Addressing Water Quality Issues of Lake Thunderbird

Final Report

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(COMCD)

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Executive Summary

From analysis of historic water quality data, the major issues identified were excessive chlorophyll-a concentrations and turbidity. To address these issues, nutrient and sediment loadings into Lake Thunderbird must be decreased by approximately 36%. A potential solution suite incorporating two techniques has been identified following alternative evaluation.

First, it is recommended that a total of 900 acres of Free Water Surface (FWS) constructed wetland is implemented, with 400 acres on the Hog Creek branch of the lake and 500 acres on the Little River branch. Constructed wetlands will retain sediments and nutrients in order to decrease loadings into the lake. The total nitrogen and total suspended solids removal efficiencies are estimated to be 69% and >80%, respectively, for both wetlands. The total phosphorus removal efficiencies are estimated to be 43% for the Little River wetland and 62% for the Hog Creek wetland. The total capital cost of the FWS constructed wetlands is $13.1 million, with a total present worth of $25.9 million.

The second recommended solution, shoreline revegetation, will decrease sediment loading into the lake through decreasing soil erosion along the shoreline. It is recommended that 5% of the total shoreline, or 22,700 ft, is targeted. Areas along the shoreline on the northwest side of the lake that experience high amounts runoff and low amount area of forestry are good candidates for revegetation. The implementation of breakwater systems is estimated to reduce soil loss by 21,800 ft^3 during the first year of operation. Once established, vegetation is expected to uptake 1600 lb/yr of nitrogen and 400 lb/yr of phosphorus. The total capital cost of shoreline revegetation is $716,200, with a total present worth of $950,400.

The total capital costs for the solution suite are $13.8 million, with a total present worth of $26.9 million after accounting for O&M over a 20-year design life. Together, these techniques are expected to provide sufficient decreases in nutrient and sediment loadings to address the turbidity and chlorophyll-a issues at Lake Thunderbird.

Chapter 1: Introduction

1.1 Site Description

Lake Thunderbird, a reservoir located 13 miles east of Norman, Oklahoma, was created by the impoundment of the Little River for the purpose of providing recreational use, flood control, and a drinking water source to the cities of Norman, Del City, and Midwest City (Simonds 1999). The Central Oklahoma Master Conservancy District (COMCD), established in 1959, has been responsible for the operation and maintenance of the water supply facilities through a contract with the U.S. Bureau of Reclamation. Water has been supplied to the above communities since the completion of the dam, pumping plants, and pipelines in 1965. Additionally, the COMCD works with the U.S. Army Corps of Engineers to regulate flood waters and aids the Oklahoma Department of Tourism and Recreation in managing recreational facilities (COMCD 2021). The COMCD board is comprised of seven members: three from Norman, three from Midwest City, and one from Del City.

The lake has approximately 86 miles of shoreline and 6,000 acres of surface water. Lake Thunderbird is the habitat for aquatic organisms such as catfish, saugeye, crappie, and largemouth bass (USBR 2017). The available water storage in the lake for flood control is about 76,600 acre-feet at a water elevation of 1,039 ft at the top of the conservation pool (Norman Dam 1969). When the water level in the reservoir exceeds the top of the flood control pool, water is released into the Little River until the water level recedes to below an elevation of 1,049 ft.

1.2 Current Status

Lake Thunderbird is classified as a Category 5a lake because it is a Sensitive Water Supply (SWS), and it cannot support Fish and Wildlife Propagation (FWP) for a warm water aquatic community. Contributing factors to poor water quality in the lake include high chlorophyll-a levels and metalimnetic anoxia due to low dissolved oxygen (DO) levels (Julian et al. 2015). Lake Thunderbird also has high turbidity levels, caused in part by shoreline erosion. Shoreline soils at Lake Thunderbird are generally acidic, non-cohesive, and nutrient-deficient, facilitating erosion and preventing natural revegetation (Allen 2001). High chlorophyll-a levels and high turbidity negatively affect water quality, leading to poor taste and odors, and can result in higher water treatment costs (Dynamic Solutions, LLC 2013).

Chlorophyll-a is produced by many photosynthetic organisms and is used as a measure of algal biomass; thus, high chlorophyll-a levels are indicative of eutrophication and excessive nutrient loads. Eutrophication is the process by which a body of water becomes overly enriched with nutrients, leading to the excessive growth of algae. Lake Thunderbird has recently been classified as either eutrophic or hypereutrophic (OWRB 2020). Excessive algal growth can create objectionable tastes and odors and has led to complaints from drinking water customers during the lake turnover period. Eutrophication also contributes to low DO, as the decomposition of dead algal biomass exerts a significant oxygen demand. The hypolimnion of Lake Thunderbird routinely experiences anoxic conditions from July to September (OWRB 2020). Anoxic conditions are harmful to aerobic biota and impair the lake’s designated use for FWP.

There are no point source discharges into the lake; the water quality is impaired by nonpoint sources, with the lake receiving drainage from Norman, Moore, and Oklahoma City (OKC). According to model results by Vieux and Vieux (2007), it was estimated that approximately 18,000 kg of phosphorous enters Lake Thunderbird each year. Since the study was conducted, phosphorus loading into the lake has likely increased due to urban growth and the increasing area of impervious surfaces, as described in Section 3.1 (OCC 2008).

1.3 Past Remediation Attempts

There have been some efforts to improve the water quality of Lake Thunderbird, utilizing both in-lake technologies and watershed-level controls. In 2011, the Supersaturated Dissolved Oxygen (SDOX) system was installed to increase DO and therefore Oxidation Reduction Potential (ORP) in the hypolimnion. This is accomplished by withdrawing water from the deepest part of the hypolimnion, supersaturating it with oxygen, then reinjecting it at a depth of 12 m (OWRB 2020). This effort would decrease internal nutrient loading from lake sediments, as nutrients such as phosphorus are released from sediments under reducing conditions. Controlling the release of sediment phosphorus may lower harmful algal blooms. However, it has been determined that the SDOX system does not significantly affect lake water quality, as it is severely undersized (OWRB 2020).

Early erosion control efforts included installing riprap and vegetation along part of the shoreline in 2000. While these measures were successful at preventing erosion, lack of funding prevented further implementation (USBR 2009). In 2003, 415 ft of breakwater were installed as an erosion control pilot project. This consisted of 272 ft of Coir Geotextile Rolls (CGR) and 143 ft of wattle branch boxes staked at 3-ft intervals (OWRB 2005). Behind a portion of the breakwater, emergent aquatic vegetation was planted (Figure 1). Branch box breakwaters performed well at slowing wave action and protecting plants. The majority of the CGR was washed out during a storm in July 2004, preventing shoreline accretion and the establishment of emergent plants (OWRB 2005). Overall, plant survival was harmed by drought conditions following planting.

On the watershed level, Low Impact Development (LID) techniques have been implemented on a small scale. In 2007, four rain gardens were installed in the public green space of Carrington Lakes, a developing residential community in the western headwaters (Coffman 2014). LID techniques were incorporated into the design of the Trailwoods Neighborhood, constructed between 2011 and 2013. Three best management practices (BMPs) were implemented in half of the lots to reduce runoff: rain barrels, rain gardens, and downspout diversions. The developer, Ideal Homes, has also implemented bio-retention strategies in other developments in the Lake Thunderbird watershed, including in Norman and Moore (Coffman 2014).

It has been estimated that water quality standards may be met by a 35% reduction in sediment and nutrient loadings from the watershed. Based on this, the Oklahoma Department of Environmental Quality (DEQ) has established Total Maximum Daily Loads (TMDLs) for sediments, nutrients, and organic matter in order to achieve adequate DO, turbidity, and

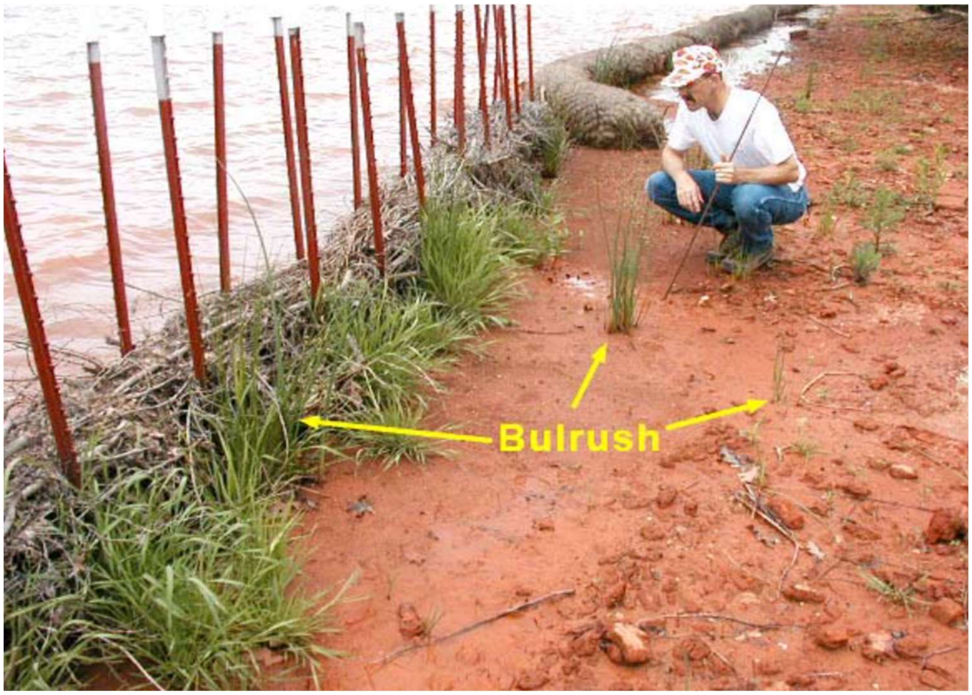


Figure 1: Softstem bulrush planted behind branch boxes, with growth limited by low lake level (OWRB 2005)

chlorophyll-a (Dynamic Solutions, LLC 2013). However, management measures to achieve these goals were not defined. Further action is needed to improve water quality and remove Lake Thunderbird from the list of impaired water bodies.

1.4 Water Quality Criteria

When a body of water is threatened or impaired, it is placed on the DEQ 303(d) list. The EPA requires states to submit their list of impaired water bodies every two years. TMDLs are then developed for the pollutants causing the impairment. A TMDL report includes a plan outlining improvements that can be made to the lake's water quality, as well as addressing non-point sources of water impairment. The impaired water body, in this case Lake Thunderbird, will stay on the 303(d) list until it meets water quality standards for its beneficial uses (USEPA 2018).

The DEQ used a sediment flux model to examine the sediment composition of Lake Thunderbird (Dynamic Solutions, LLC 2012). It was shown that decomposition of particulate matter occurs in the sediment bed, consuming DO at the sediment-water interface. Constituents such as ammonia, phosphorous, chemical oxygen demand (COD), and silica are exchanged across the sediment-water interface.

According to Oklahoma Administrative Code (OAC) 785:45-4-10 (7), in order to meet chlorophyll-a standards for an SWS, the lake should not exceed a ten-year average of 10 µg/L at a 0.5-meter depth. This criterion was exceeded substantially in years prior with an average of 24.3 µg/L in 2019 and a ten-year average of 23.2 µg/L. It has been estimated that, to meet the chlorophyll-a standard, phosphorus loading into Lake Thunderbird must be decreased by approximately 58%, or 10,000 kg/yr (OCC 2008).

In 2019, Lake Thunderbird was considered to experience metalimnetic anoxia, indicating a eutrophic system in which algal growth is increased (USBR 2020). The DO criterion levels are described in OAC 785:46-15-5. The FWP beneficial use is not supported if DO concentrations are less than 2 mg/L in more than 50% of the water column at any sample site. Additionally, to be considered supportive of FWP, no more than 10% of samples from the epilimnion, when stratified, or entire water column, when not stratified, may be less than 6.0 mg/L from April 1 through June 15 and less than 5.0 mg/L during the rest of the year (OWRB 2016).

According to OAC 785:45-5-12 (f)(7), if at least 10% of samples taken over a ten-year period exceed a turbidity of 25 NTU, the lake is considered not supportive of FWP. In 2013, about 21% of the lake samples that were collected exceeded this criterion, only increasing at the end of the year (OWRB 2014). As of 2019, the 10-year lake-wide average turbidity was 24.7 NTU, with 26.4% of samples exceeding the 25 NTU criterion (USBR 2020).

1.5 Project Goal

As the water quality continues to not meet the standards described above, complaints regarding lake aesthetics, poor taste, and poor odor have continued to grow. To combat the repercussions of increasing constituent exceedances over standard criteria placed on Oklahoma lakes, JAY Engineering evaluated watershed-level BMPs and in-lake technologies that could help alleviate the water quality issues.

The overall goals of this project were to identify the major water quality issues in Lake Thunderbird and develop a financially efficient solution to solve these problems. To this end, data collected by the COMCD Lake Thunderbird monitoring project over the last twenty years was analyzed. The information obtained through the statistical comparisons and trend analyses provided further information regarding the characteristics of the lake water and aided in developing cost-effective solutions to Lake Thunderbird's water quality issues.

Chapter 2: Water Quality Data Sources

2.1 Water Quality Parameters of Interest

Field measurements performed by JAY Engineering included turbidity, Secchi disk depth, total alkalinity, total hardness, temperature, DO, pH, ORP, specific conductance (SC), and chlorophyll-a concentrations. Field samples were analyzed for nitrate, nitrite, Orthophosphate (Ortho-P), sulfate, chloride, Total Phosphorus (TP), Total Nitrogen (TN), and Total Suspended Solids (TSS) concentrations. The justification for the use of these parameters is described in Section 2.2 below. Refer to the Sampling and Analysis Plan (SAP) in Appendix A for descriptions of sampling and analysis methods. For information on quality control and assurance measures, refer to the Quality Assurance Project Plan (QAPP) in Appendix A. The OWRB has provided historic water quality data from 2000 to 2019 on all of the above parameters, in addition to ammonia, total and dissolved iron and manganese, pheophytin-a, and total and dissolved organic carbon concentrations. For reference, the OWRB sampling sites are depicted in Figure 2.

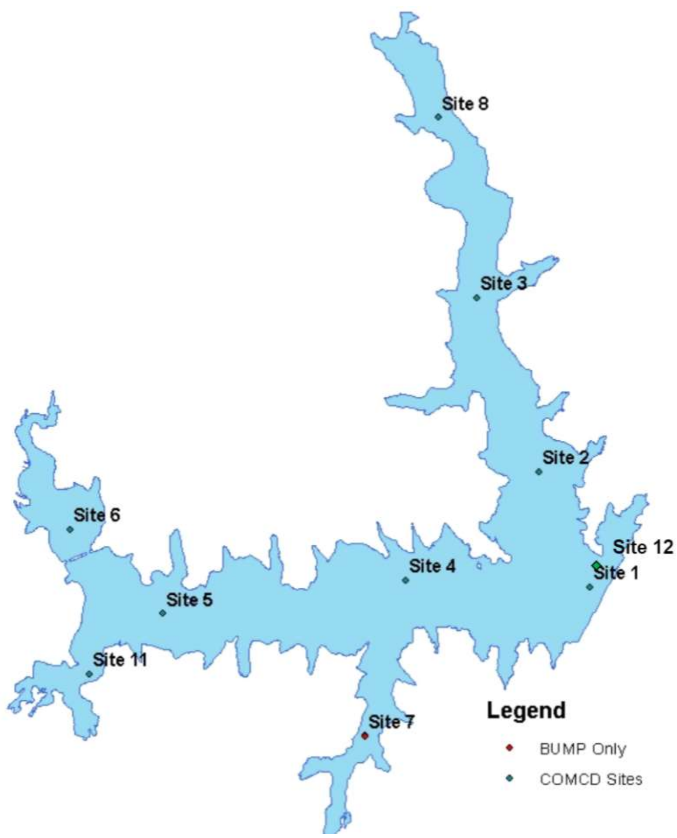


Figure 2: Location of sampling sites on Lake Thunderbird sampled by OWRB from 2000-2020 (OWRB 2020)

2.2 Justification for Chosen Parameters

Both turbidity and Secchi Disk depth are measures of water clarity. Turbidity is caused by the presence of dissolved gases and colloids in the water column. High turbidity and a shallow Secchi Disk depth may indicate the presence of suspended sediment loading (Elias et al. 2008). As outlined in OAC 785:45-5-12 (f)(7), the in-lake turbidity of Lake Thunderbird is not to exceed 25 NTU at more than 10% of samples within the most recent 10 years.

Water temperature controls the rate of chemical reactions, including metabolic reactions in organisms. All organisms have an optimal temperature range for their survival. Additionally, the saturation DO decreases with increasing temperature. A DO concentration of 5 mg/L is considered the chronic minimum for the survival of most aquatic organisms (Elias et al. 2008).

pH is a measure of the activity of free hydrogen ions in water and is measured to determine how acidic or basic a water body is. Increases in surface water pH may indicate increased primary productivity, as carbon dioxide is stripped from the epilimnion (OWRB 2020). Water pH determines the solubility and bioavailability of both nutrients, such as phosphorus, nitrogen, and carbon, and heavy metals such as lead, copper, and cadmium. Additionally, pH can alter the toxicity of compounds such as ammonia. pH is generally used to set water quality criteria for lakes and streams because of its potential impacts to the life cycle stages of aquatic macroinvertebrates and certain salmonids, which can be adversely affected when pH levels are above 9.0 or below 6.5 (Elias et al. 2008).

ORP, measured in millivolts (mV), corresponds with the ability of a system to oxidize or reduce other molecules. Positive and negative ORP respectively correspond with oxidizing and reducing conditions. Higher ORP typically signifies greater DO concentrations and thus a higher potential to oxidize other molecules. The redox potential is important to the retention and release of phosphorus by iron. The oxidized form of iron has a high affinity to bind phosphorus, while the reduced form does not. At ORP of 200mV or lower, iron will be reduced, releasing phosphorus from lake sediments due reduced iron's lower affinity to bind phosphorus (Sondergaard 2009).

SC is a measurement of the capacity of water to conduct an electrical current and serves as a surrogate for the total dissolved ion concentration for a certain temperature. The SC25, SC adjusted to a temperature of 25°C, can be used to monitor seasonal concentrations of total dissolved salts (Elias et al. 2008).

Chlorophyll-a concentrations are a universally accepted measure of algal biomass in bodies of water. Consistent trends in chlorophyll-a concentrations are good indicators of changes in a lake's trophic status (Elias et al. 2008). Algal growth is typically limited by availability of either nitrogen or phosphorus. Nutrient concentrations are expected to follow seasonal patterns. Bioavailable forms of phosphorus and nitrogen are typically highest in the spring due to the mixing of sediment nutrients during spring turnover. Nutrient levels then decrease during the summer as they are taken up by algae. When the lake is stratified, any nutrient load input may induce algal blooms (Elias et al. 2008). Ortho-P is the form of phosphorus directly taken up by phytoplankton and is therefore a good measure of the amount of phosphorus directly available for algal growth (Eldridge et al. 2014).

Chloride is a particularly good indicator of wastewater plumes as well as inputs and accumulation of road salt (Elias et al. 2008). The chloride tolerance of aquatic organisms varies between species. The Department of Environmental Management (DEM) in Rhode Island has set an acceptable acute chloride limit of 860 ppm to prevent immediate exposure effects and a chronic exposure limit of 230 ppm to prevent long term exposure effects to freshwater organisms (Hunt et al. 2012).

Sulfate is the most common form of sulfur in well-oxygenated waters. Point sources of sulfate include wastewater, municipal, or industrial discharges as well as agricultural runoff. Sulfate is an essential nutrient to plants; algal growth will not occur when sulfate concentration is less than 0.5 mg/L (Cooke n.d.).

2.3 Data Limitations

The regularity and duration of sampling varied between sites and water quality parameters. For some sites and parameters, the records were too short or there were too many gaps in the data to determine temporal trends. For example, nutrient data for Site 3 was only recorded in 2000, 2004, 2005, and 2016-2019. Where the product of seasons and years was less than 25, the Seasonal Kendall Test (SKT) was not performed. Depending upon the site, TSS data extends to either 2009 or 2012, so trends in TSS over the past 8 years could not be determined.

The sampling intervals and the months sampled were not consistent between years. This may have impacted the SKT, as accurate trends may not be discernible in months that were infrequently sampled. For a given sampling event, not all parameters were measured on the same date, making it difficult to determine correlations between two water quality parameters. If the two parameters were measured on different days, it is possible that the water quality could vary due to factors such as precipitation.

Some of the Ortho-P and TSS samples were analyzed past their hold times, which could impact the accuracy of the analysis. Hence, these measurements were not considered in the trend analysis. Some samples had a measured Ortho-P concentration that was greater than the TP concentration. Since one or both of those values must be erroneous, they were both excluded from the trend analysis.

The Detection Limit (DL) of an analysis method or piece of equipment is the lowest concentration that can be distinguished from a concentration of zero. Some of the data points were Below Detection Limit (BDL), meaning that the concentration of the analyte is an unknown value between zero and the Detection Limit (DL) of the analysis method or equipment (USEPA 2006). The value of BDL data points was set to the provided DL in the data analysis.

Chapter 3: Land Use, Population, and Hydrologic Data

3.1 Watershed Land Use and Urbanization

The Lake Thunderbird Watershed, covering approximately 257mi^2, includes two distinct ecoregions: the Central Great Plains, consisting of mixed grass prairie, and the forested Cross Timbers. The Central Great Plains comprises approximately one third of the watershed and has clay-rich soils, leading to higher runoff rates than the sandy Cross Timbers (Julian et al. 2015). The two ecoregions are shown in Figure 2, with the Central Great Plains and the Cross Timbers respectively located on the left and right sides of the bolded line dividing the watershed. Both ecoregions have experienced intense urbanization since the 1970s (Figure 3), with the Central Great Plains being more heavily urbanized. From 1975 to 2011, urban land cover increased from 13% to 33% in the Central Great Plains and from 4.8% to 8.6% in the Cross Timbers (Julian et al. 2015).

Land cover has a significant impact on surface water quality due to its regulation of pollutants in surface runoff. Agriculture and urban land use have been correlated with increased concentrations of phosphorus, nitrogen, ammonia, and other pollutants, while these concentrations are negatively correlated with the percentage of woodlands and grasslands (Chen et al. 2016). Agricultural land use can contribute to nutrient and bacteria loading from fertilizer, land application of biosolids, and animal waste runoff into streams. Cattle massing along river shorelines not only decreases the distance from animal waste to tributaries, but also increases shoreline erosion, contributing to sediment loading. Shoreline erosion can contribute to increased turbidity and nutrient loading due to the relatively greater nutrient levels in shoreline soils (OCC 2008).

The transition from agricultural to urban land use has been accompanied by stream channel losses (Figure 4). Impervious surface area tends to increase with urbanization, resulting in higher amounts of runoff that can erode stream beds. Increasing impervious surface area also decreases infiltration and the accompanying filtration of pollutants by soil and vegetation (Martin-Mikle et al. 2015). Eroded streambed materials may be carried downstream to Lake Thunderbird, contributing to sediment loading. The replacement of natural channels with stormwater systems can lead to more rapid delivery of sediments and nutrients to downstream waters. The high nutrient and sediment loadings into Lake Thunderbird come primarily from urban areas of the watershed (Julian et al. 2015). Simulations conducted by Vieux and Vieux projected that conversion from agricultural to urban land use could increase phosphorous loading to the lake by 0.1-0.4 lb/ac/yr, while nitrogen loading would increase by 0.6-2.4 lbs/ac/yr, depending upon the extent of urbanization (2007).

