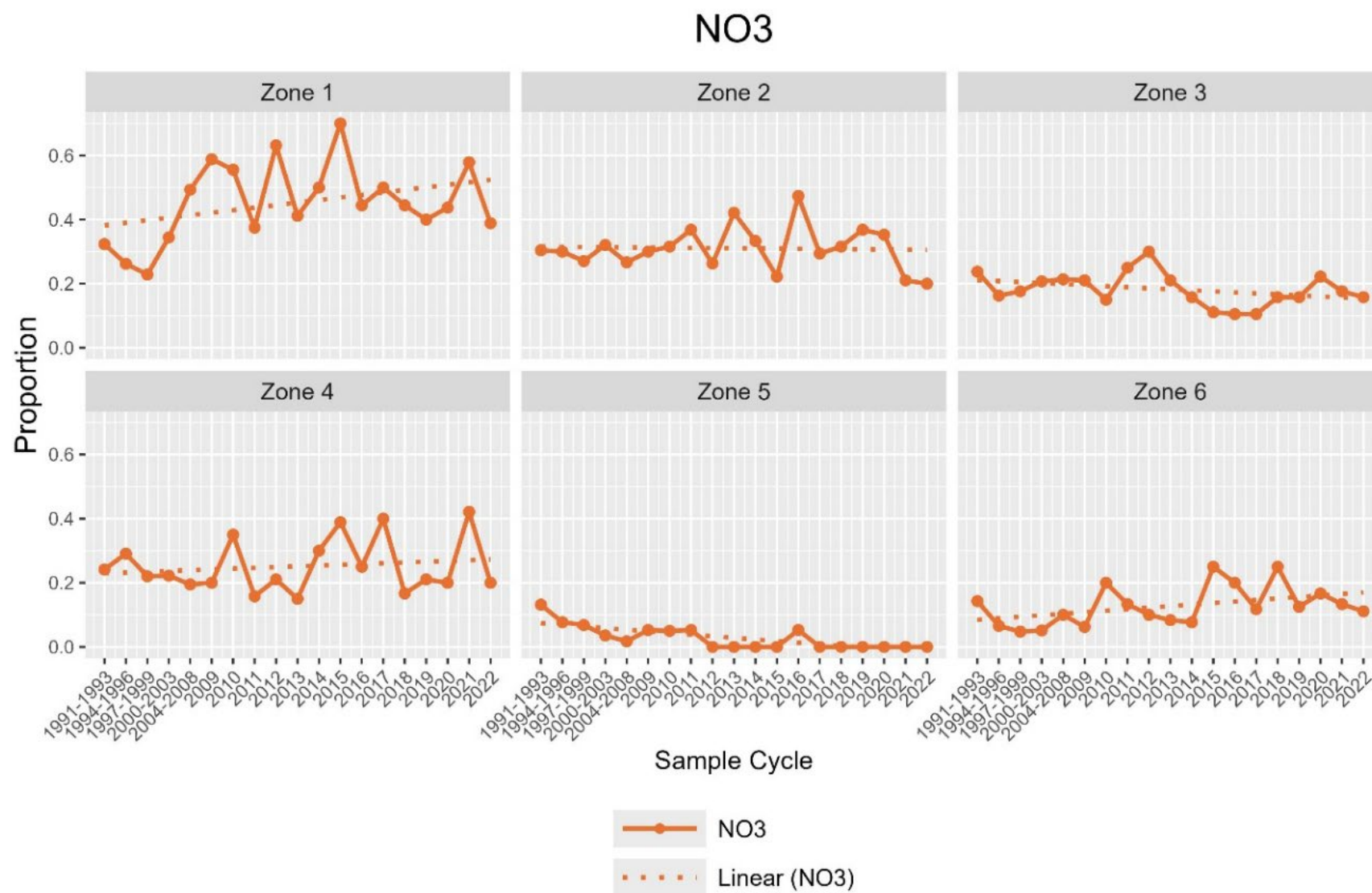


Figure 10c. Time-Series Plots of Proportions of Wells Having NO3 Concentrations Greater Than 0.35 mg/L in the UA for Zones 1-6 (1991-2022).

NO3

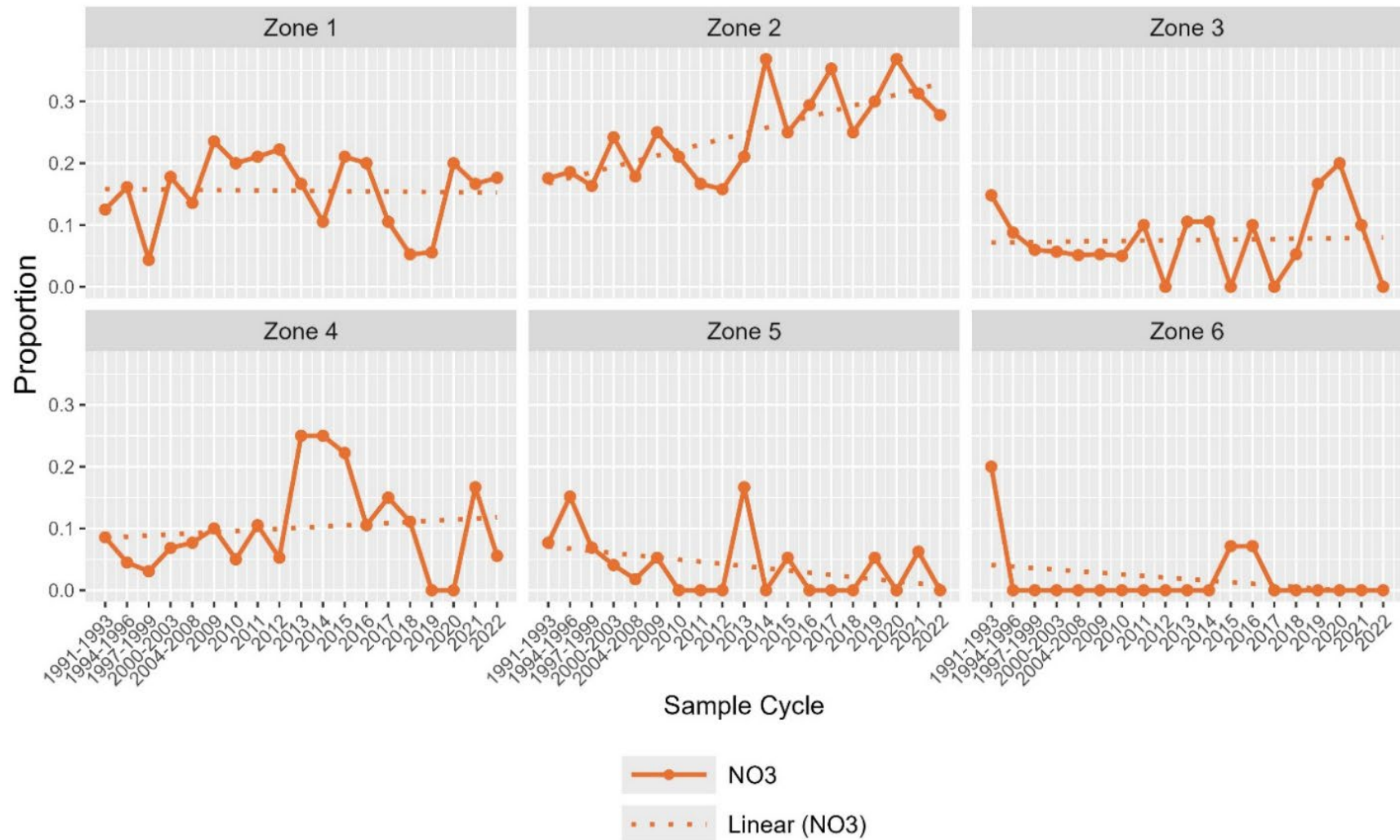


Figure 10d. Time-Series Plots of Proportions of Wells Having NO3 Concentrations Greater Than 0.35 mg/L in the CA for Zones 1-6 (1991-2022).

Figures 11a and b display time-series plots at the zonal scale for the UA and CA TP medians respectively. The only zone of an upward slope for the UA is in Z2. For the CA, TP concentrations appear to be increasing slightly in Z1. In Z2-Z6, concentrations appear to either be stable or decreasing.

Figure 12a and 12b display zonal plots of annual DO medians in the UA and CA respectively. For the UA, DO concentrations appear to be decreasing in Z1-Z5, but increasing slightly in Z6. Also, of interest is the fact that the highest concentrations of DO are in the western portion of Zone 1, where the sand and gravel aquifer is present. For the CA, DO appears to be increasing in Z1 and Z2. However, it appears to be decreasing in Z3-Z6. DO appears to be increasing in Z1 and Z2. However, it appears to be decreasing in Z3-Z6.

During Period A in the UA (Figure 13a) with a possible exception in Z2, Temp appears to be increasing in all other zones. Regarding the CA (Figure 13b), during Period A, Temp appears to be increasing in Z2, Z3, and Z5, but decreasing in Z1, Z4, and Z6. However, after about 2013, Temp appears to be increasing in each zone.

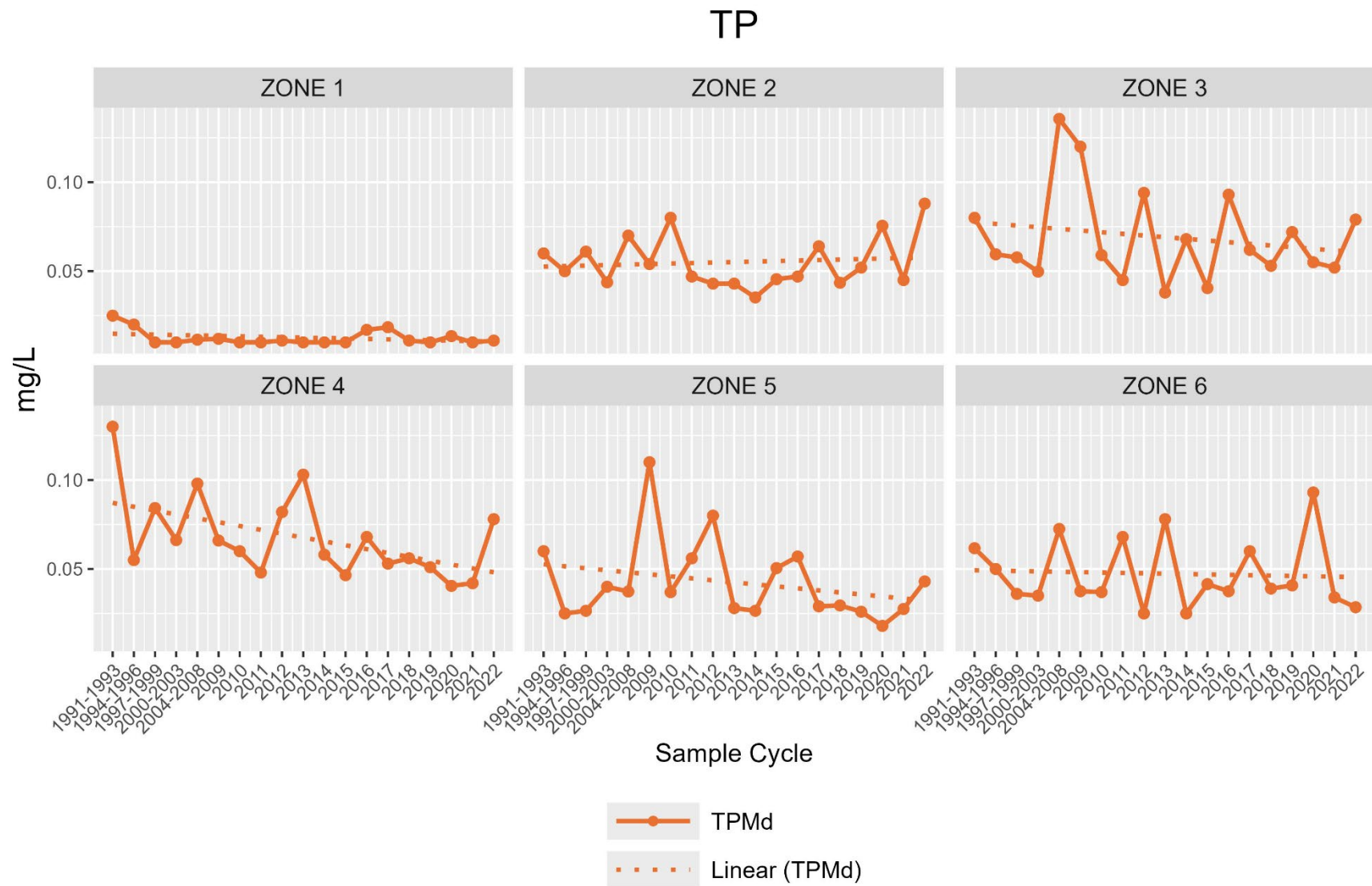


Figure 11a. Time-Series Plots of TP Medians in the UA for Zones 1-6 (1991-2022).

