Trend Characterization of Lake Thunderbird

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Executive Summary

Cultural eutrophication has been an ongoing process over the last 20 years within Lake Thunderbird. In general, the nutrient stressors for algal growth have maintained elevated concentrations throughout this time. As reported in the annual water quality report for Lake Thunderbird (OWRB, 2021), both phosphorus and nitrogen remain excessively high throughout the reservoir. Though these values are typically higher in riverine zones, they are characteristic of eutrophic to hypereutrophic conditions in the reservoir's open water areas. As such, the lake is at risk for a shift towards increased and potentially more harmful algal blooms in the future. A long-term trend analysis was conducted by the Oklahoma Water Resources Board (OWRB) providing a perspective on the current condition of Lake Thunderbird. Additionally, an extensive exploratory data analysis was conducted prior to trend analysis. The bullets below highlight the key findings from the project.

- Nutrients are at excessive levels throughout the reservoir
- Chlorophyll *a* is increasing significantly in lacustrine, transition and Little River areas
- Pheophytin is increasing, indicative of continual algal die-offs in much of the reservoir
- Transparency is significantly decreasing in much of the reservoir
- Dave Blue Creek and Hog Creek Riverine zones show a significant decrease in turbidity and chlorophyll *a*

Though typically decreasing in concentration, total phosphorus demonstrates a significant downward trend only in the Little River transition zone. Although a significant decrease of a key eutrophication stressor, the estimated decrease still represents a phosphorus rich environment. Conversely, nitrogen shows a typically increasing concentration with a significant upward trend in the lacustrine zone. The detection of an increasing trend of total nitrogen in only the lacustrine zone is noteworthy. It is possible that the anoxic hypolimnion underlying the lacustrine zone could account for this characterized trend. Partitioning the cause of increasing lacustrine zone total nitrogen between longitudinal transport (from watershed runoff) and vertical transport (from the underlying hypolimnion) processes can be a significant piece toward developing a comprehensive mitigation plan.

Cultural eutrophication shows an upward trajectory over the last 20 years. Representing the main response measure for eutrophication, chlorophyll-a is significantly increasing through much of the water body. Much of the lake is hypereutrophic and all zones of the lake show exceedance of the 10 ug/L criterion for sensitive water supplies. Pheophytin-a is also significantly increasing demonstrating continual cycling of algal blooms. Likewise, as a companion response to eutrophication, Secchi disc transparency has decreased significantly through much of Lake Thunderbird.

Interestingly, Dave Blue Creek and Hog Creek riverine zones appear to be improving in water quality for several important indicators. While still hypereutrophic, chlorophyll *a* shows a significant decreasing trend in both areas. Turbidity is also significantly decreasing, improving water clarity in these areas. Although not completely revealed by the data, it would appear that suspended solids may be decreasing in these two zones. Understanding the role of land use changes within the Hog and Dave Blue Creek watersheds may provide clues for future mitigation efforts.

Finally, from the analysis, three recommendations for future work that would prove invaluable for developing effective best management practices (BMP) can be made.

1. More intensive work to determine differences and influence on eutrophication of sediment mediated release of nutrients (internal loading) and watershed delivery of nutrients (external loading) would be helpful. This knowledge is invaluable toward estimating the cost benefit of watershed and in-lake BMPs.
2. Further investigate land use trends and changes that affect nutrient and suspended solid loadings into Lake Thunderbird. A corollary to this work would be understanding the potential deleterious effects of decreasing light limitation in riverine areas of the reservoir.
3. Refinement of the long-term monitoring program to ensure data meet the needs of reservoir management. These refinements are not wholesale changes, but involve ensuring consistency in sampling frequency, laboratory detection limits, and site locations. This data analysis can assist in prioritizing both station locations and parametric coverage.

Introduction

Trend analysis of long-term datasets provides the ability to determine if water quality is improving or declining and to what magnitude. The goal of this report is to present a clear view of water quality trends within Lake Thunderbird. Work done through annual monitoring for the Central Oklahoma Master Conservancy District (COMCD) and the Beneficial Use Monitoring Program (BUMP) provides a unique opportunity to perform this type of analysis with a 20-year dataset. As part of this project, analysis was completed for both the whole lake and at various ecological zones throughout the reservoir. The question of how changes in water quality relate to reservoir dynamics and cultural eutrophication were also explored during this process.

Eutrophication is the process by which a waterbody becomes enriched with excess nutrients that over stimulate plant growth or primary production. For Lake Thunderbird most primary production is dominated by algal growth. Water quality consequences of eutrophication include fluctuating pH, low dissolved oxygen, and excessive algal growth. Cultural eutrophication is nutrient enrichments caused by anthropogenic (human) activities. Human contributed nutrients vary from parking lot runoff to animal waste. Additionally, the delivery of these nutrients is enhanced by construction activities creating impermeable surfaces. Impermeable surfaces are places where water is not able to infiltrate into the soil, increasing the velocity of runoff. The higher the runoff velocity, the more sediment and nutrients are transporting into Lake Thunderbird. Excessive algal growth can manifest as a harmful algal bloom (HAB) threatening water supplies, public recreation, and wildlife. The opposite of eutrophication, oligotrophication, is the reduction of algae growth as less nutrients are available in the water.

Cultural eutrophication is an ongoing process and concern for the COMCD. Over time water quality impairments necessitated the need for the Oklahoma Department of Environmental Quality (ODEQ) to complete a Total Maximum Daily Load (TMDL) study in 2013 that recommended a 35% reduction of nutrient inflow to meet water quality standards. The goal of implementing the Lake Thunderbird TMDL is to reduce the amount of nutrients coming into the lake, reducing availability and in turn reducing algal growth. ODEQ's TMDL fact sheet for the Lake Thunderbird TMDL provides a concise summary problem description with extensive links for further information (PRESS RELEASE (ok.gov)).

A common method of classifying lakes based on biological response to nutrients is trophic state, which indicates the amount of biological activity sustained in a waterbody at a particular time. Lakes that have high nutrient concentrations and productive plant growth are described as eutrophic, whereas low nutrient concentrations and low plant growth lakes are characterized oligotrophic (Water on the Web, 2004). Lakes that exhibit moderate levels of nutrients and plant growth are termed mesotrophic. Carlson (1977) developed the most widely used biomass based Trophic Status Index (TSI) to classify and describe lakes. The Carlson chlorophyll TSI metric has long been used by OWRB to determine lake trophic status. **Table 1** below presents the various trophic states and associated descriptions.

Table 1. Carlson's Trophic State Categories.

Trophic State	TSI Value	Description
Oligotrophic	< 40	Low primary productivity and/or low nutrient levels
Mesotrophic	41-50	Moderate primary productivity with moderate nutrient levels
Eutrophic	51-60	High primary productivity and nutrient rich
Hypereutrophic	> 60	Excessive primary productivity and excessive nutrients

This concept has been expanded over time to classify each lake into a particular trophic state based on a series of metrics. These metrics in turn are used to assess biological processes and water quality trends; comparing each metric can shed light on what drives algal growth. Chlorophyll is the most relatable TSI metric, as it is the most direct measure of algal biomass, which is the measure of primary productivity that the trophic state seeks to classify.

Presence of an anoxic (<2.0 mg/L Dissolved Oxygen) metalimnion, high nutrients, excessive algae content, and taste and odor events that extend into the winter season are all hallmarks of advanced (hypereutrophic) eutrophication. Water quality trend analyses present the opportunity to look for change of stressors (contributors) and stressor response (algal growth) measures over the COMCD's long term dataset. Results of these analyses pose the opportunity to gain insight into Lake Thunderbird's ecology. This insight can assist development of in-lake mitigation efforts as well as serve as indicators of watershed mitigation progress.

Long Term Water Quality Trend Analyses

Water Quality Parameters

To characterize the water quality trends within Lake Thunderbird, a group of parameters were selected. These water quality parameters were prioritized and selected based on data availability, longevity, consistency, and their relationship to eutrophication. **Table 2** lists the parameters selected for trend analyses and their general relationship to key water quality variables. In general, nitrogen, phosphorus, and light are key building blocks for algal growth and exercise a direct relationship, as increased availability poses the potential for increased algal growth, as measured by chlorophyll *a*. Another important benefit of conducting a trend study is the ability to show the importance of key stressors on lake biological response. As mentioned above, chlorophyll *a* is a key biological response variable and several stressors (phosphorus, nitrogen, turbidity) influence how the chlorophyll *a* response is expressed in a lake. In this section the analysis evaluated which stressors are most associated with poor biological conditions (i.e., high chlorophyll *a* concentrations) in the lake. In excess, algal nutrients are considered stressor variables due to the pressure added to the ecosystem by stimulated algal growth. Measures of algal growth are called response variables.

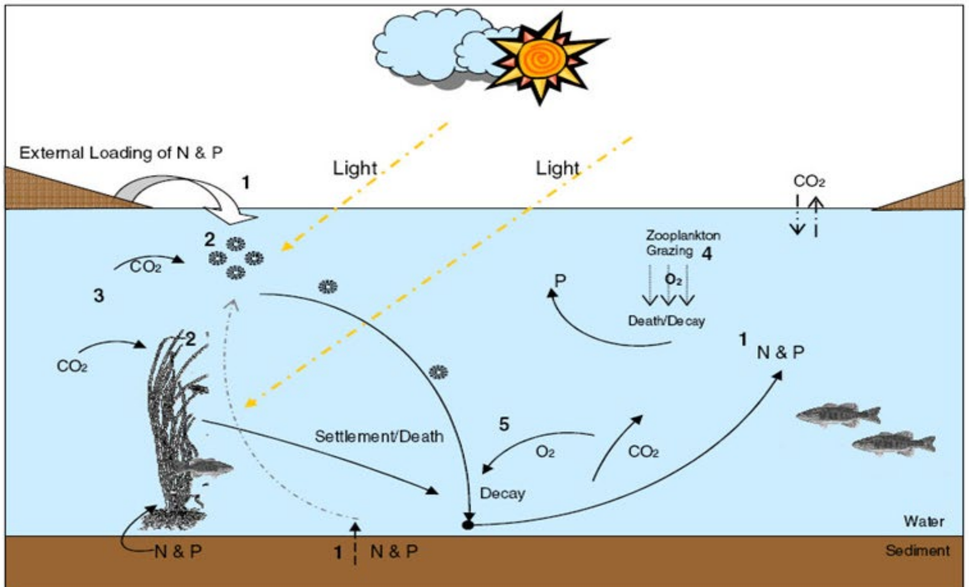
Table 2. Surface water quality variables analyzed for long term trend detection with accompanying unit of measure.

Analyzed Surface Parameters	Unit	Indicator Type
Turbidity	NTU	Eutrophication stressor and response
Secchi Disk Depth	cm	Eutrophication stressor and response
Total Alkalinity	mg/L	Watershed geology
Total Hardness	mg/L	Watershed geology
Chlorophyll *a*	µg/L	Eutrophication stressor response
Pheophytin-a	µg/L	Eutrophication stressor response
Ammonia as N	mg/L	Eutrophication stressor
Inorganic Nitrogen as N	mg/L	Eutrophication stressor
Total Nitrogen as N	mg/L	Eutrophication stressor
Total Phosphorous as P	mg/L	Eutrophication stressor

Nutrients (Phosphorus & Nitrogen)

Phosphorus and nitrogen are two essential nutrients for all aquatic life. It is a fundamental ecological process in lakes that nutrients support algal growth and algae provide the foundation for the overall lake food web. Phosphorus and nitrogen are present within waterbodies, in various organic and inorganic forms as well as dissolved and particulate forms. Phosphorus and nitrogen can come from natural sources through physical, chemical, and biological processes; but they also come from anthropogenic sources including lawn maintenance activities (synthetic fertilizer application), wastewater discharges (municipal wastewater treatment plants and faulty septic systems), industrial discharges (nitrogen fertilizer production, paper mills, and petroleum refining), and stormwater runoff.

There are several biological responses to nutrients in lakes and the graphic (**Figure 1)** below outlines the basics of nutrient cycling in lakes. The biologically available nutrients and light stimulate phytoplankton (algae) and/or macrophyte growth. As these plants grow, they provide food and habitat for other organisms such as zooplankton and fish. When these aquatic plants die, they release nutrients back into the water through decomposition. The decomposition of plant material consumes oxygen from the water column and recycled nutrients are available to stimulate additional plant growth. Physical properties include light, temperature, residence time, and wind mixing all play integral roles throughout the pathways described.



1. Nutrients (N and P) enter the lake through external loading from the surrounding watershed and internal recycling processes
2. Nutrients and light stimulate the growth of phytoplankton and macrophytes (aquatic plants)
3. Aquatic plants consume carbon dioxide and the increase the pH of the lake
4. Zooplankton (aquatic invertebrates) graze on the phytoplankton population
5. Aquatic plants break down and or die, consume oxygen as part of decomposition, and recycle ammonia, phosphorus, and carbon dioxide into the water and the sediments

Figure 1. Nutrient Cycling in Lakes (EPA, 1999).

These normal biological and chemical processes can become over stimulated by excess amounts of nutrients leading to an overabundance of plant and algal growth known as eutrophication. Eutrophication can result in several detrimental impacts to aquatic life and human health (Dorgham, 2014). For example, as the overabundance of algal growth decomposes it consumes available oxygen, which can cause oxygen concentrations to decline below the concentrations needed to sustain aquatic organisms. Persistent low dissolved oxygen concentrations in lakes can lead to the loss of habitat for fish and their food. In extreme situations this can lead to hypoxic (<4.0 mg/L DO) or anoxic (<2.0 mg/L DO) conditions causing fish kills (Horne and Goldman, 1994). Likewise, excess nutrients can lead to noxious algal scums causing drinking water taste and odor issues, as well as harmful algal blooms (HABs) (NOAA, 2018). HABs may produce toxins that can sicken people and pets recreating at lakes and contaminate drinking water sources (USEPA, 2019a, USEPA, 2019b CDC, 2017). Excessive nutrients can also lead to phytoplankton community shifts, which have cascading impacts on the overall lake food web (Havens, 2014). These impacts have considerable consequences for lake beneficial uses such as: water supply, recreational opportunities, and fisheries. Nitrogen and phosphorus pollution are among the most serious and widespread water quality challenges throughout the country, including Oklahoma (EPA, 2013).

Chlorophyll *a*

Chlorophyll *a* is the green pigment that is responsible for a plants ability to convert light energy into chemical energy. The concentration of chlorophyll *a* is used to estimate the amount of phytoplankton biomass present in the lake. Phytoplankton serve a foundational role in the lake food web as primary producers. Primary producer is a term for organisms that can utilize light to convert inorganic chemicals such as, nitrogen, phosphorus, carbon dioxide, and other minerals into living biomass (Water on the Web, 2004). Therefore, measurements of chlorophyll *a* are a useful way to estimate lake productivity. The biologic productivity of a lake, measured as chlorophyll *a*, also influences the trophic state and dissolved oxygen water quality indicators described below.

Increased lake algal productivity, measured as elevated chlorophyll *a* concentrations, can have a myriad of impacts on public water supplies including operational problems such as clogged filters, taste and odor complaints, and increased disinfection by-product formation (Jüttner & Watson, 2007, Rashash et al., 1997, Young et al., 1996, Cooke & Kennedy, 2001, Wardlaw et al., 1991). Particular algal species are known to produce musty or earthy odors that lead to taste and odor problems at drinking water treatment facilities. Many of Oklahoma's public water supply lakes are subject to nutrient pollution and elevated chlorophyll *a* concentrations; consequently, it is valuable to use chlorophyll *a* as an indicator to evaluate the condition of these lakes in the context of water supply.

Cyanobacteria are a particular group of phytoplankton that under certain conditions (e.g., excessive nutrients, warm water temperatures, and slow-moving/calm water) can rapidly multiply and produce a HAB with toxins (USEPA, 2019). The toxins produced have the potential to harm people, pets, wildlife, and livestock. Often children and dogs are most likely to be affected by HABs due to their smaller body size, increased risk of ingesting water, and tendency to stay in the water for longer periods of time (CDC, 2017). Exposure to HAB toxins in recreational waters can cause eye irritation, skin rashes, diarrhea, and cold or flu-like symptoms (CDC, 2017a). Harmful algal blooms can produce toxins, which can also pose health risk to humans through drinking water. Conventional water treatment can generally remove low levels of toxins; however, treatment facility efficacy may be tested during a severe bloom event when the toxin concentration in the lake is high (USEPA, 2019). People consuming water with HAB toxins are at risk for health affects including, vomiting and diarrhea, as well as liver and kidney damage (USEPA). The occurrence(s) of a HAB in an Oklahoma lake presents a considerable risk to recreation and drinking water beneficial uses.

As chlorophyll concentration (a measure of phytoplankton biomass) increases there is greater and greater likelihood that the phytoplankton biomass in the lake is dominated by cyanobacteria (Tetra Tech, 2018, Havens, 2014). When cyanobacteria are dominating the phytoplankton community there is a greater prospect for a HAB event when the advantageous conditions occur within the lake. Thus, excessive chlorophyll *a* concentrations can be used as a proxy for the potential presence of HAB toxins.

The process of cultural eutrophication in lakes, as described in the previous section, advances lakes toward a eutrophic or hypereutrophic condition. This is often accelerated by anthropogenic activities that introduce excess nitrogen and phosphorus into lakes.

Turbidity

Turbidity is a measure of lake water clarity and relates to erosion and sedimentation. The greater the amount of total suspended solids in the water, the less clear the water will be, and the higher measured turbidity. Suspended solids that contribute to lake turbidity include silt, clay, algae, plankton, and organic matter. Increased turbidity affects lakes in a myriad of ways. For example, the suspended particles absorb more heat, which can raise water temperature and reduce the dissolved oxygen concentration. This happens because of the water's oxygen saturation threshold being lower when water is warmer (Water on Web, 2004). Turbidity also influences lake algal growth by limiting the amount of light penetration into the water column to stimulate growth. Aquatic life is impacted by increased turbidity, as particles of silt, clay, and/or organic material settle to the lake bottom can suffocate larvae and fill in areas around rocks that serve as benthic habitat (Water on Web, 2004). Moreover, as the suspended solids settle to the lake bottom, the lake capacity decreases and can limit water supply availability. Finally, high turbidity can also negatively impact the aesthetic and recreational qualities of lakes.

Interpretation of the nitrogen and phosphorus water quality parameters are in the context of stressor variables or impact toward algal growth. For example, it is the inorganic component of nitrogen and phosphorus that serves as the macronutrient for algal growth. Chlorophyll *a* and pheophytin-a, both algal photopigments, are response variables and represent living (chlorophyll *a*) and dying (pheophytin-a) algal cells. Turbidity and Secchi disk depth are measures of water transparency and represent stressor or response variables. Turbidity is used as a measure of suspended solids, such as clay and silt and is related to the water quality standard criterion of fish and wildlife propagation. When suspended solids cause high turbidity and low Secchi disk depth, these water quality measures are stressor variables. If these measures of light transparency are due to high algae content, then they function as water quality response variables. Alkalinity and hardness are indicative of the geologic features within the watershed. Consequently, variation of these measures usually reflects natural climatic variation over time.