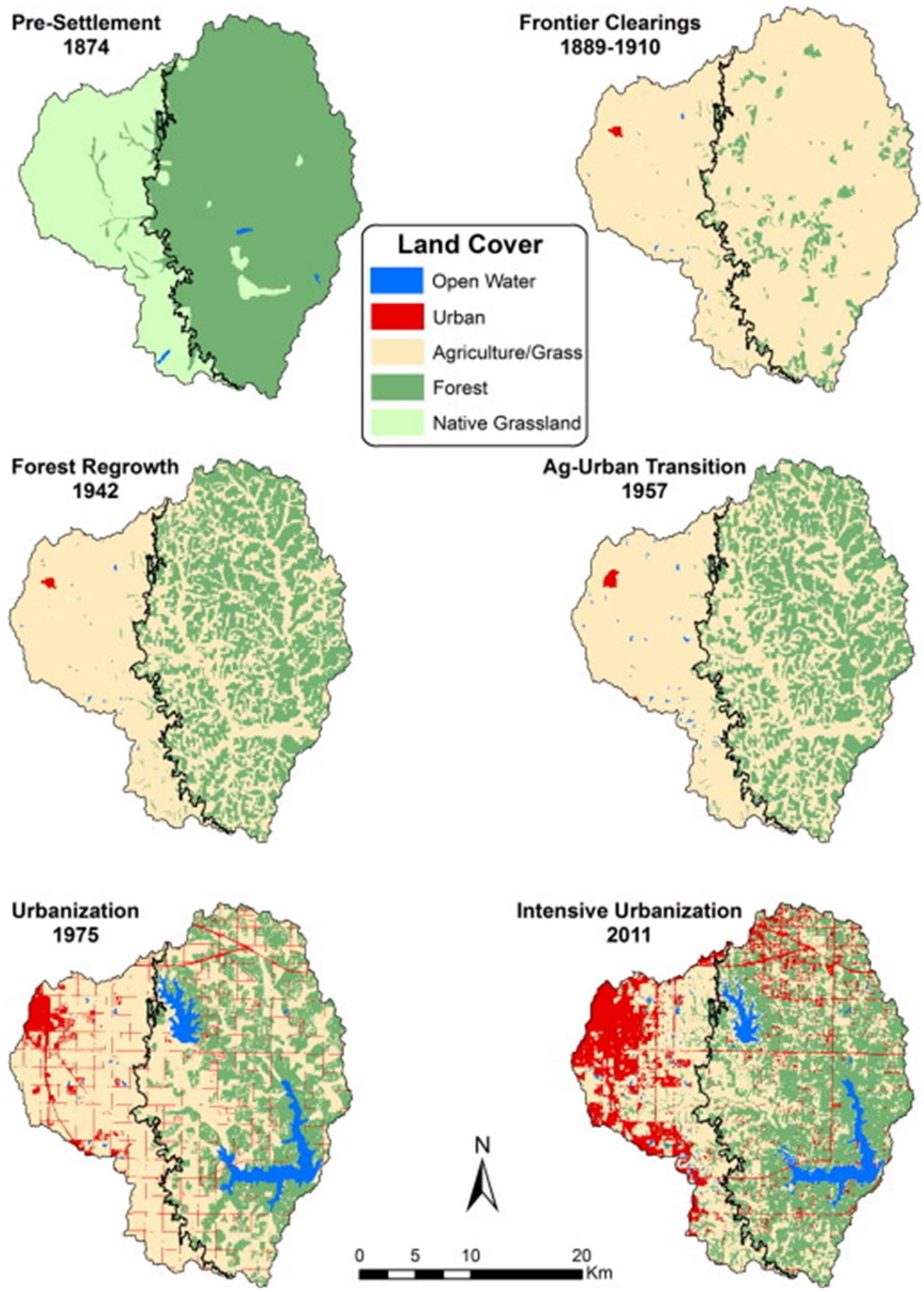


Figure 3: Land use in Lake Thunderbird Watershed over time, where the bolded line down the middle of the watershed demarcates the boundary between the Central Great Plains (left) and the Cross Timbers (right) (Julian et al. 2015)

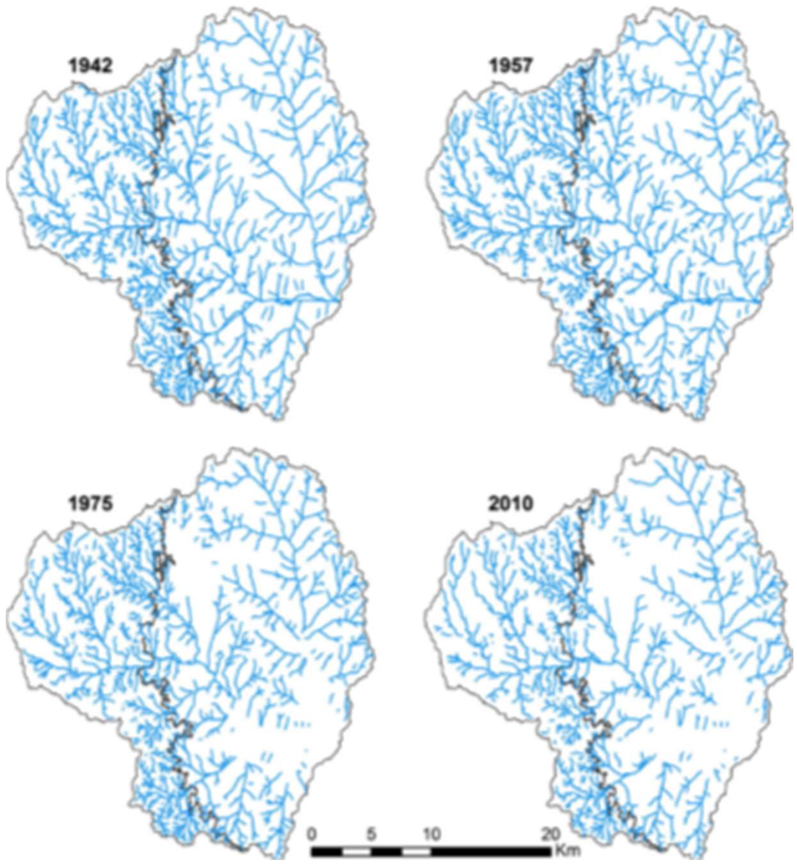


Figure 4: Stream channel losses in Lake Thunderbird Watershed over time, where blue lines represent stream channels (Julian et al. 2015)

3.2 Population Growth

Annual changes in land use are not readily available. Hence, yearly population estimates were used as a surrogate for the extent of urbanization. As shown in Table 1, the majority of external nutrient and sediment loadings into Lake Thunderbird originate from Moore, Norman, and OKC, while the contributions from other cities in the watershed such as Del City and Midwest City are relatively small. The populations of these cities have an impact on Lake Thunderbird's water quality, as these cities contribute runoff to the lake. The populations of the three cities have all increased during the study period of 2000 to 2019 (Table 2). Yearly population estimates for Norman, OKC, and Moore were taken from the U.S. Census Bureau (USCB) for 2000-2019 (USCB 2020, 2016).

Table 1: Relative contribution of point and nonpoint source loading of pollutants (Dynamic Solutions, LLC 2013)

City Name	% TN Load	%TP Load	%CBOD Load	% Sediment Load
Moore	25.4	28.1	31.5	21.1
Norman	39.5	38.0	38.5	41.0
Oklahoma City	32.4	31.1	27.7	35.1
Other Areas	2.6	2.8	2.3	2.7

Table 2: Population growth in cities contributing runoff to Lake Thunderbird, 2000 to 2019 (USCB 2020)

City	Year 2000	Year 2019
Norman	95,694	124,880
Oklahoma City	506,671	643,692
Moore	41,138	60,943

3.4 Hydrologic Parameters and Data Sources

Several hydrologic parameters, such as water inflow, precipitation, evaporation, sedimentation, and overall lake water levels can affect chemical and biological aspects of water quality over time in large bodies of water. Lake inflow and storm water runoff can add pollutants and nutrients to lakes, which can in turn affect nutrient content, sediment loading, and stratification. Lake water levels, which are affected by precipitation and temperature, can influence oxidation reduction processes and anoxia. Lake sedimentation increases over time and reduces the storage capacity of lakes.

A study performed on 11,882 lakes in the United States found that summer temperatures drastically affect water quality in the lake by causing thermal stratification and increasing primary productivity, affecting N and P cycling as well as DO concentrations (Collins et al. 2019). Since Oklahoma experiences both hot summers and cold winters, often with a lot of precipitation, both of these factors should be considered when looking at the hydrologic effects on the water quality.

Evaporation and inflow can also be used to predict and understand changes in water quality. Specifically, the ratio of evaporation to inflow, or E:I, is a common indicator of water quality. A study performed on over 50,000 lakes found a strong correlation between large E:I values and elevated nitrogen concentrations. Large E:I values were also associated with poorer biological condition (Brooks et al. 2014). These parameters may be important for the Lake Thunderbird Watershed, as major water quality issues for Lake Thunderbird include elevated nutrient and chlorophyll-a concentrations.

A common method of tracking hydrologic inputs and outputs for a large body of water is by using a water budget. The water budget equation is:

$$\frac{\mathrm{dV}}{\mathrm{dt}} = \mathrm{P} + \mathrm{I} - \mathrm{ET} - \mathrm{O} \pm \mathrm{G}$$

Equation 1: Water Budget

where dV/dt is the change in storage volume over time, P is precipitation, I is inflow, ET is evapotranspiration, O is outflow, and G is groundwater interactions, such as seepage or infiltration.

For Lake Thunderbird, most of the water budget variables can be determined by using reported values from sources such as the United States Geological Survey (USGS) and the United States

Army Corps of Engineers (USACE). Water elevations, rainfall, and evaporation are measured daily by the USACE, with daily measurements dating back to 1994 (n.d.). The major tributaries that feed into Lake Thunderbird are Little River and Hog Creek, which feed in from the north on the western and eastern sides of the lake, respectively. Inflow rates for these tributaries can be estimated using the USGS application StreamStats (n.d.).

Chapter 4: Water Quality Analysis

4.1 Water Quality Parameter 10-year Averages

Each site was evaluated using the most recent 10-year data available. Data was incorporated from all sites which had data throughout the ten-year period. Ten-year averages were calculated individually for each site and are presented in Appendix B. For each parameter, a weighted whole-lake ten-year average was calculated using the average concentrations at each site and the proportion of total samples at each site (Equation 2).

$$Weighted\ Average\ = \sum_{i=1}^{n} \bar{x}_i * \frac{m_i}{m_{total}}$$

Equation 2: Whole-lake ten-year average of water quality parameters

where $\bar{x}_i$ is the average value of the parameter at site i, and m_i is the number of data points from site i. Table 3 presents the ten-year whole-lake averages for TSS, chlorophyll-a, turbidity, nitrite-nitrate (NO_2+NO_3), TP, Ortho-P, and DO.

The standard deviation of each parameter was then calculated, incorporating all samples from all sites over the given time range. Standard deviations were very large, on the same order of magnitude as the ten-year average (Table 3). This may be due to large seasonal variations in the data. For example, higher values of chlorophyll-a and turbidity and lower values of DO were measured in the summer months of July, August and September compared to the rest of the year.

Table 3: Ten-year whole-lake averages of water quality parameters at Lake Thunderbird with standard deviations

Parameter	Years	Sites	Mean	Standard Deviation
TSS	2003-2012	1, 2, 4, 6, 11	19.82 mg/L	±21.69
Chlorophyll-a	2010-2019	1, 2, 3, 4, 5, 6, 8, 11	19.15 µg/L	±17.03
Turbidity	2010-2019	1, 2, 3, 4, 5, 6, 8, 11, 12	25.13 NTU	±27.03
NO_2+NO_3	2010-2019	1, 2, 4, 6, 8, 11	0.16 mg/L	±0.38
TP	2010-2019	1, 2, 4, 6, 8, 11	0.08 mg/L	±0.11
Ortho-P	2010-2019	1, 2, 4, 6, 8, 11	0.04 mg/L	±0.08
DO	2011-2020	1, 3, 4, 5, 6, 8, 11, 12	7.07 mg/L	±3.06

The ten-year chlorophyll-a average, at 19.15 µg/L, greatly exceeds the criterion of 10 µg/L for a SWS with 58.4% of samples across all sites exceeding 10 µg/L. The ten-year average for turbidity just exceeds the criterion of 25 NTU (Table 3). If 10% of samples collected over a period of 10 years exceeds a turbidity of 25 NTU, the lake is not supportive of FWP. This criterion was exceeded, as 28.7% of samples exceeded the 25 NTU criterion. The average DO, at 7.07 mg/L, is supportive for FWP; however, this value may be impacted by the prevalence of shallow samples.

4.2 Correlations Between Water Quality Parameters

Two water quality parameters were plotted against one another to assess whether any correlation was exhibited. The correlation coefficient was then returned through a linear regression except where noted otherwise. Only surface water samples were compared, as chlorophyll-a is typically measured at a depth of 0.5m.

There was a negative trend observed between sample turbidity and Secchi disk depth (Figure 5). Addressing the turbidity issues at Lake Thunderbird should therefore improve lake aesthetics by increasing water clarity.

Correlations between chlorophyll-a and TP concentrations have been observed since the 1960s, and empirical relationships between the two are often used in examining the primary productivity of aquatic ecosystems. Many of these models assume a positive, linear correlation between the two parameters on a log-log scale. This is because phosphorus is often the nutrient limiting algal growth and therefore chlorophyll-a production (Stow and Cha 2013). A strong positive correlation between chlorophyll-a and TP was observed at Site 1 (r^2=0.3104), while weaker positive correlations were observed at Sites 4 and 8 (Figure 6). There was no correlation between chlorophyll-a and TP at Site 6 (r^2=0.0077). This may be due to lower algal growth in the riverine area.

Little to no correlation was found between TP and turbidity at lacustrine sites (Figure 7); however, stronger positive correlations were observed between TP and turbidity at Sites 6 and 8, located in riverine areas (Figure 8). Positive correlations between TP and TSS were also observed (Figure 8). This may be because riverine areas are influenced by runoff. Correlations between turbidity and TP, as well as between TSS and TP have previously been observed in stormwater runoff (Lubliner 2007). This is because phosphorus is often bound to sediments, and sediment loading can contribute to turbidity.

These results suggest that reducing sediment loadings into Lake Thunderbird may also reduce TP concentrations by decreasing loading of sediment-bound phosphorus. Likewise, reducing phosphorus loading may lead to reductions in algal growth by restricting nutrient availability.

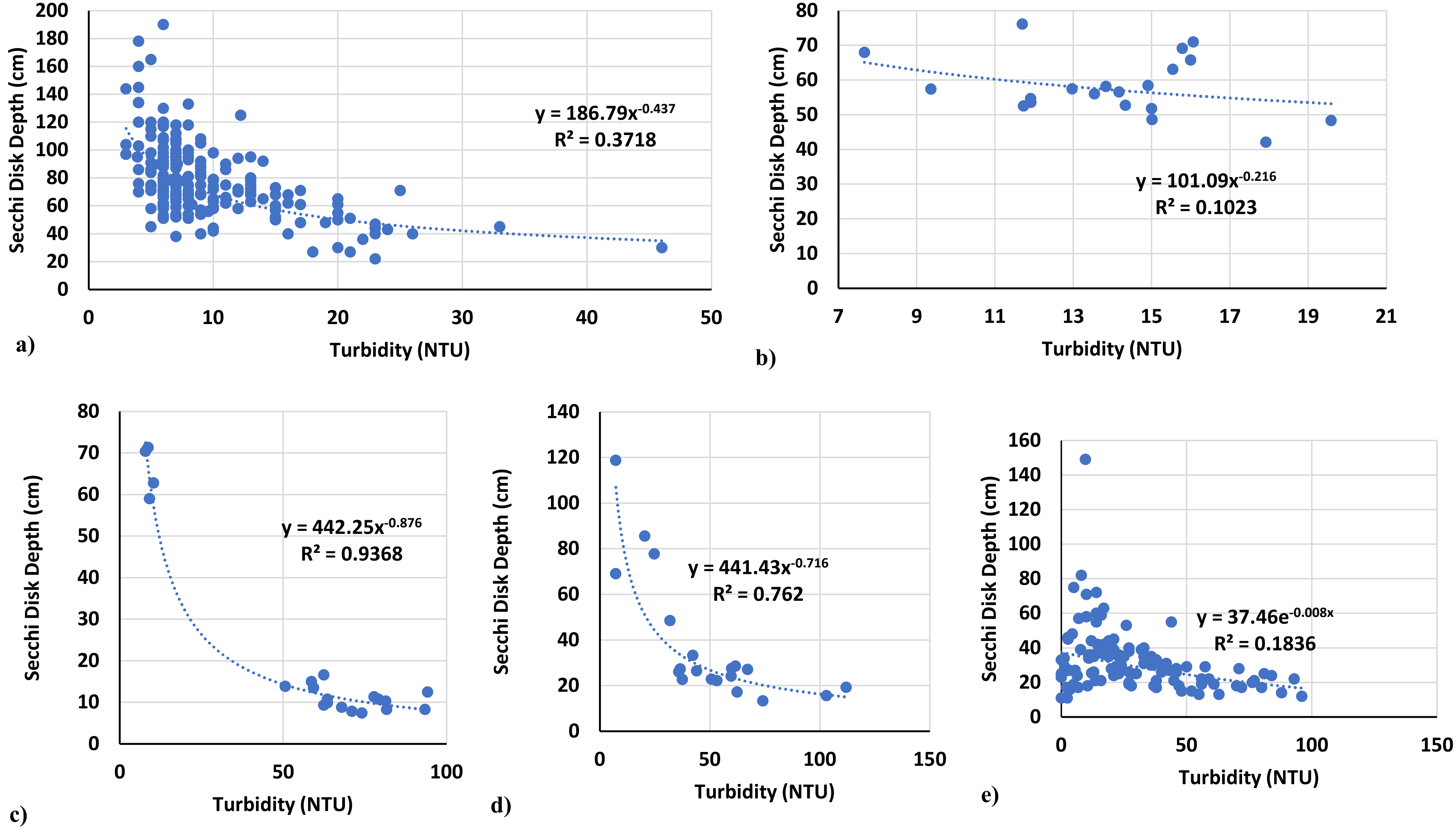


Figure 5: Relationships between turbidity and Secchi disk depth at Lake Thunderbird from 2000 to 2019 at a) Site 1, b) Site 3, c) Site 4, d) Site 6, and e) Site 8

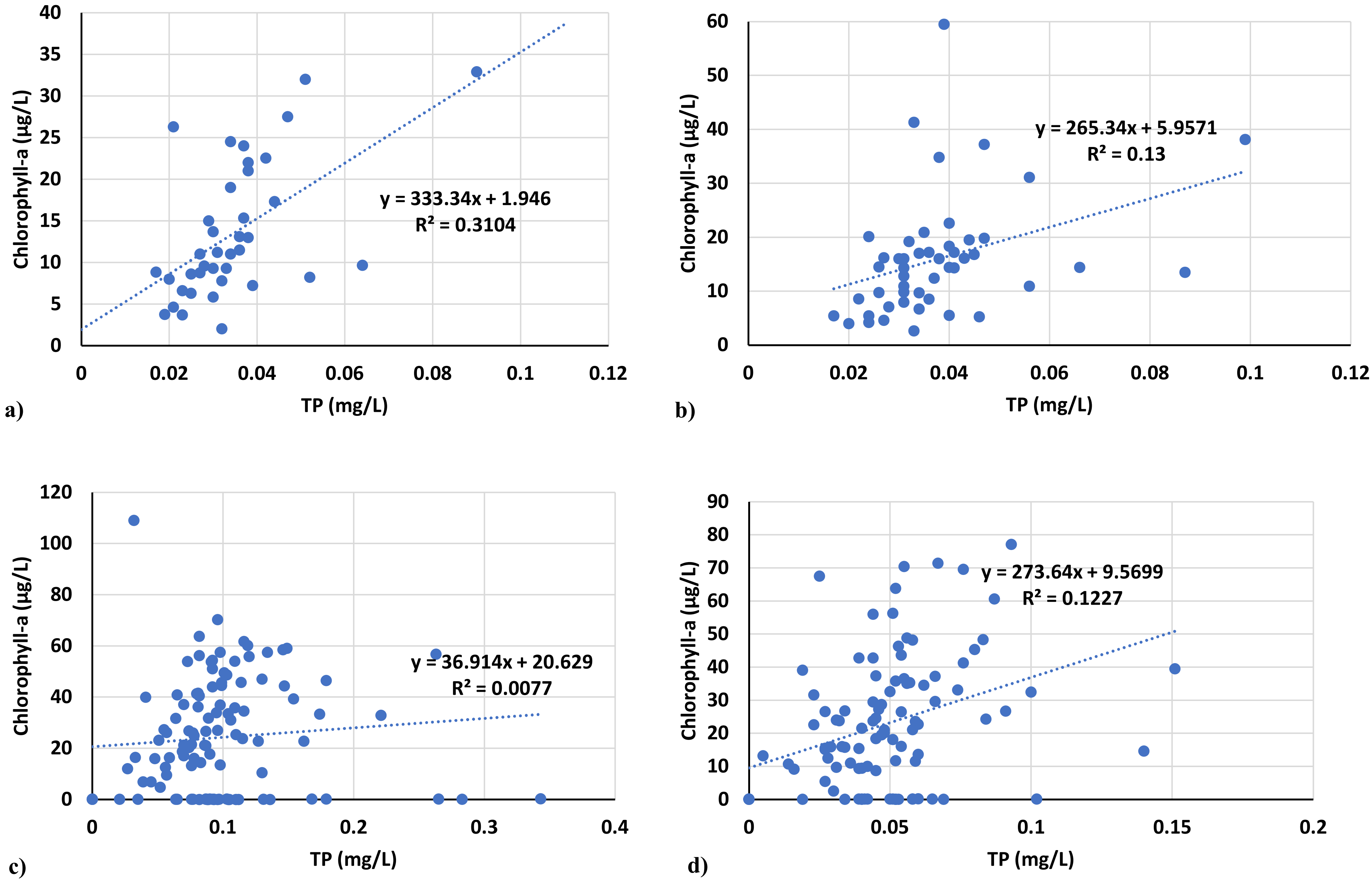


Figure 6: Relationships between TP and chlorophyll-a concentrations at Lake Thunderbird from 2000 to 2019 at a) Site 1, b) Site 4, c) Site 6, and d) Site 8