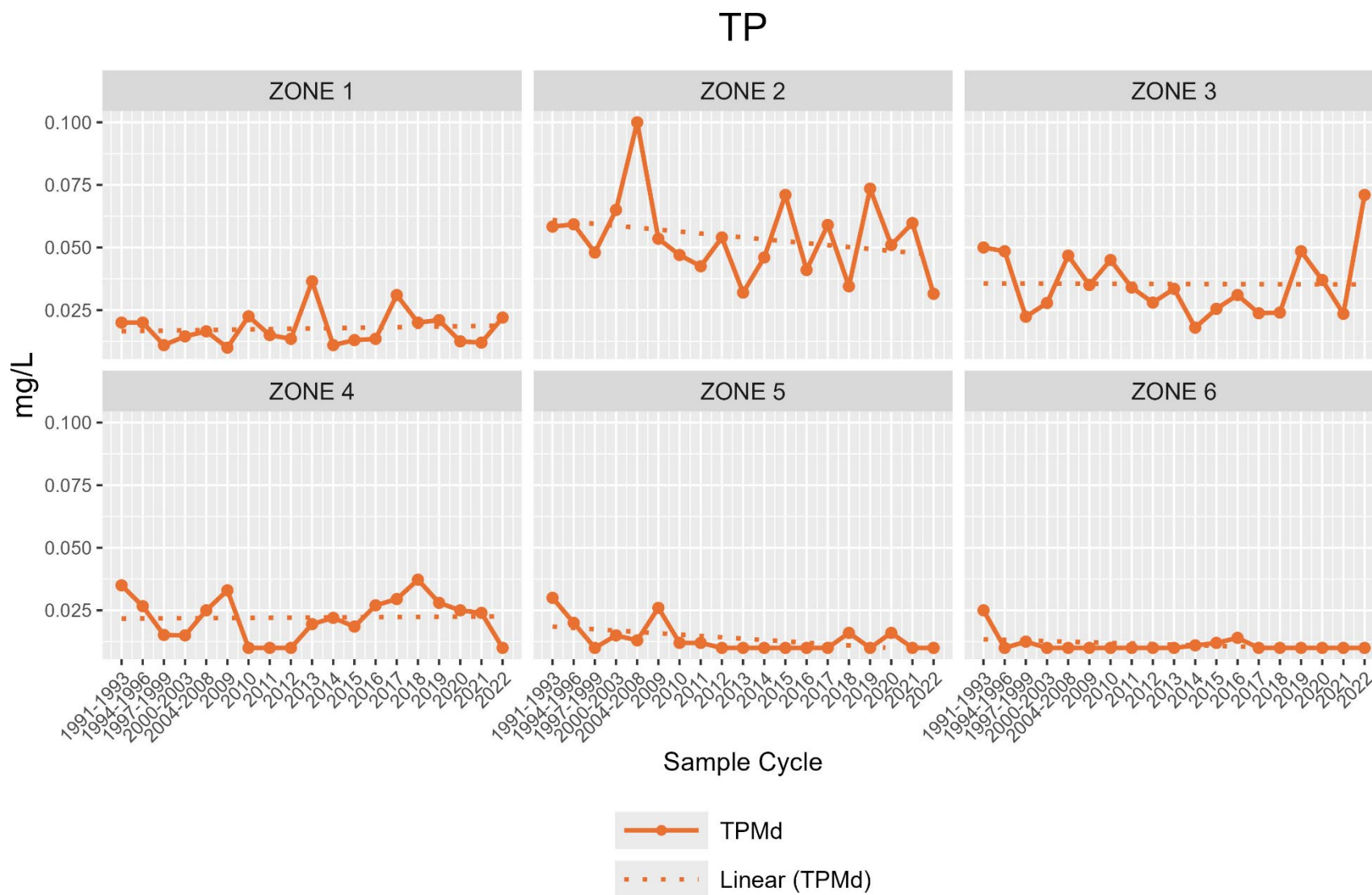


Figure 11b. Time-Series Plots of TP Medians in the CA for Zones 1-6 (1991-2022).

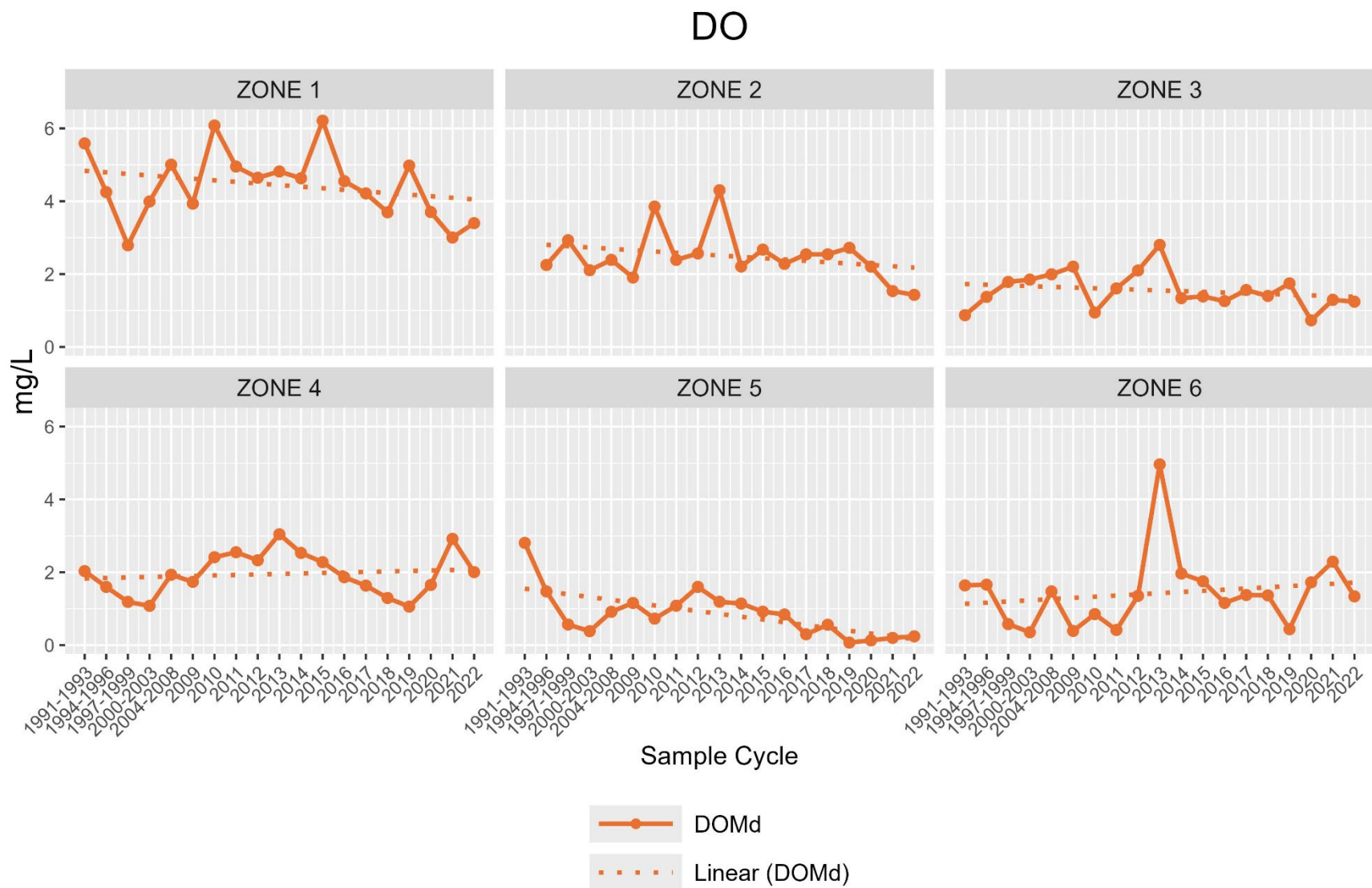


Figure 12a. Time-Series Plots of DO Medians in the UA for Zones 1-6 (1991-2022).

DO

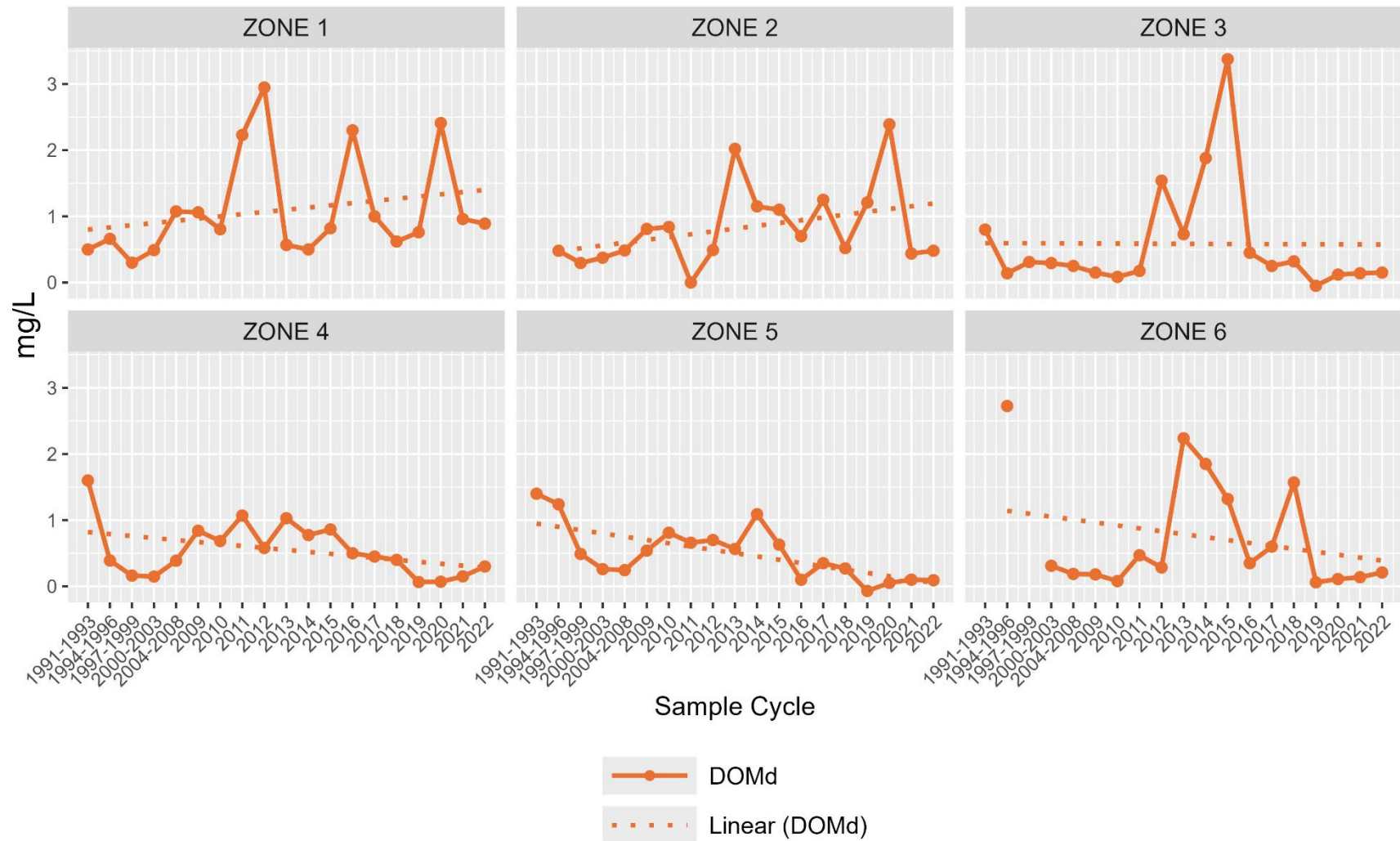


Figure 12b. Time-Series Plots of DO Medians in the CA for Zones 1-6 (1991-2022).

Temp

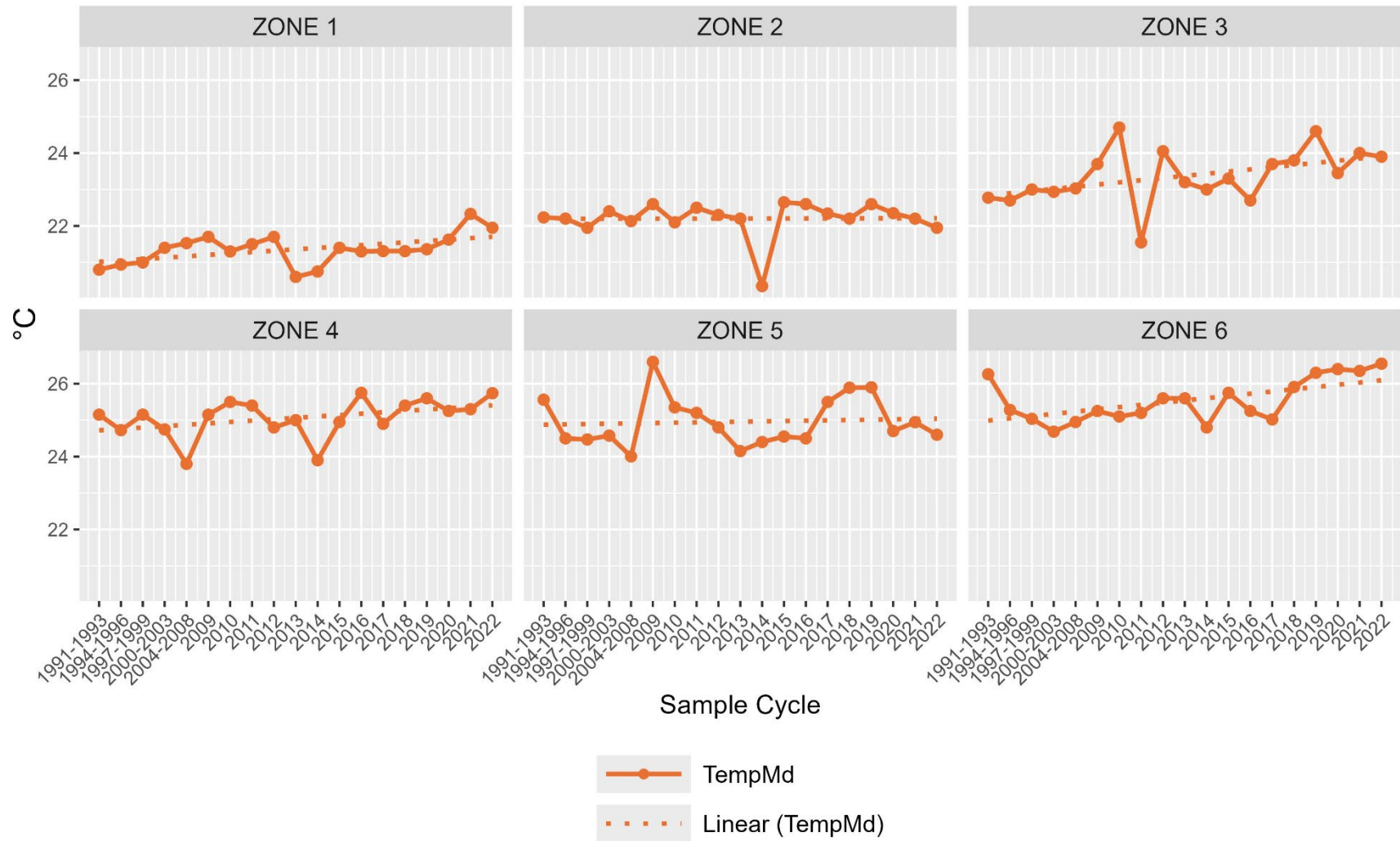


Figure 13a. Time-Series Plots of Temp Medians in the UA for Zones 1-6 (1991-2022).