Exploratory Data Analysis

Prior to beginning trend analysis, it is important to understand certain characteristics of water quality data in Lake Thunderbird. Exploratory data analysis (EDA) can answer important questions and provide information useful for decision making. The EDA helps to understand the extent of available data and the shape and distribution of the dataset. Additionally, exploratory analysis reveals important spatial variation in the dataset. A truncated or cursory exploration of data may lead to false conclusions about both magnitude and extent of trends. For example, not recognizing spatial variation may lead to important trends being muted in certain parts of the waterbody. A more detailed analysis is presented Appendix A of this report. The EDA for this project was designed to answer three specific questions.

1. Is the dataset suitable for trends analysis?
2. Does dataset shape and distribution affect the choice of analytical method?
3. What affect does spatial variation have on analysis?

A necessary initial question is how robust the dataset is for trends analysis. This is answered best by looking at both the length of the dataset period of record and the timestep of collection. For adequate trend analysis, a dataset should incorporate both hydrologic and climatologic variation. Certain environmental co-factors, such as watershed flows, lake level, temperature, rainfall, and evapotranspiration, may vary dramatically from year to year and over decadal and semi-decadal windows.

For flowing water, a minimum period of record could be as little as 5-10 years. However, because residence time in lentic waters is much higher, the effect of environmental factors may be incorporated over a much longer period. Typically, a minimum period of record of 10-15 years is desirable for lentic waters. Likewise, timestep may have an influence on the completeness of the dataset and lead to bias in decision-making. Timestep is indicative of the length between individual data collections during period of sampling. For example, a bi-annual timestep would mean that data were collected every other calendar or seasonal year. For lakes, an annual time step is optimal, but larger bi-annual or tri-annual timesteps can be explored for use. Timesteps that go beyond 2-3 years may mute the effects of the environmental co-factors discussed above and lead to biased analysis.

Second, it is important to choose an appropriate analytical method. As with most statistical tests, the assumptions of normal distribution, equal variance, and independent data are tested to determine if a parametric test such as linear regression or a non-parametric test such as a Mann-Kendall are appropriate for the dataset. Several simple methods exist to test these assumptions, most importantly that a dataset is derived from a normal distribution. A standard normal distribution is simply a symmetrically continuous distribution of data and is best represented by what is commonly known as a bell-shaped curve. The mean and median are equal at the center of the dataset with symmetrical tails of the data gradually and continuously approaching zero. Data that approximates this distribution is considered normally distributed. Hypothesis testing is the most direct way to test data normality. For example, the Anderson-Darling normality test assumes the null hypothesis of a normal distribution, and failure of the test is a good indication that data are not normally distributed. Additionally, visualizing the shape of the dataset is a useful method of understanding how data may be abnormally distributed. For example, is the data skewed to the right or the left? How does horizontal shape of the data relate to the vertical shape (i.e., kurtosis)? These concepts are discussed more fully in Appendix A.

Finally, it is important to understand how data varies across the lake. Is whole lake analysis appropriate or should the lake be divided into ecological, or limnological, zones for analysis? Is there complicating variability in certain areas of the lake? Lake Thunderbird can be divided into several ecological zones based upon the open water and riverine areas of the reservoir. The two largest riverine areas in Thunderbird are inflows from the Little River and Hog Creek. Open water areas include the lacustrine zone and transition areas that separate the riverine and dam area. Investigating variation both within (intra-zone) and between (inter-zone) these areas determine the best approach to trend analysis. For inter-zone variation, this analysis can be done visually by exploring side by side comparison of boxplots or time series data. More so, statistical analysis of variation between zone data means and medians can provide statistical certainty about what visually appears as significant variation. Intra-zone variation is best explored by noting the occurrence of outliers and by looking at the highness or flatness of the peak of the distribution using interquartile ranges (IQR) or histograms for visualization. Comparison of the data mean, and median is also useful, which can elucidate exaggerated skewness in the dataset.

The EDA explored four groups of data, including geochemical (i.e., watershed indicators), water transparency and clarity, nutrients, and nutrient response. Watershed indicator data, including hardness and alkalinity, are affected by geology and soil types, and broad variation can signal lake instability, affecting regulation of pH and lake hardness in a drinking water supply. Water transparency and clarity are explored using Secchi depth and turbidity data. These data provide information about both eutrophication and sediment delivery to the reservoir. Finally, the effect of nutrient inflow and internal nutrient cycling are directly explored using both stressor variables (total nitrogen and total phosphorus) and response variables (chlorophyll *a* and pheophytin). Each of these variables are analyzed more fully in **Appendix A – Detailed Exploratory Data Analysis.**

From these analyses, several conclusions may be made about the Lake Thunderbird dataset (See Appendix A for full analyses). First, the dataset is generally large enough both in time and variability across the lake to provide a robust look at data trends. Data have been collected for over twenty years on a yearly timestep. In areas, such as Dave Blue Creek, where data collections have been sparser, trends may not be calculated for some parameters. Second, except for watershed indicator data, all other data types are not normally distributed and are significantly skewed with mostly excessive positive and occasional negative skewness, depending on the area of the lake. Regardless of other assumptions of linear regression, these attributes alone require the use of the Mann-Kendall or Seasonal Kendall statistical test to explore trends in Lake Thunderbird. Fortunately, this is not an atypical situation with water quality data and is expected. Lastly, significant inter-zone variation exists across the open water and riverine zones of the reservoir. Secchi depth and turbidity are significantly variable throughout the reservoir. Nutrient stressor and response variables, while not significantly different in open water areas, vary significantly from riverine to open water areas. Trend analysis within different zones and not on a whole lake basis is necessary to fully explore water quality trends in Lake Thunderbird. Additionally, some notable intra-zone variation does occur. This is likely caused by seasonal effects on the data. The use of Seasonal Kendall test statistic will help to account for and attenuate these effects.

Statistical Tests and Trend Characterization

As stated previously, the primary goal of this project is to provide an analysis of water quality trends within Lake Thunderbird. Statistically based trends give the user a unique perspective of water quality over time. Monotonic trends simply analyze whether a dependent variable (e.g., chlorophyll *a*) changes in a consistent direction over time. They not only indicate whether water quality is improving or declining, but also elucidate the magnitude of that change. Additionally, these analyses characterize the level of confidence in the analysis (Helsel & Hirsch, 1993).

For this analysis, reservoir trend detection was determined using a Seasonal Kendall Test within the Sanitas™ Statistical Software package (Campbell 2020). As a non-parametric test, the Mann Kendall is useful for environmental data because a normal data distribution and equal variance are not assumed. The test is also not adversely affected by missing data or data estimated as below a reporting limit. However, assumptions of data independence and that sample data represent the underlying population are assumed. The Seasonal Kendall is a version of the Mann Kendall that accounts for affects in data distribution that are related to seasonality. The test determines trend significance using a z-statistic and calculates an estimated Sen Slope that provides both a magnitude and direction. Seasons are determined by the user and quarterly seasons were set for this analysis following the calendar year: Jan-Mar, Apr-Jun, July-Sept, Oct-Dec.

The analyses also characterize a level of confidence. Inherent biases are introduced in water quality sampling because samples are not collected continuously and a variety of factors influence a result at any point in time, including weather, reservoir dynamics, and diurnal cycling. Data can be normalized by using data transformation and other methods to adjust for seasonality or hydrologic dynamics. However, these methods only give a more "usable" dataset, but do not speak to confidence in analytical outcomes. The statistical confidence level indicates the probability that the outcome would occur in the population through multiple iterations of sampling over the same period. Significance at a 99% confidence level as opposed to 90%, indicates a higher likelihood that the demonstrated trend is occurring. Confidence level and associated likelihood of a trend are shown in **Table 3**.

Table 3. Detected confidence level and assigned likelihood thresholds using the Seasonal Kendall test statistic

Confidence Level	Trend Likelihood
<80%	Unlikely
80% to <90%	Indeterminant
90% to <95%	Likely
95% to <99%	Very Likely
99% and greater	Highly Likely

Data Aggregation for Trend Analyses

The gradients of environmental factors along a reservoir's length define ecological zones. **Figure 2** illustrates the three ecological zones commonly formed in reservoirs: the lacustrine, transition, and riverine zones.

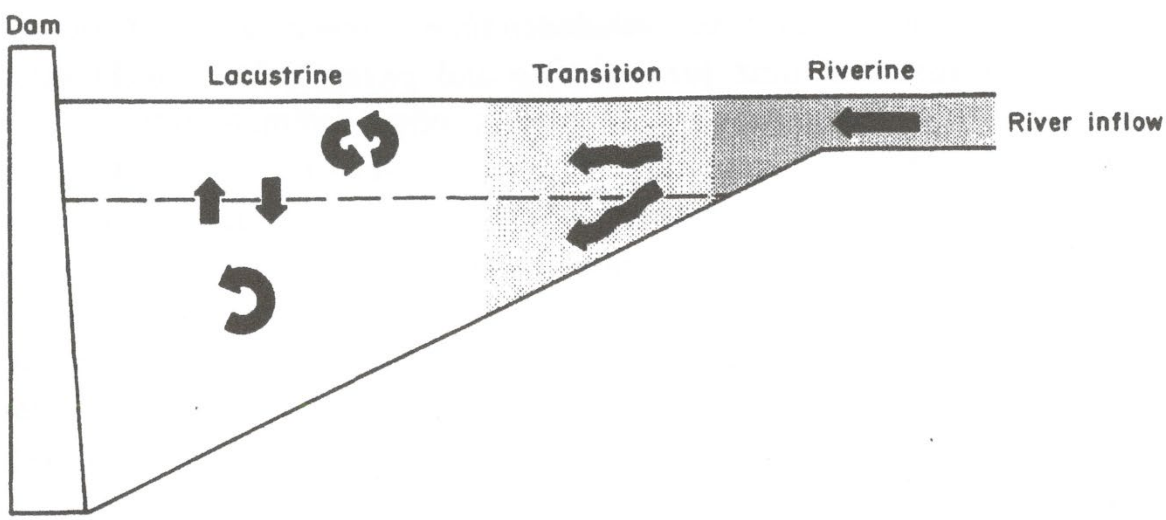


Figure 2. Illustration of common ecological zones formed within a reservoir due to longitudinal gradients (Thornton 1991). Taken from Reservoir Limnology: Ecological Perspectives.

The lacustrine zone represents open water habitat and is characterized by low water velocity, seasonal vertical stratification, higher light penetration, mostly organic suspended solids, lower nutrient content, and usually lower algal growth. The riverine zone is the upper area of the lake characterized by higher flow velocity, higher nutrient content, low light penetration, mostly inorganic suspended solids, and relatively low algal growth. Finally, the transition zone represents the section of change between the lacustrine and riverine zones: where vertical stratification starts, and inflowing water slows down. These physical traits result in settling inorganic solids, higher light penetration, higher algal growth, and lower nutrient concentration than the riverine zone.

Over the last 20 years, COMCD water quality monitoring sampling locations have changed at Lake Thunderbird. This reflects the ongoing compromise or balance between informational value and budgetary constraints. In 2000, monitoring focus was the surface of the lake main body and the impact of a point source diffuser placed on the reservoir bottom off the dam. Sample sites, frequency, and laboratory parameters were minimized to the open water area. The ODEQ's TMDL study required more intensive information across the length and depth of Lake Thunderbird (**ODEQ 2013**). The TMDL report highlighted the value of collecting data in the upper arms of the Dave Blue Creek and Hog Creek arms to capture what input to the lake and as such these sites (8 and 11) were permanently set into the monitoring plan. **Figure 3** represents the current water quality sample sites of Lake Thunderbird (**OWRB 2019**).

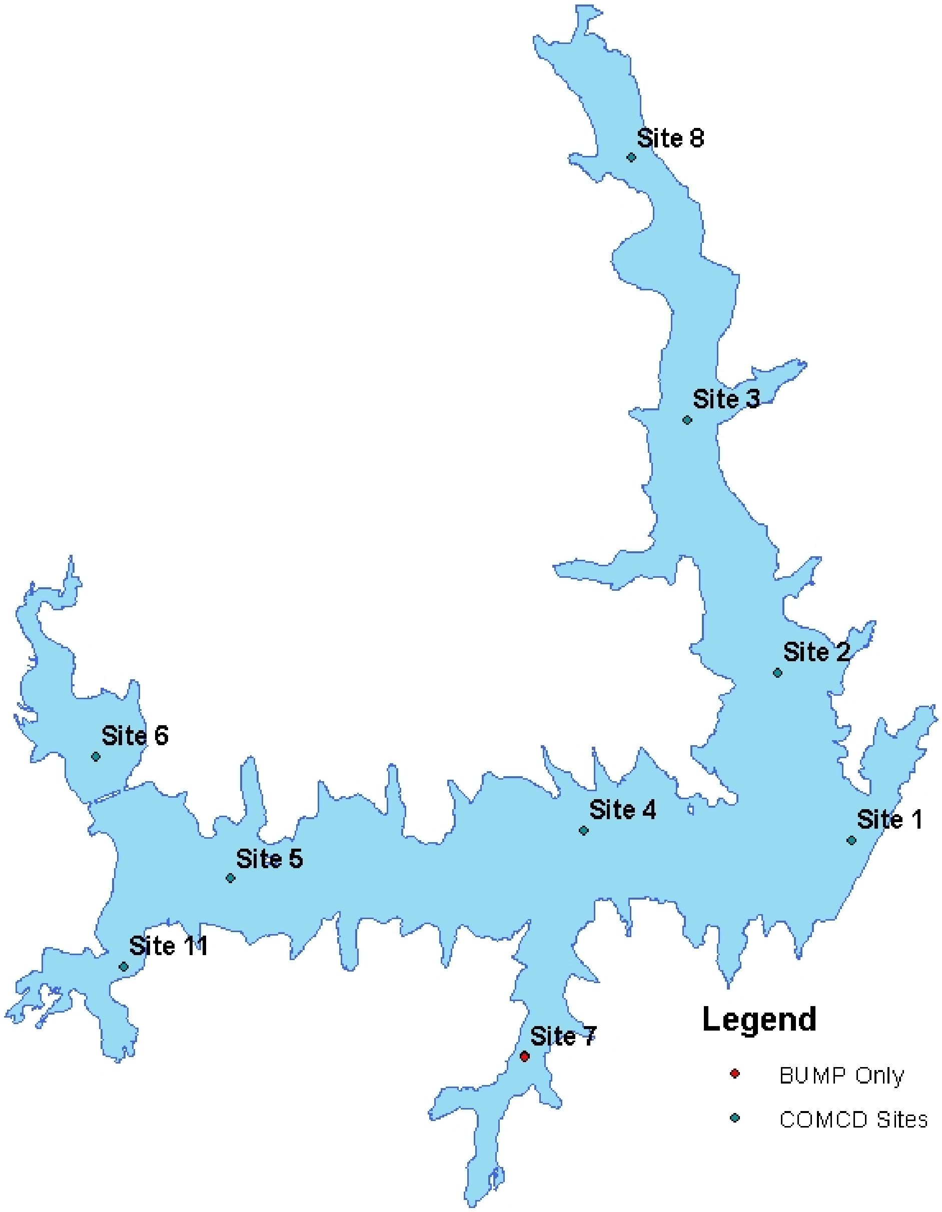


Figure 3. Water quality monitoring sample sites utilized for trend analyses. Sample sites are segregated by monitoring program: Beneficial Use Monitoring Program (BUMP) and COMCD.

Because the primary concern for Lake Thunderbird is ecological in nature, long-term trend analyses consolidated or segregated between the various ecological zones before statistical analyses. An assignment between zones was made based on site location and physical characteristics. The uppermost portion of an arm (sites 6, 7, 8 and 11) as riverine zones. Similarly, sites showing that are vertically stratified throughout the summer season (sites 1, 2 and 4) are initially assigned as lacustrine. Finally, the remaining sites (3 and 5) are assigned as transition zones. **Table 4** represents the assignment of water quality sample sites into ecological zones.

Table 4. Initial ecological zone assignments of Lake Thunderbird water quality sample sites.

Name	Monitoring Location ID	Ecological Zone Assignment
Site 1	520810000020-01	Lacustrine
Site 2	520810000020-02	Lacustrine
Site 3	520810000020-03	Hog Creek Transition
Site 4	520810000020-04	Lacustrine
Site 5	520810000020-05	Little River Transition
Site 6	520810000020-06	Little River Transition
Site 7	520810000020-07	Little River Transition
Site 8	520810000020-08	Hog Creek Riverine
Site 11	520810000020-011	Dave Blue Creek Riverine

Ecological zone assignments were evaluated statistically to suggest modifications from the aggregations. Water transparency measured by turbidity and Secchi disk depth were chosen to statistically evaluate site aggregation. These two measures encompass the inorganic (stressor) and organic (stressor response) suspended solids within the water and clearly follow the longitudinal gradients within Lake Thunderbird. An of analysis of variance (ANOVA) was used to determine where significant differences occur in parametric means between ecological zones. Where significant differences occur, the Fisher's Least Significant Difference (LSD) test was employed to make pairwise comparisons between all zones, allowing for differentiation of significantly different zones. This was applied to each water quality parameter to finalize site aggregation into ecological zones. A simple summary of the test result presents a table using letters to indicate which sites are related and which are statistically different.

The longitudinal gradient for turbidity is shown by the box and whisker plot in Figure 4. The higher turbidities seen at site 6 and Site 11 illustrate higher inorganic suspended solids within the riverine zones relative to the open water sites where flow slows down, and solids settle out of the water column. Pairwise comparisons of turbidity data were made to evaluate initial zone assignments (**Table 4)**. These results indicate a clear separation of the riverine sites (groupings A, B and C) with overlap between all other (transition zone and lacustrine) sites. To check the initial site aggregation scheme, data were evaluated following the proposed site aggregation (**Table 5**).