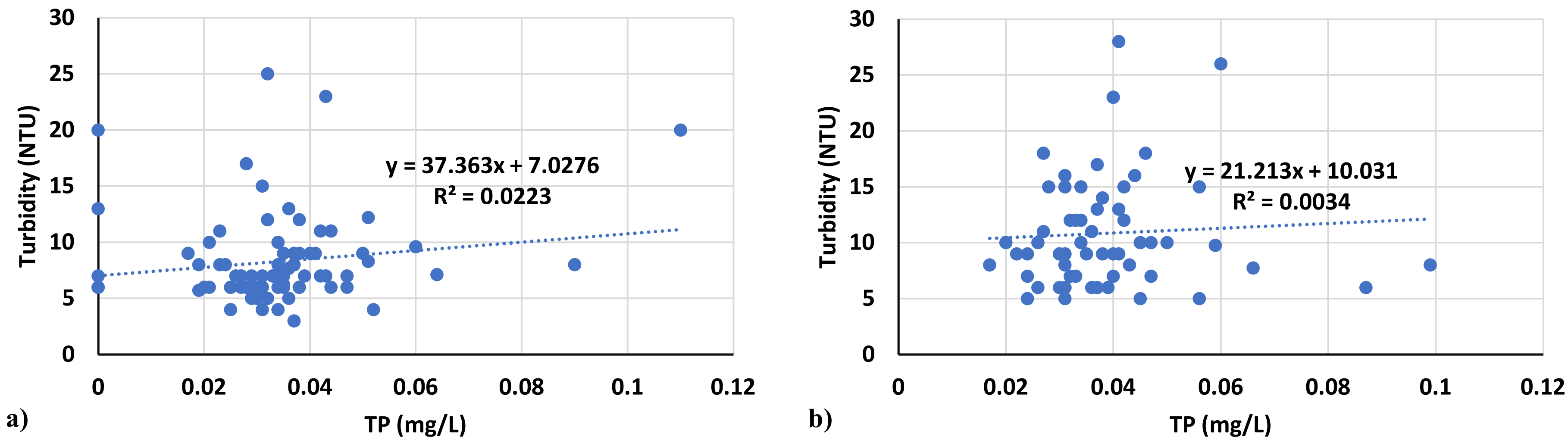


Figure 7: Relationships between TP and turbidity at Lake Thunderbird from 2000 to 2019 at a) Site 1, b) Site 4

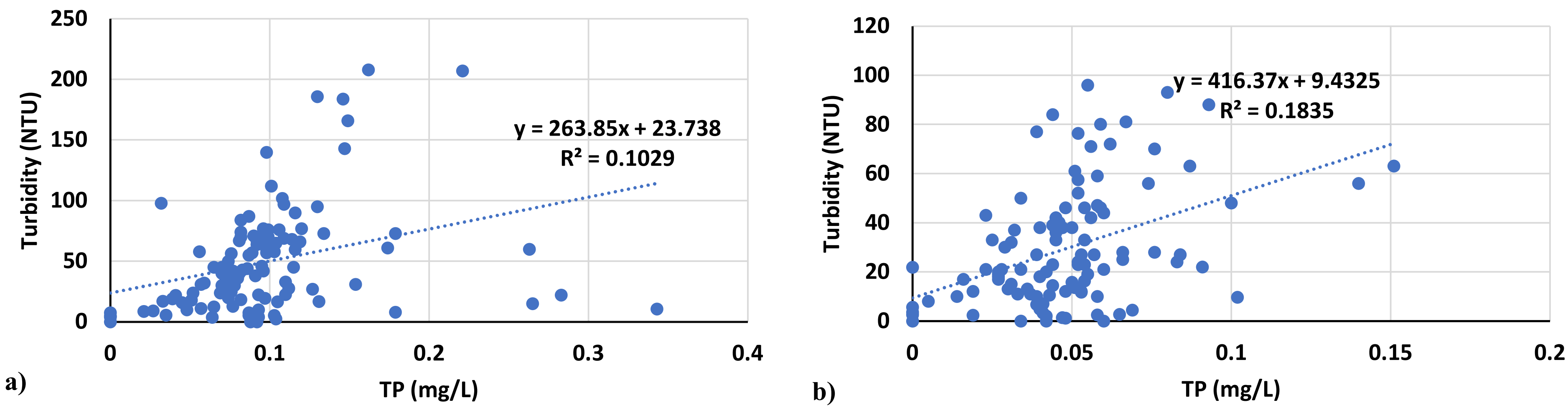


Figure 8: Relationships between TP and turbidity at a) Site 6 and b) Site 8 and between TP and TSS at c) Site 6 and d) Site 8 at Lake Thunderbird for 2000-2019

4.3 Trends in Water Quality Over Time

To identify trends in Lake Thunderbird's water quality while accounting for seasonal variation, the SKT was used (Helsel and Frans 2006, Reckhow et al. 1993). The SKT was run in R using the envstats package. For the SKT, BDL values were replaced with the DL. This was deemed sufficient as the test only requires the direction of change. For example, a detectable value following a BDL was a positive change, while two BDL readings were considered zero change. In the SKT, each sampling month was considered a separate season.

The significance for each trend was determined based on a 95% confidence interval. Reference Appendix B for the p-values returned by the SKT. The Sen Slope β represents the rate of change: the change in the value of the water quality parameter per unit time. The test statistic, τ, is analogous to the correlation coefficient, which measures the strength of the relationship between two variables (Meals et al. 2011). These parameters are presented in Table 4 for each significant trend in surface water quality. Measurements at depths of 0.5m or less were considered as surface water. All slopes are expressed as analyte unit of measurement per year.

Site 7 was not analyzed using the SKT. There was no nutrient data provided for Site 7, while no transparency or profile measurements were available from 2009 onwards. Nutrient data for Site 12 was only available for 2016-2019, and chlorophyll-a and turbidity measurements were only provided for 2019, meaning that long-term trends for these parameters could not be determined. Thus, only DO was analyzed for Site 12.

At Sites 1-5, the DO saturation increased by 0.4-1.2% from 2000-2019; however, the percent DO saturation decreased significantly at Site 12 (Table 4). Chlorophyll-a concentrations were found to increase in lacustrine sites at rates of 0.33-0.4 µg/L/yr, suggesting increasing algal growth. Conversely, chlorophyll-a decreased over time in riverine zones.

No significant trends in TP were observed. In the lacustrine zone, significant decreases in Ortho-P and NO_2+NO_3 occurred at respective rates of .00043 mg/L/yr and 0.00625 mg/L/yr (Table 4). Increasing algal growth also indicates that nutrient loadings into the lake must be reduced. Changes in nutrient concentrations of the riverine areas were insignificant, suggesting that N and P loadings from the tributaries have not decreased as a result of the TMDL.

TSS increased significantly at Sites 1, 2, 4, and 6. Changes in TSS were the largest observed, at rates of 0.83-3.5 mg/L/yr (Table 4). Trends in TSS also exhibited the highest correlation. Based on these results, the proposed solution suite must target TSS loading into the lake. The largest increase in TSS occurred at Site 6, suggesting that TSS loading from the Little River is an issue that must be addressed.

Table 5 presents the results of the SKT on deeper waters. Few significant trends were observed in water quality at deeper depths. DO saturation was observed to increase at Sites 1, 2, 4 and 12 at a rate of approximately 0.1%/y (Table 5). The decreases in nutrients observed at Site 1 were also negligible.

Table 4: Test statistics τ and β from SKT of water quality parameters with significant trends over 2000-2019 for depths of 0.5m or less at OWRB sampling locations; dashes denote insignificant relationships

Site	Statistic	DO (% Saturation)	Chlorophyll-a (µg/L)	Turbidity (NTU)	Secchi Disk Depth (cm)	Ortho-P (mg/L)	NO_2+NO_3 (mg/L)	TSS (mg/L)
1	τ	0.13981	0.087783	0.14838	-0.19286	-0.33284	-0.31854	0.49802
	β	0.6	0.33	0	-1	-0.00043	-0.00625	1
2	τ	0.24212	0.13987	-	-	-	-	0.42424
	β	0.90749	0.35	-	-	-	-	0.83333
3	τ	0.30374	-	-	-	-	-	-
	β	1.2563	-	-	-	-	-	-
4	τ	0.09611	-	0.38514	-0.38673	-	-	0.43171
	β	0.40385	-	1	-3.1177	-	-	0.85714
5	τ	0.15527	0.13440	-	-0.15234	-	-	-
	β	0.68958	0.4	-	-0.5	-	-	-
6	τ	-	-0.19761	-0.13393	0.13089	-0.30467	-0.38679	0.31179
	β	-	-0.88429	-1.3094	0.66667	-0.0025	-0.005	3.5
8	τ	-	-0.39197	-0.30144	-	-0.43601	-0.50471	-
	β	-	-2.6667	-2.3333	-	-0.00173	-0.00556	-
11	τ	-	-0.26014	-	-	-0.4098	-0.48449	-
	β	-	-1.5354	-	-	-0.00325	-0.00556	-
12	τ	-0.17311	-	-	-	-	-	-
	β	-2.3	-	-	-	-	-	-

Table 5: Test statistics τ and β from SKT of water quality parameters with significant trends over 2000-2019 for deeper waters or less at OWRB sampling locations; dashes denote insignificant relationships

Site	Depth (m)	Statistic	DO (% Saturation)	NO_2+NO_3 (mg/L)	Ortho-P (mg/L)
1	15-16	τ	-	-0.28683	-0.11916
		β	-	-0.00625	-0.0025
2	10-12	τ	0.21081	-	-
		β	0.08727	-	-
4	9-10	τ	0.14275	-	-
		β	0.1	-	-
12	12-13	τ	0.27699	-	-
		β	0.11339	-	-

4.4 Ordinary Least Squares Regressions Using Population

To explore the relationships between population and water quality parameters, an Ordinary Least Squares (OLS) analysis was conducted in R. The OLS regression was used to model the relationship between a given water quality parameter and three independent variables: the populations of Norman, Moore, and OKC. All potential explanatory variables were incorporated into an initial OLS model for a given water quality parameter. The p-value for the relationship between each independent variable and the dependent variable were returned. These p-values, as well as the adjusted r^2 value for each model, are presented in Table 6.

To improve the model, independent variables that do not have a significant relationship with the water quality parameter can be removed (Chen et al. 2016). The OLS model was performed with all of the cities' populations. When one or more of the p-values returned by the model was greater than 0.5, the population with the highest p-value was removed and the OLS model was rerun. The p-values for the remaining two populations, as well as the new adjusted r^2, are presented in Table 7.

Water quality data was analyzed from Sites 1, 4, 6, and 8. Sites 1 and 4 were taken as representative of the lacustrine zones. Sites 6 and 8 represented the two major tributaries on the northern side of Lake Thunderbird, which receive runoff from the cities in question.

Generally, there were few significant relationships between population and water quality. There were no significant trends observed between any of the three populations and TP or TSS (Table 6). Of the three cities, only Moore's population exhibited significant correlation, being significantly correlated with chlorophyll-a at Sites 1, 6, and 8, as well as turbidity at Sites 4 and 8, NO_2+NO_3 at Site 8, and Ortho-P at Site 6.

Table 6: p-Values and Adjusted r^2 from OLS model between populations of Norman, Oklahoma City, and Moore and water quality parameters; bolded values indicate significant relationships at the 95% confidence level

Site	Statistic	Chlorophyll-a (µg/L)	Turbidity (NTU)	NO_2+NO_3 (mg/L)	Ortho-P (mg/L)	TP (mg/L)	TSS (mg/L)
1	p(Norman)	0.6854	0.1839	0.439	0.396	0.999	0.908
	p(OKC)	0.6682	0.0898	0.420	0.490	0.939	0.391
	p(Moore)	**0.0314**	0.4255	0.681	0.348	0.687	0.444
	Adjusted r^2	0.4916	0.1161	0.2219	-0.1497	-0.1852	0.01462
4	p(Norman)	0.9299	0.585727	0.23891	0.798	0.522	0.364
	p(OKC)	0.6496	0.542771	0.61291	0.602	0.877	0.951
	p(Moore)	0.0739	**0.018774**	**0.00112**	0.457	0.716	0.596
	Adjusted r^2	0.3105	0.5841	0.8223	-0.2831	-0.08197	-0.07847
6	p(Norman)	0.66519	0.173	0.660	0.65157	0.619	0.310
	p(OKC)	0.47314	0.107	0.398	0.41295	0.725	0.271
	p(Moore)	**0.00742**	0.734	0.544	**0.00511**	0.647	0.582
	Adjusted r^2	0.3404	0.02603	0.102	0.4569	-0.2066	0.7372
8	p(Norman)	0.192145	0.47170	0.906	0.9877	0.1460	0.886
	p(OKC)	0.450697	0.22513	0.182	0.6086	0.6915	0.822
	p(Moore)	**0.006701**	**0.04474**	0.109	0.7115	0.1755	0.840
	Adjusted r^2	0.6922	0.645	0.1551	0.2514	0.1617	-1.166

In certain cases, the fit of the model could be improved by removing one city as an independent variable and rerunning the OLS model. When Norman was removed from the model, significant relationships were observed between the populations of Moore and OKC and chlorophyll-a at Sites 4 and 6, respectively (Table 7). The population of OKC also showed significant trends with turbidity at Site 4 and with Ortho-P at Site 6. When OKC was not included in the model, NO_2+NO_3 exhibited a significant relationship with the population of Norman (Table 7). It is possible that runoff from OKC dilutes runoff from Norman for nitrate and nitrite.

Table 7: p-Values and Adjusted r^2 from updated OLS model between populations of Norman, Oklahoma City, and Moore and water quality parameters; bolded values indicate significant relationships at the 95% confidence level, while dashes indicate population not considered

Site	Statistic	Chlorophyll-a (µg/L)	Turbidity (NTU)	NO_2+NO_3 (mg/L)	Ortho-P (mg/L)	TP (mg/L)	TSS (mg/L)
1	p(Norman)	-		0.487		-	-
	p(OKC)	0.0697		0.412		0.738	0.325
	p(Moore)	**0.0217**		-		0.633	0.368
	Adjusted r^2	0.5267		0.2800		-0.06671	0.1764
4	p(Norman)	**-**	**-**	**0.000114**	-	0.494	0.299
	p(OKC)	0.1114	**0.00235**	**-**	0.469	-	-
	p(Moore)	**0.0429**	**0.01421**	**0.000212**	0.448	0.428	0.343
	Adjusted r^2	0.3533	0.601	0.8383	-0.1129	0.06854	0.07496
6	p(Norman)	-	0.0799	-	**-**	0.608	0.188
	p(OKC)	**0.00284**	0.0834	0.1896	**0.00194**	-	0.262
	p(Moore)	**0.00402**	-	0.3314	**0.00222**	0.675	-
	Adjusted r^2	0.3736	0.07648	0.1615	0.4924	-0.1192	0.7781
8	p(Norman)			-	-	0.0679	-
	p(OKC)			0.0548	0.4230	-	0.757
	p(Moore)			0.0708	0.6758	0.0930	0.719
	Adjusted r^2			0.2475	0.3346	0.2391	-0.1183

4.5 Analysis of Hydrologic Effects

The Kruskal-Wallis test is a non-parametric method that determines whether the means of two or more independent samples are significantly different. For an explanation of the Kruskal-Wallis test, see USEPA (2006). The test was implemented by separating data for one water quality parameter into 3 different groups:

- Group 1: Data from months with precipitation in the 0^{th} to 50^{th} percentile
- Group 2: Data from months with precipitation in the 50^{th} to 90^{th} percentile
- Group 3: Data from months with precipitation in the 90^{th} to 100^{th} percentile.

Monthly precipitation data from the past 20 years were taken from USACE. Months were then ranked and grouped by percentile, and the water quality data were split into these groups based on their sampling dates. The results of the Kruskal-Wallis test are presented in Table 8.

Table 8: p-values returned by the Kruskal-Wallis test; bolded values indicate significant differences between samples collected during months with 0-50, 50-90, and >90 % rainfall

Site	DO (mg/L)	Chlorophyll-a (µg/L)	Turbidity (NTU)	TP (mg/L)	Ortho-P (mg/L)	NO_2+NO_3 (mg/L)
1	**6.1E-09**	**0.00141**	0.8436	0.05693	**0.009124**	**0.0002782**
2	**2.869E-08**	0.1922	0.2748	0.4742	0.3272	0.6648
3	**4.195E-05**	0.1273	0.3578	0.1088	0.2283	-
4	**6.633E-07**	**0.02767**	**0.00971**	0.1658	0.9693	0.1413
5	**2.296E-05**	0.05912	0.3888	**0.01988**	0.09289	-
6	**3.149E-09**	**0.003323**	0.8104	0.2614	0.2343	0.2769
8	**9.204E-05**	**0.01265**	0.1711	0.2702	0.613	0.5914
11	**4.525E-05**	0.05994	0.9227	0.2402	0.7436	0.6383
12	**1.195E-08**	0.2118	0.2795	0.5318	0.9375	**0.03292**

The results of this test show that there are significant differences in the precipitation-based groups for DO at each site; the chlorophyll-a at sites 1, 4, 6, and 8; the turbidity at site 4; the TP at site 5; the ortho-P at site 1; and the NO_2+NO_3 at sites 1 and 12 at an alpha value of 0.05. The Kruskal-Wallis test determines whether one set of samples is significantly different from the others; however, it does not indicate which sets of samples are significantly different. To determine which group of samples was significantly different, Tukey's method was followed for the sites and parameters where the p-value was below 0.05 (USEPA 1997). Table 9 summarizes which groups were significantly different.

This test shows that at each site, the group with DO concentrations in months that received precipitation from the 90^{th} to 100^{th} percentile is significantly different that the groups with DO values in months with lower precipitation amounts (Table 9). Additionally, at sites 1, 4, and 6 for chlorophyll-a, this test shows that there is a significant difference between samples from months with precipitation from the 0^{th} to 50^{th} percentile and months in the 50^{th} to 90^{th} percentile (Table 9). At site 8 for chlorophyll-a, there is a significant difference between the 0^{th} to 50^{th} percentile and both the 50^{th} to 90^{th} and 90^{th} to 100^{th} percentiles, showing that the 0-50% group is significantly different from the other two.

From these tests, it can be concluded that precipitation has an effect on water quality parameters, specifically DO. When precipitation was in the 90^{th} to 100^{th} percentile over the past 20 years, the

DO values are significantly different than when precipitation was below the 90th percentile. This may be because heavy rainfall events disrupt the stratification of the lake, increasing the DO in bottom waters.

Table 9: Summary of results from Tukey's method to determine significance of differences in water quality between water samples collected during months with 0-50, 50-90, and >90 % rainfall

Site	Groups Compared	Ortho-P	NO_2+NO_3	DO	Chlorophyll-a	Turbidity	TP
1	0-50% and 50-90%	No	Yes	No	Yes		
	0-50% and >90%	No	Yes	Yes	No		
	50-90% and >90%	Yes	No	Yes	No		
2	0-50% and 50-90%			No			
	0-50% and >90%			Yes			
	50-90% and >90%			Yes			
3	0-50% and 50-90%			No			
	0-50% and >90%			Yes			
	50-90% and >90%			Yes			
4	0-50% and 50-90%			No	Yes	Yes	
	0-50% and >90%			Yes	No	No	
	50-90% and >90%			Yes	No	No	
5	0-50% and 50-90%			No			No
	0-50% and >90%			Yes			No
	50-90% and >90%			Yes			Yes
6	0-50% and 50-90%			No	Yes		
	0-50% and >90%			Yes	No		
	50-90% and >90%			Yes	No		
8	0-50% and 50-90%			No	Yes		
	0-50% and >90%			Yes	Yes		
	50-90% and >90%			Yes	No		
11	0-50% and 50-90%			No			
	0-50% and >90%			Yes			
	50-90% and >90%			Yes			
12	0-50% and 50-90%		No	No			
	0-50% and >90%		Yes	Yes			
	50-90% and >90%		Yes	Yes			

4.6 Results of 2021 Sampling by JAY Engineering

See Appendix B for the data generated from the field sampling event. TN data did not meet quality control standards. Detectable concentrations of TN were present in both field and laboratory blanks. The percent difference between duplicate samples was 126%, 26.0%, and 97.6% respectively for Sites 2, 4, and 6, above the 20% threshold specified in the QAPP. For these reasons, the TN data was rejected.

The TP concentrations of all samples were below the DL of 1.5 mg/L. Additionally, negative TP concentrations were measured for both the field and laboratory blanks, as well as the laboratory duplicate for Site 2. Hence, the accuracy of these measurements is questionable. It should be noted that the ten-year lake-wide average TP concentration, at 0.08 mg/L, is also below the DL for the method used.

TSS data did not meet quality control standards. The field and laboratory blanks had TSS concentrations of 309.4 and 322.4 mg/L, respectively, when no suspended solids should have been present. Additionally, the duplicates for Sites 4 and 6 exhibited percent differences of 200% and 90.2%, respectively, above the 20% threshold. For these reasons, the TSS data was rejected.

All turbidities were within standard deviation for ten-year site average. Highest turbidities at Sites 6 and 11, which have the greatest long-term average turbidity. None of the turbidity measurements were above the 25 NTU standard. Generally, sites with lower average turbidity had a greater Secchi Disk depth, as expected from the trend analysis in Section 4.2. Secchi Disk depths were not measured at Site 6 due to the large distance between the water surface and the bridge deck, where observations were taken.

Due to malfunctions in the YSI optical sensors, DO and chlorophyll-a measurements for Sites 1, 3, and 6 – East Bridge were not valid and were therefore discarded. The DO measurements at Sites 4, 5, 6 – West Bridge, and 11 were all greater than the site average + one standard deviation. DO levels are expected to be higher than average in March, as DO depletion due to decomposition of algal biomass does not occur until the summer. Measured chlorophyll-a concentrations were lower than average for all sites except Site 6 – West Bridge. This result was expected, as algal growth is lower in March than during the spring and summer. All ORP values were greater than 200 mV, the threshold below which phosphorus is released from iron in lake sediments.

4.7 Required Pollutant Reductions

Previously, it has been estimated that water quality standards can be met at Lake Thunderbird with a 35% reduction in total nitrogen, phosphorus, and sediment loads (Dynamic Solutions, LLC 2013). However, these loads have likely increased due to increasing urbanization.

Changes in developed land use area from 2011 to 2016 are given in Table 10. Percent changes are in terms of the total area of the watershed, 164,505 acres.

Table 10: 2016 Lake Thunderbird watershed land use areas with percent change from 2011 (OWRB 2020)

Category	2016 Acreage	% of Watershed	% Change	Change in Acreage
Developed, Open Space	12,474	7.58%	-1.82%	-2994.0
Developed, Low Intensity	9,182	5.58%	+1.2%	1974
Developed, Medium Intensity	6,080	3.70%	+1.71%	2813
Developed, High Intensity	1,376	0.84%	+0.41%	674.5
Total Developed Area	29112	17.7	1.5	2467

Using a conservative estimate, conversion to urban land use could increase phosphorous and nitrogen loading to the lake by 0.4 lb/ac/yr and 2.4 lbs/ac/yr, respectively (Vieux and Vieux 2007). Based on a net increase of urban land use by 2467 acres, TN and TP loads would have increased by approximately 2686 kg/yr and 448 kg/yr, respectively. Table 11 provides the estimated current load and the percent load reduction required for each nutrient.

Table 11: Estimated current nutrient loads and percent load reduction required to meet water quality standards, based on changes in land use (Dynamic Solutions, LLC 2013)

	TN	**TP**
2013 Long-term Load (kg/yr)	117537.9	23086.7
Estimated Current Load (kg/yr)	120224	23534.4
Required Long-term Load (kg/yr)	76399.6	15006.4
% Reduction Required	36.5	36.2

Based on changes in land use from 2011 to 2016, the required TN and TP removal has increased slightly, from 35% to 36.5% and 36.2%, respectively (Table 11). Greater decreases in nutrient loads may be required due to further land use changes since 2016. A similar increase in required load reduction can be expected for TSS.

Chapter 5: Initial Screening of Water Quality Solutions

Individual treatment technologies and BMPs were compared and evaluated for their viability in remediating Lake Thunderbird's water quality issues. The objective of the initial screening was to identify the most promising alternatives to be evaluated in greater detail.