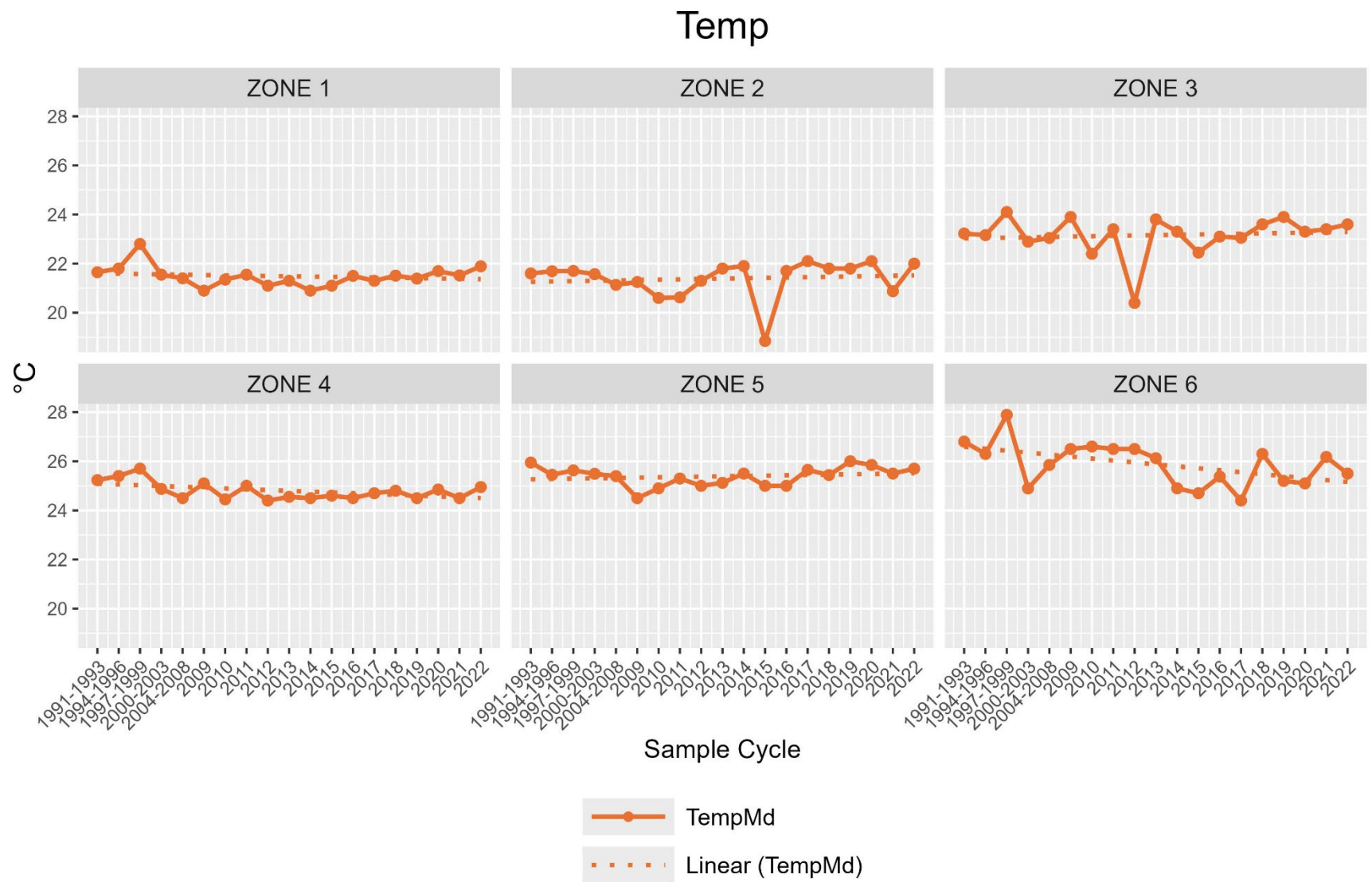


Figure 13b. Time-Series Plots of Temp Medians in the CA for Zones 1-6 (1991-2022).

Zonal Trends

Table 6a displays pertinent zonal information regarding NO₃ and TP trends. Zones, indicators, resources, tests used, number of sampling cycles, p-values, Sen slopes, and the trend directions are listed in columns 1-9 respectively. During Period A in the UA, NO₃ increased in Zone 6, but strongly decreased in Z5. TP decreased in Z4. During the same period for the CA, NO₃ increased in Z2 and strongly decreased in Z5. TP decreased weakly in Z2. It also decreased in Z5. During Period C, there were no observed trends in the UA. For the CA, NO₃ trended strongly downward in Z4.

Table 6b is analogous to Table 6a. It displays pertinent trend information for DO and Temp. During Period A in the UA, DO weakly decreased in Z5. On the other hand, Temp increased in Z3, Z4, and Z6. In the CA, DO decreased in Z4 and strongly decreased in Z5. Temp decreased in Z6. During Period B, in the UA, DO strongly decreased in Z3. Temp increased in Z4 and strongly increased in Z6. In the CA, DO decreased in Z5 and Temp decreased in Z6. During Period C in the UA, DO decreased weakly in Zone 5. Temp increased in Zones 3, 4, and 6. In the CA, DO decreased in Z3, in Z5 and Z6 and decreased strongly in Z4. Temp increased strongly in Z1.

Table 6a. Zonal Trends for NO₃ and TP, based on the Mann-Kendall (MK) and the Modified Man-Kendall (MMK) Tests, for Unconfined and Confined Aquifers for ¹Periods A, B, and C.

Zone	¹ Period	Indicator	Resource	MK or MMK	Number of Cycles	p-value	Sen Slope	Direction
4	A	TP	UA	MK	19	² <u>0.017</u>	-0.003	Down
5	A	NO ₃	UA	MMK	19	³ < 0.001	-0.002	Down
6	A	NO ₃	UA	MK	19	⁴ 0.068	0.007	Up
2	A	NO ₃	CA	MK	19	0.002	0.003	Up
2	A	TP	CA	MK	19	0.054	-0.003	Down
5	A	NO ₃	CA	MK	19	0.058	-0.003	Down
5	A	TP	CA	MK	19	<u>0.020</u>	-0.002	Down
2	B	TP	UA	MK	16	< 0.001	0.758	Up
5	B	NO ₃	UA	MMK	16	<u>0.024</u>	-0.001	Down
2	B	NO ₃	CA	MK	16	<u>0.014</u>	0.149	Up
5	C	TP	CA	MK	16	<u>0.020</u>	-0.002	Down
5	C	NO ₃	CA	MK	10	0.003	-0.026	Down

¹Period A (1991-2022). Period B (2000-2022). Period C (2013-2022).

²Underlined Italics font = moderate trend. ³**Bold font** = strong trend. ⁴Regular font = weak trend.

Of particular interest is that for the UA for any of the periods, as Temp increased, DO decreased. A similar relationship occurred for the CA, during Periods C. During Periods A and B, decreasing trends were observed for both Temp and DO. However, the decreases were not necessarily in the same zones

Table 6b. Zonal Trends for DO and Temp, based on the Mann-Kendall (MK) and the Modified Man-Kendall (MMK) Tests, for Unconfined and Confined Aquifers for Periods A, B, and C.

Zone	¹ Period	Indicator	Resource	MK or MMK	Number of Cycles	p-value	Sen Slope	Direction
5	A	DO	UA	MK	19	² 0.080	-0.108	Down
3	A	Temp	UA	MK	19	³ <u>0.016</u>	0.064	Up
4	A	Temp	UA	MI	19	<u>0.049</u>	0.035	UP
6	A	Temp	UA	MMK	19	<u>0.046</u>	0.083	Up
4	A	DO	CA	MK	19	<u>0.038</u>	-0.033	Down
5	A	DO	CA	MK	19	⁴ 0.006	-0.056	Down
6	A	Temp	CA	MK	19	<u>0.039</u>	-0.077	Down
3	B	DO	UA	MK	16	<0.001	-0.191	Down
4	B	Temp	UA	MK	16	0.058	0.049	Up
6	B	Temp	UA	MMK	16	<0.001	0.112	Up
5	B	DO	CA	MK	16	0.006	-0.056	Down
6	B	Temp	CA	MK	16	<u>0.035</u>	-0.072	Down
3	C	Temp	UA	MK	10	<u>0.012</u>	0.064	Up
4	C	Temp	UA	MK	10	<u>0.049</u>	0.035	Up
5	C	DO	UA	MK	10	0.080	-0.029	Down
6	C	Temp	UA	MMK	10	<u>0.046</u>	0.083	Up
1	C	Temp	CA	MK	10	0.005	00.73	Up
3	C	DO	CA	MK	10	<u>0.032</u>	-0.087	Down
4	C	DO	CA	MK	10	0.007	-1.108	Down
5	C	DO	CA	MK	10	<u>0.025</u>	-0.073	Down
6	C	DO	CA	MK	10	<u>0.032</u>	-0.025	Down

¹Period A (1991-2022). Period B (2000-2022). Period C (2013-2022).

²Regular font = weak trend. ³Underlined Italic font = moderate trend. ⁴**Bold font** = strong trend.

Table 7a displays the nutrients (NH₃, TKN, TN, and TOC), that display trends during any of the three periods by zone, along with the corresponding trend direction. Additional trend analyses information regarding these indicators, including p-values, Sen slopes, and strength of trends, are found in Appendix F. Of note, by lumping the three periods together for the UA, 13 of the 16 trends are downward. In CA, for the combined periods, there were 19 trends. Of these, 12 were downward.

Table 7a. Summary of Nutrient Indicators NH3, TKN, TN, and TOC, Trends.

Zone	Period	Years	¹ UA – Up	¹ UA-Down	¹ CA-Up	¹ CA-Down
1	A	1991-2022				¹ NH3, TKN, TN
2	A	1991-2022				NH3
3	A	1991-2022				² <i>TKN, TN</i>
4	A	1991-2022		NH3, TKN, TN		
5	A	1991-2022			NH3	
6	A	1991-2022			NH3	
1	B	2000-2022	<u>TKN</u>			
2	B	2000-2022				NH3
3	B	2000-2022				<i>TKN, TN</i>
4	B	2000-2022		<u>TKN, TN</u>		
5	B	2000-2022				
6	B	2000-2022		NH3, <u>TKN, TN</u>	NH3	
1	C	2013-2022				
2	C	2013-2022				
3	C	2013-2022				NH3, TOC
4	C	2013-2022	³ NH3	TKN, TN, TOC		
5	C	2013-2022		<u>TOC</u>	NH3, <u>TKN,</u> <u>TN, TOC</u>	
6	C	2013-2022		TOC		TOC

¹Empty Cell = No Trends

²Regular font = weak trend. ³*Underlined italics font* = moderate trend. ⁴**Bold font** = strong trend.

Table 7b displays the ancillary indicators, (Color, pH, SC, and Turb), that displayed trends during any of the three periods by zone, along with the trend corresponding direction. Additional trend analyses information, including p-values, Sen slopes, and strength of trends, are found in Appendix F. In the UA, the greatest frequency of trends is for pH, and SC. For the combined periods, there were 18 zonal trends. Of these, pH and SC displayed 12 upward trends and four downward trends. For the CA, by combining the three periods, there were 13 trends, of which six were for pH. All were downward. There were three SC trends, all in Period A. Two trended upward and one was downward. There were four Turb trends. All occurred during Period B. Three of them were downward.

Table 7b. Summary of Indicators Color, pH, SC, Turb Trends by Resource, Zone, Period, and Direction.

Zone	Period	Years	¹ UA – Up	¹ UA-Down	¹ CA-Up	¹ CA-Down
1	A	1991-2022	² SC		SC	pH
2	A	1991-2022	³ pH, SC			
3	A	1991-2022	pH			SC
4	A	1991-2022				pH
5	A	1991-2022	pH			
6	A	1991-2022	pH	SC	<u>SC</u>	
1	B	2000-2022				pH
2	B	2000-2022	pH, ⁴ <u>SC</u>			
3	B	2000-2022	<u>SC</u>	pH		Turb
4	B	2000-2022				<u>Turb</u>
5	B	2000-2022				pH, Turb
6	B	2000-2022	SC		<u>Turb</u>	
1	C	2013-2022				pH
2	C	2013-2022	Color, pH	<u>Turb</u>		
3	C	2013-2022		pH		
4	C	2013-2022				
5	C	2013-2022				pH
6	C	2013-2022	pH	<u>SC</u>		

¹Empty Cell = No Trends. ²Regular blue font = weak trend. ³**Bold font = strong trend.** ⁴Underlined italics font = moderate trend.