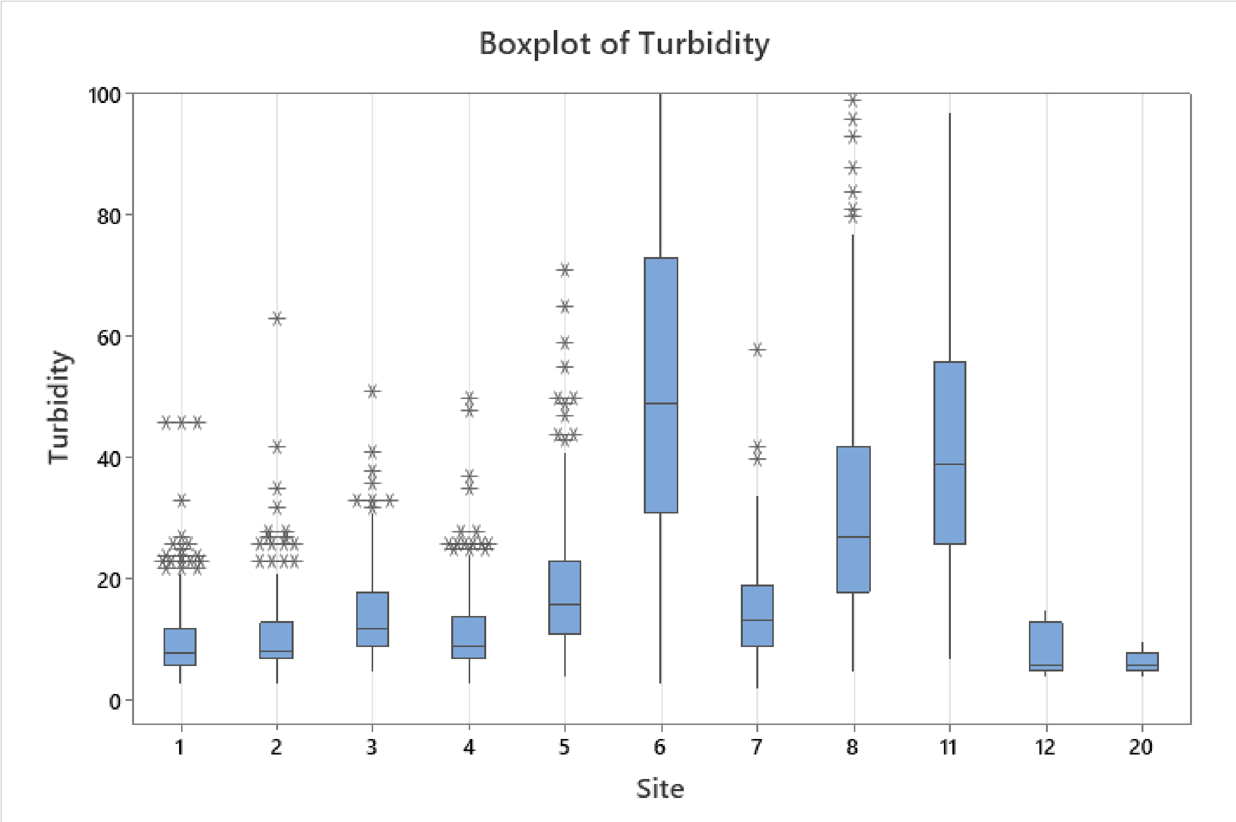


Figure 4. Box and whisker plot of Lake Thunderbird turbidity (2000 - 2020) indicating the potential to detect longitudinal gradients. Each box encompasses the middle 50% of the data distribution, the middle line indicates the median, whiskers indicate the top and bottom 25% of the data and asterisks statistical outliers. Note: the scale has been reduced to 100 NTU from 600 (Site 6 maximum report) for ease of site comparison.

Table 5. Site grouping information using Fisher's LSD and 95% confidence for the Lake Thunderbird turbidity (NTU) long-term (2000 - 2020) dataset. Sites not sharing letters are statistically separate from the others. Sites sharing a box outline suggest data aggregation can be statistically justified.

Site	N	Mean	Grouping					
6	263	63.3	A					
11	123	46.0		B				
8	143	32.7			C			
5	264	19.1				D		
7	139	15.5				D	E	
3	263	14.3					E	
4	268	11.3					E	F
2	266	10.8					E	F
1	342	10.0						F

**Means that do not share a letter are significantly different .*

Pairwise comparisons of Lake Thunderbird turbidity data clearly suggest treating each riverine zone separately and maintaining lacustrine zone site assignments. Additionally, the test suggests the two transition zones (site 3 and 5) are similar. The turbidity box and whisker plot following initial ecological zones assignment illustrates a greater separation by assigned zone than by site (**Figure 4**).

Table 6. Grouping information using Fisher's LSD and 95% confidence for Lake Thunderbird turbidity (NTU) long-term (2000 - 2020) dataset. Zones not sharing letters are statistically separate from the others. Sites within the same box are data aggregations that can be statistically justified.

Monitoring Location ID	N	Mean	Grouping				
Little River Riverine	263	63.31	A				
Dave Blue Creek Riverine	123	45.97		B			
Hog Creek Riverine	143	32.74			C		
Little River Transition	403	17.86				D	
Hog Creek Transition	263	14.32				D	
Lacustrine	896	10.54					E
**Means that do not share a letter are significantly different .*							

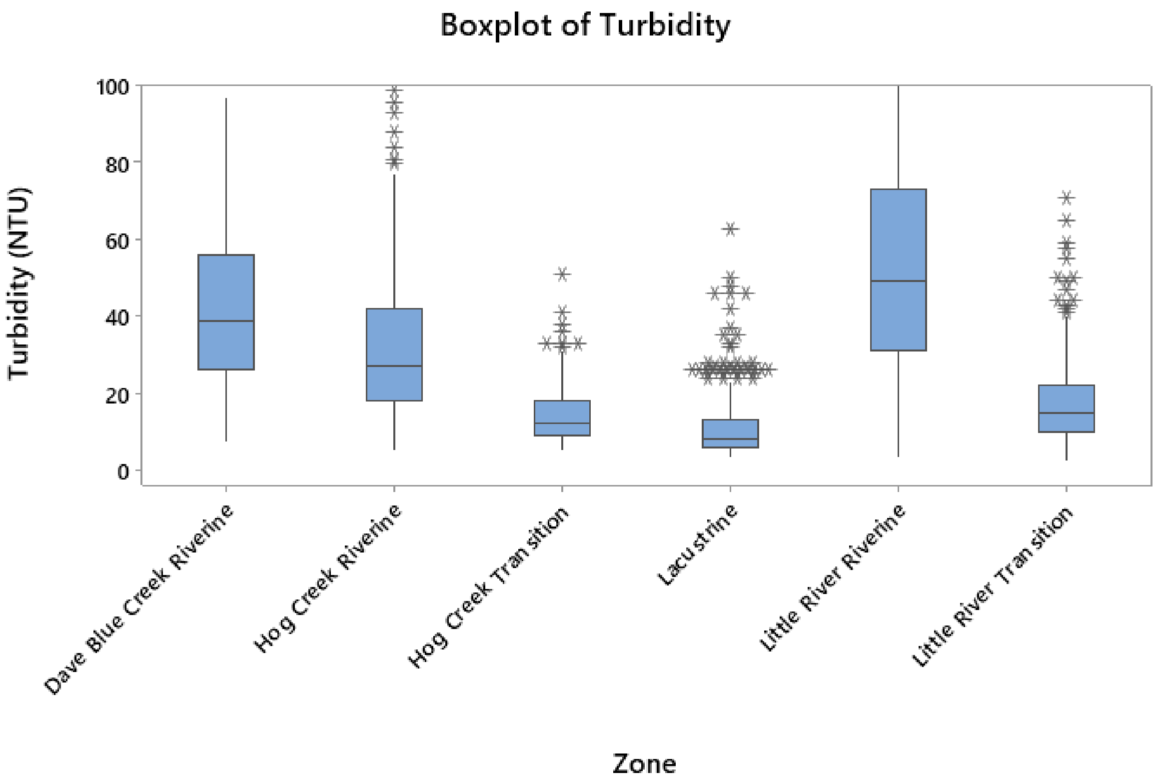


Figure 5. Box and whisker plot of Lake Thunderbird turbidity (2000 - 2020) following applying initial ecological zone site aggregation. Each box encompasses the middle 50% of the data distribution, the middle line indicates the median, whiskers indicate the top and bottom 25% of the data and asterisks statistical outliers. Note: the scale has been reduced to 100 NTU from 600 (Little River Riverine maximum report) for ease of site comparison.

The same statistical procedure to evaluate initial ecological zone assignment was performed on Secchi disk depth. The Secchi disk depth box and whisker plot by site in **Figure 6** indicate the potential for longitudinal gradients across Lake Thunderbird. Pairwise comparisons were used to evaluate data segregated by site (**Table 6)**. This test indicated Secchi disk depth sample sites can be aggregated into four separate groups. Of note is groupings A and B encompass the initial assignments for lacustrine zone. Differences in the outcome from the turbidity analyses were noted with less separation of riverine sites and some separation of transition sites. Pairwise comparisons were made on aggregated Secchi disk depth data (**Table 7)** using the initial ecological zone assignment scheme presented in **Table 4**

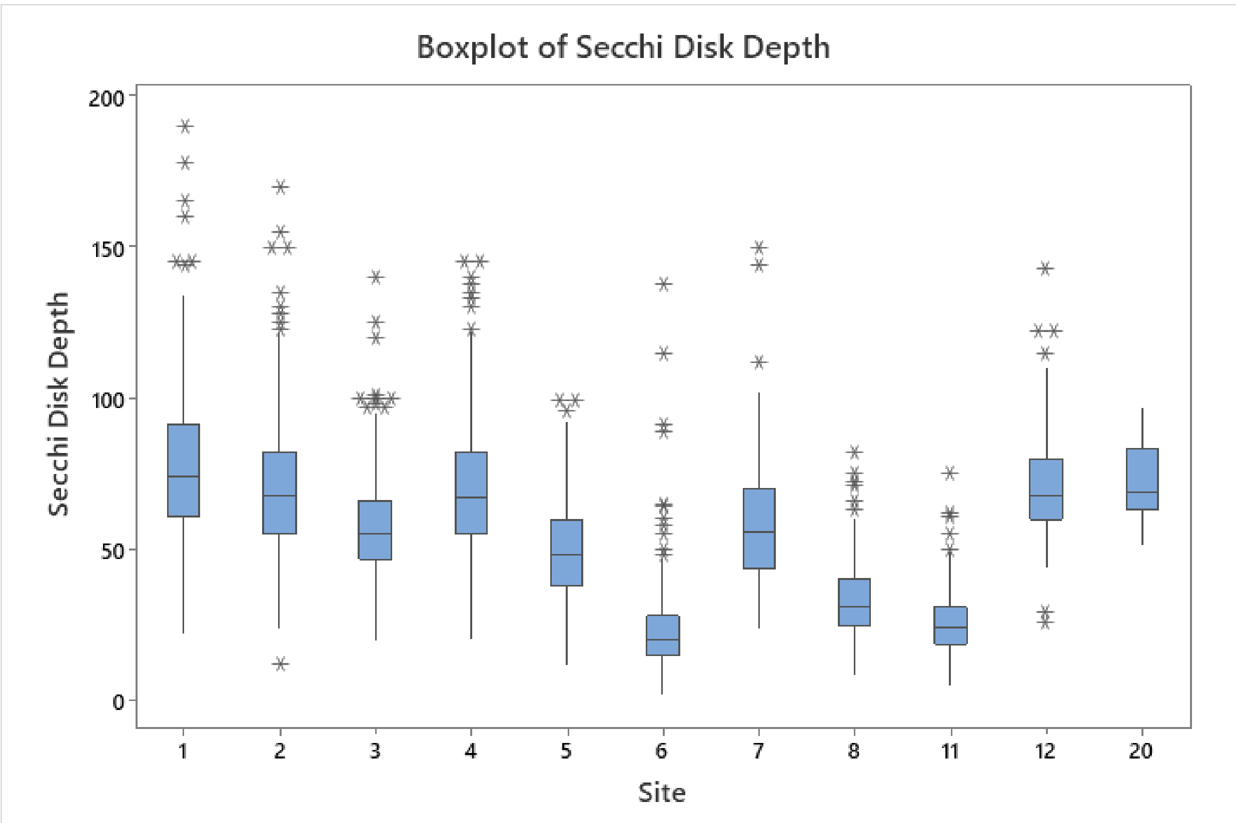


Figure 6. Box and whisker plot of Lake Thunderbird Secchi disk depth (2000 - 2020) indicating the potential to detect longitudinal gradients. Each box encompasses the middle 50% of the data distribution, the middle line indicates the median, whiskers indicate the top and bottom 25% of the data and asterisks statistical outliers.

Table 7. Grouping information using Fisher's LSD and 95% confidence for Lake Thunderbird Secchi disk depth(cm) long-term (2000 - 2020) dataset. Sites not sharing letters are statistically separate from the others. Sites within the same box are data aggregations that can be statistically justified

Site	N	Mean	Grouping					
1	287	77.7	A					
2	268	70.6		B				
4	269	70.3		B				
7	136	58.3			C			
3	266	57.8			C			
5	265	49.9				D		
8	144	33.3					E	
11	126	25.7						F
6	263	23.3						F

**Means that do not share a letter are significantly different.*

Table 8. Grouping information using Fisher's LSD and 95% confidence for Lake Thunderbird Secchi disk depth (cm) long-term (2000 - 2020) dataset. Zones not sharing letters are statistically separate from the others. Boxed ecological zone assignment indicates statistical significance from other zones.

Monitoring Location ID	N	Mean	Grouping				
Lacustrine	880	72.92	A				
Hog Creek Transition	266	57.84		B			
Little River Transition	401	52.70			C		
Hog Creek Riverine	144	33.25				D	
Dave Blue Creek Riverine	126	25.67					E
Little River Riverine	263	23.34					E

**Means that do not share a letter are significantly different.*

Pairwise comparisons applied to Lake Thunderbird turbidity ecological zone assignment clearly suggests treating each transition zone, lacustrine zone, and Hog Creek riverine zone separately and suggests the two riverine zones (site 6 and 8) may be similar. The Secchi disk depth box and whisker plot following initial ecological zones assignment illustrates a greater separation by assigned zone rather than just by site (**Figure 6).**

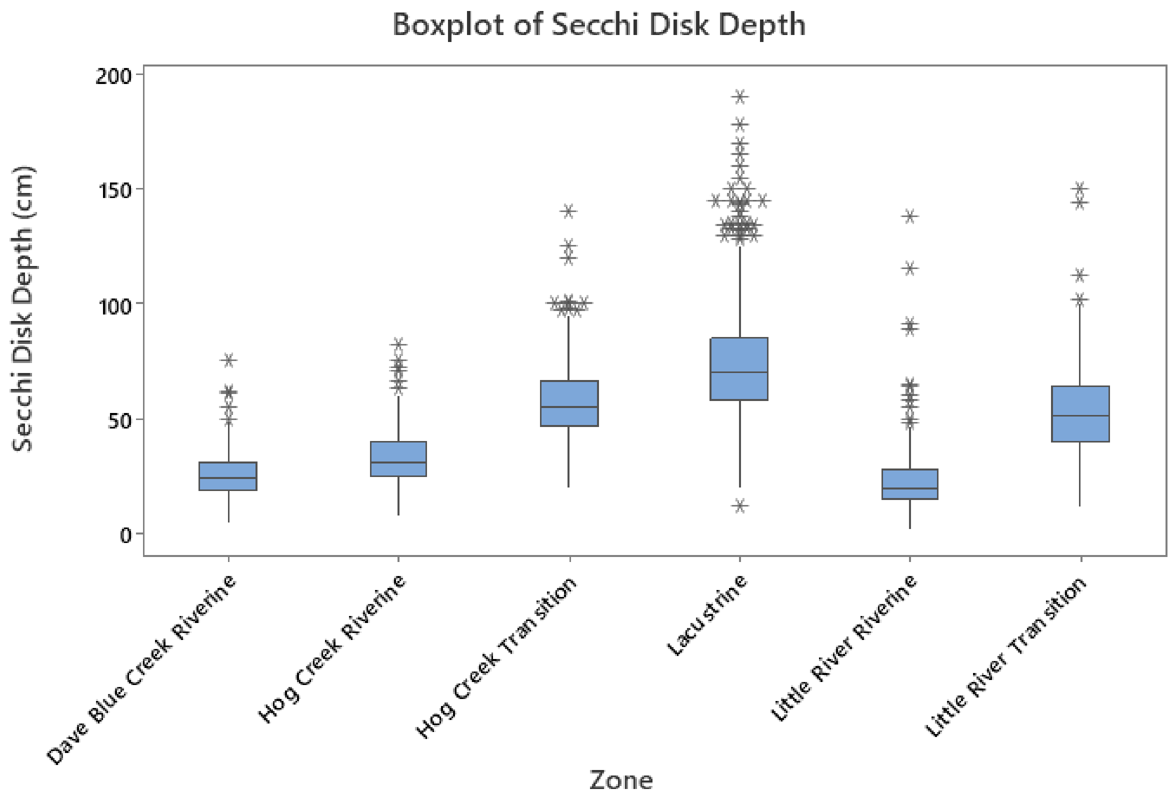


Figure 7. Box and whisker plot of Lake Thunderbird Secchi disk depth (2000 - 2020) following initial ecological zone site aggregation. Each box encompasses the middle 50% of the data distribution, the middle line indicates the median, whiskers indicate the top and bottom 25% of the data and asterisks statistical outliers.

Data Aggregation Summary

Both measures of water transparency showed longitudinal gradients within Lake Thunderbird and supported different reasons for moving from sites to ecological zones. Pairwise comparisons of turbidity data showed a clear statistical signal to treat each of the three riverine zones individually and to keep the lacustrine zone site assignments. Using Secchi disk depth, a clear statistical signal was shown to treat each transition zone individually and keep the lacustrine zone site assignment. Using a weighted evidence approach, pairwise comparison testing supports the concept of aggregating sample sites into ecological zones. Long term trend analyses will follow the ecological zone aggregation scheme presented in **Table** 4.

Lake Thunderbird Ecological Zone Trend Characterization (Results)

Each zone of Lake Thunderbird has been characterized as changing over time. Information is broken into the three zones: lacustrine, transition, and riverine. Only trends characterized at or above the 90% confidence level are discussed. A copy of **Table 3** shows the relationship between statistical confidence level and trend characterization by likelihood for ease of reference (**Table 9**).

Table 9. Representation of trend characterization based on statistical confidence level.

Confidence Level	Trend Likelihood
<80%	Unlikely
80% to <90%	Indeterminant
90% to <95%	Likely
95% to <99%	Very Likely
99% and greater	Highly Likely

Lacustrine Zone (Sites 1, 2, and 4)

Table 10 provides a summary of lacustrine zone trend characterization performed in Lake Thunderbird. The lacustrine zone represents the lake section experiencing seasonal stratification. Based on the data aggregation, sites 1,2 and 4 represent the lacustrine zone.

Table 10. Summary of trend characterization of Lake Thunderbird lacustrine ecological sites.

Constituent	Ecological Zone	Rate (unit/yr.)	Total	Duration (yr.)	Confidence Level	Likelihood	n	Start Date	End Date
Alkalinity, total (mg/l)	Lacustrine	↑ 0.1716	3.48	20.3	80%	Indeterminant	151	4/27/2000	12/8/2020
Total hardness (mg/l)	Lacustrine	↑ 0.4632	6.19	13.4	<80%	Unlikely to increase	28	10/10/2006	02-18-2020
Turbidity (NTU)	Lacustrine	↓ -0.0241	-0.46	19.3	<80%	Unlikely to decrease	263	11-02-2000	02-18-2020
Depth, Secchi disk depth (cm)	Lacustrine	↓ -0.6316	-13.03	20.6	99%	Highly Likely to decrease	265	04-27-2000	12-08-2020
Chlorophyll *a*, corrected (mg/m^3)	Lacustrine	↑ 0.4458	9.20	20.6	99%	Highly Likely to increase	261	04-27-2000	12-08-2020
Pheophytin-a (mg/m^3)	Lacustrine	↑ 0.1217	2.51	20.6	99%	Highly Likely to increase	249	04-27-2000	12-08-2020
Inorganic nitrogen (mg/l)	Lacustrine	0	0.000	20.5	<80%	Unlikely to increase	212	04-27-2000	10-14-2020
Kjeldahl nitrogen (mg/l)	Lacustrine	↑ 0.0029	0.059	20.5	85%	Indeterminant	210	04-27-2000	10-14-2020
Total nitrogen (mg/l)	Lacustrine	↑ 0.006	0.13	20.5	99%	Highly Likely to increase	210	04-27-2000	10-14-2020
Phosphorus (mg/l)	Lacustrine	↓ -0.0001	-0.0015	20.5	<80%	Unlikely to decrease	212	04-27-2000	10-14-2020

All water quality parameters within the lacustrine zone were characterized highly likely to change. Chlorophyll *a* and pheophytin-a increased (**Figure 8 and 9**) and Secchi disk depth decreased (**Figure 10**).