Based on the analysis of the water quality data provided by the OWRB, the major water quality problems identified at Lake Thunderbird are elevated chlorophyll-a concentrations and high turbidity. Low metalimnetic DO is also a known water quality issue at Lake Thunderbird (OWRB 2020). Elevated chlorophyll-a and low DO are due to the excessive growth and subsequent decay of algae. Potential solutions were considered to address this issue either by directly killing algae or by limiting algal growth through reductions in nutrient loadings.

Solutions to high turbidity levels focused on reducing sediment loading into the lake from shoreline erosion or urban runoff. Reductions in sediment loading were also deemed important due to the increasing trend in TSS in the lake over the study period.

5.1 Screening Criteria

Potential solutions were assessed according to the following criteria:

- Cost: This criterion assesses the capital costs to implement the alternative, as well as long-term Operations and Maintenance (O&M) costs. Costs were compared for alternatives producing similar results (e.g. two solutions targeting shoreline erosion).
- Ease of Implementation: This criterion addresses the technical and administrative feasibility of executing the alternative. This includes the availability of and ability to maintain technologies employed by the solution.
- Effectiveness: This criterion addresses whether the use of the alternative will be sufficient to meet water quality criteria. The use of this criterion is intended to prevent the selection of solutions that would be inefficient.
- Sustainability: This criterion addresses the degree to which the energy and resources used to develop the technology compromise the natural environment. This criterion will favor technologies that use renewable energy, recycled materials, or other sustainable practices.
- Public Acceptance: This criterion addresses the degree to which the technology or BMP would be acceptable to the public.

5.2 Summary of Primary Screening

Seventeen potential alternatives for improving the water quality of Lake Thunderbird were initially considered. See Appendix C for an outline of the treatment technologies and BMPs that were considered, as well as brief explanations as to why each alternative was accepted or rejected for further analysis.

The remediation alternatives chosen for further evaluation, detailed in Chapter 6, were:

- Bioretention Cells
- Shoreline Revegetation
- Constructed Wetlands
- Pervious Pavement
- Cisterns
- Sand Filters

High cost and difficulty of implementation were two of the most common reasons for rejecting an alternative. Some options were rejected due to their potential negative side effects.

The primary objectives for the solution suite were to reduce phosphorus and sediment loadings into the lake. It has been determined that 16% of the phosphorus load into Lake Thunderbird is due to internal loading (OWRB 2011). Preference was therefore given to alternatives that addressed external phosphorus loading. The populations of OKC and Moore exhibited positive correlations with chlorophyll-a, likely due to increased nutrient loading from continuing urbanization. Thus, the alternatives selected for further evaluation focus on treating and reducing the volume of urban runoff.

Chapter 6: Evaluation of Water Quality Solutions

6.1 Bioretention Cells

A bioretention cell is a shallow depression filled with a medium such as compost, mulch, turf, or cockle shells. It is intended to filter and retain or detain stormwater before it is discharged downstream, providing control of both water quality and quantity (Vogel and Moore 2016). Bioretention cells are often vegetated. At the bottom of the chamber there is an underdrain, or recharge zone, that ensures the facility will drain at a desired rate (Figure 9). An impervious liner can also be used to eliminate the risk for groundwater contamination in industrial or highly urbanized hot spots (Center for Watershed Protection 2020).

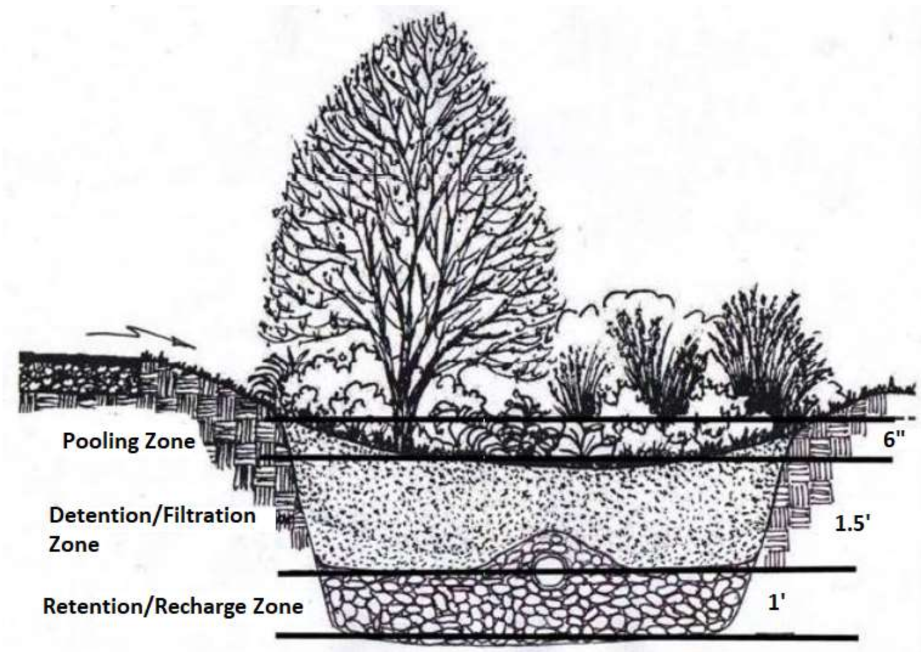


Figure 9: Cross-section of a bioretention cell incorporating an underdrain, with typical media depths (DER 2007)

The cells are designed to remove pollutants through a variety of physical, chemical, and biological treatment processes. These include mechanical filtration, sedimentation, and uptake by plants and microbes (Lucke and Nichols 2015). Bioretention cells have proven effective in treating urban stormwater. For example, a bioretention cell installed in Daly City, California, decreased the concentrations of metals, polychlorinated biphenyls, and dioxins to meet water quality standards (Vogel and Moore 2016).

Bioretention cells are generally best utilized for small contributing drainage areas, with a recommended cell surface area of 3-6% of the drainage area (Center for Watershed Protection 2020). Smaller beds are ideal so distributive flow across the entirety of the bed can be achieved. The largest drainage area that a traditional bioretention cell commonly covers is 2.5 acres, while the largest drainage area for an urban bioretention cell is 1 acre.

6.1.1 Treatment Efficacy

Bioretention systems have shown the potential to effectively remove pollutants if designed correctly. A biofiltration cell developed in Villanova was designed to catch the first 1 inch of rainfall and has shown effective capture of 85% of annual rainfall. Bioretention cells have demonstrated up to 97% removal of TSS, 35-65% removal of TP, 33-66% removal of TN, and removal rates of >90% for trace metals and oil and grease (DER 2007). Martin Mikle et al. (2015) reported lower removal efficiencies, ranging from 69-89, 0-42%, 0-58%, for TSS, TP, and TN, respectively.

Typically, bioretention cells contain a media depth of approximately 1.5 to 2 ft and can show a phosphorous removal rate of up to 25% and a nitrogen removal rate of up to 40%. Increasing the media depth up to 3 ft, as well as implementing a gravel underdrain, can allow for greater removal rates, increasing the phosphorous removal rate to up to 50% and the nitrogen removal rate to up to 60% (Sample et al. 2019). Increasing the media depth also increases the reduction in runoff volume from 40% at 1.5 to 2 ft to 80% for a 3-ft depth (Sample et al. 2019). The capacity of the cell to capture water will be greater when the soil is drier (Lucke and Nichols 2015). Thus, the reduction in runoff volume will decrease for repeated storm events.

6.1.2 Public Acceptance

One study on the public acceptance of several stormwater BMPs found a neutral to slightly-positive outlook towards rain gardens for those who are only "somewhat familiar" with the BMP. On a 5-point scale, where 1 represents total disagreement and 5 total agreement, the average scores for statements that rain gardens should be required for new streets and new parking lots were 3.22 and 3.42 respectively (Gao et al. 2018). This indicates that, on average, residents are not strongly opposed to or in favor of the implementation of bioretention cells, which are similar to rain gardens. The most common concerns that were identified included improper maintenance and potential increases in the number of insects due to increased vegetation (Gao et al. 2018). Public education could increase acceptance by dispelling misconceptions about bioretention cells.

The use of vegetation in bioretention cells can improve the aesthetics of the area where it is installed. Bioretention cells have been found to increase real estate values up to 20% due to the presence of aesthetically pleasing landscaping (DER 2007). Thus, proper landscaping and maintenance can increase public acceptance of the BMP.

6.1.3 Implementation

The effectiveness of bioretention cells depends upon them being properly maintained by property owners. Developers and property managers should be properly educated on the maintenance of bioretention cells, including:

- Keeping cells free of trash and debris
- Inspecting and repairing erosion, ruts, or bare spots in and around the cell
- Periodic weeding, trimming, and removal of dead vegetation
- Watering of vegetation as needed (DER 2007).

Educational materials such as flyers and brochures should be made readily available to developers, real estate agents, and property owners. These educational materials should also explain the benefits of bioretention cells to encourage residents to implement them on their property. City ordinances and homeowner associations may prevent the implementation of bioretention cells on certain properties. Meetings with city governments would be necessary to determine whether any building or zoning codes prevent the construction of bioretention cells and to potentially modify these codes. Homeowner associations should also be encouraged to allow or require rain gardens.

6.1.4 Cost Estimates

The installation costs of bioretention cells are highly variable depending on factors such as the medium used and the extent of excavation required. Installation costs may be as high as $32/ft^2 (Sample et al. 2019). Typically, construction costs will be greater for cells constructed in less permeable soils, as they will require an underdrain and therefore further excavation. The yearly O&M cost can be estimated as 5% of construction costs (Sample et al. 2019). For a construction cost of $32/ft^2, the corresponding O&M would be $1.60/ft^2.

The construction and landscaping costs for ten bioretention cells installed in Stillwater and Grove, Oklahoma, in 2008 are provided in Table 12 (Chavez et al. 2008). The total installation costs, including both construction and initial landscaping, ranged from $11.91/ft^2 to $37.95/ft^2. Note that landscaping costs were not available for two of the ten cells.

Table 12: Construction and landscaping costs for ten bioretention cells installed in Grove and Stillwater, Oklahoma in 2008

Area (ft^2)	**Construction Cost ($)**	**Construction Cost per Unit Area ($/ft^2)**	**Landscaping Costs ($)**	**Landscaping Cost per Unit Area ($/ft^2)**
678	12496	18.43	1690	2.49
248	8847	35.74	546	2.21
1604	17071	10.64	2030	1.27
1851	29173	15.76	4481	2.42
1249	13796	11.05	1370	1.10
517	10715	20.74	849	1.64
1087	13271	12.21	1244	1.14
323	7368	22.82	526	1.63
301	4753	15.77	-	-
1722	11479	6.67	-	-

6.2 Shoreline Revegetation

Shoreline revegetation is the planting of native vegetation along the shoreline and littoral zone to reestablish plant communities. The main goal of shoreline revegetation is to prevent soil erosion. Plant roots help to anchor the soil, and both submerged and emergent plant biomass can dampen wave energy, preventing erosion (Sistani and Mays 2001). Vegetation can also sequester excess nutrients in the form of biomass and compete with algae for sunlight. Decreases in soil inorganic nitrogen have been observed after shoreline revegetation due to plant uptake. Additionally, shoreline vegetation can help control nutrient leaching from soils (Ye et al. 2015). When properly vegetated, the shoreline and littoral zone can act as a buffer, potentially reducing primary production and algal growth by filtering out nutrients and sediments (Abrahams 2006).

Revegetating shorelines can also have recreational benefits. Increasing foliage improves habitat for fish and other wildlife, potentially leading to better fishing and birdwatching opportunities. Revegetation can also improve aesthetics over bare shorelines, providing a better boating experience (SWRCP 2010). Preventing shoreline erosion can also protect structures such as benches and picnic tables near the water's edge.

6.2.1 Revegetation Methods

Direct Planting

In this approach, sprigs of emergent aquatic plants and cuttings of wetland woody plants are planted into the soil or water with no additional anchoring. Woody plants should be placed from the conservation pool level upwards, while emergent aquatic vegetation can be planted from conservation pool level to a depth of 1.5 meters (Allen 2001). For species such as bulrush, rootstocks may be planted in water; however, seeds must be planted on an exposed mudflat (Shuttleworth 1997). Direct planting is suited for flat shorelines with a low grade that are not exposed to large waves.

Vegetative Anchoring Systems

In this treatment, materials such as fabrics, stakes, brush mats, or wattling are used to secure plants to the ground until their root systems are able to provide sufficient support. One such method is the plant roll, wherein emergent aquatic plants are placed in soil, then wrapped in a fabric such as burlap and secured by hog-ring wires (Allen and Klimas 1986). These rolls are then buried in the substrate.

In the erosion control mat method, layers of materials such as coconut fiber or geotextiles are placed directly on the substrate. Seeds or rootstock are then planted into slits in the material. Plant roots can interlock with the mat fibers, securing the vegetation. In addition to anchoring vegetation, substrate support structures such as geotextiles can also provide further erosion protection while the plant community is established (Abrahams 2006).

Escarpment Treatment

Escarpments form when wave action scours the toe of the shoreline, leading to the creation of near-vertical banks. Escarpments may be revegetated using plant rolls made from coir, a coconut-husk fiber. Alternatively, woody plants may be planted behind coir rolls filled with soil or rock (Figure 10). Coir is biodegradable and will decompose over time, leaving a mass of intertwined roots to hold the bank (Allen 2001). Escarpment areas may also be filled in with substrate and compacted before planting.

6.2.2 Breakwater Systems

Revegetation may be accompanied by the implementation of breakwater systems to dampen wave energy. Breakwaters can be floating or attached to the lake bottom. The use of breakwater

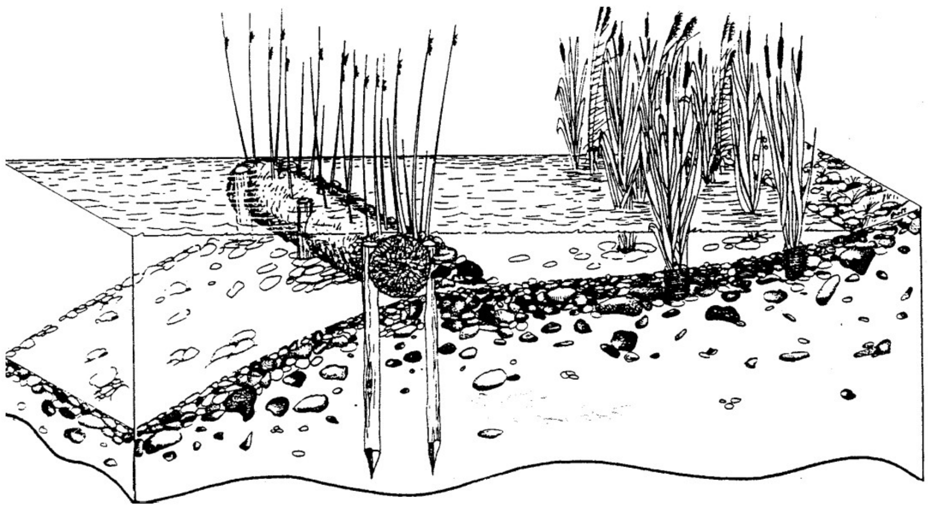


Figure 10: Drawing of plant roll made from coir geotextile with emergent aquatic vegetation planted shoreward (Allen 2001)

systems is advised in areas subject to waves one foot in height or greater (Allen 2001). Coir rolls with emergent aquatic vegetation may be used as breakwaters. Wire-wrapped straw bales, coconut fiber logs, and pine logs have proven effective at controlling wave action and trapping sand in order to develop a suitable surface for planting (Sistani and Mays 2007). Vegetation is then planted behind the breakwater using direct planting or a vegetative anchoring system.

Branchboxes, large bundles of branches and woody debris, have been found to be highly effective at dampening wave energy (Figure 11); however, they are more labor intensive than other breakwaters. Thus, it is recommended that their use is reserved for short reaches with the heaviest amount of erosion (OWRB 2005). Straight shorelines with longer wind fetch and deeper nearshore water are vulnerable to more frequent and higher waves and are candidates for branchbox installation (Allen 2001).

Figure 11: Branchbox breakwater with shoreward vegetation at Lake Wister, OK (Allen 2001)

Several months should be allowed between breakwater installation and planting to allow sediments to accumulate behind the breakwater (Sistani and Mays 2007). After planting, breakwaters must be in place for at least two growing seasons in order for emergent plant communities to be successfully established (OWRB 2005).

6.2.5 Treatment Efficacy

Shoreline revegetation is expected to provide a minimal reduction in nutrient loading. Most nutrient loading into Lake Thunderbird is due to runoff from urban areas, which enters the lake through tributaries rather than from the shoreline. However, a small decrease in nutrient loading is expected due to reductions in shoreline erosion. Some nutrient uptake is also expected. Softstem bulrush was found to have maximum above-ground nitrogen and phosphorus uptake rates of 0.3 and 0.1 g m^{-2} d^{-1} (Tanner 2001). The level of uptake was found to increase with increasing influent nutrient concentrations. In winter, net belowground accumulation of nutrients occurred at rates varying from 0.05-0.2 g N m^{-2} d^{-1} and 0.01-0.02 g P m^{-2} d^{-1} (Tanner 2001).

The main objective of shoreline revegetation is to reduce shoreline erosion. When appropriate planting methods and breakwaters are used, shoreline revegetation has been shown to be effective at limiting erosion. A study conducted by Kalibová et al. found that the use of jute and coir mats as erosion control drastically reduced soil loss (2016). This may be due in part to the reductions in runoff that occurred when these methods were used (Table 13). The results of the OWRB erosion control pilot project suggest that breakwaters significantly reduced erosion at Lake Thunderbird. The average elevation change at the study site was a 0.11-ft loss of sediment, with an average of 0.24 ft of loss at points nearest the water's edge. However, elevation loss was only 0.04 ft at points closest to branch boxes and 0.03 ft behind the breakwaters that were still in place (OWRB 2005).

Table 13: Impact of geotextile erosion control mats on runoff and soil loss; all values are percentages relative to control conditions (Kalibová et al. 2016)

Erosion Control Method	Soil Loss (%)	Mean Runoff (%)	Peak Discharge (%)
500 g m^{-2} Jute	0.6	62	74
400 g m^{-2} Coir	6.2	79	87
700 g m^{-2} Coir	2.1	31	37

Revegetation of the shoreline and littoral zone may address in-lake turbidity issues. Limiting shoreline erosion will decrease soil loading into the lake, which can contribute to turbidity. Additionally, vegetation in the littoral zone may reduce the resuspension of sediments. In one study, the presence of eelgrass and calamus respectively lead to 66.8–88.0% and 96.0–99.7% reductions in suspended sediment concentrations, as compared to a no-vegetation control. This is because plant matter provides a resistance to flow and lowers the shear stress on the sediment surface (Wu and Hua 2014).

6.2.4 Public Acceptance

Revegetation efforts will likely be well-received by the public. In a survey of public perception on lakes in Minnesota, the loss of vegetation was not frequently cited as impacting water quality (Anderson et al. 1999). Thus, the public may regard revegetation as insufficient remedial action if it is not used in conjunction with treatment of more-commonly recognized causes of impairment such as urban runoff. Loss of vegetation was the third most-mentioned factor impacting scenic quality (Anderson et al. 1999). Shoreline revegetation is therefore expected to be perceived as improving the aesthetic quality of the lake. In the same survey, 2% of respondents said that there was “too much” natural vegetation near lake shores, compared to 16% of respondents saying there was “too little” vegetation (Anderson et al. 1999). It is therefore unlikely that the public would be opposed to shoreline revegetation.

It has been recommended to prioritize public use areas such as near campgrounds and picnic tables for revegetation efforts (Allen 2001). These areas are subject to erosion due to heavy foot traffic; additionally, revegetation would be most visible to the public, which would help to improve reception of the project. Using volunteer labor from boating, fishing, and wildlife organizations has also been recommended for shoreline planting (Allen 2001). In addition to lowering costs, getting the community involved in the project would likely improve its reception.

6.2.5 Cost Estimates

Capital costs for shoreline revegetation will depend upon the planting method used and may include obtaining plant stock, erosion control or breakwater materials, and labor to plant and install erosion control methods or breakwaters. Regrading may be also be deemed necessary. Potential cost-saving measures include using volunteer labor and obtaining plant stock by harvesting from elsewhere in the park. Operation and maintenance costs may include monitoring, breakwater repair, and replanting in areas where vegetation establishment fails.

The Santa Ana Watershed Project Authority estimated the capital costs of shoreline revegetation at approximately \$35,000/converted acre, or \$0.80/ft^2 (SAWPA n.d.). This includes the costs of obtaining plants, installation, and labor. In a 2013 urban reservoir restoration project, establishing shoreline vegetation zones had an average cost of \$1.07/ft^2, with estimated annual operating costs of \$0.06/ft^2 (Jurczak et al. 2019).

6.3 Constructed Wetlands

Constructed wetlands can be engineered to reduce loads of sediments, nitrate, phosphorous, metals, and other pollutants that may enter the lake. Wetlands can improve the water quality of a body of water through biogeochemical transformation, formation of carbonates, solids filtration, and plant uptake (Halverson, 2004). The US Midwest region has found that wetlands have decreased up to 43% phosphorous and up to 68% nitrate loads in drainage water, although this will vary based upon location, hydrology, and design. Based upon the area in which a constructed wetland is implemented, the depth is a maximum of 10 ft deep, and the size of the constructed wetland is approximately 0.5%-2% as a ratio of wetland/watershed area (Tyndall and

Bowman 2016).

6.3.1 Types of Constructed Wetland

Wetlands can provide many benefits to an ecosystem such as improvement of water quality, nutrient reduction, and flood mitigation. There are three types of constructed wetlands: Free Water Surface (FWS), Vertical Subsurface Flow (VSF), and Horizontal Subsurface Flow (HSF). FWS wetlands are the most common type of wetland used in North America (USDA 2009).

Free Water Surface (FWS)

FWS wetlands are typically shallow with a media depth of 6-18 inches planted with emergent vegetation, and do not contain a sloped bottom. The treatment uses micro-organisms such as fungi and bacteria that attach to the plant stems or roots to aid in water treatment (USDA 2009). While subsurface flow (VSF, HSF) wetlands are designed to maintain a water level below the gravel media, FWS wetlands are designed to maintain the water flow above ground (Figure 12). FWS wetlands can efficiently remove organic materials through particle settling. While suspended solids and nitrogen removal are efficient, retention of phosphorous is limited due to the lack of extended contact between water and soil. Phosphorous can be removed through plant uptake, although it is essential to harvest the plants to ensure the phosphorus is not released back into the water body once the plant dies (Meulen 2016). FWS wetlands typically include plants such as common reeds, bulrush, cattails, and herbs. While FWS wetlands require the largest amount of land area to implement, they are most similar to a natural wetland (Stefanakis 2018).