Plausible Reasons or Drivers of Observed Change

Table 8 displays plausible drivers for observed changes displayed in Tables 5 - 7. The drivers are based on the work of Upchurch (1992) and Upchurch et al. (2019). The table includes most, but not necessarily all, drivers of change. The potential drivers were originally established for springs. The verbiage in the table has been modified by this author to be more generally applicable to groundwater across the extent of aquifers in Florida. In Table 8 for each indicator, Column 1 discusses potential drivers of increasing trends. Column 2 does the same for decreasing trends. In Table 8, increase is abbreviated “INC” while decrease is abbreviated “DEC”. In the table, nutrients are presented first.

Upchurch et al. (2019) made comparisons of conduit to diffuse flow. They mentioned that diffuse flow systems are those where groundwater is typically moving through small passages where residence time is relatively long, and the water is in intimate contact with the host rock. This often results in more time for water/rock chemical interactions and typically results in groundwater having greater concentrations of host rock ions (e.g. calcium, magnesium, and bicarbonate in carbonate aquifers). In conduits, groundwater flows relatively rapidly through larger passages with relatively short residence time with host aquifer rocks. With shorter residence times, analyte concentrations are typically lower than in diffuse-flow systems. For the discussion below, instead of referring to conduit and diffuse, reference to age is used. Note that surface water (SW) is generally much younger than groundwater (GW). Relative to diffuse groundwater, SW and freshly

recharged GW typically have low concentrations of aquifer host rock ions.

Some field indicators occasionally can be the drivers of change for the other field indicators or nutrients. For this reason, in the discussions that follow, field indicators are presented first.

Table 8. Interpretation of the Origins/Drivers of Temporal Trends in Florida's Groundwater Resources
(Modified from Upchurch (1992), Upchurch et al. (2019) and Upchurch (Personal Communications. 2021).

Indicator	Increasing Trend	Decreasing Trend
Ammonia/ Ammonium (NH ₄)/(NH ₃)	-INC in use of, or change in formation of, fertilizers. -New sources of Waste Disposal. -Change in waste management (new septic tanks, landfills, feedlots etc.). -INC in natural sources of chemically reduced nitrogen. -DEC in reduction/oxidation potential of GW that causes an inc. in nitrate reduction.	-Dec in use of, or change in formation of fertilizers -Reduction of sources of water disposal. -Changes in waste management (Reduction of septic tanks, landfills, feedlots etc). -DEC in natural sources of chemically reduced nitrogen -INC in reduction/oxidation potential of GW that causes an inc. in nitrate reduction.
Kjeldahl Nitrogen Total (TKN)	-Influx of organic materials to aquifer swallets, siphons, injection wells, drainage wells, sinkholes, and storm-water basins. -INC in proportion of SW component of fresh recharge water to an aquifer relative to GW having long residence times and filtration.	-Reduction of the influx of organic materials to aquifer via swallets, siphons, injection wells, drainage wells, sinkholes, and storm-water basins.
Nitrate (NO ₃ + NO ₂ as N) (NO ₃)	-INC in use of nitrate-based fertilizers in land use activities such as turf management, row crops, golf courses etc. -INC in human and animal waste -INC in rate of nitrification of reduced forms of nitrogen (e.g.NO₂) such as the lowering of the water table or the addition of nutrients that promotes growth of microbes in soils. -INC in nitrate-rich SW runoff to swallets, drainage wells etc.	-DEC in use of nitrate-based fertilizers. -DEC in human and animal waste -DEC in rate of nitrification of reduced forms of nitrogen (e.g.NO₂) such as the lowering of the water table or the addition of nutrients that promotes growth of microbes in soils. -DEC in nitrate-rich SW runoff to swallets, drainage wells etc.
Nitrogen Total (TN)	-See Nitrate (above).	-See Nitrate (above).
Phosphorus Total (TP)	-INC in acid, phosphate-rich flows supplied by SW sources such as storm-water disposal into sinkholes, swallets, and siphons. -Inc inflow components derived from contact with the Hawthorn Group in the IAS. -INC in waste, including human and animal waste. -INC industrial activity in GW basins. -INC in pH of GW.	-INC in low phosphate-recharge via SW sources. -DEC in conduit flow, relative to the low phosphate diffuse-flow component in GW. Potential sources include storm-water disposal into sinkholes, swallets and siphons. -DEC in flow components derived from contact with the Hawthorn Group. -DEC in, or improvement in, phosphate fertilizer use. - DEC in animal / human / waste / improved waste management activities. -DEC industrial activity in GW basins. -DEC in pH of GW.

Table 8. Continued

Indicator	Increasing Trend	Decreasing Trend
Organic Carbon Total (TOC)	-See TKN (above).	-See TKN (above).
Color	-Influx of organic, fine-grained rock or clay materials to aquifer, via swallets, siphons, injection wells, drainage wells, sinkholes, storm-water basins, etc. -INC of SW component in aquifer, relative to GW with long residence times and filtrations.	-DEC input of organic, fine-grained rock or clay materials to aquifer, via swallets, siphons, injection wells, drainage wells, sinkholes, storm-water basins, etc. -DEC of SW component in aquifer, relative to GW with long residence times and filtrations
Oxygen Dissolved (DO)	-INC in SW component, inc. in conduit flow relative to diffuse flow in aquifer. -DEC in ambient water temperature.	-DEC in SW component, inc. importance of diffuse flow relative to conduit flow in aquifer. -DEC in ambient water temperature.
pH	-Reduction in amount of more alkaline diffuse flow relative to acidic conduit flow, such as springs. -Inc. use of soil amendments to buffer acidic soils. -Inc. in highly soluble, carbonate dust related to the establishment of an upgradient quarry.	-INC amount of more alkaline, diffuse flow relative to more acidic conduit flow such as springs. -DEC use of soil amendments to buffer acidic soils. -DEC in highly soluble, carbonate dust related to the establishment of an upgradient quarry.
Specific Conductance (SC)	-INC in proportion of diffuse, relative to, conduit flow. -Saline-water encroachment.	-DEC in proportion of diffuse, relative to, conduit flow. -Reduction in saline-water encroachment.
Turbidity (Turb)	-Introduction of SW to aquifer. -INC in turbulent flow in conduits, such as springs. -Introduction of particulates (sediments) in conduits.	-Reduction of SW to aquifer. -DEC in turbulent flow in conduits, such as springs. -Flushing of particulates (sediments) in conduits.
Water Temperature (Temp)	-Climate cycles resulting in an inc. of annual mean air temperature. -Change in the proportion of conduit, relative to diffuse, flow. -DEC in influx of seasonally cool water via swallets, siphons, drainage wells, storm-water basins, etc.	-Climate cycles resulting in a dec. of annual mean air temperature. -Change in the proportion of conduit, relative to diffuse, flow. -INC in influx of seasonally cool water via swallets, siphons, drainage wells, storm-water basins, etc.

¹INC = Increase ²DEC = Decrease

Field Indicators

Temp. Figure 14 depicts the statewide mean annual air temperature during Period A in °F (Florida Climate Center, 2023). Comparison of Figure 14 with Figures 11a and 11b indicates that as air temperature increased groundwater Temp tended to increase in both the UA and CA. Regarding air Temp, serial correlation was found to be present. An MMK test was then performed on the statewide air temperature data to determine if an upward trend occurred. The resulting p-value was 0.015, indicating a strong upward trend.

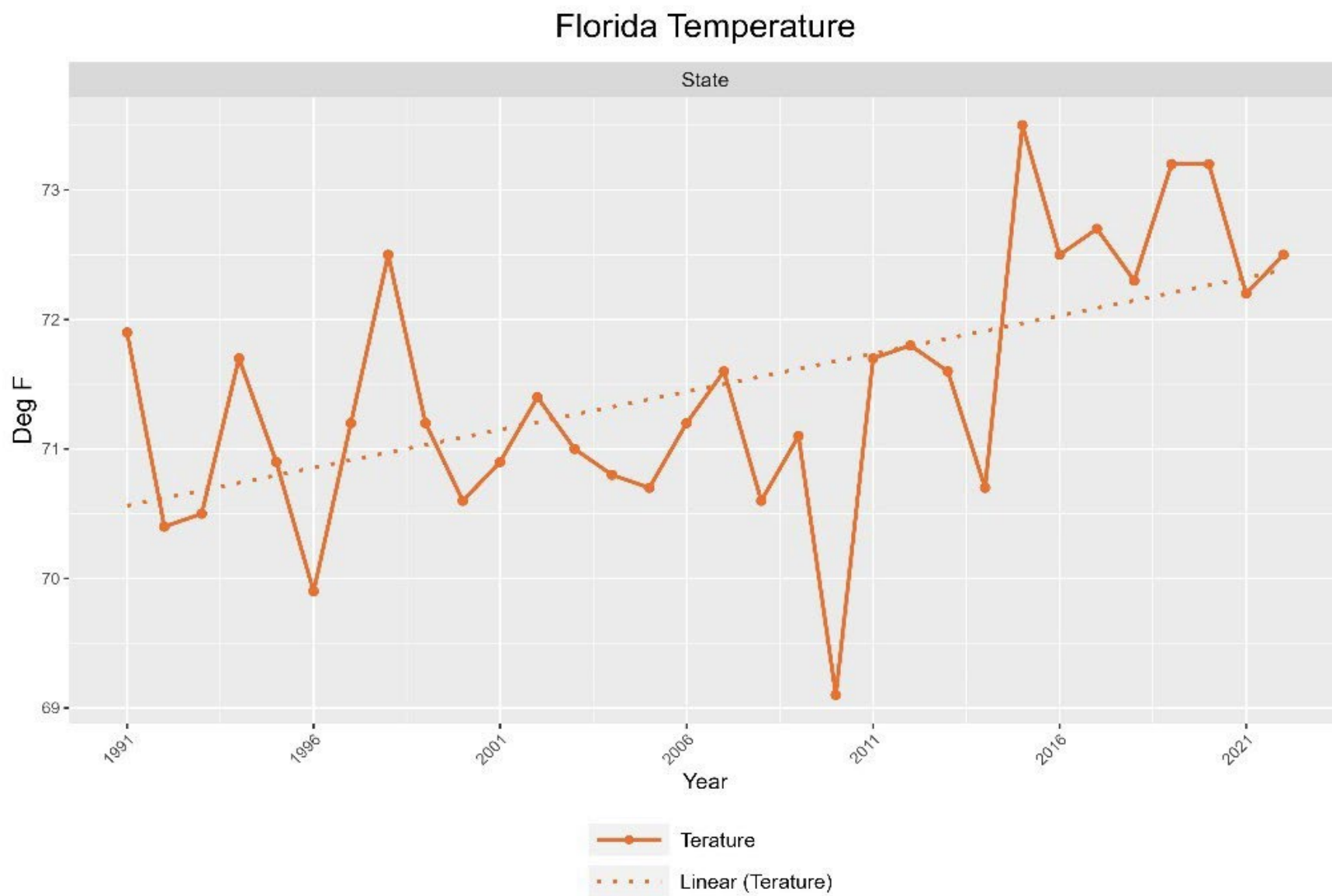


Figure 14. Florida Statewide Mean Annual Air Temperature (1991-2022) (Florida Climate Center, 2023). Note: $^{\circ}\text{F} = (^{\circ}\text{C} * 9/5) + 32$.

Table 8 indicates that one plausible driver of increasing water Temp is increasing air Temp related to climate cycles. During Period A, air temperatures increased across the entire planet (Florida Climate Center, 2023). Thus, a reasonable driver for increased Temp in groundwater in Florida is the increase in air temperature.

DO. Table 6b and Figures 10a-b indicate DO tended to decline during each period. Table 8 discusses two potential drivers for the lowering of DO. One is a decrease in the amount of surface water and/or recharge entering the groundwater regime. Related to this is the relative importance of older to younger water in the aquifer. With increasing older, diffuse flow, the residence time (age) of the groundwater increases, and the relative concentration of DO decreases. Figure 15 displays the statewide mean annual rainfall during 1991-2022 (Florida Climate Center, 2023) decreased. The decrease in rainfall may be causing net recharge to Florida's aquifers to decline. This may have, in turn, caused an increase in older, diffused flow, causing DO concentrations to decline. However, note that beginning in 2007, rainfall began to increase. As will be discussed later, during the latter portion of the study, the increased rainfall could have affected nutrient concentrations during Periods B and C. Another reason for declining DO levels (Table 8) is an increase in temperature. As mentioned, temperature increased throughout the investigation. Reasons for increases in Temp may be the most important reason for decreasing DO concentrations. An increase in temperature can provide sufficient energy to break the molecular bonds between hydrogen and oxygen, allowing DO to escape from water (Drever, 1997; and Hem, 1985).