One stressor, total nitrogen, was characterized highly likely (99% confidence level) to have increased (**Figure 11**).

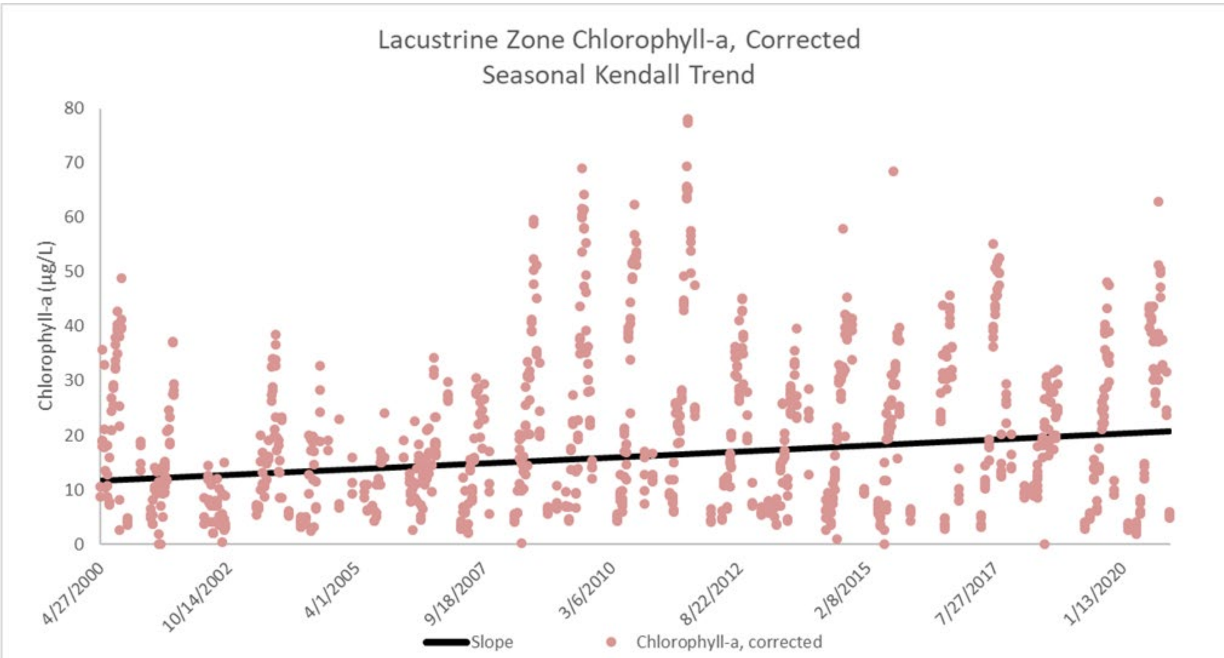


Figure 8. Graphic shows period of record chlorophyll *a* data for Lake Thunderbird lacustrine zone with a fitted trend line adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely increasing trend.

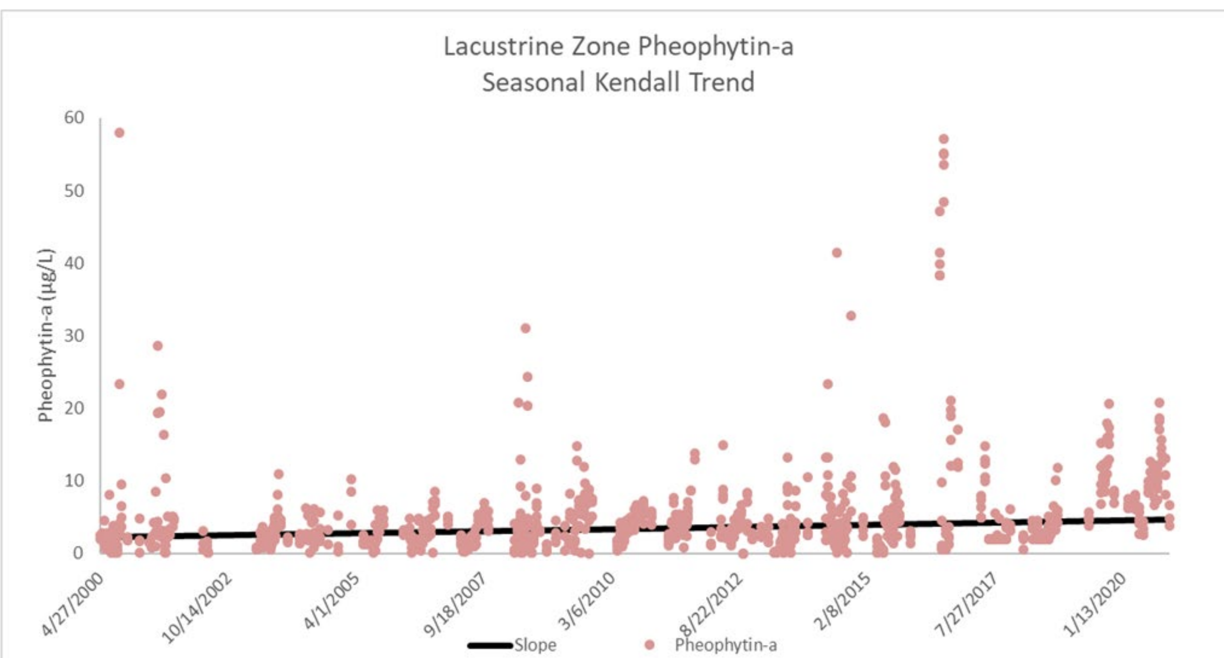


Figure 9 Graphic shows period of record pheophytin data for Lake Thunderbird lacustrine zone with a fitted trend line adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely increasing trend.

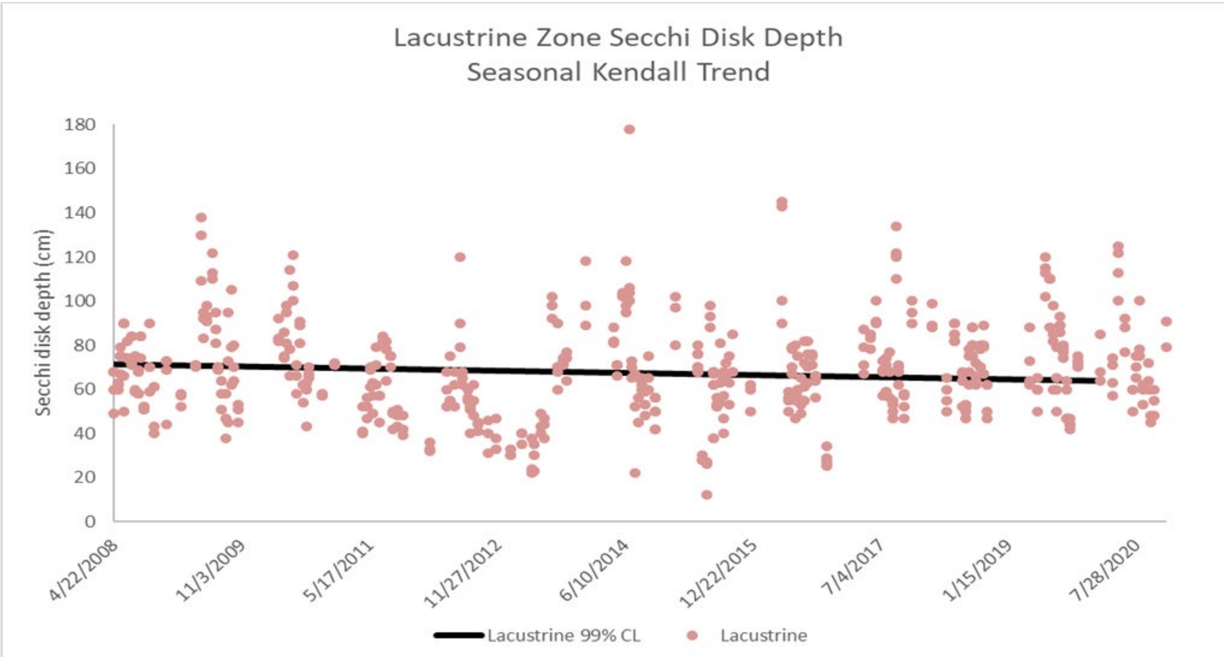


Figure 10 Graphic shows period of record Secchi depth data for Lake Thunderbird lacustrine zone with a fitted trend line adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely decreasing trend.

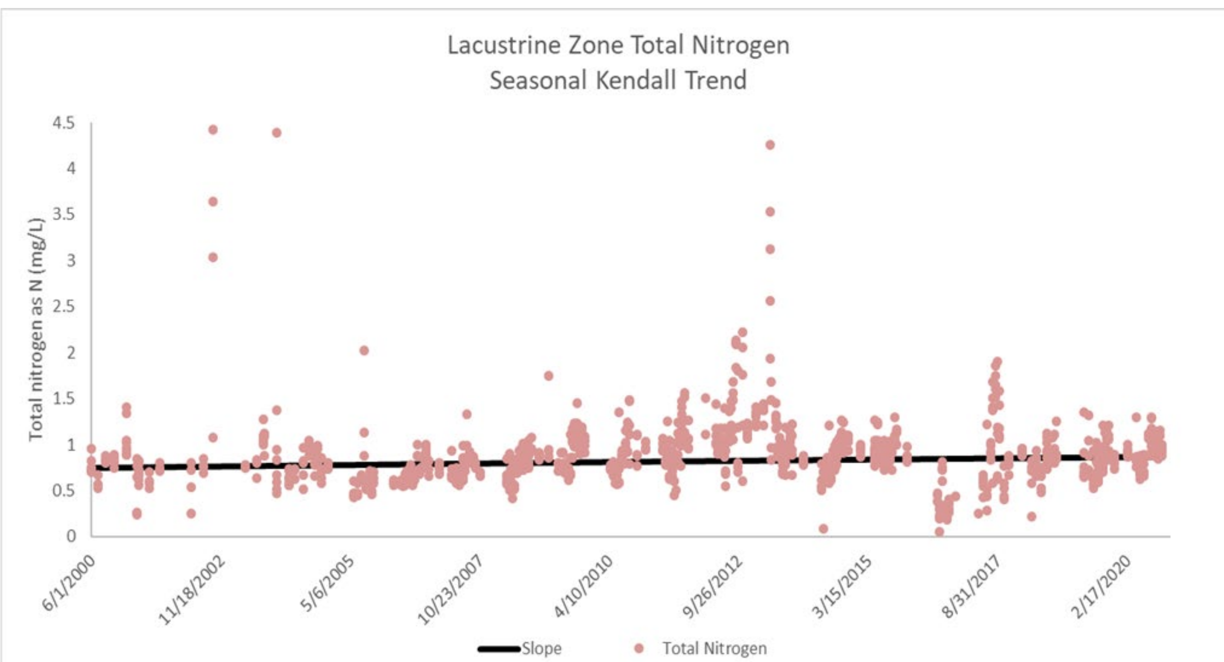


Figure 11. Graphic shows period of record total nitrogen data for Lake Thunderbird lacustrine zone with a fitted trend line adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely increasing trend.

Transition Zones (Sites 3, 5, and 7)

Table 11 provides a summary of trend characterization analyses performed on the Lake Thunderbird transition zones. Transition zones represent the link between riverine lake zones and the lacustrine zone of the lake. Two main tributaries feed into Lake Thunderbird: The Little River from the west and Hog Creek from the north. Transition zones will often show stratification; however, but not throughout the entire season. Based on the data aggregation, sites 3 and 5 represent the transition zone.

Table 11 Summary of trend characterization of Lake Thunderbird transition ecological sites.

Constituent	Transition Zones	Rate (unit/yr.)	Total	Duration (yr.)	Confidence Level	Likeliness	n	Start Date	End Date
Alkalinity, total (mg/l)	Little River	↑ 0.67	13.9	20.6	90%	Likely to increase	45	04-27-2000	12-08-2020
Total hardness (mg/l)	Little River	↓ -0.30	-4.0	13.4	<80%	Unlikely to decrease	28	10-10-2006	02-18-2020
Turbidity (NTU)	Little River	↑ 0.00	0.0	19.3	<80%	Unlikely to increase	256	11-02-2000	02-18-2020
Depth, Secchi disk depth (cm)	Little River	↓ -0.56	-11.4	20.5	99%	Highly Likely to decrease	257	04-27-2000	10-13-2020
Chlorophyll *a*, corrected (mg/m^3)	Little River	↑ 0.639	13.08	20.5	99%	Highly Likely to increase	249	04-27-2000	10-14-2020
Pheophytin-a (mg/m^3)	Little River	↑ 0.132	2.71	20.5	99%	Highly Likely to increase	235	04-27-2000	10-14-2020
Inorganic nitrogen (mg/l)	Little River	0	0.000	20.4	<80%	Unlikely to decrease	35	04-27-2000	09-16-2020
Total nitrogen (mg/l)	Little River	↑ 0.004	0.07	20.4	85%	Indeterminant	35	04-27-2000	09-16-2020
Total phosphorus (mg/l)	Little River	↓ -0.0006	-0.0115	20.4	90%	Likely to decrease	35	04-27-2000	09-16-2020
Alkalinity, total (mg/l)	Hog Creek	↑ 0.53	10.9	20.5	95%	Very Likely to increase	46	06-01-2000	12-08-2020
Total hardness (mg/l)	Hog Creek	↓ -0.38	-5.1	13.4	<80%	Unlikely to increase	28	10-10-2006	02-18-2020
Turbidity (NTU)	Hog Creek	↓ -0.07	-1.4	19.3	85%	Indeterminant	255	11-02-2000	02-18-2020
Depth, Secchi disk depth (cm)	Hog Creek	↓ -0.45	-9.1	20.5	99%	Highly Likely to decrease	258	04-27-2000	10-14-2020
Chlorophyll *a*, corrected (mg/m^3)	Hog Creek	↑ 0.598	12.24	20.5	99%	Highly Likely to increase	250	04-27-2000	10-14-2020
Pheophytin-a (mg/m^3)	Hog Creek	↑ 0.116	2.37	20.5	99%	Highly Likely to increase	236	04-27-2000	10-14-2020
Inorganic nitrogen (mg/l)	Hog Creek	0	0.000	20.3	<80%	Unlikely to increase	34	06-01-2000	09-16-2020
Total nitrogen (mg/l)	Hog Creek	↑ 0.004	0.08	20.3	<80%	Unlikely to increase	34	06-01-2000	09-16-2020
Total phosphorus (mg/l)	Hog Creek	↓ -0.0002	-0.0047	20.3	<80%	Unlikely to decrease	35	06-01-2000	09-16-2020

Alkalinity, a watershed, or geological variable was characterized as increased for Hog Creek (at 95% confidence level) and Little River (at 90% confidence level) transition zones (**Figure 12**). All response variables were characterized highly likely (99% confidence level) toward eutrophication: chlorophyll *a* to increase, pheophytin-a to have increased (**Figure 13 and Figure 14**) and Secchi disk depth to have decreased (**Figure 15**). The stressor variable, total phosphorus, was characterized likely (90% confidence level) to have decreased in the Little River transition zone (**Figure 16**).

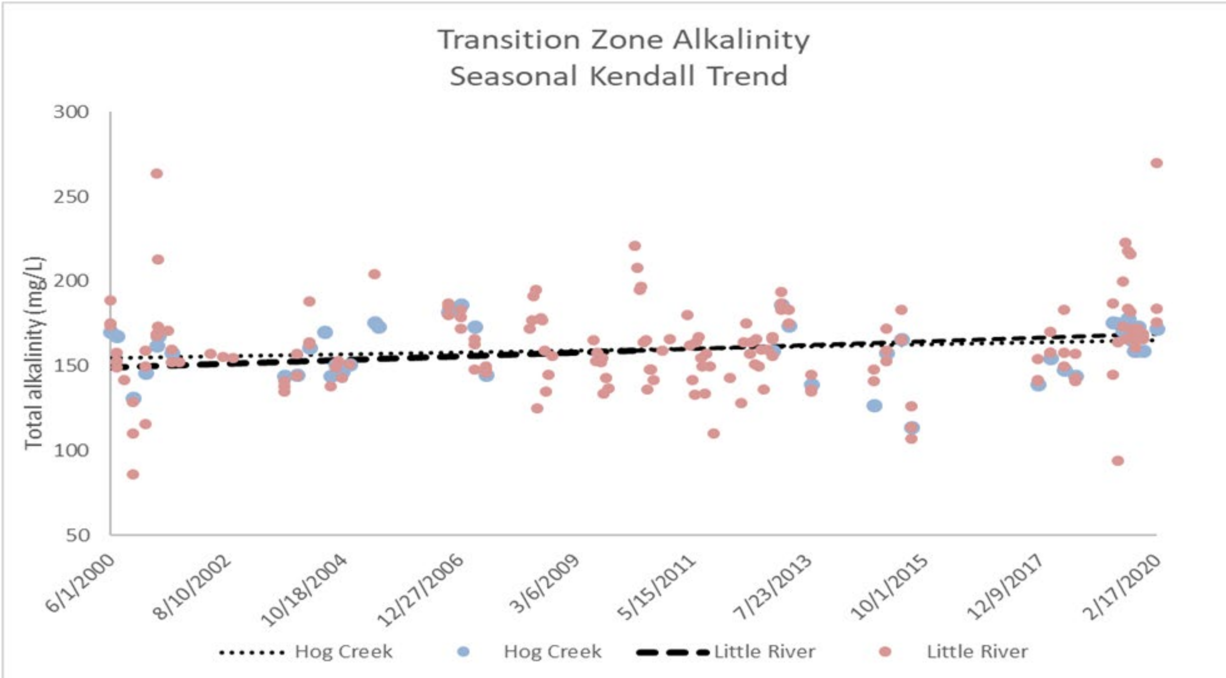


Figure 12. Graphic shows period of record total alkalinity data for the Little River and Hog Creek transition zones of Lake Thunderbird with fitted trend lines adjusted for seasonality. Seasonal Kendall analysis was significant for both areas and demonstrates a likely increasing trend in the Little River area and a marginally likely increasing trend in the Hog Creek area.