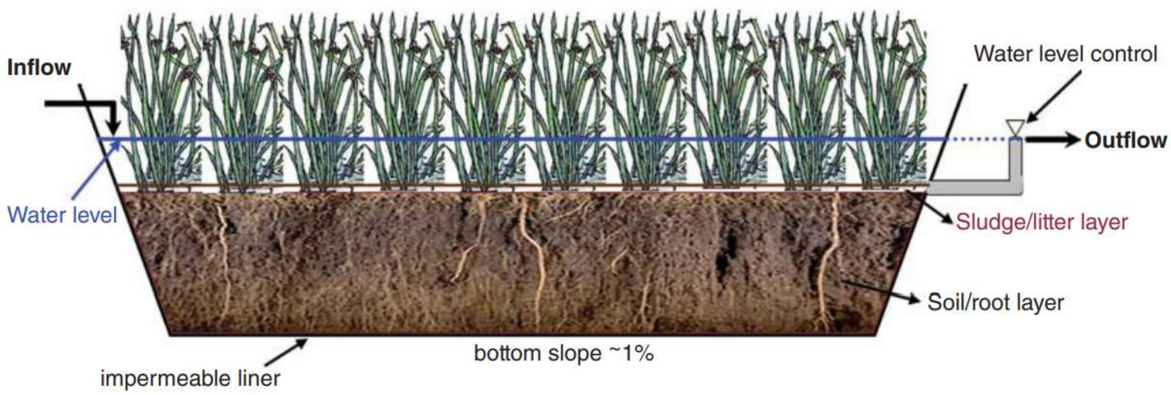


Figure 12: Schematic of a typical free water surface constructed wetland (Stefanakis 2018)

Subsurface Flow (VSF, HSF)

Subsurface flow wetlands consist of a gravel or rock bed, overlaid by a vegetated media such as wood chips or pine straw through which the water flows. The bottom of a subsurface flow wetland is sloped to maintain the water level above the plant roots downstream and ensure the water does not flood the surface. If it is possible for ground water to infiltrate the bed of the subsurface constructed wetland, an impervious liner should be implemented. Subsurface flow constructed wetlands are optimal for smaller flows and flows that have lower solids content compared to surface flow constructed wetlands (USDA 2009). Higher contaminant removal rates have been observed using a subsurface flow rather than an FWS wetland; hence, a subsurface flow wetland can be built on a smaller scale yet maintain the same contaminant removal rate as a larger FWS wetland (Halverson, 2004). Subsurface flow wetlands are also more effective at phosphorus removal, with removal rates of 60% to 80% (Meulen 2016)

Vertical Subsurface Flow (VSF)
A VSF has shown to be more effective than an HSF at reducing nutrient concentrations while requiring a smaller footprint. VSF wetlands typically contain a sand bed in which the plants are established with a gravel bottom (Figure 13). Water seeps downward through the sand bed and gravel which filters out contaminants (Meulen 2016). The most commonly used plants in VSF wetlands include cattails and common reeds. An aeration tube can be implemented to provide aeration in the deepest parts of the wetland. Because VSF wetlands have better aeration than HSF wetlands, they require a smaller area (Stefanakis 2018).

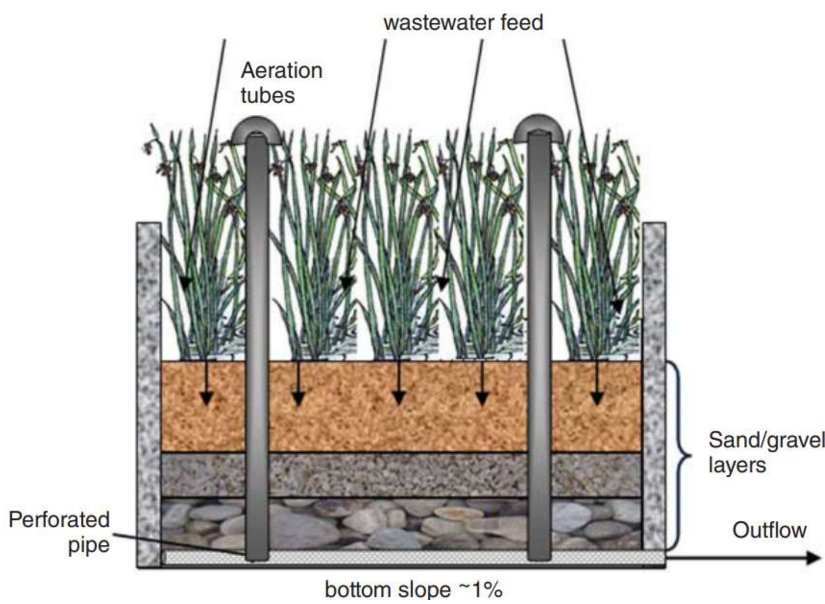
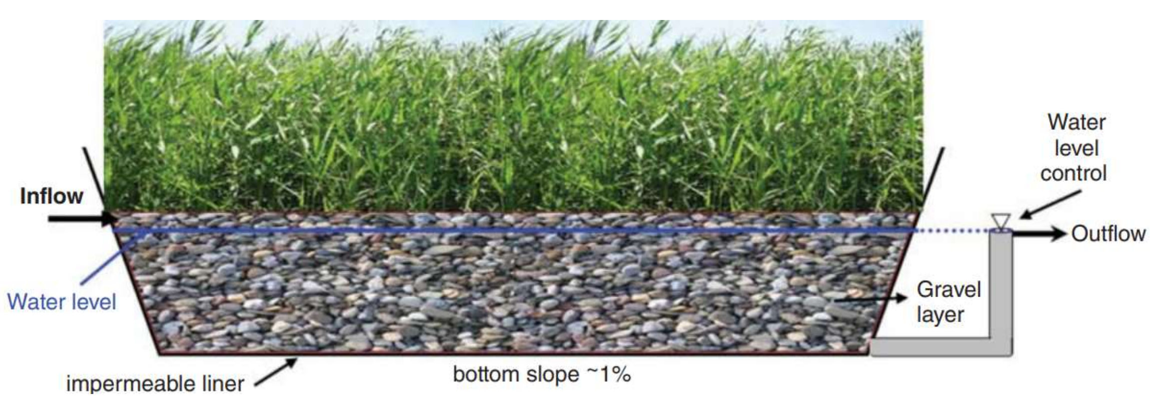


Figure 13: Schematic of a typical vertical subsurface flow constructed wetland with aeration tubes (Stefanakis 2018)

Horizontal Subsurface Flow (HSF)
In an HSF constructed wetland, the water is designed to flow horizontally through a porous medium, commonly a gravel bed. Common plants that are established in an HSF include common reeds, latifolia, and lacustris. As with a VSF wetland, the water level is maintained



below the gravel surface. While an HSF wetland requires more area to implement than a VSF wetland, this is still smaller than the area requirements for a FWS wetland (Stefanakis 2018).

Figure 14: Schematic of a typical horizontal subsurface flow constructed wetland (Stefanakis 2018)

6.3.2 Cost Estimates

FWS wetlands can be used to treat greater flowrates and can sustain greater biodiversity; however, they require more land than subsurface flow wetlands and can potentially cause odor problems. Subsurface flow wetlands can achieve greater contaminants removal rates with a smaller footprint. While it is more expensive to construct a subsurface flow wetland than an FWS wetland, operation and maintenance costs are lower for a subsurface flow wetland (Halverson 2004). In 2016, the average capital cost of a 1-acre constructed wetland to treat approximately 100 acres of drainage was a little over $10,000 (Tyndall and Bowman 2016). Table 14 presents the breakdown of these costs. A shallow wetland system should encompass approximately 100-150 plants per acre (Tyndall and Bowman 2016).

Table 14: Cost breakdown of constructed wetlands in Iowa in 2016 (Tyndall and Bowman 2016)

Capital Cost Activities/Items	Mean Price per Square Foot of Wetland	Mean Price per Square Foot Treated
Wetland Designer/Engineer	$0.02	$0.0002
Constructing Basin	$0.03	$0.0003
Wetland Plants (Seeds and Plugs) and Planting	$0.01	$0.0001
Wetland Buffer Seed	$0.003	$0.00003
Seeding Buffer (Broadcast with Tractor)	$0.0009	$0.000009
Weir Plate	$0.01	$0.0001
Control Structure	$0.05	$0.0001

The O&M costs for an FWS constructed wetland system is estimated to be $141.60 per month which accounts for energy, labor, and other expenses. The O&M costs for a VSF constructed wetland system is estimated to be $8.82 per pump per month, $588 per month salary for the operator, and $15 per month for other expenses (Akratos et al. 2007). The O&M costs for HSF constructed wetland systems observed in Louisiana and Vermont were shown to be $\$0.03/ft^2$ and $\$0.02/ft^2$ respectively (Gunes et al. 2011).

6.3.3 Treatment Efficacy

A study conducted by Li et al. on Taihu Lake in China used constructed wetlands to remedy eutrophication (2008). Three 30 m^2 units were placed in parallel in 2004. The constructed wetland consists of a VSF, HSF, and FWS, all containing the same plant species. Throughout the one-year study, the rate of nutrient removal fluctuated due in part to the weather. The VSF and HSF showed higher removal rates of nitrate, TP, and COD than the FWS system (Li et al. 2008). The nitrate-nitrogen removal efficiencies were 65%, 63%, and 34% for HSF, VSF, and FWS, respectively, due to greater denitrification in the HSF and VSF. The TN removal rates for the VSF and HSF, at 52%, were greater than in the FWS, with a value of TN removal of only 20% due to the shorter contact time (Li et al. 2008). The VSF and HSF also showed higher phosphorous removal rates of 64% and 66%, respectively, than the FWS.

6.3.4 Implementation

When evaluating the viability of the wetland implementation, one of the most important factors is the land availability. An estimated 3,277 to 8,192 acres of wetlands have the potential to be built in Lake Thunderbird's 163,840-acre drainage basin (Nairn 2014). Adequate land area is more likely to be available near new construction sites than in previously developed areas. While larger wetlands have proven to effectively retain sediments, smaller scale wetlands have shown to be equally or even more effective at removing bacteria, oxygen demanding substances, and metals. Smaller scale wetlands, however, require frequent maintenance such as reconstruction and replanting (Nairn 2014).

6.3.5 Public Acceptance

The public community has shown a greater acceptance for larger scale wetlands that are located downstream, rather than smaller scale wetlands that are located upstream. This is because downstream wetlands are located away from most neighborhoods and therefore have a smaller impact on the community's activities (Nairn 2014). Larger scale wetlands also have the potential to provide recreational benefits. For example, wetlands located in places such as Hackberry Flat and Grassy Slough have attracted visitors. The public has shown acceptance to constructed wetlands with the mindset that it does not directly affect them and will improve lake water quality (Nairn 2014).

6.4 Cisterns and Pervious Pavement

Pervious pavement is designed so that water can infiltrate through it into the underlying aggregate and soil to reduce the quantity of runoff (Vogel and Moore 2016). Pervious pavement consists of a thin, porous surface layer or interlocking permeable pavers underlaid by layers of open-graded aggregate to provide structural support and void space for stormwater infiltration and storage (Winston et al. 2020). As stormwater seeps through the surface layer and aggregate, pollutants may be filtered out. Pervious pavement has been demonstrated to have a high removal efficiency for metals and hydrocarbons (Nnadi et al. 2015). This solution is ideal for highly developed areas such as parking lots, driveways, and roads that receive lower traffic volumes.

Pervious pavement may be connected to a cistern, which allows stormwater to be captured, stored, and used for purposes such as irrigation (Figure 15). Pervious pavement systems have been found to recycle water at a quality suitable for agricultural irrigation (Nnadi et al. 2015). Incorporating a cistern can also increase TSS removal, as sediments settle out while being stored.

6.4.1 Treatment Efficacy

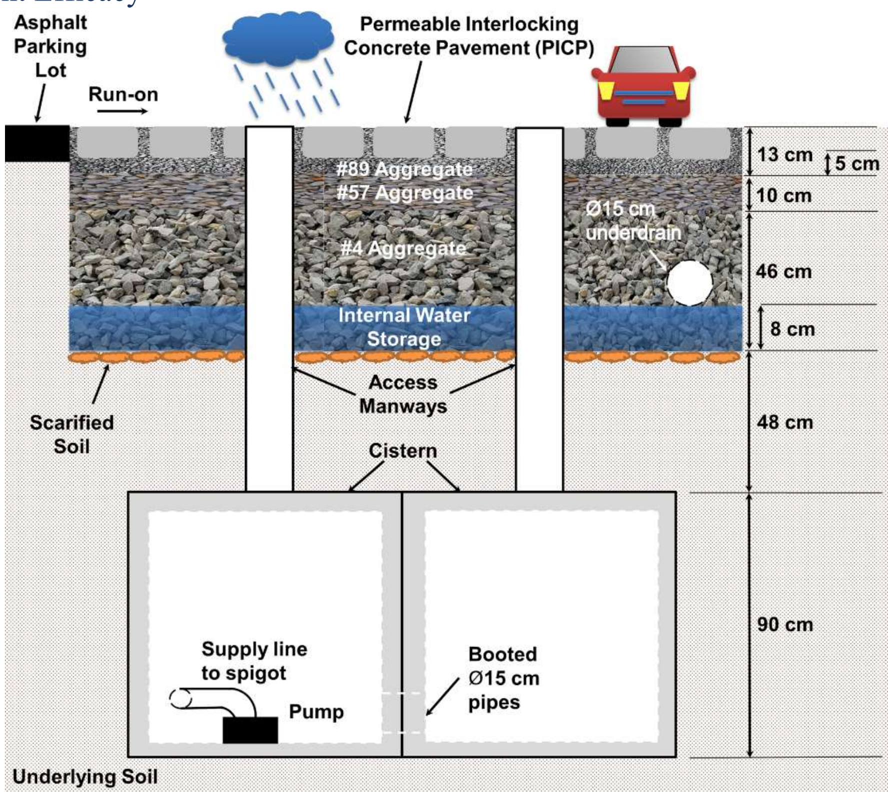


Figure 15: Cross-section of a pervious pavement and cistern stormwater treatment train (Winston et al. 2020)

Pervious pavement alone has achieved removal rates of 25-50% of TP, 0-42% of TN, and 68-86% of TSS from runoff (Martin-Mikle et al. 2015). A treatment train consisting of pervious pavement connected to a cistern was found to reduce runoff volume by 27%, with a non-pervious to pervious area ratio of 1.7:1 (Winston et al. 2020). Combined, the pervious pavement and cistern achieved 96%, 99.5%, 59%, and 78% reductions in the turbidity, TSS, TN, and TP of the outflow, respectively. The treatment train was effective at removing sediment-bound phosphorus but not dissolved Ortho-P; thus, the efficacy of the treatment will depend upon what fraction of TP is bound to sediments. In the study, 97% of the TP from the asphalt runoff was sediment bound (Winston et al. 2020); thus, 78% presents an upper bound on TP removal efficiency.

6.4.2 Implementation

Pervious pavements and cisterns could be installed throughout the watershed. To encourage the use of pervious pavements and cisterns, educational materials explaining their benefits should be made readily available to developers, property owners, and citizens. Public education is necessary to improve public opinion of these BMPs. Educational materials explaining maintenance requirements should also be made available to property owners to ensure that treatment systems are properly maintained. City ordinances may prevent the implementation of pervious pavement on certain properties. For instance, a special dispensation was required to install a small section of pervious pavement in the Trailwoods neighborhood in 2010 (Coffman 2014). Meetings with city governments would be necessary to determine whether any building or zoning codes prevent the construction of pervious pavements or cisterns. If necessary, these codes would need to be modified by local governments.

Local plumbing codes will determine the feasibility of installing cisterns, as they define the allowable uses and required treatment of captured water, as well as the design of distribution pipes. Space availability is also a restraint, as cisterns and their associated distribution system must work around existing underground utilities (Center for Watershed Protection 2020). Other factors that affect the feasibility of implementing cisterns include site topography and water table elevation. The feasibility of installing pervious pavements will depend on the soil characteristics at the site of interest. In Oklahoma, the implementation of technologies involving percolation will be limited by the presence of clay soils with low permeability.

6.4.3 Public Acceptance

The use of pervious pavements is likely to be accepted by the public. In a survey of users of pervious concrete and porous asphalt parking lots at Villanova University, more than half of respondents (54%) did not exhibit a preference for the look of pervious or conventional pavements. The fractions of those preferring the look of conventional asphalt (18%) and pervious pavement (14%) were about equal (Welker et al. 2012). The public is likely to accept pervious pavements in terms of aesthetic. In terms of performance, a majority of respondents (62%) had no opinion on whether conventional or pervious pavements had better traction, while 24% said the pervious pavements gave better traction. Overall, 73% of respondents had a positive opinion of pervious parking lot, while 27% had a neutral opinion (Welker et al. 2012). None of the respondents had an overall negative opinion of the pervious lots.

In another survey, the average rating of pervious pavement was a 3.4 out of 5, where 1 represents total rejection of the BMP, and 5 represents total acceptance (Loc et al. 2017). Based on the results of this survey, the public would likely have a neutral to slightly positive opinion of pervious pavements. Rainwater harvesting had an average rating of 3 out of 5, indicating a neutral opinion (Loc et al. 2017). Thus, a neutral opinion of cisterns may be expected. Public education could be used to raise awareness and improve acceptance of these BMPs.

Pervious pavements are being adopted in Oklahoma. A study conducted in 2013 by Dr. Jason Vogel assessed five different pervious concrete mixes made by local Tulsa concrete companies for a 10-stall demonstration parking lot in Tulsa, Oklahoma (Stotts 2013). By the end of the pilot study, the Oklahoma Ready-Mixed Concrete Association, the South-Central Cement Promotion Association, and Dr. Vogel had trained and certified 20 new pervious concrete technicians. This project went on to win the 2013 Nania Sustainability Award (Stotts 2013). Oklahoma continues to incorporate more pervious paving contractors into its economy.

6.4.4 Cost Estimates

The cost of pervious pavement will depend upon the type of pavement used. Construction costs vary from $2/ft^2 to $6.50/ft^2 for porous concrete, $0.50/ft^2 to $1/ft^2 for porous asphalt, and $5/ft^2 to $10/ft^2 for interlocking pervious pavers (CTC & Associates, LLC 2012). For a small paved area at the Trailwoods neighborhood, porous paving cost $6/ft^2 to install (Coffman 2014). Other costs for a pervious pavement system include excavation, aggregate, and geotextile membranes. Geotextile fabric ranges from $0.70/ft^2 to $1/ft^2. Excavation costs from $8/yd^3 to $10/yd^3, while aggregate costs between $30/yd^3 to $35/yd^3. The combined base and subbase depth varies between 18 and 36 inches (CTC & Associates, LLC 2012). Thus, excavation and aggregate costs may respectively range from $0.10/ft^2 to $0.25/ft^2 and from $0.37/ft^2 to $0.86/ft^2.

Underground cisterns are typically more expensive to install than aboveground cisterns. An underground 5500-gallon concrete cistern could cost anywhere from $17,000 to $21,000 to install, including excavation, backfilling, grading, and water filtration (HomeAdvisor 2021). The costs of several polyethylene underground cisterns are listed in Table 15.

Table 15: Material cost for different sizes of polyethylene underground cistern (HomeAdvisor 2021, RMS 2021)

Brand	Price	Size (gallons)
Norwesco	$810	600
RTS	$2715	1175
Rainwater Management Solutions	$3165	2500
Platin	$22,300	6600

Pervious pavements experience loss in permeability over time due to clogging. Hence, the detritus that accumulates on the pavement must periodically be removed. Vacuum sweeping a half-acre lot is estimated to $400 to $500 a year, or about $0.02/ft^2 (CTC & Associates, LLC 2012). Periodically, cisterns must be dewatered and cleaned to remove accumulated sediments. A cistern should be cleaned at least every two years, with an average cost of $650/service (HomeAdvisor 2021).

6.5 Sand Filters

Sand filters consist of layers of sand that filter stormwater runoff to remove sediments, metals, hydrocarbons, and other pollutants. Sand filters consist of two chambers: a sedimentation chamber and a filtration chamber. Runoff enters the sand filter through grates and overflows through a weir from the sedimentation chamber into the filtration chamber. The stormwater then passes through the filtration chamber and into a drain bed, typically made of gravel. After this, the water is collected in a pipe and is captured in a clearwell chamber (Barr Engineering 2001). While sand filters and bioretention cells are similar in that they both trap stormwater and filter pollutants, bioretention filters use soil and vegetation for filtration and uptake, while sand filters use sand and gravel for solely filtration. Sand filters are typically more focused on TSS and sediment treatment, while bioretention cells are more focused on nutrient removal. Sand filters are versatile and can be implemented in locations such as urban streetscapes, transportation fueling and maintenance areas, industrial sites, small tributaries that feed lakes, and parking lots (Barr Engineering 2001).

6.5.1 Types of Sand Filters

There are two main types of sand filters: intermittent and recirculating. Intermittent Sand Filters (ISFs) are single pass systems that are made up of a primary treatment unit and a sand filter (USEPA 1999a). Recirculating Sand Filters (RSFs) are modified single pass systems that eliminate odor through recirculation (USEPA 1999b). Both filter types remove contaminants through biological processes and have several subtypes. Advantages of both types of sand filter include:

- Flexible design
- High quality effluent that is suitable for irrigation
- No chemical inputs
- No specialized personnel needed for maintenance
- Small land area required (USEPA 1999a,b).

Disadvantages of sand filters are their requirement for regular maintenance, potential for the filter media to clog, and sensitivity to cold temperatures (USEPA 1999a,b).

Intermittent Sand Filters (ISFs)

ISFs collect stormwater and filter it through layers of rock, sand, and pea gravel. Then, water is collected in an underdrain and is transported for either further treatment or disposal. A typical intermittent sand filter is shown in Figure 16.

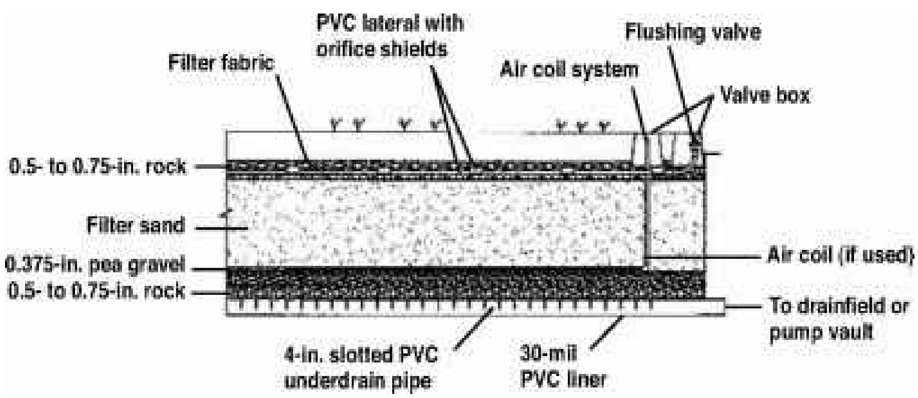
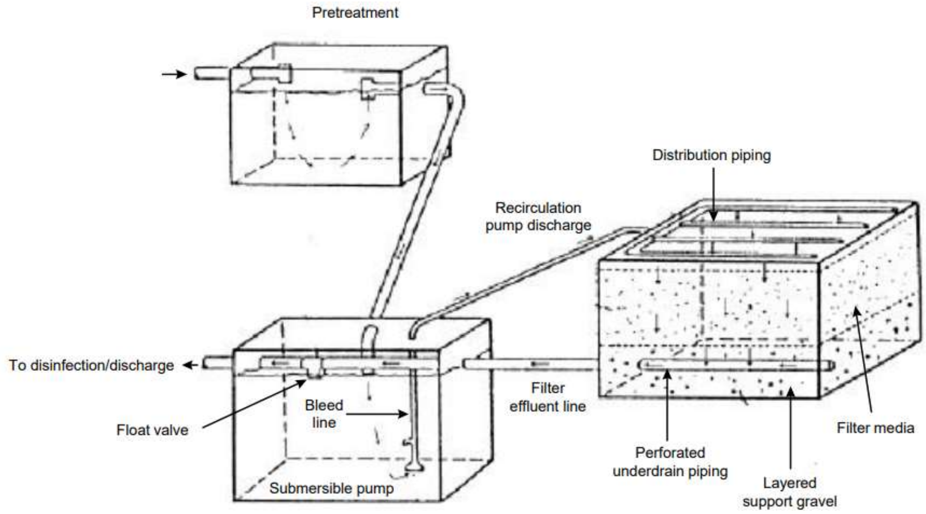


Figure 16: Schematic of a typical intermittent sand filter (USEPA 1999a)

The types of ISFs include gravity discharge, pumped discharge, and bottomless ISFs. Gravity discharge ISFs are typically located on an incline perpendicular to the slope of a hill. In this case, the effluent flows out of the filter by gravity, so the bottom of the filter must be several feet higher than the drain field area. Gravity discharge ISFs are often constructed partially above ground to account for the difference in elevations (USEPA 1999a). Pumped discharge ISFs are located on level ground, and the effluent is discharged to the drain field with a pump. Bottomless ISFs have no impermeable liner, and the effluent drains directly into the soil below the sand filter. ISFs are advantageous because they require small energy inputs and do not have high construction costs (USEPA 1999a). The main disadvantage of ISFs is odor problems.