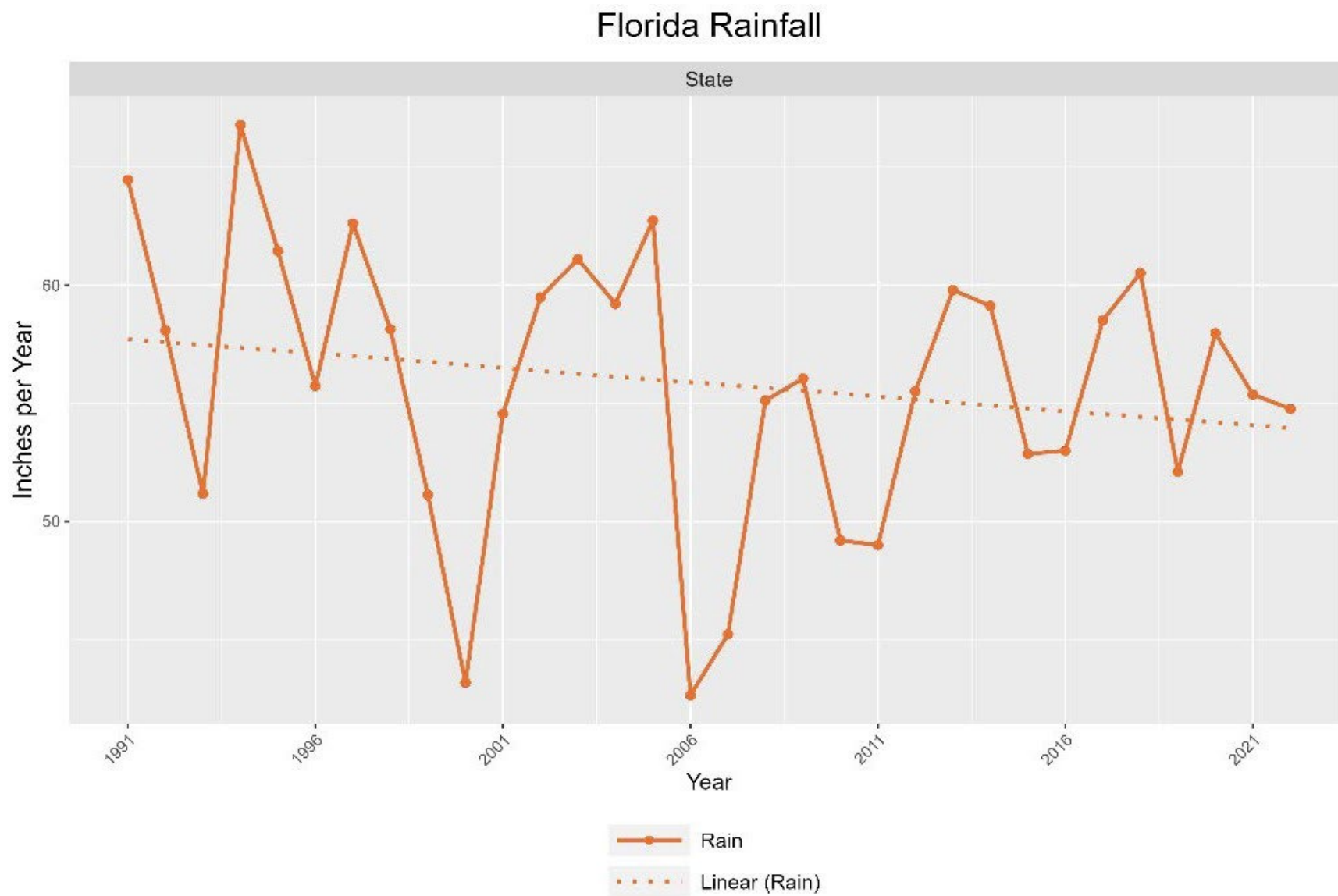


Figure 15. Florida Statewide Mean Annual Rainfall (Precipitation) (1991-2022) (Florida Climate Center, 2023). (One inch = 2.54 cm.)

pH. Table 8 indicates that one driver which might produce downward trends on a statewide scale is an increase in the relative importance of older, diffuse flow. Copeland and Woeber (2021) observed increases in diffuse flow in the CA between 1991-2011.

SC. Table 8 indicates that two drivers that can contribute to increasing SC trends are: (1) an increase in the proportion of older (diffuse) groundwater in aquifers and (2) saline-water encroachment. Again, as with DO and pH, increasing trends in SC might be related to decreases in recharge. Another possibility is saline encroachment. Copeland and Woeber (2021) observed that slow, passive, saline encroachment occurred over the state within Florida's CA, and to a lesser extent, within the UA resources (1991-2011). They found that as chloride increased, so did SC. For this investigation, the positive correlation between SC and chloride, along with the observed increase in SC on the statewide scale, suggests that passive encroachment is continuing to occur over the state.

Color and Turb. Potential drivers of increasing and decreasing trends are found in Table 8. One cause of an increasing trend in Color can be related to the introduction of fine-grained rock or clays to an aquifer. A decrease is often due to the reduction of fin-grained rock and clays.

Nutrient Indicators

TOC. No statewide trends were observed for TOC (Table 5). Table 8 indicates that potential drivers of TOC concentration changes are the same as those for TKN (to be discussed shortly).

NH3. Table 8 indicates that land-use activities, such as: (1) increases in the use, or changes in the formulation, of fertilizers and (2) increases in waste disposal activities, such as septic tanks, landfills, feedlots etc. can cause increases of NH3 concentrations. Other potential drivers include: (3) increases in the introduction of natural sources of chemically reduced nitrogen, and (4) a decrease in the oxidation/reduction potential of groundwater that otherwise would cause an increase in nitrate reduction.

TKN. Table 8 lists several potential drivers of increases in TKN concentrations. They include: (1) an influx of organic material to aquifers via swallets, siphons, injection wells, drainage wells, sinkholes, and storm water ponds, (2) an increase in the younger, surface water component in an aquifer relative to groundwater. As mentioned previously, the drivers of changes in TOC concentrations are essentially the same as those for TKN.

TN. If TKN concentrations are known, then TN concentrations are essentially equal to the concentrations of nitrate + nitrite + TKN. Under typical conditions in natural water, nitrite oxidizes to nitrate (Center for Disease Control, 2021). Thus, the drivers of change of TN concentrations are often governed by drivers of change in NO3. Table 5 indicates no statewide trends were observed for NO3, TN or TKN during any period in the UA. In addition, in the CA at the zonal scales, NO3 trended both upwards and downwards, Depending on the period and the

zone. All TN trends, and all but one of the TKN trends were downward (Tables 6a and 7a). This is mildly surprising because by 2000, it was known that concentrations of NO₃ in spring discharge had been increasing for decades (Springs Task force, 2000; Scott et al. 2004) and unconfined groundwater is believed to be more susceptible to contamination based on human land use activity, relative to confined aquifers. On a statewide basis, for the CA, during Periods A and B, upward trends were observed for concentrations of NO₃ (Table 5). At the zonal scale it was observed that upward NO₃ trends were observed in Z2 during Periods A and B. Regarding TKN and TN, most, but not all, of the observed trends were downward, (Table 6a).

Discussion of Total Phosphorus and Nitrate

Introduction

Recall, the two nutrients that FDEP is most concerned with for restoration purposes are phosphorus and nitrogen. TP is the most important phosphorus indicator in terms of concern by FDEP. For nitrogen in groundwater, the indicator of most concern is NO₃. In addition to Upchurch (1992) and Upchurch et al. (2019), several other authors have written about phosphorus and nitrogen in both natural and impaired water resources. They include Katz (1992), Drever (1997), and Hem (1985). Since the early 2000s, FDEP has initiated plans to restore water bodies with elevated nutrient levels (FDEP, 2008). For this reason, this discussion emphasizes TP and NO₃ concentrations during Periods B and C.

Total Phosphorus

Recall from Figures 7a-b that downward slopes of TP medians occurred in the UA and CA resources during Period A on the statewide scale. However, on the zonal scale, statistically, TP concentrations weakly declined in Z2 in the CA during Period B (Table 5). On the zonal scale, no trends were observed. At the current time, TP trends in groundwater on the statewide and zonal scales are not a major concern.

Although not included in Table 8, Cerozi and Fitzsimmons (2016) discussed an additional potential driver of change in TP concentrations. They mentioned that changes in pH can potentially cause changes in concentrations of TP. In an investigation of aquaculture, the authors stated that increasing pH levels resulted in a decrease in TP concentrations. They mentioned that with increasing pH levels, phosphorus binds to calcium, leaving less free phosphate ions available in solution. Sprinkle (1989), in an investigation of groundwater quality in the Floridan aquifer system, also stated there was an inverse relationship between pH levels and TP concentrations.

Is there a correlation between pH and TP in this investigation? Recall, TP trends were observed at the statewide scale in the CA and on the zonal scales in (UA) Z2 and (CA) Z5. Using only annual medians, both TP and pH values are displayed in

Table 9. Years are listed in Column 1. Statewide annual CA median values of the two variables are listed in Columns 2 and 3. Annual medians for TP and pH in UA in Zone 2 are found in Columns 4 and 5. For CA in Zone 5 the medians are found in Columns 6 and 7. For this exercise, since the objective is to correlate annual values, only data from 2009-2022 were used. (Recall that prior to 2009 multiple years were needed to complete a statewide sampling cycle.)

Regarding the statewide correlation in CA, at the bottom of the table, the Spearman correlation coefficient between TP and pH is -0.287. The p-value of the correlation is 0.320, indicating no statistical relationship. For the UA in Z2 the correlation is 0.098 and the p-value of this correlation is 0.739. For the CA in Z5, the correlation is -0.201 and the p-value is 0.490. For this investigation, using annual median values (Table 9), no meaningful correlations between TP and pH exist on either the statewide scale, or on the zonal scale.

Table 9. Annual Median TP and pH values in the UA of Z2 in the CA in Z5 (2009-2022).

Year	CA State TP	CA State pH	UA Zone 2 TP	UA Zone 2 pH	CA Zone 5 TP	CA Zone 5 pH
2009	0.025	7.40	0.054	6.90	0.026	7.50
2010	0.014	7.40	0.080	6.55	0.012	7.30
2011	0.016	7.50	0.047	6.80	0.012	7.30
2012	0.012	7.50	0.043	7.00	0.010	7.50
2013	0.022	7.50	0.043	7.10	0.010	7.50
2014	0.018	7.50	0.036	7.10	0.010	7.50
2015	0.016	7.40	0.046	6.95	0.010	70.35
2016	0.020	7.40	0.047	7.25	0.010	7.40
2017	0.021	7.38	0.064	7.15	0.010	7.45
2018	0.020	7.32	0.044	7.29	0.016	7.16
2019	0.027	7.38	0.052	7.31	0.010	70.35
2020	0.014	7.44	0.076	7.13	0.016	7.39
2021	0.019	7.27	0.045	6.96	0.010	7.30
2022	0.015	70.35	0.088	7.37	0.010	7.29

Nitrate

Of particular interest to the FDEP are nitrogen restoration projects. They are designed to restore nitrate concentrations and to reduce nitrogen loading to groundwater and to springs (FDEP, 2008). Table 8 indicates that several of the potential drivers of increases in NO₃ concentrations in groundwater are related to nitrogen loading from land surface activities. Evaluating modifications in NO₃ concentrations can potentially supply clues as to changes in the loading of nitrogen. The NO₃ proportions GT0.35 per sample cycle for both the UA and the CA during Period A on a statewide scale are displayed in Figures 6a-d. In the UA the slope declined but there was not a statistical trend. Note that on the statewide scale, the NO₃ slopes in the UA were downward, while they were upward in the CA. However, from about 2013 through 2022, concentrations in CA tended to decline (Figures 6c and d).

An inspection of the slopes of the NO₃ proportions' GT0.35 in each zone for the UA and CA reveals the following: For the UA in Figure 10c slopes are increasing in Zones 4 and 6 (Period B (2000-2022)). They are decreasing in Zones 1, 2, 3, and 5. Regarding zonal trends, Table 6a indicates the slope in Zone 5 is associated with a downward trend.

In CA, a different story emerges. Figure 10d shows downward slopes in Zones 1, and upward slopes in Zones 2, 3, 5, and 6. There is an almost flat slope in Zone 4. Table 6a indicates the slope in Zone 5 represents a downward trend in Periods A and B. In addition, during Period C, there is a downward trend in the CA in Zone 4. Regarding upward trends, there are two, and both are in Zone 2. Figure 10d shows a major increase in the proportions GT0.35 in the CA. Slopes are decreasing in Zone 1, increasing in Zones 2 and 3, and relatively stable in Zones 5 and 6. Table 6

indicates that NO₃ trends are in Zone 2 during Periods A and B.

High NO₃ Concentrations in Zone 2. What might have caused the major pulse in the concentrations of NO₃ in Zone 2 in CA (Figures 10b and 10d)? From Table 8, one possibility is a correlation with land use. Agriculture is a major economic driver in Zone 2. Although land use data varies within each hexagon, at the individual well level it is possible to obtain site-specific land use data. For this reason, but restricted to this exercise, data from wells, instead of composite data from hexagons, are used.

Since 1998, beginning in the 1996-1999 sampling cycle (Table 2), as part of the Status Network well sampling procedures, land use within a radius of 300 feet of each sampled well has been obtained during each sampling cycle. Referred to as micro land use (MLU), samplers classify the well as being into one of the following MLU categories: (1) Low Impact (LI), (2) Urban/Suburban (US), (3) Mining (ME), (4) Intense Agriculture (AG), and (5) Industrial (IN).

As it turns out, in 2013, the number of wells in the Zone 2 sampling listframe for the UA increased by over 2000. The same is true for the CA listframe. Are a higher proportion of the additional wells in the SRWMD listframes located in agricultural land use? Are wells with high NO₃ concentrations more frequently found in agricultural areas?

For this exercise, during each sampling cycle sampled well were “pigeon-holed” into two MLU groups: (1) wells classified as AG, and (2) wells classified as Non-AG (NAG). NAG was represented by the LI, SU, ME, and IN classifications. During each sampling cycle, each well’s NO₃ concentrations were paired to their MLU classification. Table 10 lists the sampling cycle ID and the years of the cycle. It also displays the number wells classified as AG ($n(AG)$), the proportion of AG wells ($Prp(AG)$), the proportion of AG wells with concentrations greater than (GT) the 0.35 mg/L threshold, the number of NAG wells ($n(NAG)$), the proportion of NAG wells, ($Prp(NAG)$), and the proportion of NAG wells GT0.35.