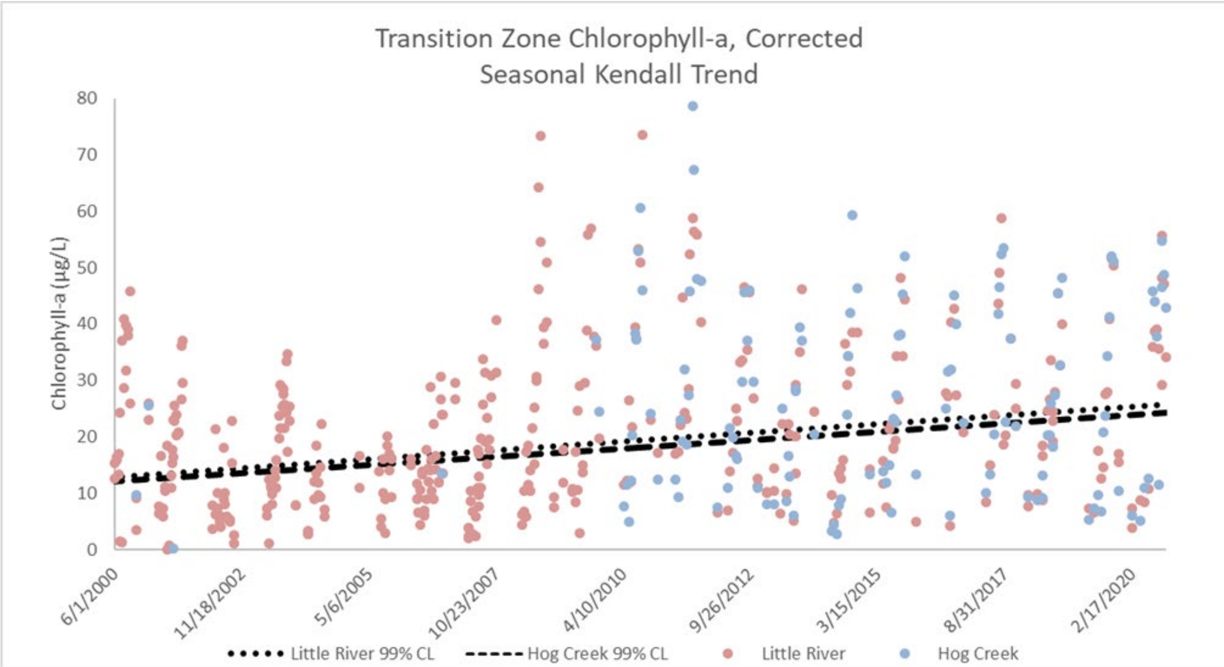


Figure 13. Graphic shows period of record chlorophyll *a* data for the Little River and Hog Creek transition zones of Lake Thunderbird with fitted trend lines adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely increasing trend for both areas.

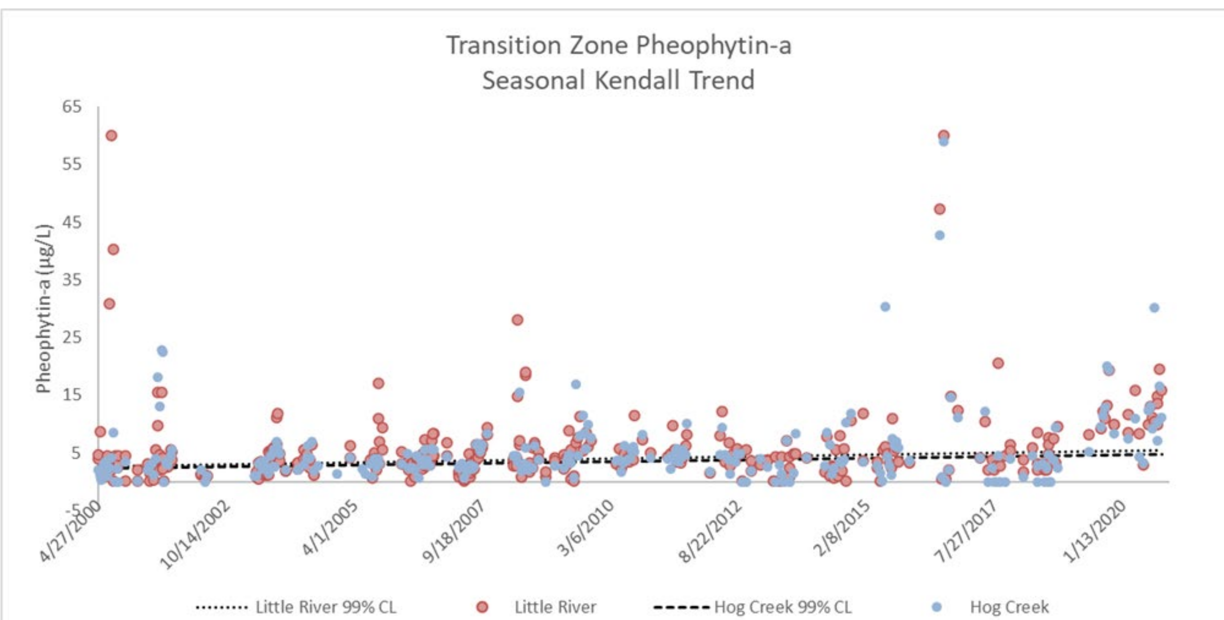


Figure 14. Graphic shows period of record pheophytin-a data for the Little River and Hog Creek transition zones of Lake Thunderbird with fitted trend lines adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely increasing trend for both areas.

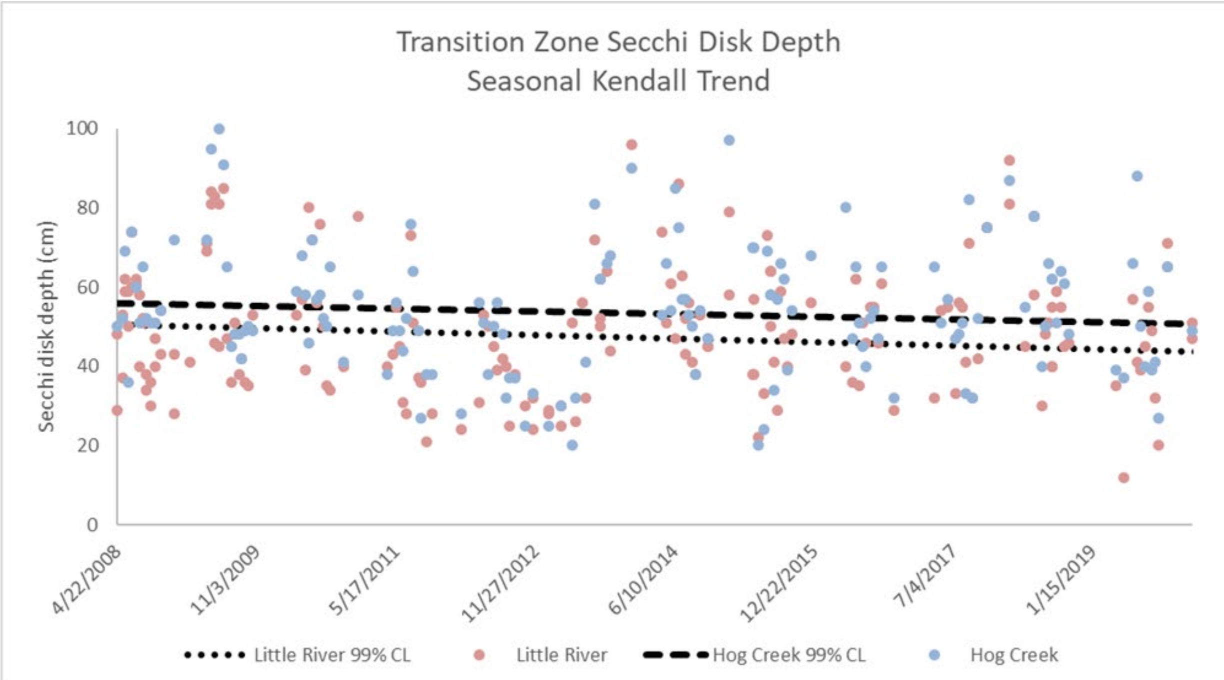


Figure 15. Graphic shows period of record Secchi Depth data for the Little River and Hog Creek transition zones of Lake Thunderbird with fitted trend lines adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely increasing trend for both areas.

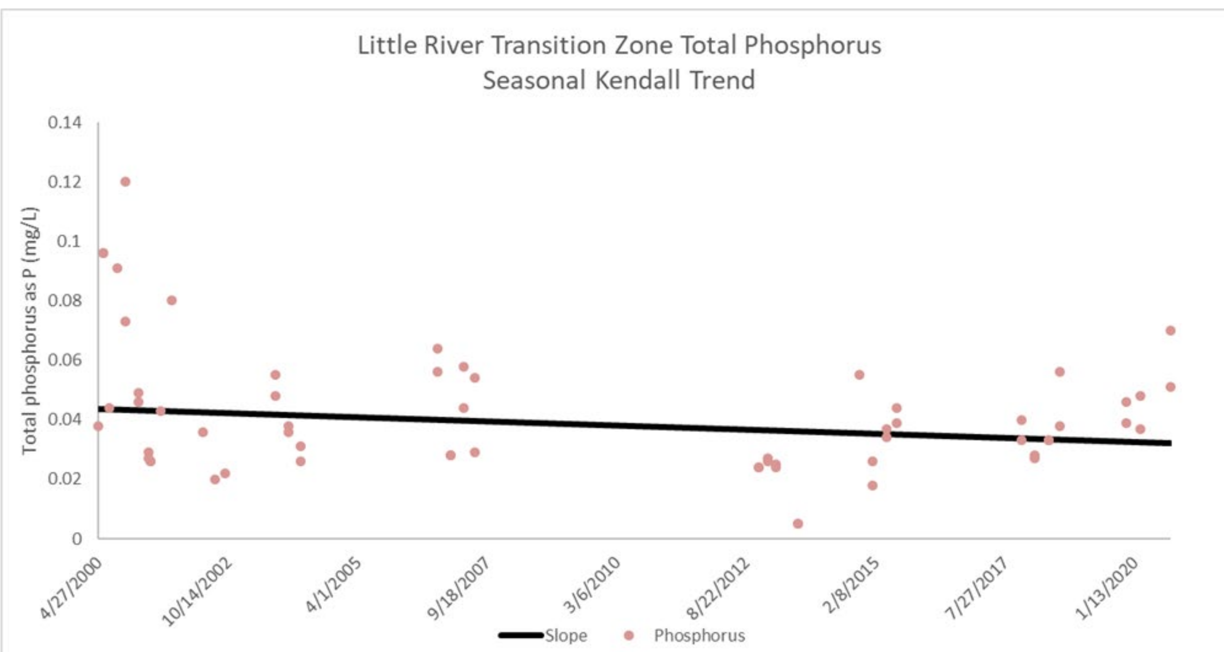


Figure 16. Graphic shows period of record total phosphorus data for the Little River transition zone of Lake Thunderbird with a fitted trend line adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a highly likely decreasing trend.

Riverine Zones (Sites 6, 8, 11)

Table 12 provides a summary of trend characterization analyses performed on the Lake Thunderbird riverine zones. Riverine zones reflect the water tributary to that arm of the lake. Three separate tributaries are represented as riverine in Lake Thunderbird. Based on the data aggregation, sites 6,8 and 11 represent the riverine zone.

Table 12. Summary of trend characterization of Lake Thunderbird riverine ecological sites.

Constituent	Riverine Zones		Rate (unit/yr.)	Total	Duration (yr.)	Confidence Level	Likeliness	n	Start Date	End Date
Alkalinity, total (mg/l)	Dave Blue Creek				Inadequate data for analysis			54	07-09-2009	10-09-2019
Total hardness (mg/l)	Dave Blue Creek				Inadequate data for analysis			10	04-17-2019	09-10-2019
Turbidity (NTU)	Dave Blue Creek	↓	-1.10	-21.2	19.3	90%	Likely to decrease	123	11-02-2000	02-18-2020
Depth, Secchi disk depth (cm)	Dave Blue Creek	↓	-0.12	-1.4	11.3	<80%	Unlikely to decrease	126	07-09-2009	10-14-2020
Chlorophyll *a*, corrected (mg/m³)	Dave Blue Creek	↓	-1.12	-12.32	11.0	99%	Highly Likely to decrease	121	10-09-2009	10-14-2020
Pheophytin-a (mg/m³)	Dave Blue Creek	↑	0.26	2.90	11.3	90%	Likely to increase	115	07-09-2009	10-14-2020
Inorganic nitrogen (mg/l)	Dave Blue Creek				Inadequate data for analysis			97	10-09-2009	10-14-2020
Total nitrogen (mg/l)	Dave Blue Creek				Inadequate data for analysis				07-09-2009	10-14-2020
Total phosphorus (mg/l)	Dave Blue Creek				Inadequate data for analysis			120	07-09-2009	10-14-2020
Alkalinity, total (mg/l)	Little River	↑	0.98	20.1	20.5	90%	Likely to increase	98	06-01-2000	12-08-2020
Total hardness (mg/l)	Little River	↑	0.97	13.0	13.4	85%	Indeterminant	27	10-10-2006	02-18-2020
Turbidity (NTU)	Little River	↑	0.45	8.7	19.3	85%	Indeterminant	255	11-02-2000	02-18-2020
Depth, Secchi disk depth (cm)	Little River	↓	-0.35	-7.1	20.5	99%	Highly Likely to decrease	256	04-27-2000	10-14-2020
Chlorophyll *a*, corrected (mg/m³)	Little River	↑	0.667	13.65	20.5	99%	Highly Likely to increase	253	04-27-2000	10-14-2020
Pheophytin-a (mg/m³)	Little River	↑	0.249	5.09	20.5	99%	Highly Likely to increase	238	04-27-2000	10-14-2020
Inorganic nitrogen (mg/l)	Little River		0	0.000	20.4	<80%	Unlikely to increase	161	06-01-2000	10-14-2020
Total nitrogen (mg/l)	Little River	↑	0.004	0.07	20.4	<80%	Unlikely to increase	159	06-01-2000	10-14-2020
Total phosphorus (mg/l)	Little River		0.0000	0.0000	20.4	<80%	Unlikely to increase	160	06-01-2000	10-14-2020
Alkalinity, total (mg/l)	Hog Creek				Inadequate data for analysis			63	04-22-2008	09-24-2019
Total hardness (mg/l)	Hog Creek				Inadequate data for analysis			9	04-17-2019	09-24-2019
Turbidity (NTU)	Hog Creek	↓	-0.98	-18.9	19.3	99%	Highly Likely to decrease	143	11-02-2000	02-18-2020
Depth, Secchi disk depth (cm)	Hog Creek	↑	0.12	1.5	12.5	<80%	Unlikely to increase	144	04-22-2008	10-14-2020
Chlorophyll *a*, corrected (mg/m³)	Hog Creek	↓	-0.560	-6.99	12.5	95%	Very Likely to decrease	139	04-22-2008	10-14-2020
Pheophytin-a (mg/m³)	Hog Creek	↓	-0.019	-0.24	12.5	<80%	Unlikely to decrease	133	04-22-2008	10-14-2020
Inorganic nitrogen (mg/l)	Hog Creek		0	0.00	12.5	80%	Indeterminant	133	04-22-2008	10-14-2020
Total nitrogen (mg/l)	Hog Creek	↓	-0.003	-0.035	12.5	<80%	Unlikely to decrease	131	04-22-2008	10-14-2020
Total phosphorus (mg/l)	Hog Creek	↑	0.0001	0.0011	12.5	<80%	Unlikely to increase	133	04-22-2008	10-14-2020

The watershed indicator alkalinity at the Little River riverine site was characterized likely (90% confidence level) to have increased (**Figure 17**). Chlorophyll *a*, a measure of algal biomass, was characterized a highly likely (99% confidence level) to have increased in the Little River and highly likely (99% confidence level) to have decreased in the Dave Blue Creek and Hog Creek zones (**Figure 18**). Pheophytin-a, a measure of dead algae, was characterized highly likely (99% confidence level) and likely (90% confidence level) to have increased in the Little River and Dave Blue Creek zones respectively (**Figure 19**). Secchi disk depth a stressor response was characterized highly likely (99% confidence level) to have decreased in the Little River zone (**Figure 20**).

Turbidity, a stressor, was characterized likely (90% confidence level) and highly likely (99% confidence level) to have decreased in the Dave Blue Creek and Hog Creek zones respectively (**Figure 21**). No other stressors are characterized with a trend in any riverine zones.

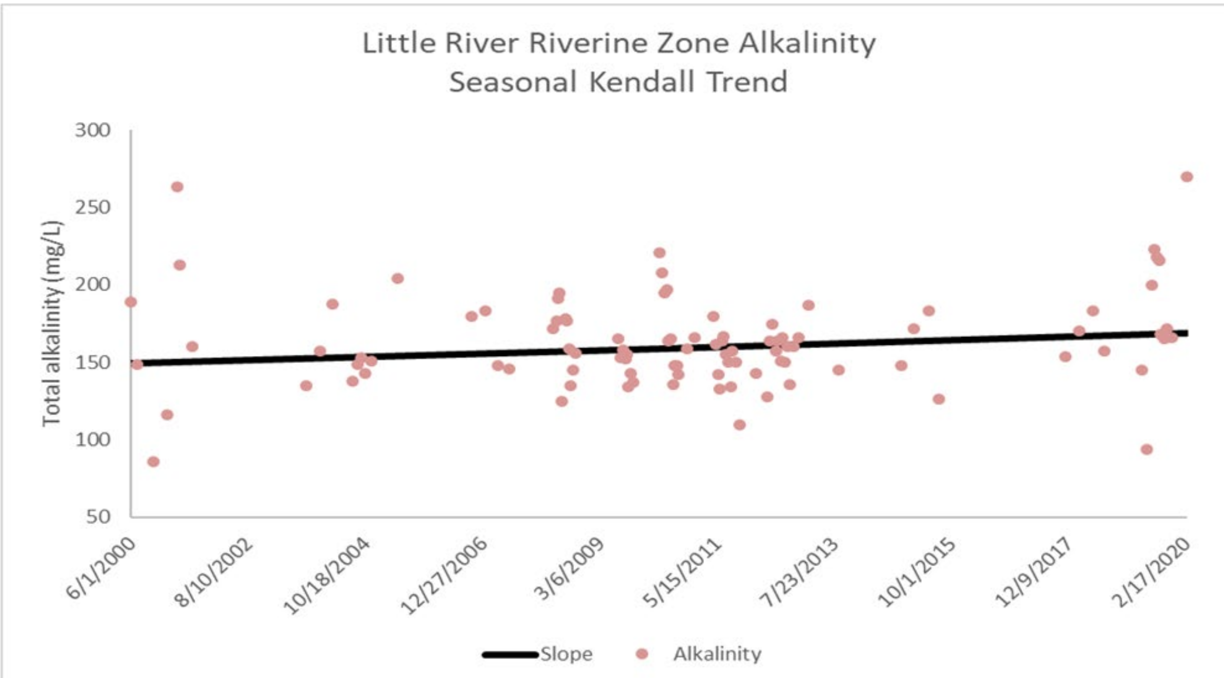


Figure 17. Graphic shows period of record total alkalinity data for the Little River transition zone of Lake Thunderbird with a fitted trend line adjusted for seasonality. Seasonal Kendall analysis was significant and demonstrates a marginally likely increasing trend.