Recirculating Sand Filters (RSFs)
RSFs address the odor problem from open sand filters through recirculation that increases the oxygen content in the effluent. In RSFs, water flows into one or more tanks for pretreatment and



is partially clarified. The water then flows into the recirculation tank and is mixed with sand filter filtrate. Last, the mixture of water and filtrate is pumped into the sand filter bed. A typical recirculating sand filter is shown in Figure 17.

Figure 17: Schematic of a typical recirculating sand filter (USEPA 1999b)

RSFs are advantageous because they:

- Reduce odor issues
- Provide over 95% removal of BOD and TSS
- Reduce nitrogen levels significantly
- Require less land than single-pass sand filters (USEPA 1999b).

RSFs can be disadvantageous because they require larger energy inputs and can have higher construction costs than ISFs.

6.5.2 Treatment Efficacy

The purpose of sand filters is to filter sediments, nutrients, metals, hydrocarbons, and other pollutants from stormwater. Various sand filter designs can result in different levels of pollutant removal. Table 16 provides standard and optimal pollution removal rates for sand filers.

Table 16: Standard and optimal nutrient and suspended solids removal rates for sand filters (Charlotte-Mecklenburg Stormwater Services 2013)

Sand Filter Design	Detention Time (days)	Media Depth (ft)	TSS Removal (%)	TP Removal (%)

Optimal Efficiency	2	2.5	85	70
Standard Efficiency	1	2	70	35

Table 17 lists the range of TSS, TN, and TP removal efficiencies for sand filters in the U.S., (Center for Watershed Protection 2007). From these studies, it is evident that sand filters are best at removing TSS from stormwater and good at removing both TP and TN.

Table 17: Range and median TSS, TN, and TP removal efficiencies for sand filters in the U.S. (Center for Watershed Protection 2007)

Region	**# of Studies**	**TSS Removal (%)**		**TN Removal (%)**		**TP Removal (%)**	
		Range	Median	Range	Median	Range	Median
U.S.	18	80-92	86	30-47	32	41-66	59

6.5.3 Implementation

Sand filters could be implemented by placing them near the tributaries that feed into Lake Thunderbird. For example, sand filters could be placed along the Little River and Hog Creek, since these are the main sources of water into Lake Thunderbird. Analysis of flow from StreamStats could be performed to determine which tributaries contribute the highest flow into Lake Thunderbird.

However, if sand filters are not placed within Lake Thunderbird State Park, landowners and regulators must be prepared for the somewhat-extensive maintenance that sand filters require. During maintenance, workers must check the filters for standing water, a thin layer of film, or any discoloration and may need to remove debris, scrape silt, till and aerate the area, replace filtering medium, repair leaks, and clean out sediment from all parts of the filter (Barr Engineering, 2001).

Additionally, in order to increase public acceptance, public education and information on sand filters may be necessary. Educational flyers or pamphlets outlining the benefits of sand filters should be given to any potential landowners, developers, and maintenance workers.

6.5.4 Public Acceptance

Sand filters typically have moderate to high public acceptance. According to the NCDENR Stormwater BMP Manual, on a scale from low to high, sand filters as a BMP ranked medium in community acceptance (2009). If sand filters were placed near areas with homes, homeowners may question a large open area with a detention basin and have concerns over odor and bug issues. Bioretention cells rank higher than sand filters in community acceptance since they are covered with vegetation which can be seen as aesthetically pleasing to home and business owners (NCDENR 2009).

6.5.5 Cost Estimates

The cost of a sand filter depends on the filtering media, pipe material, inlet and outlet structure type, cost of excavation, cost of land, and cost of maintenance (Barr Engineering 2001). An estimated range for construction costs is $0.23 to $0.32 per impervious square foot being treated (Schueler 1994). The cost per square foot will be greater for smaller filters. For example, in 1994, the cost of sand filters was $0.37 per impervious square foot if fewer than two acres were treated (Schueler 1994). Table 18 gives the cost of various sand filters in locations throughout the United States. These cost estimates exclude real estate, design, and contingency costs. Additionally, annual maintenance costs are estimated to be between 11 and 13% of the construction costs (Livingston et al. 1997).

Table 18: Sand filter installation costs in the U.S. per square foot of drainage area treated (EPA 1999)

Region / Design	**Cost/Impervious Square Foot**
Delaware	$0.23
Alexandria, VA	$0.54
Austin, TX (<2 acres)	$0.37
Austin, TX (>5 acres)	$0.08
Washington, D.C. / underground	$0.32
Denver, CO	$0.69-$1.15

Chapter 7: Recommendations

7.1 Scoring of Alternatives

Each alternative was given a score from 1 to 5 for each category, with 5 being the best score. These are provided in Table 19. The weights for each category were determined by JAY Engineering. Cost and effectiveness were the factors weighted most heavily, at 25% each. Cost was weighted the highest because a project cannot be implemented unless adequate funding is secured. The effectiveness of the alternative was also weighted the most heavily because the goal of the project is to address the water quality issues at Lake Thunderbird.

Public acceptance and ease of implementation were each weighted at 20%. The level of public acceptance is an important consideration, as public opposition to a project can prevent its implementation. The ease of implementation is also ranked relatively heavily because a project with low feasibility will be prone to failure. However, cost was considered the largest obstacle to implementation and was therefore given a higher weight.

Lastly, sustainability had the lowest influence on the total score, at 10%. While sustainable development is important, the sustainability of a project is irrelevant if the project cannot be supported financially, is deemed ineffective, or is too difficult to implement.

Table 19: Scoring of potential remediation alternatives based on five evaluation criteria

Technique	Cost (25%)	Ease of Implementation (20%)	Effectiveness (25%)	Sustainability (10%)	Public Acceptance (20%)	Total
Bioretention Cells	3	3	5	4	5	**4.00**
Shoreline Revegetation	4	4	3	5	5	**4.05**
Constructed Wetlands	5	4	5	4	4	**4.50**
Cisterns and Pervious Pavement	2	2	4	2	4	**2.90**
Sand Filter	3	3	4	3	3	**3.25**

The alternatives were scored on the basis of construction cost per unit area of the treatment technology. Constructed wetlands and shoreline revegetation were the most cost-effective solutions, costing on the order of less than $\$0.10/ft^2$ and $\$1.0/ft^2$, respectively. Sand filters and bioretention cells tended to have similar construction costs per square foot; thus, they were given an equal score. Pervious pavements were scored the lowest due to the high cost associated with installing an underground cistern.

Bioretention cells, sand filters, and pervious pavements would need to be installed throughout the watershed. They were therefore given lower scores in Ease of Implementation because COMCD cannot implement them directly. Of these three, pervious pavement was given a lower score due to the difficulty of installing underground cisterns. Shoreline revegetation and constructed wetlands may be implemented within the boundaries of Lake Thunderbird State Park.

Effectiveness was scored based on the sediment and nutrient removal efficiencies of each treatment technology. It is unclear how much sediment and nutrient loading will be reduced by shoreline revegetation; however, it is likely to be less than the other alternatives because it does not treat urban runoff. For this reason, it was given the lowest score in effectiveness.

Shoreline revegetation was given the highest score in sustainability due to its use of natural and biodegradable materials and lower need for construction activity. Sand filters were scored lower than bioremediation cells and constructed wetlands due to the heavy maintenance requirements. Pervious pavements were considered the least sustainable due to the use of materials such as concrete or asphalt that would not be utilized in other technologies.

Scores in the Public Acceptance category were based on survey results, detailed in Chapter 6. Solutions incorporating vegetation tend to have higher public acceptance due to their aesthetic value and therefore have higher scores.

Based on the evaluation, two alternatives were selected for incorporation into the solution suite: constructed wetlands and shoreline revegetation. Conceptual designs were based on a design life of twenty years.

7.2 Constructed Wetland Conceptual Design

An FWS wetland was determined to be the most feasible and cost-effective type of constructed wetland to implement to reduce nutrient loading into the lake. An FWS wetland is preferrable to a subsurface wetland because of its lower capital and O&M costs.

7.2.1 Wetland Sizing and Location

The area of a constructed wetland should be 0.5-2% of the drainage area (Tyndall and Bowman 2016). Therefore, for the 164,505-acre Lake Thunderbird watershed, between 823 and 3290 acres of wetland area are needed.

Two locations have been recognized as potential sites for constructed wetland development: approximately 500 acres north of Alameda Drive bridge on the Little River arm and approximately 750 acres on the Hog Creek arm north of Hickory Road (Nairn 2014). These areas are shown in Figure 18. A total wetland size of 900 acres is recommended, where the wetland will occupy 500 acres on the Little River arm and 400 acres on the Hog Creek arm. As seen in Figure 19, the majority of the sediment and TP loading into Lake Thunderbird originates from the portion of the watershed north of the lake. The wetland locations were chosen because the Little River and Hog Creek are the two largest inflows into the lake and contribute the largest nutrient loadings. The recommended width to length ratio of the wetlands is between 1:3 and 1:5. The length of the wetland should be much longer than its width to ensure plug flow (Stefanakis 2018).

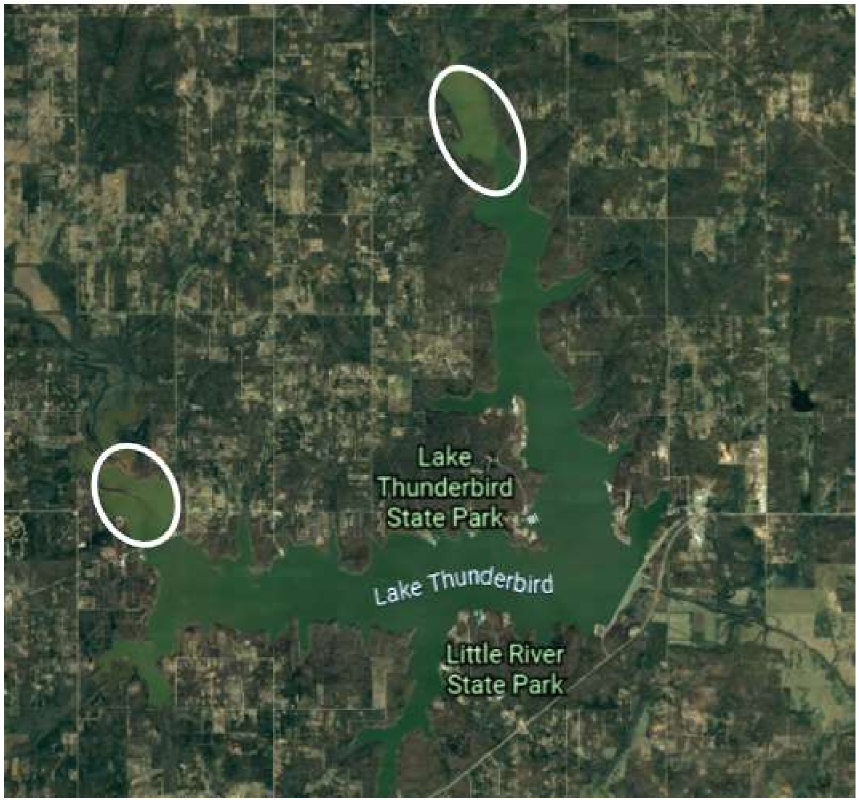


Figure 18: Areas identified for creation of constructed wetlands on Little River (left) and Hog Creek (right) arms of Lake Thunderbird

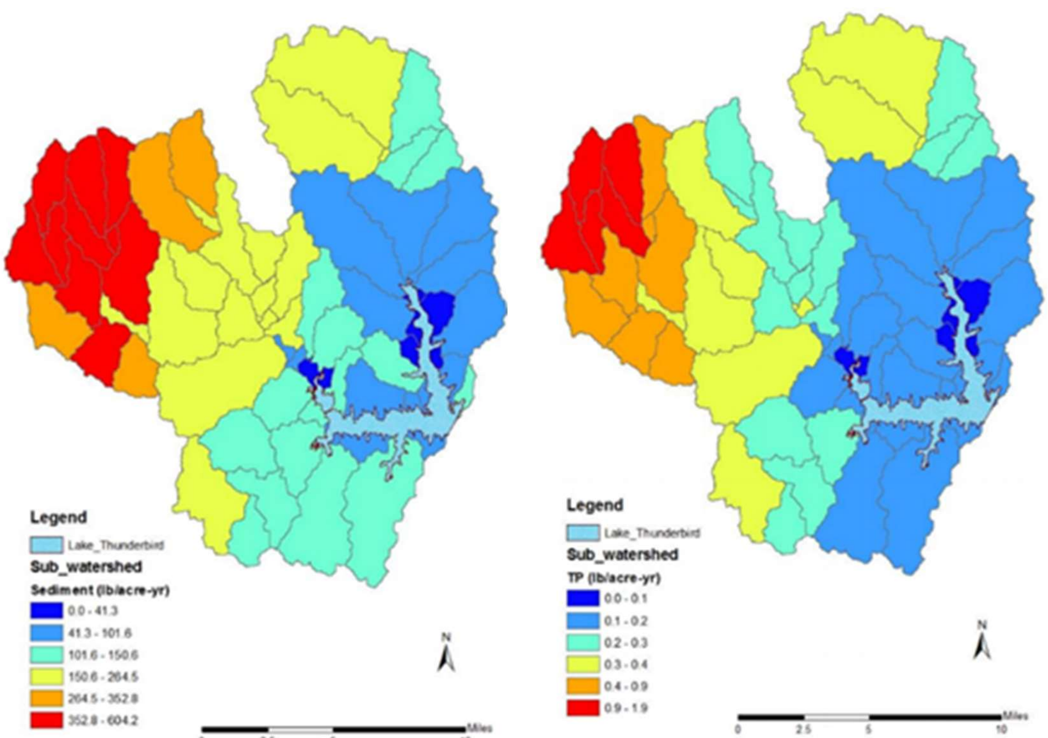


Figure 19: Sediment and total phosphorus loadings into Lake Thunderbird by catchment (Dynamic Solutions, LLC 2013)

The FWS system includes a soil layer 12-16 inches in depth, with an overlying water column 4-20 inches in depth. The bed of the wetland will be layered with an impermeable geo-textile liner to prevent groundwater contamination. The water is designed to flow horizontally through the FWS system to contact rhizomes and plant stems in order to increase pollutant removal efficiency (Stefanakis 2018). A soil depth of 12 inches was selected. It is recommended that soil removed during site excavation be backfilled and used as the planting medium to decrease capital costs.

To ensure sufficient nutrient and sediment removal rates, the wetland must have the proper Hydraulic Retention Time (HRT). Removal efficiencies can be improved by increasing the HRT, with an HRT of 3-12 days providing moderate nutrient removal (Li et al. 2018). An HRT of 8 days was selected. The required water depth h can then be calculated using Equation 3, where Q is the design flowrate and A is the surface area of the wetland.

$$h = \frac{HRT * Q}{A}$$

Equation 3: Required wetland water depth calculated from flowrate, HRT, and surface area

The design flowrates were the average daily streamflow entering Lake Thunderbird from the Little River and Hog Creek. Using USGS StreamStats, these values were estimated as 39.9 ft^3/s and 18.5 ft^3/s, respectively (USGS n.d.). To achieve an 8-day HRT, water depths of 15.2 in and 8.8 in are respectively required for the Little River and Hog Creek wetlands. These values fall within the typical range of water column depths.

Another important parameter in wetland design is the Hydraulic Loading Rate (HLR), which is the ratio of the influent flowrate to the surface area of the wetland (Equation 4). At lower HLR, the water flows through the wetland more slowly and is in contact with the medium for a longer period, increasing pollutant removal rates. For example, when the HLR in one constructed wetland increased from 2.8 to 8.3 in/d, the TN removal efficiency decreased from 30 to 20% (Rahman et al. 2020).

$$HLR = \frac{Q}{A}$$

Equation 4: Hydraulic loading rate of constructed wetlands

A high wetland surface area is therefore desirable to decrease the HLR and improve pollutant removal efficiencies. Based on the average daily streamflow estimates from StreamStats, the HLR for the Little River and Hog Creek wetlands are 1.9 in/d and 1.1 in/d, respectively.

7.2.2 Wetland Plant Selection

The most commonly used plant species in constructed wetlands include common reed, broadleaf cattail, and California bulrush (Stefanakis 2018). A study conducted by Finlayson and Chick compared the nutrient removal efficiencies of species from these three genera (1983, Table 20). Softstem bulrush demonstrated the greatest removal efficiencies for TSS, TN, TP, and Ortho-P.

While common reed was more effective at removing nitrogen, the southern cattail and bulrush species had greater removal efficiencies for TP and Ortho-P (Finlayson and Chick 1983). Since phosphorus loading is the greater concern for Lake Thunderbird, southern cattail and bulrush are recommended.

Table 20: Nutrient and suspended solids removal efficiencies of plant species most commonly used in constructed wetlands (Finlayson and Chick 1983)

	TSS	TN	TP	Ortho-P
Typha domingensis (Southern cattail) and *T. orientalis* (Cumbungi)	83%	42%	53%	48%
Phragmites australis (Common reed)	84%	62%	37%	26%
Schoenoplectus tabernaemontani (Softstem bulrush)	89%	74%	61%	60%

Softstem bulrush has also been shown to have more effective TN and TP removal than lake sedge, reed canary grass, and broadleaf cattail, with reed canary grass the least effective at removing both nutrients. However, broadleaf cattail has been shown to significantly outperform soft rush and woolgrass. Some studies have suggested that polycultures can provide greater and more consistent nutrient removal (Vymazal 2011); hence, it is recommended that a mixture of different species are planted in the FWS wetlands.

In addition to the species mentioned above, several other local or ornamental plants have been incorporated into FWS wetlands (Table 21). It is important to avoid using invasive species in a constructed wetland, as they can spread and displace native species. Preference should also be given to native species because they are adapted to local conditions. The National Resources Conservation Service Plant Database was utilized to determine whether species are native to Oklahoma (n.d.). Common bulrush, southern cattail, softstem bulrush, and California bulrush are all native to Oklahoma. Both common reed and reed canary grass are generally considered exotic or invasive in the U.S. and are therefore not recommended (Vymazal 2011).

Table 21: Examples of ornamental or local plants used in constructed wetlands that are native to Oklahoma (Sandoval et al. 2019)

Scientific Name	Common Name
Equisetum hyemale	Rough horsetail
Hibiscus moscheutos	Hibiscus
Iris brevicaulis	Zigzag iris
Iris cristata	Dwarf crested iris
Iris virginica	Virginia iris
Nasturtium officinale	Watercress
Neobeckia aquatica	Lakecress

Softstem bulrush should be planted in the FWS wetlands because it has shown high removal efficiencies for nitrogen, phosphorus, and sediments compared to other species and is native to Oklahoma. As previously mentioned, planting multiples species can improve wetland performance compared to a monoculture. Broadleaf cattail and southern cattail are also recommended due to their high nutrient removal efficiency and widespread use in FWS wetlands. To increase the aesthetic value and therefore public acceptance of the wetlands, native ornamental species such as hibiscus, zigzag iris, and watercress may also be incorporated.

7.2.3 Cost Estimates

Table 22 lists cost estimates for the implementation of the two FWS constructed wetlands. The two largest capital costs for an FWS wetland are excavation and land acquisition. Leasing or purchasing land was not considered in the cost estimate. According to Cao et al., excavation using a hydraulic digger costs $0.32/ft^3 (2021). The total volume to be excavated is 900 acre-feet, or 39.2 million ft^3.

Depending on site conditions, a geomembrane liner may be required. If the soil below the wetland is an impermeable clay, it may be sufficient to prevent groundwater contamination. Given local soil conditions, it is likely that that a geotextile liner will not be required. Cost estimates have been included with and without the installation of a liner. A geotextile liner 0.06 inches thick with a density of 0.034 lb/ft^3 was selected (NILEX n.d). The total volume of liner required for both wetlands would be 196,000 ft^3 and would weigh 5.2 million kg. According to Cao et al., geotextile liner costs $0.023/kg (2021).

According to Tyndall and Bowman, planting 150 plugs per acre is sufficient to establish a wetland community in deep water areas (2016); this amounts to a total of 135,000 plugs. Additionally, one third of the total wetland area should be seeded with a wetland plant seed mixture at about 5 pounds per acre by seed drill (Tyndall and Bowman 2016). This amounts to a total of 1500 pounds of seed. All costs were updated to 2021 values using Equation 5, assuming an inflation rate of 2%.

$$P' = P(1+r)^n$$

Equation 5: Adjustment of past value *P* to present worth *P'* over a period of *n* years with inflation rate *r*

The annualized costs for a constructed wetland over a 40-year design life has been estimated at $785/acre/year (Tyndall and Bowman 2016). This is equivalent to $867 in 2021 and was taken as the yearly O&M cost. The present worth of O&M over the 20-year design life was calculated using Equation 6, assuming an inflation rate of 2%.

$$P = \frac{A(1 - \frac{1}{(1+r)^n})}{r}$$

Equation 6: Present worth *P* of *n* yearly payments *A* with inflation rate *r*

Table 22: Estimated capital cost and present worth for 900-acre Lake Thunderbird constructed wetland system

Item	Unit Cost	Quantity	Total Cost	Source
Design Cost (Engineer)	\$47/hr	720 hr	\$28,800	Christianson et al. 2013
Contractor Fees	\$16.32/acre	900 acres	\$14,700	Christianson et al. 2013
Site Preparation and Excavation	\$0.32/ft^3	39.2 million ft^3	\$12.5 million	Cao et al. 2021
Plant Plugs	\$1.66/plug	135,500 plugs	\$224,400	Tyndall and Bowman 2016
Plant Seeds	\$4,245.75/50 lbs	1500 lbs	\$127,400	Roundstone 2021
Geotextile Liner	\$0.023/kg	5.2 million kg	\$120,000	Cao et al. 2021
Planting (Labor)	\$39.88/acre	900 acres	\$35,900	Sahs 2020
Seed Drilling (Labor)	\$15.64/acre	300 acres	\$4700	Sahs 2020
Inlet/Outlet Structures	\$25,137	2	\$50,300	Gunes et al. 2011
Flow Control Structures	\$2,029.46	2	\$4,100	Agri Drain Corporation 2021
Total Capital Cost (with Liner)			**\$13.1 million**	
Total Capital Cost (without Liner)			**\$13.0 million**	
O&M	\$780,000/yr	20 years	\$12.8 million	Tyndall and Bowman 2016
Total Present Worth (with Liner)			**\$25.9 million**	
Total Present Worth (without Liner)			**\$25.8 million**	

7.2.4 Expected Performance

Based on land use changes from 2011 to 2016, the required removal efficiencies for TP and TN increased by 1.2 and 1.5%, respectively. Assuming similar trends in urbanization from 2016-2021 and over the 20-year design life, 42.2% and 44% reductions in TP and TN loadings would be required at the end of the design life. A similar removal efficiency will be required for TSS.