An inspection of Table 10 suggests the following regarding AG land use. After 2012, the proportion of AG wells in Zone 2 increased, as did the proportion of sampled wells with NO₃ concentrations exceeding 0.35 mg/L. Data in the table also suggest that the proportion of NAG wells decreased, as did the proportion of NAG well with concentrations GT.035. To test these hypotheses, a series of two-sample proportion tests were conducted. First, from Table 10 (columns 3 and 6), prior to 2013, five of the 287 sampled wells were AG (proportion = 0.017). From 2013 onward, 33 of 196 sampled wells were AG (proportion = 0.168). From a two-sample proportion test, the resulting p-value is <0.001. This indicates that beginning in 2013 the proportion of sampled AG wells increased in the SRWMD (Zone 2). Also of interest are the proportion of samples exceeding the 0.35 mg/L NO₃ threshold. Table 11a-d addresses exceedances for all well types. Table 12a-d does the same but restricted to AG wells.

Table 10. NO3 Concentrations in Zone 2 by Sampling Cycle.

Cycle ID	Year(s)	n(AG)	¹ Prp(AG)	Prp(AG GT 0.35)	n(NAG)	Prp(NAG)	Prp NAG GT0.35)
1	1998-1999	0	0.000	0.000	89	1.000	0.190
2	2000-2003	1	0.011	1.000	90	0.989	0.211
3	2004-2008	4	0.114	0.500	31	0.886	0.161
4	2009	0	0.000	0.000	18	1.000	0.097
5	2010	0	0.000	0.000	20	1.000	0.200
6	2011	0	0.000	0.000	19	1.000	0.158
7	2012	0	0.000	0.000	20	1.000	0.150
8	2013	1	0.050	1.000	19	0.950	0.158
9	2014	3	0.150	0.670	17	0.850	0.294
10	2015	7	0.350	0.714	13	0.650	0.308
11	2016	1	0.059	1.000	16	0.941	0.177
12	2017	4	0.200	0.500	15	0.800	0.375
13	2018	5	0.250	0.600	15	0.750	0.133
14	2019	2	0.100	1.000	18	0.900	0.222
15	2020	6	0.300	0.667	14	0.700	0.214
16	2021	2	0.100	0.500	18	0.900	0.308
17	2022	2	0.100	0.500	18	0.900	0.167

¹Prp = proportion.

Table 11 indicates that 5 of 292 sampled CA wells had at least one exceedance of the 0.35 mg/L threshold for NO3 during the Early (E) period (pre-2012). The proportion of exceedances was 0.017. During the Late (L) period (2013-2022), 32 of 197 sampled wells had an exceedance. The proportion was 0.162. Column 7 indicates that the resulting p-value of the two-sample proportion test is <0.001. There were proportionally more exceedances for NO3 in CA wells during the L period. For UA wells, Table 11 indicates that during the E period, nine of 249 wells had at least one exceedance (0.036). During the L period, 24 of 179 (0.132) sample wells exceeded the threshold. The resulting p-value was <0.001. There were proportionally more exceedances in UA wells during L period, relative to the E period.

Table 11 indicates that during the E period, five of 292 (0.018) CA wells exceeded the threshold, while 9 of 249 (0.036) UA wells had at least one exceedance during the E period. The resulting p-value was 0.186, indicating no evidence of a difference in the proportion of exceedances in CA and UA during the E period. During the L period, 32 of 197 (0.162) CA wells had an exceedance, while 24 of 179 (0.132) UA wells had an exceedance during the same period. The resulting p-value was 0.454, indicating no evidence of a difference in the proportion of exceedances in the two resources during the L period.

Table 11. SRWMD Proportion Test Results for Number of AG Wells vs. Total Number of Wells.

Well Type	Early Period # AG Wells / Total # Wells	Early Period AG Well Proportion	Late Period # AG Wells / Total # Wells	Late Period AG Well Proportion	Adjusted p-value
CA Wells	5/292	0.017	32/197	0.162	<0.001
UA Wells	9/249	0.036	24/179	0.132	<0.001

Table 12 indicates that 3 of the 5 AG wells in the SRWMD in the CA had at least one exceedance during the E period (pre-2012). The proportion of exceedances was 0.600. During the L period (2013-2022), 22 of 32 sampled wells had an exceedance. The proportion was 0.688. Column 7 indicates that there were insufficient data to conduct an analysis of the two-sample proportion test. For UA AG wells, Table 12 indicates that 4 of 9 (0.444) wells had an exceedance of NO₃ during the E period. During the L period, 8 of 24 sampled AG wells had at least one exceedance (0.333). There were insufficient data to conduct an analysis of the two-sample proportion test.

Table 12 indicates that during the E period, 3 of the 5 (0.600) CA AG wells had at least one exceedance. During the same period, 4 of the 9 (0.444) UA AG wells had an exceedance. There were insufficient data to conduct an analysis of the two-sample proportion test. During the L period, 22 of 33 (0.686) CA sampled AG wells had an exceedance for NO₃. During the same period, 8 of the 24 (0.333) UA AG wells had at least one exceedance for NO₃. The resulting p-value was 0.009. During the L period, the proportion of exceedances of the 0.35 mg/L threshold in CA AG wells was greater, relative to UA AG wells.

Table 12. SRWMD Proportion Test Results for Number of NO₃ Threshold Exceedances In AG wells.

Comparison	Early Period AG Wells NO ₃ >0.35 mg/L	Early Period Proportion	Late Period AG Wells NO ₃ >0.35 mg/L	Late Period Proportion	Adjusted p-value
CA Wells Early to Late	3/5	0.600	22/33	0.667	⁵ ISD
UA Wells Early to Late	4/9	0.444	8/24	0.333	ISD

The proportion of sampled AG wells increased after 2012, when the size of the list frame increased. In addition, the information found in Tables 11 and 12 indicates several important issues. They are summarized below:

1. There is insufficient data to compare AG exceedance proportions for:
CA wells, E to L periods,
UA wells, E to L periods,
For E period, CA to UA wells,
2. During E period, there is no difference in proportion of exceedances, CA to UA,
3. During L period, there is no difference in proportion of exceedances, CA to UA,
4. For all CA wells, the proportion of exceedances is greater in L relative to E period,
5. For all UA wells, the proportion of exceedances is greater in L relative to E period,
6. During L period, the proportion of exceedances is greater in CA relative to UA.

In addition, the proportion of exceedances during the L period was greater in CA than in the UA. This issue is surprising and will be addressed later.

Reduction of NO₃ Concentrations in the UA During Latter Part of Study. For the remainder of this investigation, when discussing NO₃ concentrations, reference will return to hexagon medians and proportions GT0.35. There are no significant natural sources of NO₃ in Florida's groundwater (Upchurch, 1992; Upchurch et al., 2019). The authors stated that the source of most NO₃ in groundwater comes from anthropogenic activities such as use of fertilizers, waste disposal, and industrial applications (N loading). Most of the drivers of increasing NO₃ trends discussed in Table 8 are related to an increase of N loading. Conversely, a major driver of decreasing trends is a reduction in N loading.

Table 8 indicates another plausible cause of decreasing NO₃ concentrations in groundwater: an increase in recharge that has low concentrations of nitrogen.

Regarding nitrogen loading, sufficient data are not available for trend analyses. However, the effect of increased rainfall and subsequent dilution of NO₃ concentrations can be investigated. For an unconfined aquifer, if rainfall and subsequent recharge increase sufficiently, then after a lag, an eventual reduction of NO₃ concentrations is predicted. Mean NO₃ concentrations in Florida's rainfall is generally 0.40 to 0.50 mg/L (National Atmospheric Deposition Program (2021). Nonetheless, if there is not a direct pathway to groundwater (e.g. swallets, drainage wells, etc.), biota typically consumes the nitrogen by the time vadose water recharges the UA (Upchurch et al., 2019). Under natural conditions, NO₃ concentrations in recharge in unconfined aquifers are near background conditions (<0.0 mg/L). Regarding confined aquifers, the physical recharge process is more complex than for unconfined aquifers. Nevertheless, under natural conditions, by the time recharge to the CA occurs, NO₃ concentrations are typically at background concentrations.

Although annual recharge data are not readily available, annual rainfall data are. For this reason, the author decided to compare annual NO₃ concentrations to rainfall, with the assumption that after a lag, recharge to the UA follows rainfall.

Earlier, Figure 15 displayed annual mean rainfall (precipitation) in inches (in) (Florida Climate Center, 2023) for the period 1991-2022. The figure displayed that, overall, the slope of rainfall is downward. Following a drought (Verdi et al., 2006) in 2000, plus two additional very dry years in 2006 and 2007, rainfall has increased (Figure 16). In addition, except for the southeastern portion of the Florida peninsula, in general, annual historical rainfall decreases in Florida from northwest to southeast (Fernald and Purdum, 1998, p. 17). Has the increased rainfall affected NO₃ concentrations in groundwater?

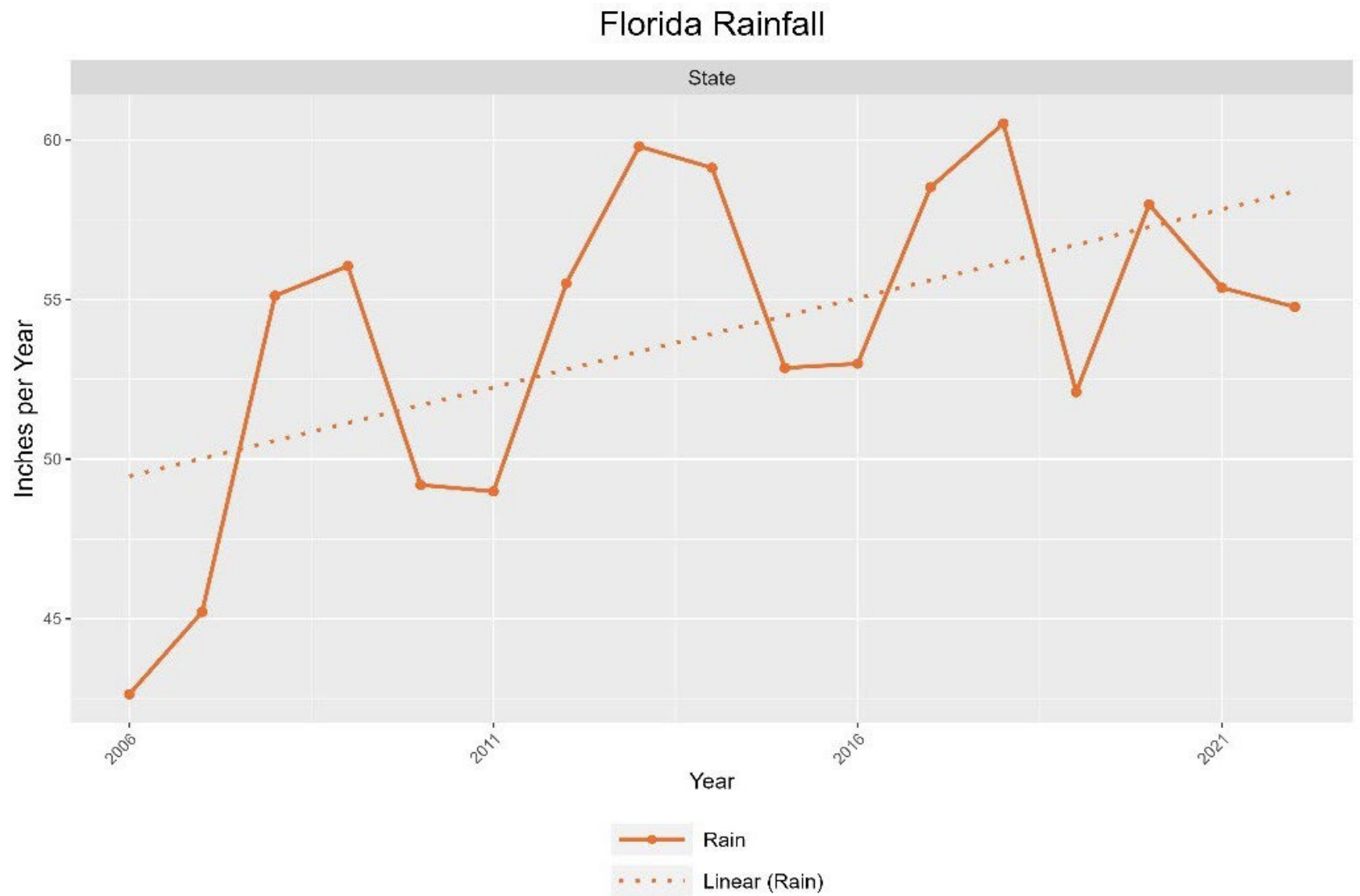


Figure 16. Annual Statewide Rainfall (2006-2022) (Florida Climate Center, 2023).

Consider the UA. Figure 17 displays annual NO₃ proportions GT0.35 during Period C (2013-2022) for Zones 1-6 (Z1-Z6). An inspection of slopes suggests GT0.35 concentration slopes decreased in Z1, Z2, and Z5 and possibly increased in Z3, Z4, and Z6. However, Table 6 indicates none of them were significant.

For this exercise, for the reasons given above and because rainfall generally decreases from northwest to southeast, the author decided to combine Zones 1 and 2, Zones 3 and 4, and Zones 5 and 6. The three regions are referred to as: (a) Z1Z2, (b) Z3Z4, and (c) Z5Z6. The regions move from northwest to south; analogous to the rainfall patterns presented in Fernald and Purdum (1998) that moved from northwest to southeast. Concentrations of NO₃ were compared to changes in rainfall in each of the three regions.