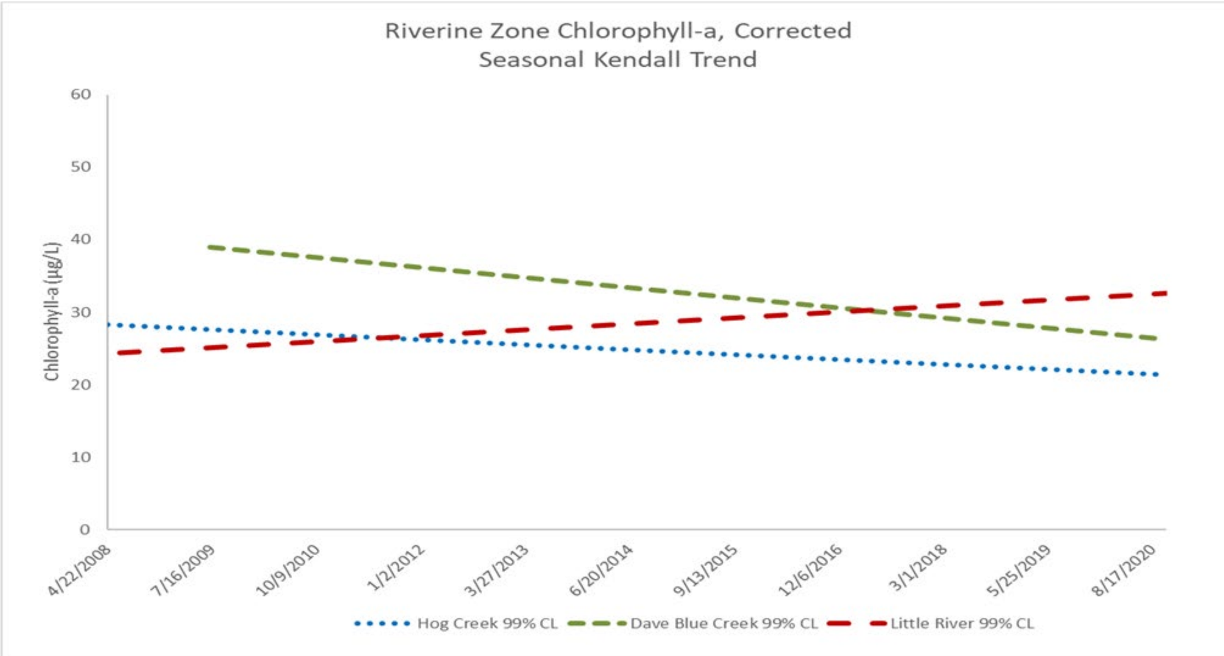


Figure 18. Graphic shows fitted trend lines adjusted for seasonality in the riverine zones of Lake Thunderbird. Seasonal Kendall analysis was significant for all three zones. The Little River shows a highly likely increasing trend. Conversely, the Hog Creek demonstrates a likely decreasing trend and Dave Blue Creek and highly likely decreasing trend.

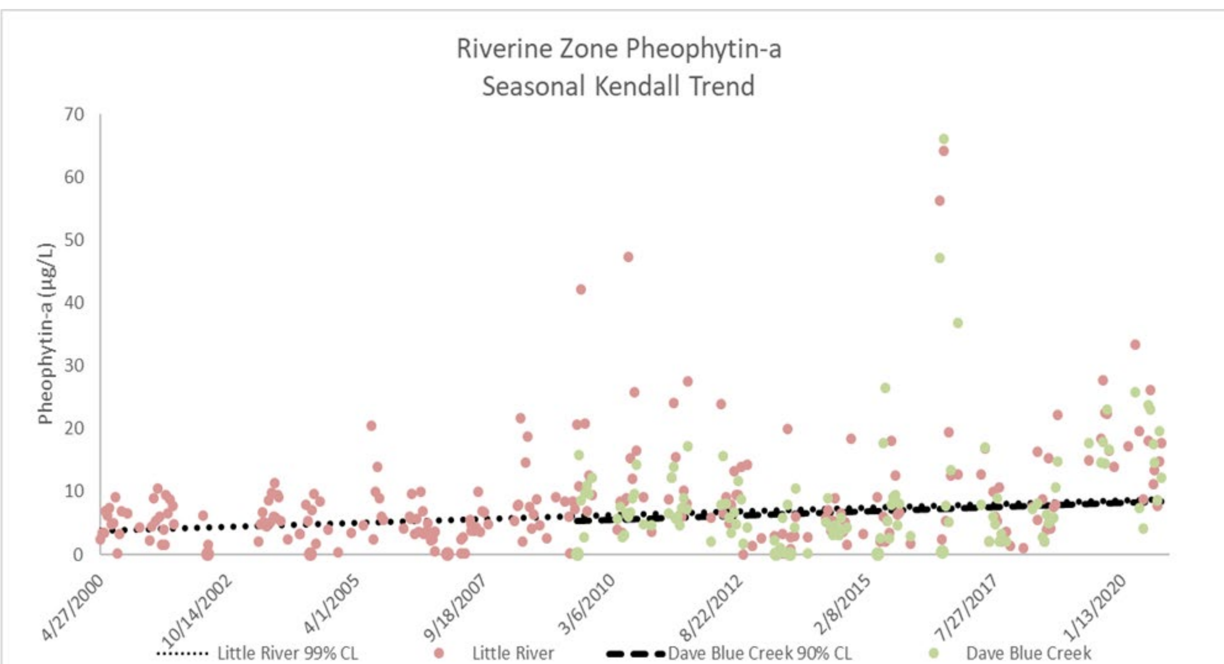


Figure 19. Graphic shows period of record pheophytin data for the riverine zones of Lake Thunderbird with fitted trend lines adjusted for seasonality. Seasonal Kendall analysis was significant for both areas. The Little River shows a highly likely increasing trend, while Dave Blue Creek shows marginally likely increasing trend.

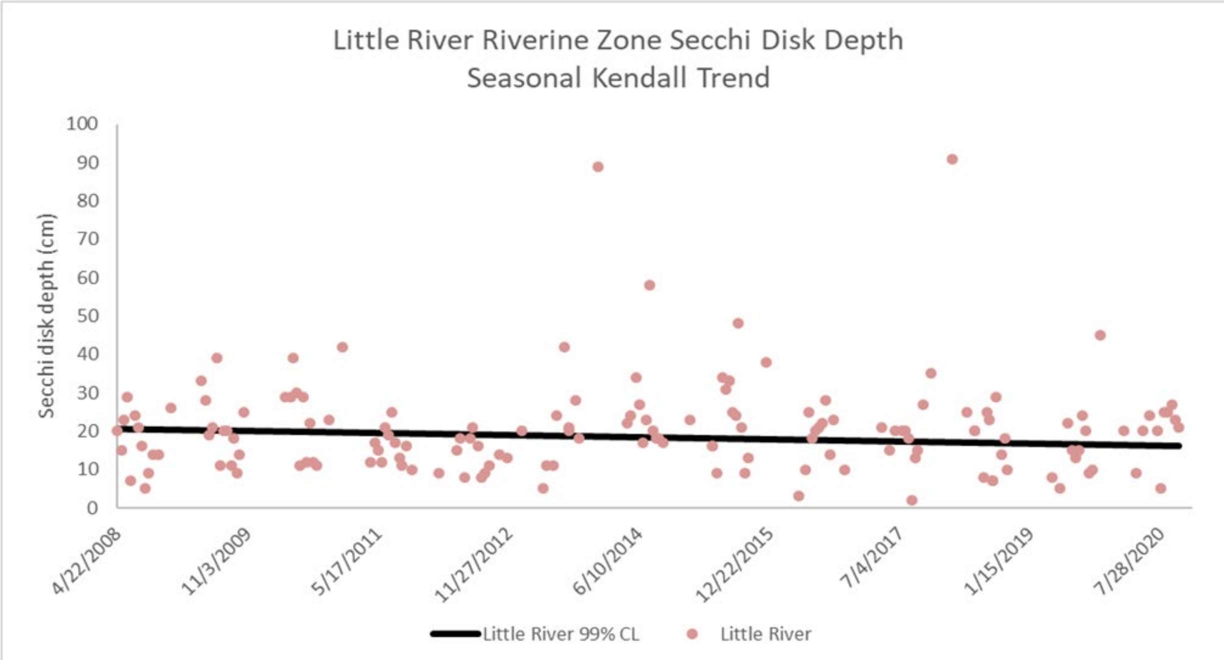


Figure 20. Graphic shows period of record Secchi disk data for the Little River riverine zone of Lake Thunderbird with a fitted trend line adjusted for seasonality. Seasonal Kendall analysis was significant shows a highly likely decreasing trend.

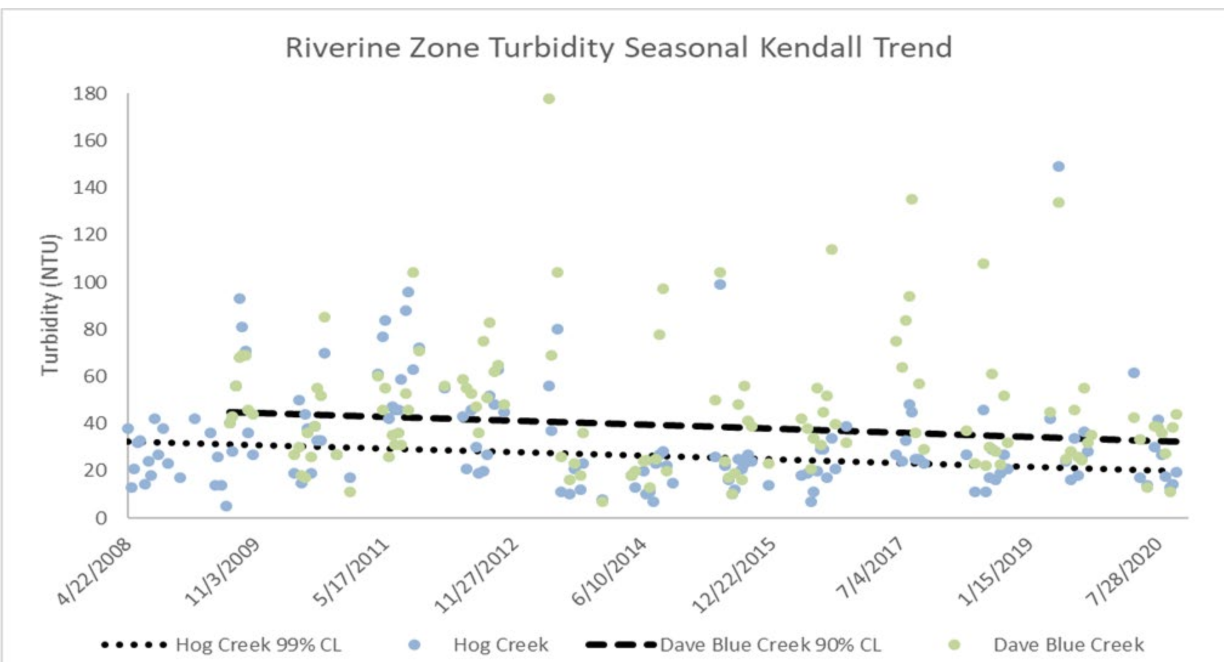


Figure 21. Graphic shows period of record turbidity data for the riverine zones of Lake Thunderbird with fitted trend lines adjusted for seasonality. Seasonal Kendall analysis was significant for both areas. The Hog Creek zone shows a highly likely decreasing trend, while Dave Blue Creek shows a marginally likely decreasing trend.

Discussion and Conclusions

As discussed previously, watershed indicators, such as alkalinity and hardness, provide some information about general environmental stability. Only alkalinity was characterized as having a significantly increasing trends in both the Little River riverine and transition zones. Alkalinity for these sites varied from 155 mg/L in 2000 and near 170 mg/L in 2020. Though this increase is significant, it may not be ecologically significant. Alkalinity values between 100-200 ppm are generally considered adequate to buffer fresh waters. No significant trends were detected for any ecological zone for total hardness. No characterizations of the Hog Creek and Dave Blue Creek riverine zones were possible due to inadequate data of alkalinity and hardness.

Prior to discussing trends of both stressors and response variables, it is important to have a discussion of general lake dynamics. Specifically, under normal conditions, how a reservoir is characterized through its longitudinal gradient (riverine to transitional to lacustrine). Common ecological zone attributes are detailed in **Figure 22**. Following these attributes, eutrophication stressors (nutrients and suspended solids) should go from high in the riverine to relatively low in the open water areas of the reservoir. As a result, the reservoir would be light-limited in the riverine zone and nutrient-limited in the lacustrine zone, where much of the nutrient concentration should be supplied by internal cycling. As response occurs, riverine zones should be more eutrophic, with decreasing response through the reservoir leading to oligotrophic conditions through much of the open water. In the case of Lake Thunderbird, there is significant deviation from these general reservoir attributions. Viewed through the lens of trend analysis, there is little to no difference across ecological zones for the nutrient stressors and algal content response variables chlorophyl *a* and pheophytin-a. These deviations are warning signs for the ecological health of Lake Thunderbird.

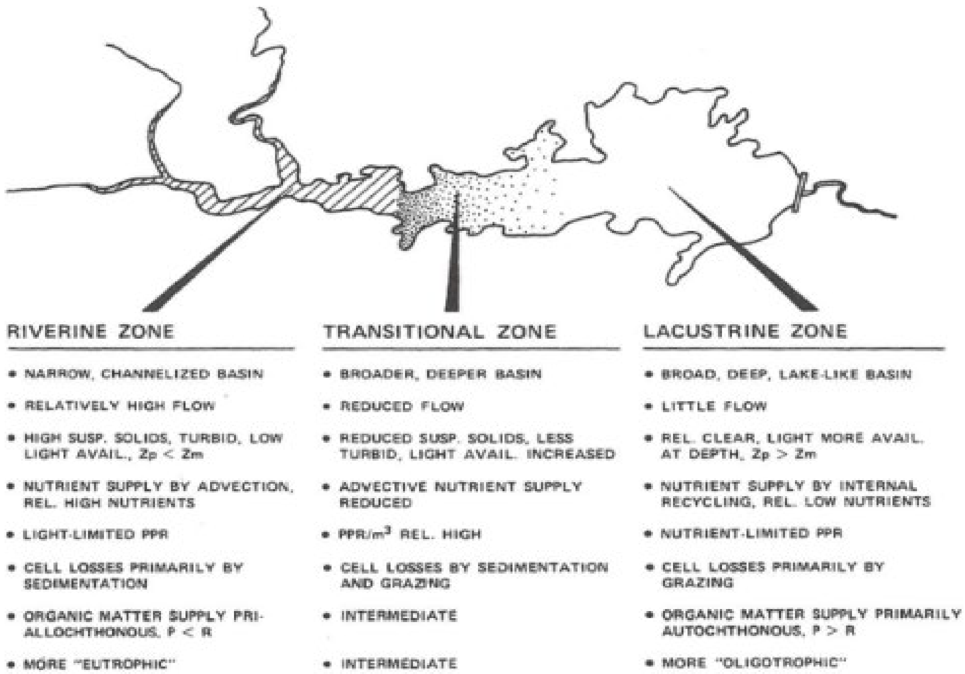


Figure 22. Illustration of reservoir ecological zones detailing common attributes of each zone. Kimmel et al., 1991.

As reported in the annual water quality reports for Lake Thunderbird (OWRB, 2021), both phosphorus and nitrogen remain excessively high throughout the reservoir. Though these values are typically higher in riverine zones, they are characteristic of eutrophic to hypereutrophic conditions in the reservoir's open water areas. Though typically decreasing in concentration, total phosphorus demonstrates a significant downward trend only in the Little River transition zone. The magnitude of change was estimated at 0.012mg/L dropping from 0.044mg/L to 0.032 mg/L; a significant decrease of a key eutrophication stressor. However, the estimated decrease still represents a phosphorus rich environment. Similarly, the significant trend of increasing total nitrogen within the lacustrine zone brings the estimated 2020 concentration within the range of the other zones.

Cultural eutrophication has been an ongoing process over the last 20 years within Lake Thunderbird. In general, the nutrient stressors for algal growth have maintained elevated concentrations. The detection of an increasing trend of total nitrogen in only the lacustrine zone is noteworthy. It is possible that the anoxic hypolimnion underlying the lacustrine zone could account for this characterized trend. Partitioning the cause of increasing lacustrine zone total nitrogen between longitudinal transport (from watershed runoff) and vertical transport (from the underlying hypolimnion) processes can be a significant piece toward developing a comprehensive mitigation plan.

Sediment is an important vehicle for nutrient transport in freshwater systems. As discussed earlier and without suspended sediment data, turbidity is the most readily available in situ water quality parameter for understanding potential changes in sediment transport. Comparison across Lake Thunderbird's longitudinal gradient shows a steady decrease of inorganic solids, as estimated by turbidity, from the upper riverine end to the lacustrine. Lake Thunderbird is listed as impaired for turbidity and generally shows elevated levels of turbidity throughout the Little River area of the lake and in the Hog Creek riverine zone. The Lacustrine zone and Hog Creek transition zones generally are not turbid. In open waters, turbidity shows either no significant trend in the lacustrine zone or indeterminant trends in the transition zones. Conversely, in the riverine zones, both Dave Blue Creek and Hog Creek show significant decreasing trend in turbidity, at a rate of nearly 1 NTU per year. The Little River is indeterminant but does show an uptick of nearly 0.5 NTU per year. These trend characterizations may hold some significance to lake management. While the turbidity starting and end point values are high and not likely to have an ecological impact, the substantial reductions (magnitude of change) may be linked to land use changes within the Lake Thunderbird watershed (**Table 13**). A comparison of land use changes may yield valuable information to apply watershed wide for further reductions. Exploring land use features within these watersheds and changes across time could yield insight toward effective reduction controls of inorganic suspended solids. It is, however, imperative that these suspended solids reductions accompany nutrient reductions. The expected higher light transparency from reduced suspended solids predicts higher concentrations of the response variables chlorophyll *a* and pheophytin-a.

Table 13. Tabular summary of turbidity (NTU) long-term trends by ecological zone.