An FWS wetland system has the potential to show greater than 70% removal of TSS, 40-50% removal of TN, and 40-90% removal of TP. Removal efficiency is dependent on factors including the inflow pollutant concentration, site hydrology, and types of vegetation present (Chen 2011). TP removal rates for a FWS wetland are typically in the range of 30-50% (Muelen 2016).

Removal rates for TN and TP were calculated using Equations 7 and 8, where HRT is in days and HLR is in meters per day (Economopoulou and Tsihrintzis 2004). Nitrogen removal may occur through nitrification or denitrification. Nitrification was assumed because oxidation is expected to occur in the aerobic FWS wetland. The rate constant K_T for nitrogen removal is dependent on temperature and was calculated using Equation 9. The temperature measurements recorded at Sites 6 (11.71°C) and 2 (11.52°C) during the March 2021 sampling event were respectively used for the Little River and Hog Cree. The rate constant K_1 for phosphorus removal was 0.0273 (Economopoulou and Tsihrintzis 2004).

$$R = (1 - e^{-K_T * HRT}) * 100\%$$

Equation 7: Wetland TN removal efficiency *R* based on HRT (Economopoulou and Tsihrintzis 2004)

$$R = (1 - e^{\frac{-K_1}{HLR}}) * 100\%$$

Equation 8: Wetland TP removal efficiency *R* based on HLR (Economopoulou and Tsihrintzis 2004)

$$K_T = 0.2187(1.048^{T-20})$$

Equation 9: Rate constant for TN removal through nitrification for T>10°C (Economopoulou and Tsihrintzis 2004)

TN removal rates were estimated to be 69% for both the Little and Hog Creek wetlands. Observed TN removal rates in FWS constructed wetlands are lower than these values; the actual TN removal efficiency of the proposed wetlands can be expected to be in the upper end of the typical range, or about 50%. TP removal rates were estimated to be 43% for the Litter River wetland and 62% for the Hog Creek wetland. Based on the selected plant species, TSS removal efficiency is expected to be 80% or greater. The proposed wetland system is therefore expected to achieve sufficient nutrient and sediment load reductions.

7.3 Shoreline Revegetation Conceptual Design

7.3.1 Planting Methods

The most appropriate revegetation method will depend upon the extent of erosion. Five different erosion categories have been identified at Lake Thunderbird and are listed in Table 23, along with the recommended revegetation method.

Breakwaters with vegetation planted shoreward should be primarily considered for Category 4 (Figure 20) and 5 (Figure 21) erosion situations. On steeper slopes erosion control mats should be implemented in combination with breakwaters to further aid in plant establishment (Allen 2001). Near vertical slopes will also require grading to allow for greater wave dissipation potential and a suitable revegetation slope for herbaceous species.

Branchbox breakwaters were selected due to their past successful use in Oklahoma. Branchboxes were installed in April 2000 at Lake Wister, Oklahoma as a demonstration project. After 18 months, sediments had accumulated and vegetation had successfully grown behind the breakwater (Maynord et al. 2006). Branchboxes were also found effective in dampening wave energy and protecting shoreward vegetation in the 2003 Lake Thunderbird erosion control pilot project (OWRB 2005).

While effective, branchboxes are also labor-intensive to construct. Hence, they should be implemented for short reaches with the heaviest amount of erosion (OWRB 2005). In other areas, CGRs should be implemented as breakwaters. Coir logs have proven effective at controlling wave action and trapping sediments to develop a suitable planting surface (Sistani and Mays 2007).

Table 23: Categories of shoreline erosion at Lake Thunderbird with recommended revegetation methods (Allen 2001)

Category	Description	Revegetation Method
1	No noticeable erosion, established emergent aquatic vegetation at shoreline	No treatment needed
2	≤1-2 ft of escarpment, shallow area lakeward covered in part with emergent aquatic vegetation	Direct planting or vegetative anchoring
3	2-4 ft of escarpment, some toe lakeward with no vegetation	Vegetative anchoring and escarpment treatment
4	≥4 ft of escarpment present, some toe lakeward with substantial rocks and/or logs mixed with plants	Vegetative anchoring with breakwater system
5	≥4 ft of escarpment present, little to no toe present and no vegetation noticeable in water	Vegetative anchoring with breakwater system

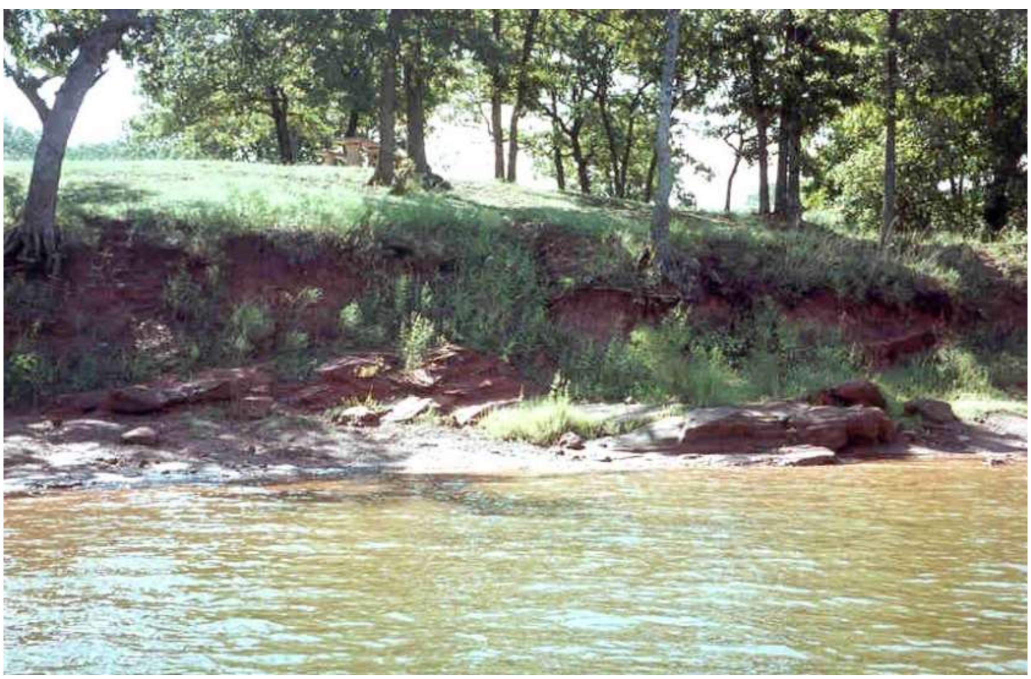


Figure 20: Example of Category 4 erosion at Lake Thunderbird: >4-ft escarpment with rocks and vegetation present (Allen 2001)

Figure 21: Example of Category 5 erosion at Lake Thunderbird: >4-ft escarpment little to no toe in an area exposed to >4-mile fetch (Allen 2001)

Biodegradable erosion control mats made of coir or jute can help prevent soil erosion in the period before vegetative community establishment and act as an anchor for new vegetation. Jute erosion control mats are recommended due to their lower cost and greater reduction in soil loss compared to coir (Kalibová et al. 2016). Jute has also been shown to be more effective in lowering runoff volumes and peak discharges than coir at various rainfall intensities (Kalibová et al. 2017). Erosion control mats should be installed as soon as possible after seeding.

Planting events should not occur during the months prone to flooding to prevent washout of vegetation. Based on OWRB data, the high point of the Lake Thunderbird conversation pool occurs in April, at about 3.5 ft above the average level. However, prolonged dry periods must also be avoided, as they can inhibit vegetative establishment and kill vegetation (Allen 2001).

Planting is restricted to either dormant periods or the growing season depending on the selection of vegetation. In general, seeding is performed during the growing season, while woody live cuttings should be transplanted during dormant periods. The growing season approximately lasts from March to mid-November (Landphair and Li 2002). Seeding is lower cost than transplanting live plants; however, transplanting has the advantages of quicker vegetative establishment and more control over plant spacing.

7.3.2 Extent and Location of Revegetation

Due to the extent of erosion at Lake Thunderbird, it would not be feasible to revegetate the entire shoreline. It is recommended that 5% of the total shoreline, equal to 4.3 miles or 22,700 ft, is targeted for revegetation. Revegetation efforts should be focused on Category 4 and 5 areas, which have experienced the most severe erosion. Category 4 and 5 shorelines have a height of erosion greater than 4 ft and would therefore require at least 12 ft of new vegetation if graded to a 3:1 slope. Assuming an average width of 15 ft from the waterline to the edge of the eroded areas, 340,560 ft^2 or 7.82 acres would be revegetated.

Preference should also be given to areas that receive large volumes of foot traffic or are near structures such as picnic tables, benches, and campgrounds. COMCD will need to survey the lakeshore to identify areas most in need of erosion control efforts. These areas will likely be exposed to longer fetches of a half mile or more. The longer the fetch from a shoreline of concern, the stronger the wind and wave action will be. Areas with low forest abundance and those that experience high runoff, such as the northwest of the lake, are also likely candidates for revegetation (Allen 2001).

Breakwaters should be installed at an elevation of 1038 ft, one foot below the typical water line. Due to their labor-intensive installation, branch boxes should be placed along 20% of the targeted shoreline, or 4,540 ft. Branchboxes should be placed in areas exposed to the longest fetches and exhibiting the most severe extent of erosion. CGRs should be installed along the remaining 18,164 ft of shoreline. Breakwaters should be in place for several months before planting in allow sediments to accumulate and form a suitable planting surface.

More gradual slopes are preferrable for plant establishment. For toes with slopes greater than 3:1, it is recommended that jute erosion control mats are placed after seeding. Erosion control mats should also be placed on looser, sandier soils, as they are more prone to erosion. For shorelines that have a near vertical slope due to erosion, grading is required to decrease the erosion potential of waves hitting the shoreline. While woody vegetation such as black willows can grow on a near vertical shoreline, herbaceous plants will be unable to establish along steep slopes.

7.3.3 Plant Species Selection

Numerous factors must be considered in the selection of plant species. Vegetation should be adapted to local conditions; thus, a preference should be given for native species. Using rootstock from established beds nearby can ensure that transplants are adapted to the local environment, as well as reduce costs compared to obtaining rootstock from nurseries (Shuttleworth 1997). Ideal plant species are those that quickly develop extensive roots or rhizomes and have rapid height growth (Allen and Klimas 1986).

Factors affecting plant survivability include the depth, duration, and timing of inundation, amount of rainfall, and winter conditions (Lester et al. 1986). Changes in water elevation from drawdown and reflooding impact littoral ecology, determining the composition of vegetation in wetland areas. The length of inundation influences germination success and growth rate, with emergent plant species typically more tolerant of water level fluctuations than submerged vegetation (Abraham 2006). In the erosion control pilot project at Lake Thunderbird, plant survival was limited due to extended drought and lake drawdown (OWRB 2005). Several plantings may be required over the course of multiple seasons to overcome losses due to drought or prolonged flooding.

Ideally, the area to be revegetated should have a gentle slope and a hard and sandy soil to limit the amount of anchoring required. Species selection must consider substrate characteristics. For example, both softstem bulrush and river bulrush are tolerant of a wider range of substrates than hardstem bulrush and thus may be preferable at sites with softer substrates (Shuttleworth 1997).

A study conducted at Lake Texoma in Oklahoma identified seven species with potential for use in shoreline revegetation (Lester et al. 1986). These species are listed in Table 24 with their erosion control value and maximum annual flood tolerance. From the erosion control pilot project conducted in at Lake Thunderbird in 2003, it was determined that softstem bulrush, common bulrush, and water willow were preferred emergent aquatic species for revegetation due to their drought hardiness and fast spread (OWRB 2005). Information on additional species is also provided in Table 25. Flood tolerance and erosion control value were not available for water willow. It was also determined whether each species was native to either of the ecoregions that make up the Lake Thunderbird watershed.

Table 24: Erosion control value and flood tolerance of species identified as useful for shoreline revegetation based on a study conducted at Lake Texoma, Oklahoma (Lester et al. 1986)

Type	Species	Common Name	Erosion Control Value	Maximum Annual Flood Tolerance (Weeks)	Present in Watershed (OCES 1998)
Herbaceous	*Arundo donax*	Giant reed	High	7	No
	Panicum virgatum	Kanlow switchgrass	Moderate	7	CGP, CT
	Panicum obtusum	Vine mesquite	Moderate	4	CGP
	Spartina pectinata	Prairie cordgrass	High	6	CGP, CT
Woody	*Amorpha fruticose*	Lead plant	Moderate	3	CT
	Diospyros virginiana	Persimmon	Moderate	3	No
	Salix nigra	Black willow	High	6	CGP, CT

CGP = Central Great Plains
CT = Cross Timbers

It is recommended that the Lake Thunderbird shoreline is planted with a mixture of softstem bulrush and prairie cordgrass. Prairie cordgrass was chosen based on its high flood tolerance and erosion control value, while Softstem bulrush was selected for its success in the erosion control pilot project at Lake Thunderbird.

Additionally, it is recommended that black willow is planted further shoreward for its high erosion control value. A woody species such as black willow is also expected to have a greater rate of nutrient uptake than herbaceous species. Black willow was selected over other woody species due to its greater flood tolerance. All three of the selected species are native to both ecoregions in the Lake Thunderbird watershed.

Table 25: Erosion control potential and flood tolerance of other herbaceous species with potential use for shoreline revegetation (Allen and Klimas 1986)

Species	Common Name	Erosion Control Value	Flood Tolerance	Present in Watershed (OCES 1998)
Juncus effusus	Common rush	Moderate	Somewhat Tolerant	CT
Justicia americana	Water willow	-	-	CT
Schoenoplectus americanus	Chairmaker's bulrush	Moderate/High	6 Weeks	CGP, CT
Schoenoplectus tabernaemontani	Softstem bulrush	Moderate	Moderately Tolerant	CGP, CT
Typha latifolia	Broadleaf cattail	High	Somewhat Tolerant	CGP, CT

CGP = Central Great Plains
CT = Cross Timbers

7.3.4 Estimated Cost

Tables 26 lists cost estimates for shoreline revegetation at Lake Thunderbird. All costs were updated to 2021 values using Equation 5, assuming an inflation rate of 2%. Where labor costs are not specified, a rate of $10/hr was assumed. For cost estimates, it was assumed that jute erosion control mats are placed over 20% of the revegetation area, or 68,112 ft^2.

It is estimated that willow cuttings will take up approximately 10% of the revegetation area, equal to 34,056 ft^2 or 0.78 acres. Equal amounts of prairie cordgrass and softstem bulrush should be planted, each covering 45% of the total revegetation area: 153,252 ft^2 or 3.52 acres. Based on the results of the erosion control pilot project at Lake Thunderbird, two or three planting efforts will be required over different growing seasons (OWRB 2005). This is done to counteract plant losses due to drought, excessive inundation, or other factors. For cost estimates, three planting and seeding efforts are assumed. A total of 21.1 acres are seeded and sprigged over the three events.

Seeds for prairie cordgrass and softstem bulrush should be planted by broadcast seeding, where seeds are scattered by hand over a large area. It is recommended that seeds are applied at a rate of 5 pounds per acre (Tyndall and Bowman 2016). Assuming each type of seed is broadcast on 45% of the design area over three growing seasons, 53 pounds of each type are required. Live plant plugs should be sprigged with 5.4 ft^2 center spacing (Allen 2001). Assuming three planting events covering 45% of the target area, 85,140 plugs of each species are required.

The spacing between black willows should be about 21 times the mean stem diameter of 14 inches (Tesky 1992). This is equal to 24.5 ft. With this spacing, 927 willows will be planted. Black willows should be planted furthest from the waterline to reduce competition between herbaceous and woody plants for light and nutrients.

Table 26: Estimated capital cost and total present worth for revegetation of 5% of Lake Thunderbird shoreline

Item	Unit Cost	Quantity	Total Cost	Source
Branch Box	$15.48/ft	4,540 ft	$70,300	Allen 2001
Branch Box Installation	4.3 ft/hr	4,450 ft	$10,300	Allen 2001
CGR Rolls	$1,000/60 ft	18,164 ft	$303,000	Rolanka International, Inc. 2021
CGR Installation	5 ft/hr	18,164 ft	$36,300	Allen 2001
Jute Erosion Control Mats	$0.09 /ft^2	68,112 ft^2	$6,100	Kalibová et al. 2016
Jute Mat Installation	40 ft^2/hr	68,112 ft^2	$17,000	Allen 2001
Prairie Cordgrass Plugs	$0.90/plug	85,140 plugs	$76,600	Mid Atlantic Natives Inc. 2021
Softstem Bulrush Plugs	$72.99/100 plugs	85,140 plugs	$62,200	Tennessee Wholesale Nursery 2021
Sprigging (Labor)	$39.88/acre	21.1 acres	$840	Sahs 2020
Prairie Cordgrass Seed	$40/lb	53 lbs	$1,400	Western Native Seed 2021
Softstem Bulrush Seed	$60/lb	53 lbs	$2,200	Western Native Seed 2021
Seed Broadcasting (Labor)	$10.46/acre	21.1 acres	$220	Sahs 2020
Willow Cuttings	$149/100 cuttings	927	$1500	Native Wildflowers Nursery 2021
Planting Live Cuttings	40 cuttings/hr	927	$230	Allen 2001
Site Grading	$29,070/mile	4.3	$125,000	USFS 2020
Total Capital Cost			**$716,200**	
O&M	2% capital cost/yr	20 years	$234,200	Tyndall and Bowman 2016
Total Present Worth			**$950,400**	

It is assumed that all of the target areas will require grading, as Category 4 and 5 sites exhibit escarpments of 4 ft or greater. For a width of 14 ft, grading may cost as much as $28,500 per mile, equal to $29,070 in 2021 dollars (USFS 2020).

Yearly O&M costs are estimated as 2% of the capital cost (Tyndall and Bowman). The total O&M costs over the twenty-year design life were converted to present worth using Equation 6. O&M includes system monitoring to determine the need for replanting and breakwater repair as well as the repair of the breakwaters. For CGRs, coir logs may need to be shifted and staked, and logs that have been washed away may need to be replaced. Branchbox breakwater maintenance may include replacing branches that have broken or floated away or installing additional stakes to provide more support to collapsing sections (Maynord et al. 2006).

7.3.5 Performance Estimates

For softstem bulrush, the net maximum above-ground nitrogen and phosphorus uptake rates are respectively 0.001 and 0.0003 oz ft^{-2} d^{-1} during the growing season. In winter, new belowground nutrient accumulation occurs at a rate of about 0.0004 oz N ft^{-2} and 0.00005 oz P ft^{-2} (Tanner 2001). Both the growing season and period of below-ground nutrient accumulation last for approximately three months or 90 days. Assuming that prairie cordgrass exhibits similar rates of nutrient uptake, the total uptake of nutrients would be 1600 lb N/yr and 400 lb P/yr.

During the Lake Thunderbird erosion control pilot project, the average elevation change at the study site was a 0.11-ft loss of sediment, compared to 0.04 ft at points closest to branch boxes (OWRB 2005). The reduction in sediment loss can be approximated as the product of the revegetated area and the difference in sediment loss due to the breakwater, 0.07 ft. This is equal to 15,900 ft^3 over a period of one year.

Where jute erosion control mats are implemented, mean runoff volume is expected to decrease by 38%, and the peak runoff discharge may decrease by 26%. Soil losses may be as little as 0.6% of the amount that would be lost if no erosion control measures were implemented (Kalibová et al. 2016). Assuming an average loss of 0.11 ft of sediment when no erosion control measures are implemented, this would result in a 5,900 ft^3 decrease in soil loss.

Chapter 8: References

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Appendix A: Project Documents

HEALTH AND SAFETY PLAN

Addressing Water Quality Issues of Lake Thunderbird

Prepared by:

JAY Engineering

202 W Boyd St, Norman, OK 73019

Prepared for:

Central Oklahoma Master Conservancy District

(COMCD)

February 23, 2021

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1.0 Introduction

The information in this Health and Safety Plan (HSP) is provided for use in ensuring the continual health and safety of all personnel involved in the assessment of Lake Thunderbird water quality and subsequent solution design conducted by JAY Engineering. This document presents all necessary background, hazard, and contact information for the safe completion of this project.

2.0 Project Information

2.1 Site Description

Located 13 miles east of Norman, Lake Thunderbird is a reservoir created by the impoundment of the Little River, a tributary of the Canadian River that runs through central Oklahoma. The lake has 86 miles of shoreline and a surface area of roughly 6,070 acres (USBR 2009). The reservoir was constructed to provide flood control and to serve as a water supply for Norman, Del City, and Midwest City and was completed in 1965 (Simonds 1999). Lake Thunderbird continues to supply raw municipal and industrial water for these communities. The reservoir and surrounding state park also serve as recreational facilities and habitats for fish and wildlife. Recreational resources have included hunting, fishing, swimming, and boating (Simonds 1999). The Lake Thunderbird watershed encompasses 257 square miles, with agriculture and forest as the primary land uses (Julian et al. 2015). The lake does not have any point sources of pollution but receives drainage from three cities: Norman, Moore, and Oklahoma City.

Lake Thunderbird is considered an impaired body of water for public/private water supply and warm water aquatic community (Dynamic Solutions, LLC 2013). Water quality issues include high turbidity, low dissolved oxygen (DO), and high chlorophyll-a (Julian et al. 2015). High turbidity is due, in part, to shoreline erosion, which has been an ongoing problem. Shoreline soils at Lake Thunderbird are generally acidic, non-cohesive, and nutrient-deficient, facilitating erosion and preventing natural revegetation (Allen 2001). Chlorophyll-a is produced by many photosynthetic organisms and used as a measure of algal biomass; thus, high chlorophyll-a levels are indicative of eutrophication and excessive nutrient loads. Lake Thunderbird has recently been classified as either eutrophic or hypereutrophic (OWRB 2020). Excessive algal growth can createobjectionable tastes and odors, impairing use as a water supply. Eutrophication also contributes to low DO, as the decomposition of dead algal biomass exerts a significant oxygen demand. The hypolimnion of Lake Thunderbird routinely experiences anoxic conditions in the summer (OWRB 2020). Anoxic conditions are harmful to aerobic biota and impair the lake's designated use for fish and wildlife propagation.

There have been ongoing efforts to improve the water quality of Lake Thunderbird, utilizing both in-lake technologies and watershed-level control. In 2011, the SDOX system was installed to increase DO in the hypolimnion; however, it has been determined that the system is undersized and does not affect lake water quality (OWRB 2020). Erosion control efforts have included installing riprap and vegetation (USBR 2009). The Oklahoma Department of

Environmental Quality (DEQ) has established Total Maximum Daily Loads (TMDLS) for sediments, nutrients, and organic matter in order to achieve adequate DO, turbidity, and chlorophyll-a (Dynamic Solutions, LLC 2013). However, management measures to achieve these goals were not defined. Further action is needed to improve water quality and remove Lake Thunderbird from the list of impaired water bodies. Water sampling will be conducted to measure DO, turbidity, and other parameters and to identify existing water-quality issues.