Since Period C consisted of ten years (2013-2022), an attempt was made to compare rainfall in those years to the 10 years preceding Period C (2003-2012), and then to NO₃ concentrations GT0.35. However, Cycle C01 represents (2000-2003) and Cycle C02 represents (2004-2008). Lindsey and Rupert (2012) indicated that because of the relative slow velocity of groundwater, if one desires to conduct a step trend test between an E and L time, it is advisable, but not a requirement, to use a gap of at least three years between them. Therefore, it was decided to set an E subperiod as 2004-2011 (C02-C05) and a L subperiod as 2015-2022 (C09-C16). Both subperiods represent eight years. Recall that in the previous exercise, the time of interest was also divided into two subperiods. However, there was not an interlude between them. The reason was as follows: The interest was to determine if the addition of wells to the UA and CA frames in 2013 were potentially causing the observed NO₃ pulse. There were two distinct subperiods: (1) prior to 2013 and (2) 2013 through 2022. Removing three years of crucial data between the two subperiods would only diminish the ability to make interpretations.

NO3



Figure 17. Time-Series Plots of Proportion of Wells Having NO3 Greater Than 0.35 mg/L in the UA for Zones 1-6 (2013-2022).

Returning to the current exercise, annual rainfall values (Florida Climate Center, 2023) were determined for each sampling cycle (Appendix H). Zonal rainfall means were based on long-term precipitation stations. For each zone, the means were based on data from all precipitation stations within each zone (Appendix I).

Zones weights are based on area and the proportion of area of each zone, relative to Florida (Appendix G). The proportion of Florida in Z1Z2 is 0.332. Of this proportion, and rounding to two significant figures, the sub-proportion of Z1 is 0.60 and Z2 is 0.40. The proportion of Florida in Z3Z4 is 0.382. Of this amount, 0.55 is in Z3; 0.45 is in Z4. The proportion of Florida in Z5Z6 is 0.286. Of this proportion, 0.50 is in Z5 and 0.50 is in Z6. The sub-proportion of each of the three regions are considered the weight (wt) of the region.

Using the “shapiro.test” function in R, it was inferred that Florida’s mean annual rainfall (1991-2022) can be considered normally distributed. The resulting p-value was 0.447. To determine the sampling cycle mean of rainfall for each region (Reg), the weighted (wt) mean formula was used (Triola, 2021).

$$\text{wt mean (Reg)} = \Sigma(\text{wt} * (\text{annual mean rainfall})) / \Sigma(\text{wts}). \quad (1)$$

As an example, suppose for 2005, rainfall was 57.54 inches in Z1 and 52.13 inches in Z2. The weighted mean rainfall is:

$$\text{wt mean} = [(0.60 * 57.54) + (0.40 * 52.13)] / (0.60 + 0.40) = [(34.52 + 20.85) / (1.00)] = 55.37.$$

Equation (1) was used to determine Z1Z2, Z3Z4, and Z5Z6 regional means for each sampling cycle for rainfall, and for proportions of NO3 GT0.35 in the UA and CA, GT0.35 of NO3 were substituted for rainfall in equation (1). For the 2004-2008 Sample Cycle, the five-year averages were first determined prior to using equation (1).

Table 13 displays both proportions of NO3 GT0.35 and rainfall data used for the exercise. Column 1 displays the year(s). Columns 2, 4, and 6 show annual (or cycle) proportion of NO3 concentrations GT0.35, while Columns 3, 5, and 7 display rainfall. Rows 6-8 represent the gap between the two periods. Table 14 Depicts analogous data for NO3 and rainfall data for CA. The rainfall data are identical to those presented in Table 13.

Table 13. UA Nitrate Proportions GT0.35 and Rainfall Data for Three Regions (2004-2022).

Year(s)/ (Period)	Z1Z2 NO3 (Prop GT 0.35 mg/L)	Z1Z2 Rain (An Mean) (in)	Z3Z4 NO3 (Prop GT 0.35 mg/L)	Z3Z4 Rain (An Mean) (in)	Z5Z6 NO3 (Prop GT 0.35 mg/L)	Z5Z Rain (An Mean) (in)
2004-2008 (E)	0.430	52.13	0.505	50.630	0.059	54.48
2009 (E)	0.300	57.54	0.205	51.34	0.057	48.50
2010 (E)	0.3160	49.84	0.250	43.08	0.125	48.99
2011 (E)	0.368	36.41	0.2058	49.06	0.053	54.57
2012 (Gap)	¹ NA	NA	NA	NA	NA	NA
2013 (Gap)	NA	NA	NA	NA	NA	NA
2014 (Gap)	NA	NA	NA	NA	NA	NA
2015 (L)	0.222	53.21	0.250	51.19	0.111	52.27
2016 (L)	0.474	52.46	0.179	51.46	0.128	55.01
2017 (L)	0.294	69.37	0.256	53.66	0.065	59.09
2018 (L)	0.316	71.76	0.162	57.92	0.139	49.88
2019 (L)	0.368	46.63	0.184	56.14	0.057	55.44
2020 (L)	00.353	58.25	0.211	52.58	0.088	66.49
2021 (L)	0.211	63.56	0.306	49.28	0.057	49.78
2022 (L)	0.200	58.49	0.179	55.72	0.054	59.84

¹NA = not applicable.**Table 14. CA Nitrate Proportions GT0.35 and Rainfall Data for Three Regions (2004-2022).**

Year/ Period	Z1Z2 NO3 (Prop GT 0.35 mg/L)	Z1Z2 Rain (An Mean) (in)	Z3Z4 NO3 (Prop GT 0.35 mg/L)	Z3Z4 Rain (An Mean) (in)	Z5Z6 NO3 (Prop GT 0.35 mg/L)	Z5Z Rain (An Mean) (in)
2004-2008 (E)	0.147	52.13	0.063	50.63	0.015	54.48
2009 (E)	0.250	57.54	0.077	51.34	0.036	48.50
2010 (E)	0.211	49.84	0.050	43.08	0.000	48.99
2011 (E)	0.167	36.41	0.103	49.06	0.000	54.57
2012 (Gap)	¹ NA	NA	NA	NA	NA	NA
2013 (Gap)	NA	NA	NA	NA	NA	NA
2014 Gap)	NA	NA	NA	NA	NA	NA
2015 (L)	0.250	53.21	0.105	51.19	0.061	52.27
2016 (L)	0.294	52.46	0.103	51.46	0.030	55.01
2017 (L)	00.353	69.37	0.079	53.66	0.000	59.09
2018 (L)	0.250	71.76	0.081	57.92	0.000	49.88
2019 (L)	0.300	46.63	0.083	56.14	0.031	55.44
2020 (L)	0.368	58.25	0.103	52.58	0.000	66.49
2021 (L)	0.313	63.56	0.132	49.28	0.031	49.78
2022 (L)	0.278	58.49	0.029	55.72	0.000	59.84

¹NA = not applicable.

For each of the three regions, Mann-Whitney (MW) tests were conducted to compare differences between rainfall during the E and L subperiods. Table 15 displays the results for the three regions of the state. Regarding Z1Z2, the mean rainfall in inches during the E sub-period was 48.98(Table 15a). In the L subperiod it was 59.22. The result of a MW test (“wilcox.test” function in R) was 0.073. Thus, there was an increase (weak) in rain. During E in Z3Z4, mean rainfall was 48.53 in. During L, it was 53.49 in. The result of a MW test in Z3Z4 was 0.028 (a moderate increase). In Z5Z6, rainfall in the E and L subperiods were 53.49 and 51.63 inches, respectively. However, the increase had insufficient statistical strength to consider it a step trend (p-value = 0.109).

For the next task, MW tests were used to determine if the proportion of NO3 concentrations

GT0.35 statistically changed in three regions between the two subperiods in the UA. For UA, for Z1Z2, the E and L subperiod NO₃ exceedances of the 0.35 mg/L threshold were 0.342 and 0.305, respectively. The p-value was 0.349. For Z3Z4, exceedances decreased from 0.228 to 0.197. The p-value was 0.393. In Z5Z6, the proportion of exceedance increased slightly (0.074 to 0.076). The p-value was 1.000. In each region, there was insufficient evidence of a statistical change.

For CA, for Z1Z2, the E and L subperiod NO₃ exceedances of the 0.35 mg/L threshold were 0.189 and 0.297, respectively. The p-value was 0.013, indicating a moderate increase. For Z3Z4, exceedances increased from 0.070 to 0.093. The p-value was 0.199. In Z5Z6, the proportion of exceedance increased (0.008 to 0.015). The p-value was 0.928. The proportions of exceedances increased in Z1Z2, no statistical evidence of change were observed in either Z3Z4, or Z5Z6.

Table 15. 2004-2011 vs. 2015-2022 Mann-Whitney Test Results for 2004-2011 vs. 2015-2022 Rainfall and Proportion of NO₃ Threshold Failures.

Region	Mean Rainfall 2004-2011 / 2015-2022	Rainfall p_value	UA NO ₃ Threshold Failure Proportions 2004-2011 / 2015-2022	UA NO ₃ Proportion p_value	CA NO ₃ Threshold Failure Proportions 2004-2011 / 2015-2022	CA NO ₃ Proportion p_value
Z1Z2	48.95 / 59.23	0.073	0.342 / 0.305	0.349	0.189 / 0.297	<u>0.013</u>
Z3Z4	48.53 / 53.49	<u>0.028</u>	0.228 / 0.197	0.393	0.070 / 0.093	0.199
Z5Z6	51.63 / 55.98	0.109	0.074 / 0.076	1.00	0.008 / 0.015	0.928

Visually, Figure 18 displays boxplots of mean annual rainfall in Z1Z2 (blue), in Z3Z4 (orange), and in Z5Z6 (green) during the E and L subperiods. Note that in each of the three regions, rainfall was greater in the L subperiod, compared to the E subperiod.

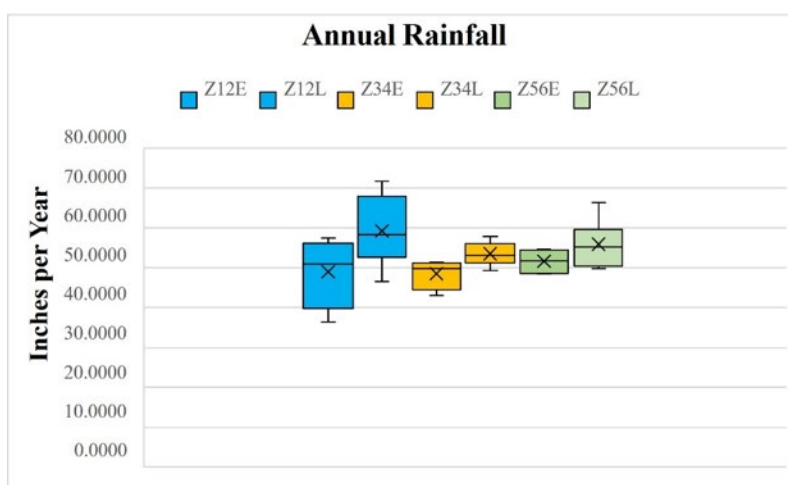


Figure 18. Boxplots of E (2004-2011) and L (2015-2022) Annual Rainfall in three Regions of Florida, Z1Z2 (blue), Z3Z4 (orange), and Z5Z6 (green). Lines within boxes represent the median value, the x within boxes represents the mean of the means.

Figure 19 shows boxplots of the proportion of NO₃ GT0.35 for Z1Z2, Z3Z4 and Z5Z6) in the UA during the E and L subperiods. The boxplots suggest NO₃ exceedances decreased during the L subperiod in Z1Z2 and in Z3Z4 but no change in Z5Z6. However, with a lack of supporting statistical evidence (Tables 15a-c), the hypothesis that increased recharge to the UA caused a dilution of NO₃ concentrations is not supported.

Figure 20 displays boxplots of the proportions of NO₃ GT0.35 in CA during the E and L subperiods in each region. Table 15 indicates that in Region Z1Z2, there exists sufficient evidence of an increase, not a decrease, in NO₃ concentrations, but not in either Z3Z4 or Z5Z6. Regarding Z1Z2, an inspection of Figures 10a and b indicates that most of the increases occurred in Zone 2 of the Z1Z2 region.

The increase of NO₃ in Z2 could easily be related to the veneer of the intermediate confining unit (ICU) overlying the Upper Floridan aquifer (UFA) in that portion of Florida. Based on data from statewide search in the FDEP Water Information System database, most CA wells tap the UFA. Across Florida, the thickness of the ICU is generally the thinnest (USGS, 2024; USGS 1997) over portions of Z1, Z2, Z3, and the northern portion of Z4 (Figure 21). This is true over a vast majority of Z2 (Figure 22). This results in the underlying UFA being either unconfined or poorly confined at best.

Figures 10a-b indicate that concentrations of NO₃ are greater in the UA than in CA. However, this is not always true in Zone 2 (e.g. the CA pulse during Period C). In this investigation, of all wells sampled across Florida during Period C, nine individual wells had NO₃ sample concentrations exceeding the 10.00 mg/L Primary Drinking Water Standard (F.A.C. Chapter 62-550.310), at least one time. Of the nine wells, seven are in Z2, where the confining unit above the FAS is generally the thinnest (Figures 21 and 22). Figure 23 shows the location of wells that exceeded the standard in Z2.