Ecological Zone		2000	2020	Trend Likelihood	slope (NTU/L*yr^{-1})
Lacustrine		8.9	8.3	Unlikely	-0.02
Transition	Little River	14.9	14.9	Unlikely	0.00
	Hog Creek	12.7	11.0	Indeterminant	-0.07
	Little River	44.6	53.7	Indeterminant	0.45
Riverine	Hog Creek	32.5	20	Highly Likely to decrease	-1.00
	Dave Blue Creek	45	32.5	Likely to decrease	-1.11

Secchi disk depth also followed the expected longitudinal gradient within Lake Thunderbird. As Figure 12 discusses, light limitation is typically present in the upper end of reservoirs, while clarity increases gradually toward the lacustrine zone. In **Table 14,** Secchi values clearly demonstrate a rise in water clarity from 16-31 cm in riverine zones to greater than 64 cm in the lacustrine zone. However, all open water lacustrine and transition zone sites showed significant reduction of Secchi disk depth over the 20-year study period. Because inorganic turbidity is relatively low, Increased algae are the likely cause of decreased Secchi disk depth. As discussed earlier, Secchi disk depth measures the water clarity or ability of light to travel straight through the water, while turbidity measures the scattering of light. Because clay particles scatter light as opposed to absorbing it, turbidity can be a good indicator of inorganic solids, and in the absence of clay (e.g., in the lacustrine zone), Secchi disk depth becomes a particularly good indicator of algae content.

Table 14. Tabular summary of Secchi disk depth (cm) long-term trends by ecological zone.

Ecological Zone		2000	2020	Trend Likelihood	slope (cm/L*yr^{-1})
Lacustrine		76.7	64.2	Highly Likely	-0.63
Transition	Little River	54.9	43.7	Highly	-0.35
	Hog Creek	59.1	50.2	Highly	-0.45
	Little River	21.4	16.3	Highly	-0.35
Riverine	Hog Creek	29.9*	31.8	Unlikely	0.12

Dave Blue Creek	24.9**	23.4	Unlikely	-0.12

* *Upper Hog Creek sampling started in 2008*

**** Dave Blue Creek sampling started in 2009**

As discussed before, chlorophyll *a* is the most measurable direct response variable of eutrophication. In Figure 22, it assumes under normal conditions that eutrophication would decrease longitudinally from the riverine to the lacustrine zone of reservoir. Light limitation would decrease in the open water areas, but because most nutrient availability is driven by internal cycling, the lacustrine as well as transition zones would be nutrient limited. Trend analysis shows an opposite affect occurring in Lake Thunderbird (**Table 15**). In both the lacustrine and transition zones as well as the Little River riverine zone, chlorophyll *a* is highly likely increasing from mesotrophic/eutrophic to hypereutrophic values. Conversely, the Dave Blue Creek and Hog Creek riverine zones that are beginning to show significant decreases in suspended solids are also demonstrating significant decreases in chlorophyll *a* concentrations.

Table 15 Summary of Lake Thunderbird chlorophyll *a* (µg/L) trend characterization values.

Ecological Zone		2000	2020	Trend Likelihood	slope (µg/L*yr^{-1})
Lacustrine		11.6	20.8	Highly	0.45
Transition	Little River	12.8	25.7	Highly	0.64
	Hog Creek	12.0	24.3	Highly	0.60
	Little River	19.0	32.7	Highly	0.67
Riverine	Hog Creek	28.3*	21.3	Very	-0.56
	Dave Blue Creek	39**	26.3	Highly	-1.12

* *Upper Hog Creek sampling started in 2008*
*** Dave Blue Creek sampling started in 2009*

The main stressor response parameter, chlorophyll *a*, is moving toward hypertrophy across all zones. Should this trend continue, chlorophyll *a* will become significantly higher in the open water zones than in riverine zones. It is also important to note that pheophytin-a is significantly increasing in the open water areas, as well. Pheophytin-a is representative of dead algal cells. In hypereutrophic conditions, it is reasonable to expect regular die off algal cells and an increase in pheophytin-a.

Next Steps:

Sediment mediated release of nutrients vs watershed loading.
Partitioning the phosphorus and nitrogen transport to the lacustrine zone between longitudinal and vertical processes have not been clearly documented. The completed internal loading study should begin to provide better comparative understanding of these processes. This knowledge is invaluable toward estimating the cost benefit of watershed and in-lake Best Management Practices (BMP).

Land use attributes effecting nutrient and suspended solids loading to Lake Thunderbird.
Further investigation of the effect of land use changes on long-term trends would provide valuable insight

for developing watershed BMPs. A corollary to this work would be understanding the potential deleterious effects of decreasing light limitation in riverine areas of the reservoir.

Long Term Water Quality Monitoring Program.

Trend analyses has shown the value of the COMCD's consistent collection of quality data over the long term. Suggestions to further improve the dataset include:

- Continue maintaining consistent laboratory detection limits over time. This is a particular issue with the nitrogen series and is not unique to Lake Thunderbird.
- Maintain consistency in sampling frequency. Over time, changing sampling frequencies may affect the ability to adequately account for seasonality in datasets. This can decrease certainty and confidence in statistical results.
- Utilize the site segregation analysis to prioritize monitoring stations. Data clearly shows differentiation along the longitudinal gradient of the reservoir and between riverine sites.
- Continue prioritizing the parameters used in this analysis. Each of the four sets of parameters allowed for greater understanding of change in the reservoir

References

Center for Disease Control and Prevention (2017 a, December 13). Harmful Algal Bloom (HAB) Associated Illness, Freshwater Environments. Retrieved from https://www.cdc.gov/habs/illness-symptoms-freshwater.html

Center for Disease Control and Prevention (2017, December 13). Harmful Algal Bloom (HAB) Associated Illness. Retrieved from https://www.cdc.gov/habs/illness.html

Cooke, Dennis., Kennedy, Robert. 2001. Managing Drinking Water Supplies, Lake & Reservoir Management, 17:3, 157-174

Dorgham, M. 2014. Effects of Eutrophication. In: Ansari A., Gill, S. (eds) Eutrophication: Causes, Consequences, and Control. Springer, Dordrecht

Havens K. 2014. Lake Eutrophication and Plankton Food Webs. In: Ansari A., Gill, S. (eds) Eutrophication: Causes, Consequences, and Control. Springer, Dordrecht

Helsel, D., Hirsch, R. (1993). Statistical Methods in Water Resources. Netherlands: Elsevier Science.

Jüttner, Friedrich., Watson, Susan. July 2007. Biochemical and Ecological Control of Geosmin and 2-Methylisoborneol in Source Waters. Applied and Environmental Microbiology. Vol. 73, No. 14. Pages 4395-4406

Minitab, Inc. 2021 Minitab Statistical Software version 20.4. State college, PA

National Oceanic and Atmospheric Administration (NOAA) (2018, June 25). Why do harmful algal blooms occur? Retrieved from https://oceanservice.noaa.gov/facts/why_habs.html

ODEQ 2013. Lake Thunderbird Report for Nutrient, Turbidity, and Dissolved Oxygen TMDLs Lake Thunderbird TMDL Project - Oklahoma Department of Environmental Quality

OWRB 2019. 2019 Oklahoma Lakes Report Beneficial Use Monitoring Program Oklahoma Beneficial Use Monitoring Program Lakes 2019

OWRB 2021. Lake Thunderbird Water Quality 2020 Final Report 2020ThunderbirdWaterQuality.pdf (ok.gov)

Rashash, D., Dietrich, A., and Hoehn, R. 1997. Flavor profile analysis of selected odorous compounds. Journal American Water Works Association, 89(2):131-142.

USEPA (2019 a, December 19) *Harmful Algal Blooms*. Retrieved from https://www.epa.gov/nutrientpollution/harmful-algal-blooms

USEPA (2019 b, June 10). Managing Cyanotoxins in Public Drinking Water Systems. Retrieved from https://www.epa.gov/ground-water-and-drinking-water/managing-cyanotoxins-public-drinking-water-systems

USEPA. (2019, June 4). Learn about Cyanobacteria and Cyanotoxins. Retrieved from https://www.epa.gov/cyanohabs/learn-about-cyanobacteria-and-cyanotoxins

USEPA Harmful Algal Blooms and Drinking Water, Fact Sheet. EPA:810-F-16-006 U.S. Environmental Protection Agency, Washington, DC

Sanitas, Inc. 2021 Sanitas Statistical Software version 9.6.30 Loveland, CO

Thornton, Kent W., Bruce L. Kimmel, Forrest E. Payne (editors). 1991. Reservoir Limnology: Ecological Perspectives. 256 Pages ISBN: 978-0-471-88501-6

Wardlaw, V., Perry, R. Graham, N. 1991 The Role of Algae as Trihalomethane Precursors- A review. Journal of Water Supply Research & Technology-Aqua, 40(6):335.

Water on the Web (2004, May 11). Understanding: Water Quality. Retrieved from https://www.waterontheweb.org/curricula/ws/ws_index.html

Appendix A – Detailed Exploratory Data Analysis

Exploratory Data Analysis

Prior to beginning trend analysis, it is important to understand certain characteristics of water quality data in Lake Thunderbird. Exploratory data analysis (EDA) can answer important questions and provide information useful for decision making. The EDA helps to understand the extent of available data and the shape and distribution of the dataset. Additionally, exploratory analysis reveals important spatial variation in the dataset. A truncated or cursory exploration of data may lead to false conclusions about both magnitude and extent of trends. For example, not recognizing spatial variation may lead to important trends being muted in certain parts of the waterbody. A more detailed analysis is presented Appendix A of this report.

A necessary initial question is how robust the dataset is for trends analysis. This is answered best by looking at both the length of the dataset period of record and the timestep of collection. For adequate trend analysis, a dataset should incorporate both hydrologic and climatologic variation. Certain environmental co-factors, such as watershed flows, lake level, temperature, rainfall, and evapotranspiration, may vary dramatically from year to year and over decadal and semi-decadal windows. For flowing water, a minimum period of record could be as little as 5-10 years. However, because residence time in lentic waters is much higher, the effect of environmental factors may be incorporated over a much longer period. Typically, a minimum period of record of 10-15 years is desirable for lentic waters. Likewise, timestep may have an influence on the completeness of the dataset and lead to bias in decision-making. Timestep is indicative of the length between individual data collections during period of sampling. For example, a bi-annual timestep would mean that data were collected every other calendar or seasonal year. For lakes, an annual time step is optimal, but larger bi-annual or tri-annual timesteps can be explored for use. Timesteps that go beyond 2-3 years may mute the effects of the environmental co-factors discussed above and lead to biased analysis.

Second, it is important to choose an appropriate analytical method. As with most statistical tests, the assumptions of normal distribution, equal variance, and independent data are tested to determine if a parametric test such as linear regression or a non-parametric test such as a Mann-Kendall are appropriate for the dataset. Several simple methods exist to test these assumptions, most importantly that a dataset is derived from a normal distribution (Table 1). A standard normal distribution is simply a symmetrically continuous distribution of data and is best represented by what is commonly known as a bell-shaped curve. The mean and median are equal at the center of the dataset with symmetrical tails of the data gradually and continuously approaching zero. Data that approximates this distribution is considered normally distributed. Hypothesis testing is the most direct way to test data normality. For example, the Anderson-Darling normality test assumes the null hypothesis of a normal distribution. Failure of the test is a good indication that data are not normally distributed. Additionally, visualizing the shape of the dataset is a useful method of understanding how data may be abnormally distributed. Data skewness, which, is an asymmetrical shift to the left (negative) or right (positive) of most of the dataset, is useful in understanding the longitudinal shape of the dataset. For water quality data, left skewed data may indicate lower values that negatively skew the mean and/or median to the left of the distribution (e.g., periodic dilution or high numbers of values below reporting limits). Conversely, positively skewed data indicates the influence of many outliers, or values greater than the 75th percentile that skew the mean and/or median to the right of the distribution (e.g., turbidity affected by sediment transport events).

Furthermore, visualizing the relationship of the vertical versus the horizontal shape (i.e.., peak shape or kurtosis) can also provide information about what influences the dataset. Is data distribution broad (low peaked) or narrow (high peaked)? The narrowness of the data peak (kurtosis) indicates effects that the tails, or ends of the dataset, may have on the center (median/mean) of the data.

Table 1. Distribution analysis of Lake Thunderbird water quality data.

Parameter	A-D Normality Test	Symmetry	Peak and Tailedness (Kurtosis)
Alkalinity	Mostly Normal	Symmetric	Narrow Peak; Little Tailedness
Hardness	Mostly Normal	Moderately Skewed	Broad Peak; Bi-Directionally Tailed
Chlorophyll *a*	Failed	Highly Skewed	Broad Peak; Right Tailed
Pheophytin	Failed	Highly Skewed	Narrow Peak; Right Tailed
Total Nitrogen	Failed	Highly Skewed	Narrow Peak; Right Tailed
Total Phosphorus	Failed	Highly Skewed	Narrow Peak; Right Tailed
Turbidity	Failed	Highly Skewed	Narrow Peak; Right Tailed
Secchi Depth	Failed	Highly Skewed	Broad Peak; Right Tailed

Third, it is important to understand how data varies across the lake. Is whole lake analysis appropriate or should the lake be divided into ecological, or limnological, zones for analysis? Is there complicating variability in certain areas of the lake? Lake Thunderbird can be divided into several ecological zones based upon the open water and riverine areas of the reservoir. The two largest riverine areas in Thunderbird are inflows from the Little River and Hog Creek. Open water areas include the lacustrine zone and transition areas that separate the riverine and forebay area. Investigating variation both within (intra-zone) and between (inter-zone) these areas determine the best approach to trend analysis. For inter-zone variation, this analysis can be done visually by exploring side by side comparison of boxplots or time series data. More so, statistical analysis of variation between zone data means and medians can provide statistical certainty about what visually appears as significant variation. Intra-zone variation is best explored by noting the occurrence of outliers and by looking at the highness or flatness of the peak of the distribution using interquartile ranges (IQR) or histograms for visualization. Comparison of the data mean and median is also useful, which can elucidate exaggerated skewness in the dataset.

The EDA explored four groups of data, including geochemical (i.e., watershed indicators), water transparency and clarity, nutrients, and nutrient response. Watershed indicator data, including hardness and alkalinity, are affected by geology and soil types, and broad variation can signal lake instability, affecting regulation of pH and lake hardness in a drinking water supply. Water transparency and clarity are explored using Secchi depth and turbidity data. These data provide information about both eutrophication and sediment delivery to the reservoir. Finally, the effect of nutrient inflow and internal nutrient cycling are directly explored using both stressor variables (total nitrogen and total phosphorus) and response variables (chlorophyll *a* and pheophytin).

Total hardness and total alkalinity data are generally evenly distributed, and both pass the Anderson-Darling normality test (Table 1 and Figure 1). Alkalinity data are symmetrical for all lake and lake ecological zone datasets (Figure 1A). The median and mean nearly equivalent with some low and high outliers. Alkalinity is also relatively stable throughout the reservoir. For both the whole lake and ecological zones, there is little IQR variation (~145-175 mg/L), and between these zones, data means demonstrate no significant variation (Figure 1C). Additionally, alkalinity values indicate a well-buffered system (>50 mg/L) throughout the waterbody, which is important in maintaining pH in hypereutrophic conditions. Hardness data are moderately skewed towards to the right, with the mean slightly higher than the median and some outliers (Figure 1B). As with alkalinity, hardness is relatively stable throughout the reservoir. For both the whole lake and ecological zones, there is little IQR variation (~150-200 mg/L), and between these zones, data means demonstrate no significant variation (Figure 1D). With most values between 150-190 mg/L, data is moderately hard but at no time becomes excessively hard.

Water transparency and clarity are represented by an exploration of both Secchi depth and turbidity data. Both parameters are not normally distributed, as indicated both visually and by failure of the Anderson-Darling normality test (Table 1 and Figure 2). Secchi depth is asymmetrical for all lake and ecological zone datasets (Figure 2A). The central tendency (mean and median) of the data shows little variation, but the data are highly skewed to the right with many higher value outliers. Despite a high number of outliers, Secchi is relatively stable in certain ecological zones with interquartile ranges from <20cm in riverine zones to only as high as 30cm in the lacustrine zone. The whole dataset represents the highest variation at 34cm. Despite relative intra-zone stability, Secchi depth is highly variable throughout the reservoir, as indicated by visually by boxplot distributions and statistically by a comparison of the data means (Figure 2C). Transition zones are not significantly different and approximate the whole lake dataset. However, with a mean of 73cm, the lacustrine is significantly higher than all other zones, and with of means of 24 and 33 cm respectively, the Little River and Hog Creek riverine zones are significantly lower than all other areas of the lake. Likewise, turbidity is asymmetrical for all lake and ecological zone datasets (Figure 2B). In both the transition zones and lacustrine area, the central tendency (mean and median) of the data shows little variation, but the data are highly skewed to the right with many higher value outliers. In the riverine areas, the means are significantly higher than the medians, with generally fewer outliers than the other areas of the reservoir, which would demonstrate a tighter, but still abnormal distribution. Similarly, intra-zone variability is relatively stable in the lacustrine and transition zones with interquartile ranges from 6-12 NTU but are noticeably variable in riverine areas (IQR from 27-41 NTU). Additionally, all lake zone means and the whole dataset mean are significantly different, demonstrating high variability in water clarity throughout the reservoir (Figure 2D). The lacustrine and transition zones have high water clarity (11-18 NTU) with little variation around the mean. Conversely, the riverine areas are relatively impacted by higher volumes of sediments, with a mean of 35 NTU in Hog Creek and 60 NTU in Little River and relatively high variation around the mean, similar to the overall distribution.

Total phosphorus and total nitrogen are representative of nutrient stressors in Lake Thunderbird. For both nutrients, data are not normally distributed, as indicated both visually and by failure of the Anderson-Darling normality test (Table 1 and Figure 3). Like turbidity, the general distribution is high peaked and very compacted, but is heavily influenced by outliers (Figure 3A). High value outliers are indicative of both periodic nutrient cycling and nutrient-laden stormwater inflows, while lower value outliers indicate the occasional value at the reporting limit. Except for outliers, intra-zone distribution is relatively stable with IQR values ranging from 0.17-.30 mg/L for total nitrogen and 0.01 to 0.04 mg/L for total phosphorus. For nitrogen, inter-zone variation appears visually stable in the boxplot and is mostly verified statistically. Means range from 0.85 mg/L at the lacustrine zone to 1.02 mg/L in the riverine area of the Little River (Figure 3C). The lacustrine, Hog Creek and Little River transitions, and Hog Creek Riverine zones are all not significantly different for both data means and data medians (0.83-0.89 mg/L). However, the riverine mean of Little River is significantly different from all but the Little River transition, and the median (1.01

mg/L) is significantly differently from all other zone medians. Total phosphorus is distributed much like nitrogen, as inter-zone variation appears visually stable in the boxplot (except for Little River) and is mostly verified statistically (Figure 3B). Means range from 0.04 mg/L at the lacustrine zone to 0.11 in the riverine area of the Little River (Figure 3D). The Hog Creek riverine, lacustrine and transition zones are all not significantly different for both data means (0.04-0.05 mg/L) and data medians (0.03-0.05 mg/L). However, the riverine mean and median (0.09 mg/L) of Little River is significantly different from all other zones.

Finally, chlorophyll *a* and pheophytin represent response variables in the exploratory analysis (Figure 4). Both parameters are not normally distributed, as indicated both visually and by failure of the Anderson-Darling normality test (Table 1 and Figure 4). Chlorophyll *a* distribution is uniquely highly peaked to the left with a gradual sloping as values increase to the right, up to a 75^{th} percentile of greater than 30 ug/L for nearly all areas of the lake (Figure 4A). This represents the diversity of chlorophyll *a* in the system and high intra-zone variability, as generally greater than 70-85% of values exceed the 10 ug/L chlorophyll *a* WQS criterion and IQR ranges from 19-23 ug/L. Likewise, lake wide data medians range from 16-25 ug/L lake wide, indicating a eutrophic to hypereutrophic system, and data means range from 20-28 ug/L, indicating the regular influence of hypereutrophic values. Inter-zone variability is relatively stable in the open areas of the lake, with both transition zones and the lacustrine showing no significant variation in the mean (20-23 ug/L) or median (16-18 ug/L) of the datasets (Figure 4C). However, the riverine zones are like each other but significantly higher than other parts of the lake for both the mean (28 ug/L) and median (25 ug/L). Pheophytin shows less intra-zone variation and is generally highly peaked like turbidity (Figure 4B). Additionally, pheophytin has a much higher number of values considered outliers. As with chlorophyll *a*, inter-zone variability is relatively stable in the open areas of the lake, with both transition zones and the lacustrine showing no significant variation in the mean (5 ug/L) or median (3-4 ug/L) of the datasets (Figure 4D). However, the riverine zones are like each other but significantly higher than other parts of the lake for both the mean (8-9 ug/L) and median (5.5-6 ug/L).

From these analyses, several conclusions may be made about the Lake Thunderbird dataset (See Appendix A for full analyses). First, the dataset is generally large enough both in time and variability across the lake to provide a robust look at data trends. Data have been collected for over twenty years on a yearly timestep. In areas, such as Dave Blue Creek, where data collections have been sparser, trends may not be calculated for some parameters. Second, except for watershed indicator data, all other data types are not normally distributed and are significantly skewed with mostly excessive positive and occasional negative skewness, depending on the area of the lake. Regardless of other assumptions of linear regression, these attributes alone require the use of the Mann-Kendall or Seasonal Kendall to explore trends in Lake Thunderbird. Fortunately, this is not an atypical situation with water quality data and is expected. Lastly, significant inter-zone variation exists across the open water and riverine zones of the reservoir. Secchi depth and turbidity are significantly variable throughout the reservoir. Nutrient stressor and response variables, while not significantly different in open water areas, vary significantly from riverine to open water areas. Trend analysis within different zones and not on a whole lake basis is necessary to fully explore water quality trends in Lake Thunderbird. Additionally, some notable intra-zone variation does occur. This is likely caused by seasonal effects on the data. The use of Seasonal Kendall will help to account for and attenuate these effects.

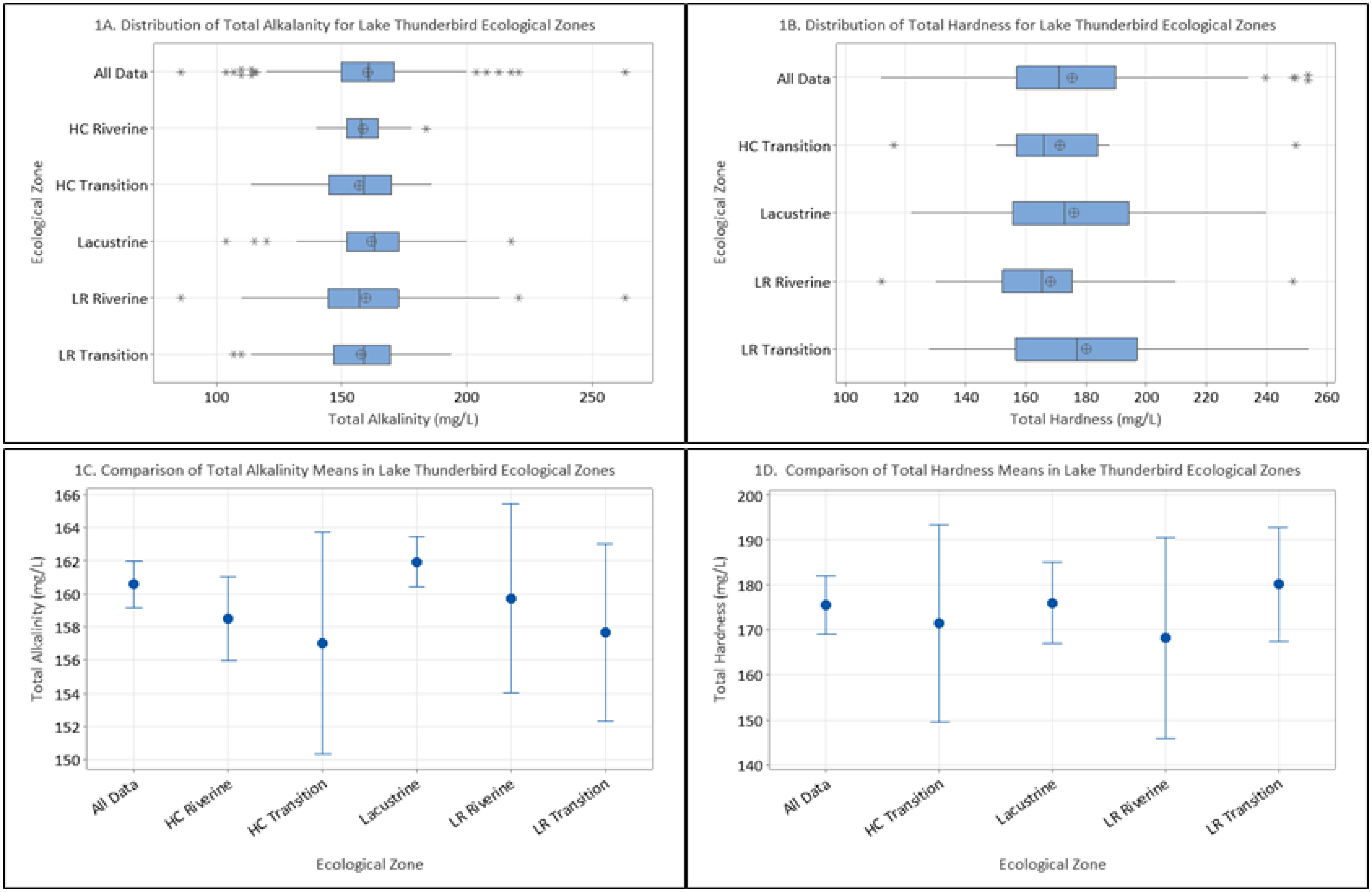


Figure 1A-D. Upper graphs compare distributions of period of record total alkalinity and total hardness for whole lake and major ecological zones of Lake Thunderbird. The box represents the quartiles of the data, and the crosshair symbol displays the mean. Lower graphs compare means for the same data. The bars around the mean represent the 95% confidence interval.

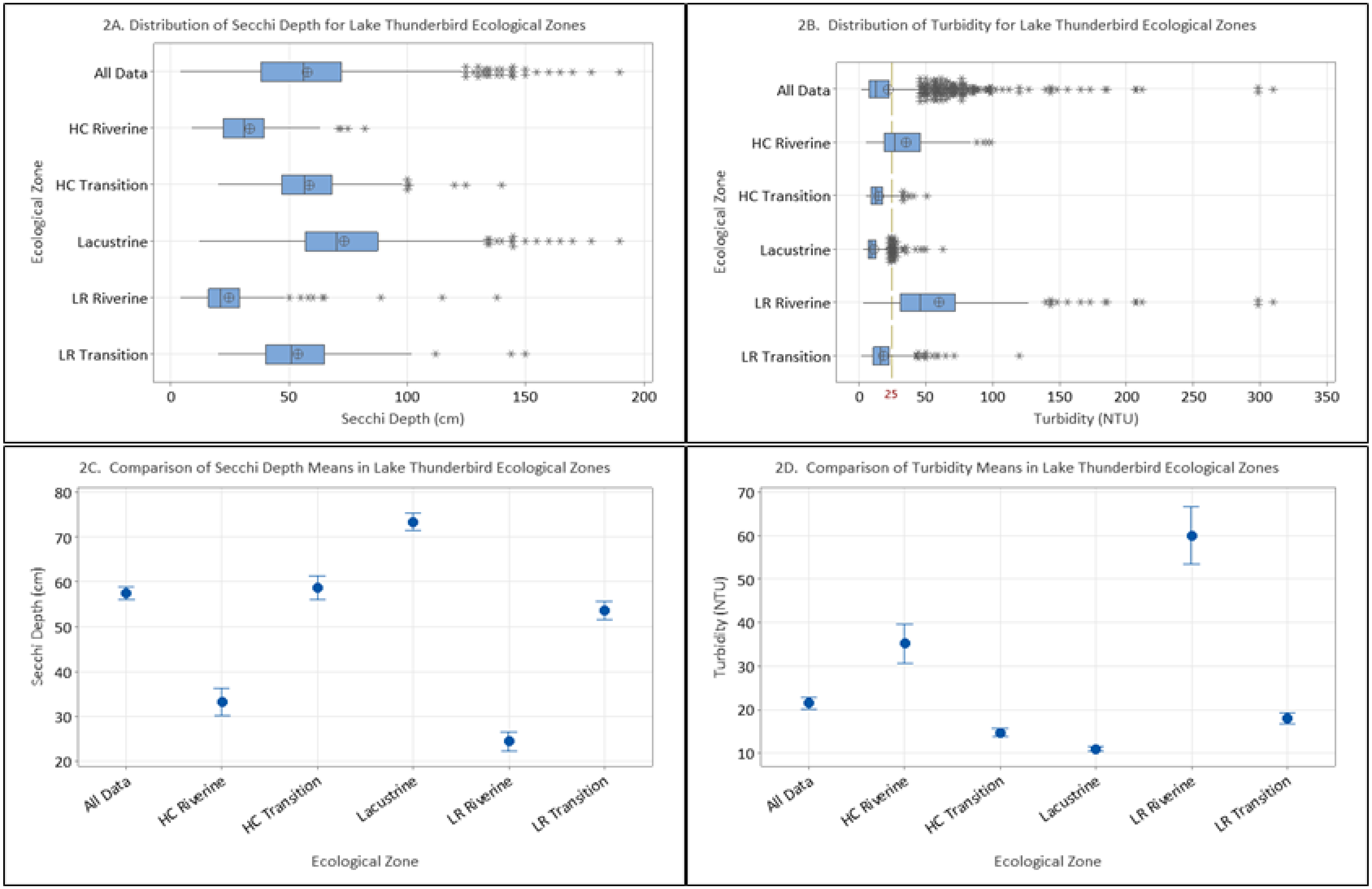


Figure 2 A-D. Upper graphs compare distributions of period of record Secchi depth and turbidity for whole lake and major ecological zones of Lake Thunderbird. The box represents the quartiles of the data, and the crosshair symbol displays the mean. Lower graphs compare means for the same data. The bars around the mean represent the 95% confidence interval. Dashed line on turbidity graph is WQS criterion of 25 NTU.

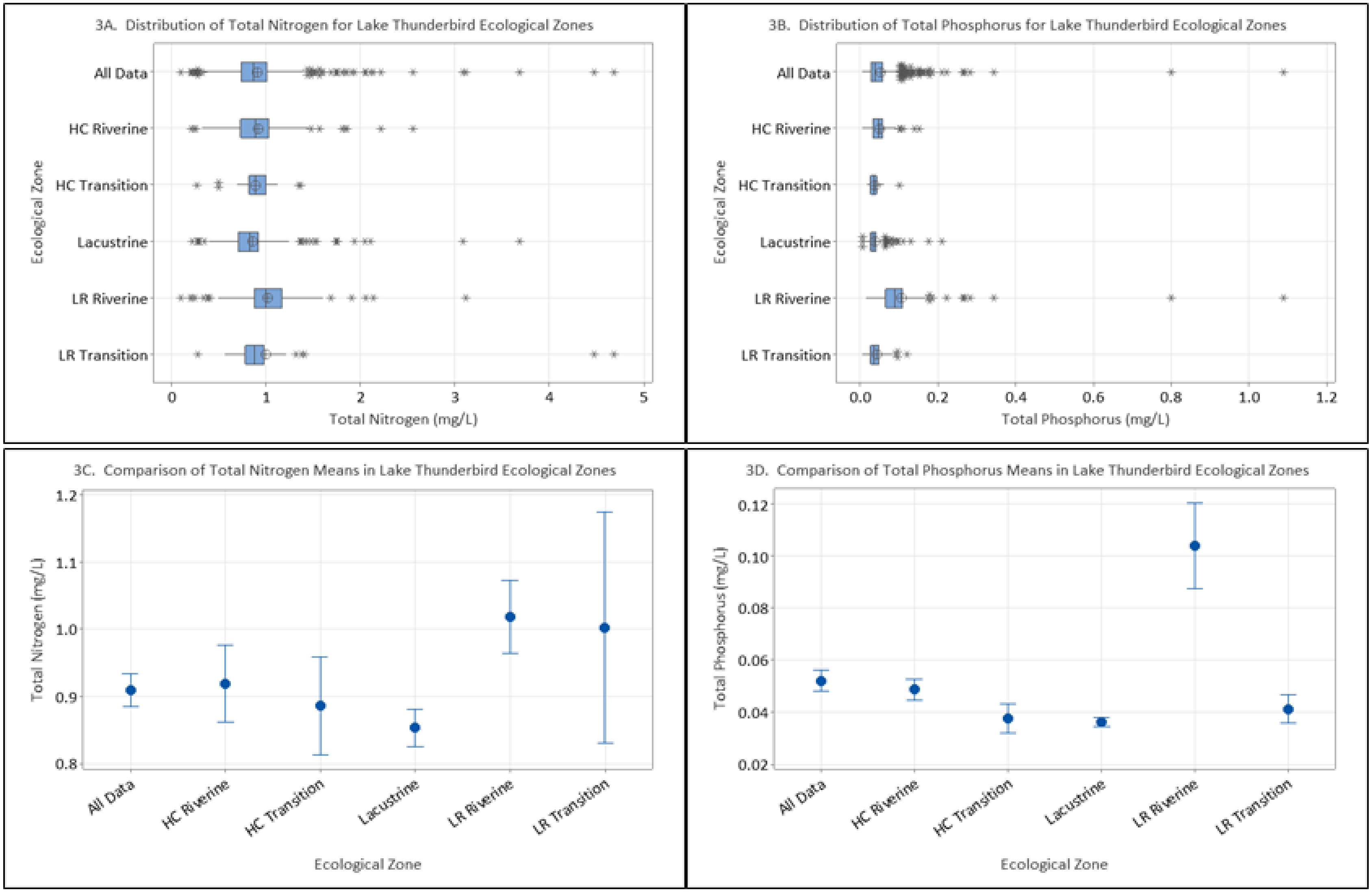


Figure 3 A-D. Upper graphs compare distributions of period of record total nitrogen and total phosphorus for whole lake and major ecological zones of Lake Thunderbird. The box represents the quartiles of the data, and the crosshair symbol displays the mean. Lower graphs compare means for the same data. The bars around the mean represent the 95% confidence interval.

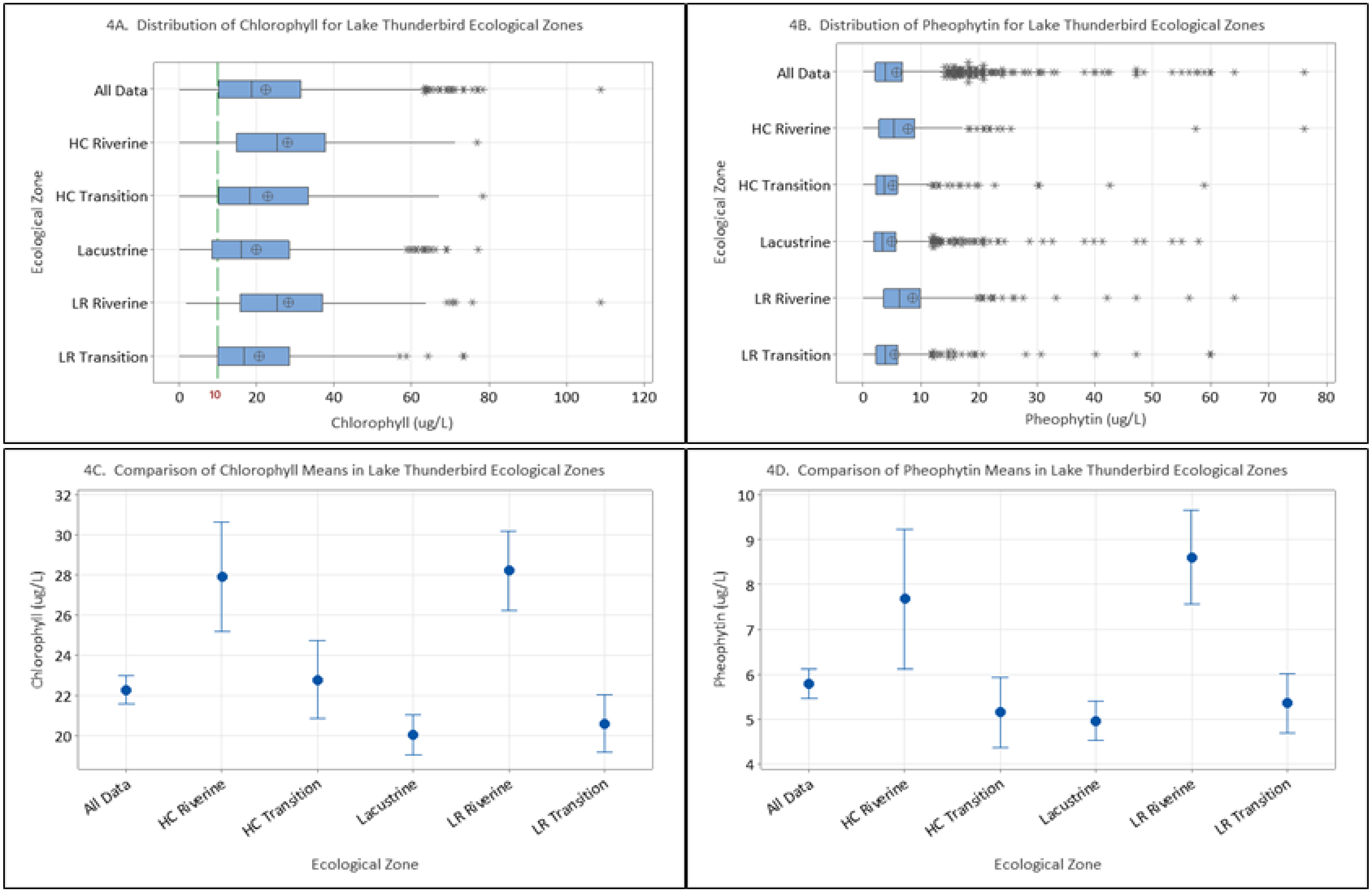


Figure 4 A-D. Upper graphs compare distributions of period of record chlorophyll *a* and pheophytin for whole lake and major ecological zones of Lake Thunderbird. The box represents the quartiles of the data, and the crosshair symbol displays the mean. Lower graphs compare means for the same data. The bars around the mean represent the 95% confidence interval. Dashed line on *chlorophyll a* graph is WQS criterion of 10 mg/L.