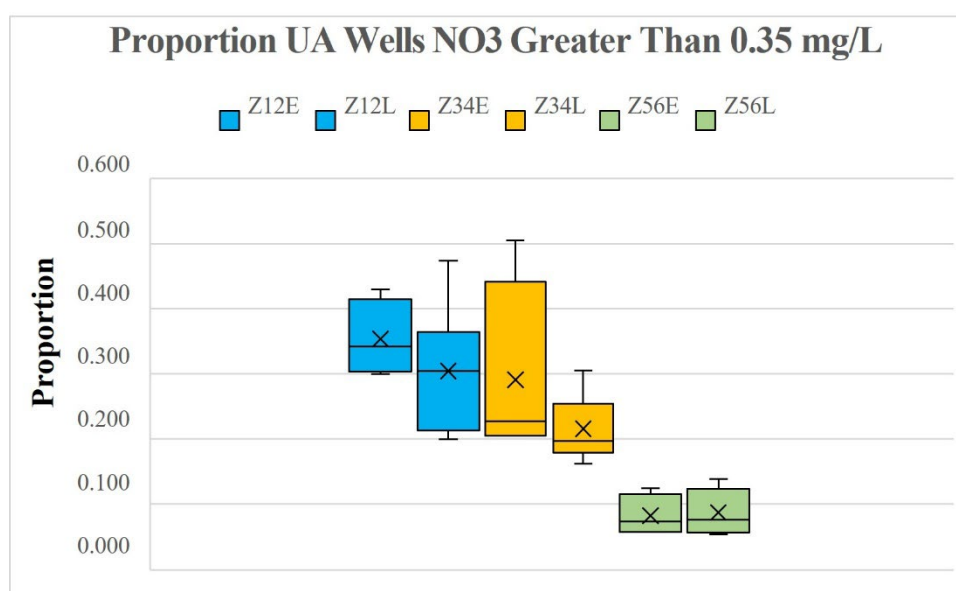


Figure 19. Comparison of UA NO₃ Proportions GT 0.35 mg/L in Regions: Z1Z2 (blue), Z3Z4 (orange), and Z5Z6 (green), during the E (2004-2011) and L (2015-2022) Sub-periods. Lines within boxes represent the median value, the x within boxes represents the mean of the means.

With the thin overlying sediments, the high NO₃ concentrations in the CA are suggestive of significant nitrogen loadings taking place at, or near, the well locations. There are several plausible explanations for the exceedances. First, UA wells were misclassified. However, each well is scrutinized prior to being classified into either the UA or CA categories by both the local water management district and the FFDEP staff. Second, nitrogen quickly finds its way downward from land surface through the relatively thin ICU sediments to the UFA (Figure 20). Third, agricultural land use in this area is intense (U.S. Department of Agriculture, 2025). Fourth, nitrogen is being transported downward, through direct pathways, such as swallets, to the FAS.

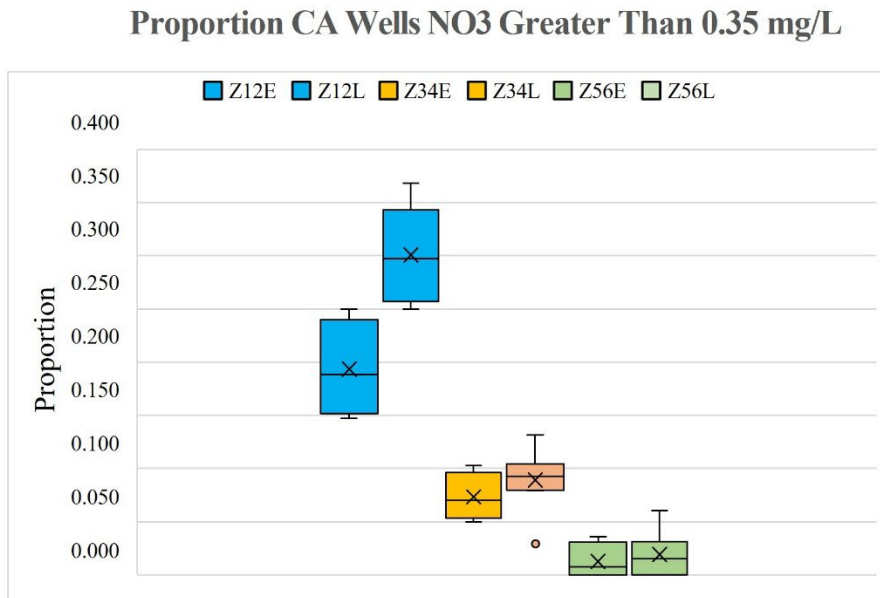


Figure 20. Comparison of CA NO₃ Proportions GT 0.35 mg/L in Regions: Z1Z2 (blue), Z3Z4 (orange), and Z5Z6 (green), During the E (2004-2011) and L (2015-2022) Sub-periods. Lines within boxes represent the median value, the x within boxes represents the mean of the means, the single small circle represents an outlier.

Regardless of the various scenarios, it appears that nitrogen loading was high at these sites within Zone 2 during the early portion of Period C. Fortunately, since 2016, NO₃ concentrations have been decreasing (Figure 16), possibly by: (1) a reduction in nitrogen loading, (2) increased rainfall/recharge and subsequent dilution in the CA, or (3) both; all of which are positive indicators of improvement.

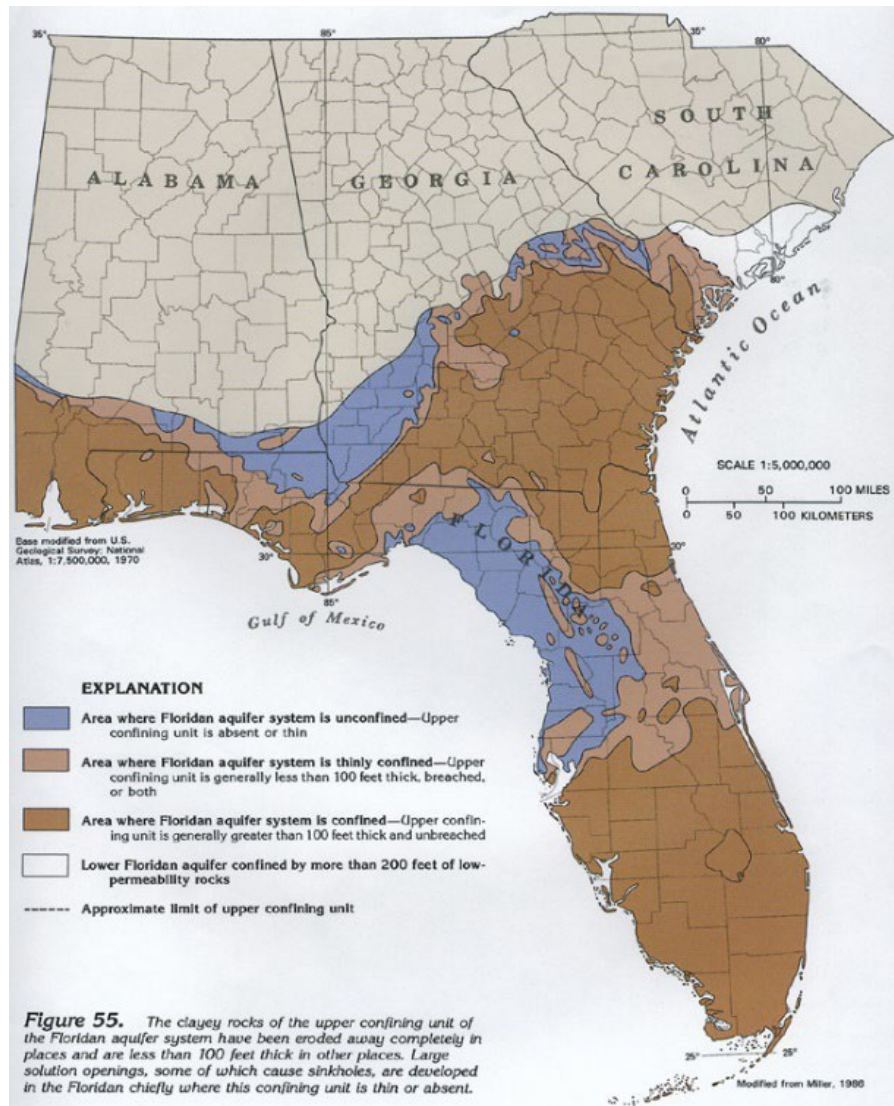


Figure 21. Intermediate Confining Unit Overlying the Floridan Aquifer System (Figure 55, Miller, 1990).

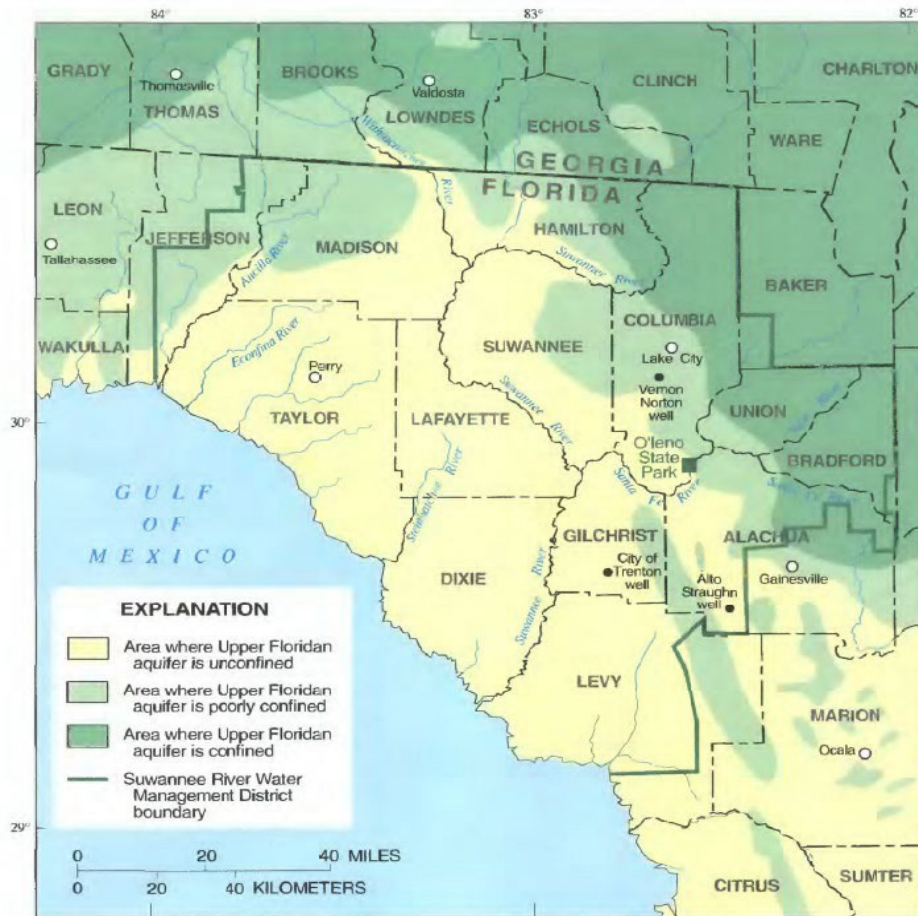


Figure 22. Portions of Z2 where the Upper Floridan aquifer is Unconfined, Poorly Confined, and Confined (Grubbs, 1997).

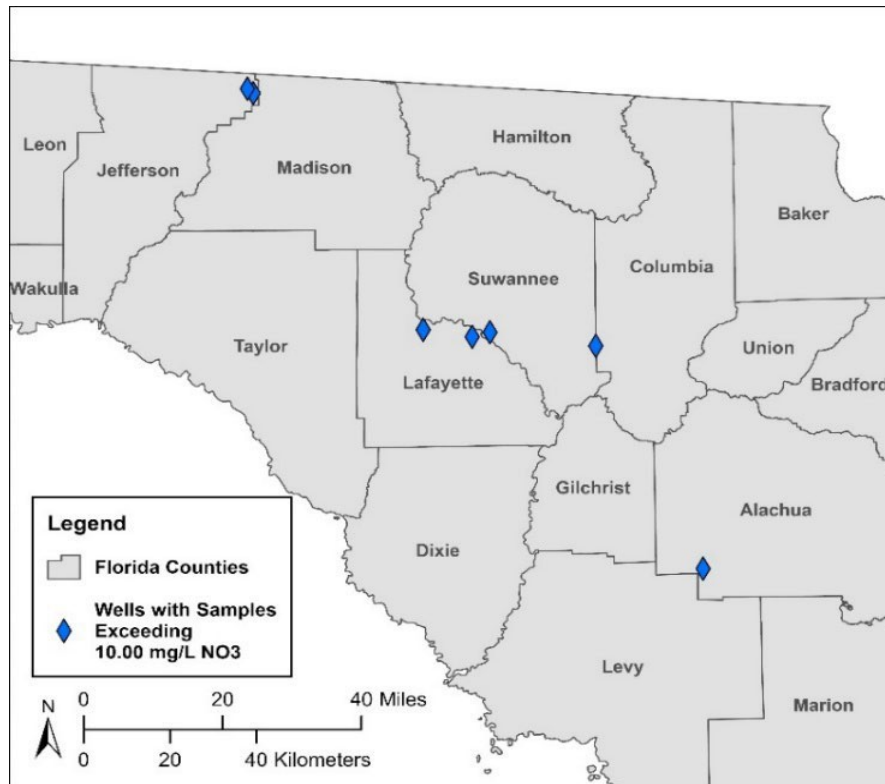


Figure 23. Location of Wells in Z2 with at least one Sample Exceeding 10.00 mg/LNO3 (2013-2022).

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Supplemental Information / Appendices

Supplemental information including the following appendices are available from the author by contacting the Watershed Monitoring Section at **850-245-8080**.

Appendix A: Data Prep, Data Analyses, and Data Qualifiers

Appendix B: R-Scripts

Appendix C: ACF and PACF Plots

Appendix D: Time-Series Plots

Appendix E: Diagnostics Results

Appendix F: Zonal Trend Data for Selected Indicators

Appendix G: Areas of State and Six Zones

Appendix H: Annual Precipitation and Air Temperature Data

Appendix I: Precipitation by Region