2.2 Scope of Work

Lake Thunderbird is subject to ongoing water quality issues, including erosion and eutrophication, that led to its status as an impaired body of water. The aim of this project is to develop enduring and sustainable solutions that will address these concerns. This project will evaluate existing data collected by the Oklahoma Water Resources Board to identify the extent of Lake Thunderbird's water quality issues and determine areas for improvement. These data will be supplemented by field sampling. In-lake and watershed-level technologies will be identified and compared, leading to the development of a solution suite. Final deliverables for this project include a written document presenting the proposed solution suite and an oral presentation to the Central Oklahoma Master Conservancy District board and stakeholders.

3.0 Communication

3.1 Personnel and Emergency Contact Information

Table 1 provides the contact information for the closest hospital and police department for use in the event of an emergency. Directions to the nearest hospital are given as a map in Figure 1.

Table 1: Emergency Response Contacts Nearest to Lake Thunderbird

Name	Address	Phone Number
Norman Regional Hospital	901 N Porter Ave, Norman, OK 73071	405-307-1000
Noble Police Department	115 N 2^{nd} St, Noble, OK 73068	405-872-9231

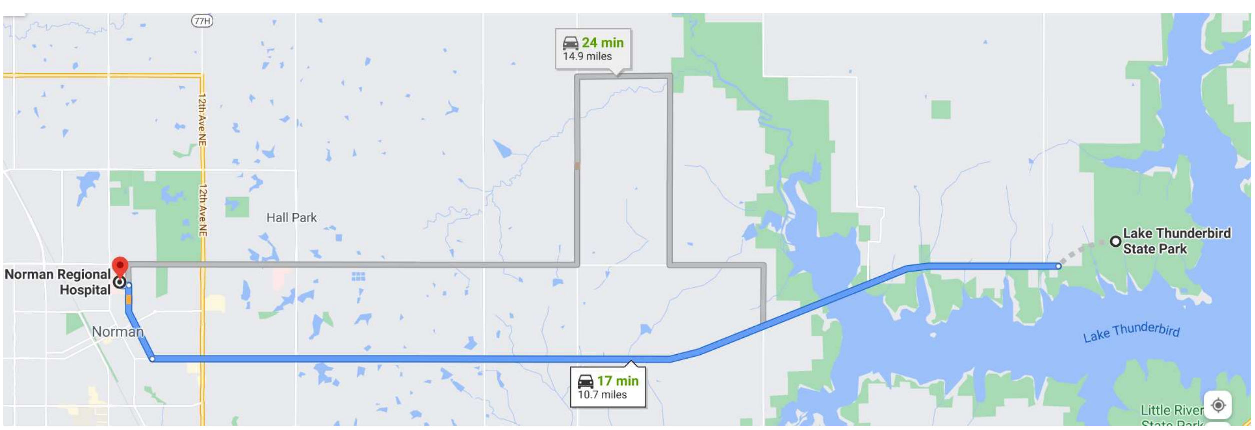

Figure 1: Directions to Norman Regional Hospital from Lake Thunderbird (Google 2020)

In the event of an emergency, the information provided in Table 2 will be used to reach the personnel's emergency contact.

Table 2: Individual Emergency Contact Information for Members of JAY Engineering and Their Advisors

Name	Address	Phone Number	Emergency Contact Name	Emergency Contact Number
Addisyn Clagg	1351 Edgewood Terrace Norman, OK 73026	405-593-6251	Kaleigh Clagg	405-618-8899
Hannah Curtis	1306 Cherry Stone St. Norman, OK 73072	405-816-1167	Terri Curtis	405-514-5841
Rodrigo Peralta	101 South 5th St. Noble, OK 73068	405-623-6193	Leslie Leigh	405-397-3615
John Puzz	722 Mossy Rd Norman, OK 73069	713-715-9451	Davis Puzz	405-227-5303
Kristen Soucheck	1800 Beaumont Dr Apt 1223 Norman, OK 73071	732-570-0112	John Soucheck	732-933-9574
Robert Knox	824 South Flood St. Norman, OK 73069	405-550-2355	Linda Georinger	405-249-8893
Robert Nairn	1629 Wilderness Drive, Norman, OK 73071	405-388-8819	Kathryn Amanda Nairn	405-664-0989

3.2 Field Communication

Communication is essential to conducting field work safely. Before each field activity, safety briefings will be given that overview potential hazards, proper PPE, and precautions to be taken. To maintain communication in the field, all personnel will carry personal cellular devices.

4.0 Field Hazards

4.1 General Hazards

- Lifting: Proper lifting technique shall be used when necessary. Personnel will not overestimate their load capacity and will ask for assistance when needed.
- Housekeeping: All personnel will clean up after themselves. All work at the field site will be performed during daylight hours.

4.2 Weather Hazards

- Cold Exposure: Prolonged cold exposure can cause hypothermia and frostbite. Heat loss is exacerbated if damp clothing is worn. Team members will wear multiple layers of warm clothing to allow them to adjust to different levels of physical activity.
- Heat Exposure: Heat exposure can lead to dehydration, Personnel will drink plenty of fluids, take frequent rest breaks, and seek shade as needed to prevent dehydration and overheating. UV exposure can cause sunburn. Proper personal protective equipment (PPE) and/or sunscreen will be worn to prevent sunburn.

4.3 Physical Hazards

- Trips/Falls: Uneven terrain, large rocks, and slippery surfaces could be encountered at the worksite. These hazards increase the risk of trips and falls. Members will wear proper footwear and work in adequate lighting to prevent falls.
- Plants: Plants may cause skin irritation and/or be poisonous. Poison ivy, poison oak, poison sumac, and stinging nettle, shown in Figures 2 and 3, can irritate the skin (Hamilton 1980). Clothing such as long pants, closed-toed shoes, and long-sleeved shirts will be worn to prevent contact with irritants. Personnel will not ingest any plant material.

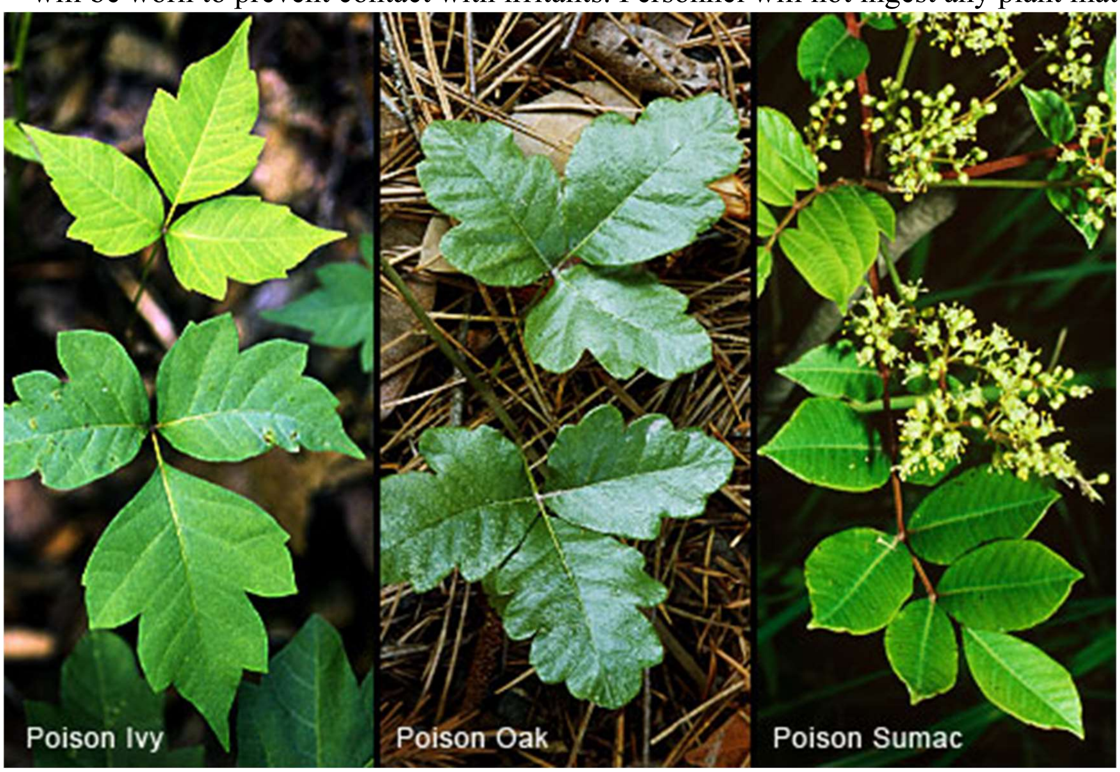

Figure 2: Left to Right - Poison Ivy, Poison Oak, and Poison Sumac (WebMD 2020)

Figure 3: Stinging Nettle Plants (Killebrew 2017)

- Animals: Two types of venomous snakes are common to central Oklahoma and may be encountered at Lake Thunderbird: the western pygmy rattlesnake and the copperhead, (OCPDI n.d.). These species are shown in Figures 4 and 5, respectively. Bites from non-venomous animals are also hazardous, as they may cause blood loss or become infected. Infectious diseases may be transmitted by insect bites. Long pants and long-sleeved shirts will be worn to prevent bites. Personnel are responsible for keeping alert while at the worksite.

Figure 4: A Venomous Western Pygmy Rattlesnake (oksnakes.org n.d.)

Figure 5: A Venomous Copperhead Snake (oksnakes.org n.d.)

4.4 Water Hazards

- Wading: Wading may be necessary to collect samples. In that case, water depth may pose a concern. Personnel will wear flotation devices if entering the water, and only experienced swimmers will be allowed to enter the water. Natural water may contain pathogens and is unsafe to drink. Personnel will not drink any natural waters.
- Boating: Water samples will likely be collected by boat. Only competent swimmers will board the boat and will wear flotation devices while aboard. The boat will be anchored before samples are taken. The following safety guidelines are adapted from the United States Coast Guard (2014):
    - Ensure the boat is free from tripping hazards.
    - Always maintain safe speeds.
    - Be alert for changing weather conditions. In case of severe weather, approach the nearest shore that can be accessed safely.
    - Maintain a lookout to avoid collisions.
    - Do not overload the boat and distribute the load evenly.
    - Keep seated at all times. Do not stand inside the boat.

5.0 Laboratory Hazards and Housekeeping

- Chemicals: Acids, bases, and other harmful chemicals may be used for water quality analyses. Methods are outlined in the Sampling and Analysis Plan. Closed-toed shoes, long-sleeved shirts, pants, safety goggles, and gloves will be worn while performing laboratory analyses. Team members will be familiar with procedures and their associated hazards before beginning any analysis. All chemicals will be stored and disposed of and any spills cleaned up as indicated in the appropriate Material Safety Data Sheet. Supervisors will be notified of any spills.

- Glassware: The glassware used in laboratory analyses may become chipped or shatter if handled improperly or exposed to excessive heat or pressure. Members will be cautious in using glassware. Any broken glass will be disposed of immediately. Cut-resistant gloves will be worn if handling broken glass. Supervisors will be notified of any breakage.
- Housekeeping: Team members will keep workstations clean and free from debris. All glassware will be washed with deionized water and left to dry in appropriate places after use. Chemical containers will be closed and placed in the proper location and all waste materials will be properly disposed of.

6.0 COVID-19 Concerns

The spread of COVID-19 is an ongoing concern. The following measures will be taken to prevent the spread of COVID-19:

- All JAY Personnel will take personal vehicles to and from the sampling site and the laboratory.
- Masks will be worn by all personnel at all times.
- Social distancing of at least 6 feet will be maintained whenever possible.
- No more than 7 people will be allowed in the sampling boat at all times.
- Laboratory usage will be restricted to no more than two people at any time.

7.0 Personal Protective Equipment

Accidents can be prevented or mitigated by wearing proper PPE. Long pants and closed-toed shoes are required for site and laboratory work.

7.1 Fieldwork

Jackets and gloves will be worn in cold conditions. Latex or nitrile gloves are required when sampling or performing field analysis. Cut-resistant gloves will be worn when moving debris. Flotation devices must be worn while in the water or on a boat.

7.2 Laboratory Analysis

Latex or nitrile gloves will be worn when performing all analyses. Cut-resistant gloves will be worn in the event of cleaning broken glassware. Goggles will be worn at all times.

8.0 Safety Documents

Table 3 provides phone numbers and email addresses for all JAY engineering personnel, including advisors. Emergency response contact information is repeated in Table 4.

Table 3: Individual Contact Information for all JAY Engineering Personnel

Name	Position	Phone Number	E-mail
Robert Knox	Advisor	405-550-2355	rknox@ou.edu
Robert Nairn	Advisor	405-888-3812	nairn@ou.edu
Kristen Soucheck	Team Leader	732-570-0112	kristensoucheck@ou.edu
Addisyn Clagg	Sediments Specialist	405-593-6251	addisyn.c.clagg-1@ou.edu
Hannah Curtis	Chief Editor	405-816-1167	hannahcurtis@ou.edu
Rodrigo Peralta	Hydrologic Specialist	405-623-6193	rodrigo.peralta@ou.edu
John Puzz	Data Analysis Lead	713-715-9451	john.a.puzz-1@ou.edu

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PROJECT WORK PLAN
Addressing Water Quality Issues of Lake Thunderbird

Prepared by:
JAY Engineering
202 W Boyd St, Norman, OK 73019

Prepared for:
Central Oklahoma Master Conservancy District
(COMCD)

February 23, 2021

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1.0 Introduction

The Project Work Plan (PWP) is designed to ensure the timely completion of the project. To this end, this document assigns tasks and provides deadlines. The PWP provides documentation of the goals and objectives for this project and the strategy by which JAY plans to approach them. In addition to the PWP, the Health and Safety Plan (HSP), Sampling and Analysis Plan (SAP), and the Quality Assurance Project Plan (QAPP) were developed concurrently to develop a strategy for obtaining quality results with minimal risk.

2.0 Project Overview

2.1 Lake Thunderbird

Located 13 miles east of Norman, Lake Thunderbird is a reservoir created by the impoundment of the Little River, a tributary of the Canadian River that runs through central Oklahoma. Lake Thunderbird was formed for the purpose of providing flood control and recreational use, as well as providing a drinking water source to the cities of Norman, Midwest City, and Del City. The Central Oklahoma Master Conservancy District (COMCD), established in 1959, has been responsible for maintaining the operation and maintenance of the water supply facilities through a contract with the U.S. Bureau of Reclamation. Water has been supplied to the above communities since the completion of the dam, pumping plants, and pipelines in 1965. Additionally, the COMCD works with the U.S. Army Corps of Engineers to regulate flood waters and aids the Oklahoma Department of Tourism and Recreation in managing recreational facilities (COMCD 2021). The COMCD board is comprised of seven members: three from Norman, three from Midwest City, and one from Del City.

The lake has approximately 86 miles of shoreline and 6,000 acres of surface water. Lake Thunderbird is the habitat for aquatic marine organisms such as catfish, saugeye, crappie, and largemouth bass (USBR 2017). The available water storage in the lake for flood control is about 76,600 acre-feet at elevations of 1,039 feet and 1,049 feet at the top of the conservation pool and the flood control pool, respectively (Norman Dam 1969). When the water level in the reservoir exceeds the top of the flood control pool, water is released into the Little River until the water level recedes to below an elevation of 1,049 feet.

2.2 Current Status

Lake Thunderbird is considered a Category 5a lake because it is as a Sensitive Water Supply (SWS), and it cannot support Fish and Wildlife Propagation (FWP) for a warm water community due to high chlorophyll-a levels. Lake Thunderbird also has high turbidity levels, caused in part by shoreline erosion, which has been an ongoing problem. Shoreline soils at Lake Thunderbird are generally acidic, non-cohesive, and nutrient-deficient, facilitating erosion and preventing natural revegetation (Allen 2001). High chlorophyll-a levels and high turbidity affect the water quality immensely, leading to poor taste and odors, and can result in higher water treatment costs (Dynamic Solutions, LLC 2013).

Chlorophyll-a is produced by many photosynthetic organisms and used as a measure of algal biomass; thus, high chlorophyll-a levels are indicative of eutrophication and excessive nutrient loads. Eutrophication is the process by which a body of water becomes overly enriched with nutrients, leading to the excessive growth of algae. Lake Thunderbird has recently been classified as either eutrophic or hypereutrophic (OWRB 2020). The chemicals geosmin and 2-methylisobromiol, commonly produced by cyanobacteria, also indicate the presence of blue-green algae (OWRB 2014). Excessive algal growth can create objectionable tastes and odors and has led to complaints from the community during the turnover period. Eutrophication due to excessive nutrient concentrations also contributes to low DO, as the decomposition of dead algal biomass exerts a significant oxygen demand. The hypolimnion of Lake Thunderbird routinely experiences anoxic conditions in the summer (OWRB 2020). Anoxic conditions are harmful to aerobic biota and impair the lake's designated beneficial use for fish and wildlife propagation.

There are no point source discharges into the lake; the water quality is impaired by nonpoint sources, with the lake receiving drainage from Norman, Moore, and Oklahoma City. According to the SWAT model results by Vieux and Vieux (2007), it is estimated that approximately 18,000 kg of phosphorous enters Lake Thunderbird each year. This can mainly be attributed to urban growth and the increasing area of impervious surfaces (OCC 2008).

2.3 Criteria and Standards

When a body of water is placed on Oklahoma Department of Environmental Quality's (DEQ) 303(d) list, the water body is threatened or impaired. The EPA requires states to submit their list of impaired water bodies every two years. The impaired water body, in this case Lake Thunderbird, will stay on the 303(d) list until a TMDL, or Total Maximum Daily Load, is developed (EPA 2018). A TMDL report includes a plan outlining improvements that can be made to the lake's water quality, as well as addressing non-point sources of water impairment.

The DEQ used a sediment flux model to examine the sediment composition of Lake Thunderbird (Dynamic Solutions, LLC 2012). It was shown that decomposition of particulate matter occurs in the sediment bed, consuming dissolved oxygen at the sediment-water interface. Constituents such as ammonia, phosphorous, chemical oxygen demand (COD), and silica are exchanged across the sediment-water interface. To meet chlorophyll-a standards, the lake should not exceed a ten-year average of 10 µg/L at a 0.5-meter depth. This criterion was exceeded substantially in years prior with an average of 24.3 µg/L in 2019, with a ten-year average of 23.2 µg/L.

The dissolved oxygen (DO) criterion levels are described in Oklahoma Administrative Code (OAC) 785:46-15-5. In 2019. Lake Thunderbird was considered to experience metalimnetic anoxia, indicating a eutrophic system in which algal growth is increased (OWB 2020).

According to OAC 785:45-5-12 (f)(7), if at least 10% of samples taken over a ten-year period exceed a turbidity of 25 NTU, the lake is considered not supportive of Fish and Wildlife Propagation. In 2013, about 21% of the lake samples that were collected exceeded this criterion, only increasing at the end of the year (OWRB 2014). In 2019, the average turbidity for the lake was measured at 27.4 NTU, with 26.1% of the samples collected exceeding the 25 NTU criterion (OWRB 2020).

As the water quality continues to not meet the standards described above, complaints regarding lake aesthetics, poor taste, and poor odor have continued to grow. To combat the repercussions of increasing constituent exceedance over standard criteria placed on Oklahoma lakes, JAY will evaluate best management practices (BMPs) and technologies that will help alleviate the water quality issues.

3.0 Goals and Objectives

3.1 Purpose

There have been ongoing efforts to improve the water quality of Lake Thunderbird, utilizing both in-lake technologies and watershed-level control. In 2011, the SDOX system was installed to increase DO in the hypolimnion; however, it has been determined that the system is undersized and does not affect lake water quality (OWRB 2020). Erosion control efforts have included installing riprap and vegetation (USBR 2009). The DEQ has established a TMDL for sediments, nutrients, and organic matter in order to achieve adequate DO, turbidity, and chlorophyll-a (Dynamic Solutions, LLC 2013). However, management measures to achieve these goals were not defined. Further action is needed to improve water quality and remove Lake Thunderbird from the list of impaired water bodies. Water sampling will be conducted to measure DO, turbidity, and other parameters and to identify existing water-quality issues.

The Oklahoma Water Resources Board (OWRB) has provided data regarding the water quality for Lake Thunderbird spanning over the previous two decades. JAY will evaluate the data sets for several parameters including DO, total phosphorous, nitrogen, chlorophyll-a, and sediments in relation to the growth of algal composition. From this analysis, JAY will determine best management practices (BMP) and technologies that will improve the water quality in Lake Thunderbird. Final deliverables for this project include a written document presenting the proposed solution suite and an oral presentation to the Central Oklahoma Master Conservancy District (COMCD) and stakeholders.

3.2 Issues of Concern

One of the primary concerns with Lake Thunderbird water quality is excessive nutrient concentrations and corresponding algal growth. High concentrations of algae can result in DO depletion due to the decomposition of organic matter. Dissolved oxygen in the lake is essential for the survival of aquatic organisms and higher mortality rates result if DO concentration decreases. During the summer, the ability for fish to survive in Lake Thunderbird decreases substantially. This is due to warming of the surface water in the epilimnion, forcing the fish to migrate to the hypolimnion where there is little to no DO for them to survive (USGS, n.d.). The other major concern that must be addressed is the lake's high turbidity. This is due to algal growth, erosion, and sediment loadings from nonpoint sources.

3.3 Key Stakeholders

Central Oklahoma Master Conservancy District: The COMCD is responsible for managing the water supply facilities associated with Lake Thunderbird. COMCD regularly monitors the reservoir's water quality through a Beneficial Use Monitoring Program (BUMP).

Del City, Midwest City, and Norman: These three cities rely on Lake Thunderbird for their municipal water supply. Any changes in water quality will impact their water treatment operations. All three would benefit from improved water quality in the lake.

Norman, Moore, and Oklahoma City: Lake Thunderbird receives drainage from these three cities. Any water-shed level controls, such as Best Management Practices (BMPs), recommended would be applied to all three. This may impact urban development.

Oklahoma Department of Environmental Quality: The DEQ was responsible for developing the TMDLs for Lake Thunderbird. The project aims to design a solution that will reduce nutrient and sediment loadings to below the TMDLs.

Oklahoma Water Resources Board (OWRB): The OWRB monitors water quality data and standards as well as conducts research. This project aims to provide a solution that will produce water quality data that meets the water quality standards.

3.4 Goals and Objectives

The overall project goal is to generate data for chemical parameters from samples collected from Lake Thunderbird of sufficient precision to incorporate into analysis of the lake's water quality. To maintain organization through the entirety of this project, objectives were developed using the S.M.A.R.T (Specific, Measurable, Achievable, Relevant, and Time Bound) criteria.

The objectives of this project are to identify the major water quality issues of Lake Thunderbird and develop cost-effective solutions to address this problem by collecting water samples from the lake and analyzing the data for different parameters outlined in the SAP. To this end, water quality sampling will be performed on-site. Safety is very important, both in the field and in the laboratory. While collecting and analyzing samples from Lake Thunderbird, personnel will follow safety precautions outlined in the HSP. The HSP includes precautions that should be taken in order to prevent a hazardous event from occurring, as well as actions that should be taken in the case of an incident. Personnel will be required to review this document before engaging in field or laboratory work. While in the field, personnel will communicate using personal cellular devices.

Before and during sampling, JAY personnel will review the SAP as well as the QAPP to ensure the correct guidelines are followed while collecting, labeling, transporting, and analyzing samples. Following these documents will minimize error in sampling and analysis.

Since sampling will be limited, data sets provided by COMCD for the past 20 years will also be analyzed. Using this data, contaminants of concern can be identified, and potential technological solutions can be evaluated. Solutions explored will include technologies and BMPs at the watershed level, as well as solutions that can be implemented in-situ.

4.0 Project Constraints

This project will be advised by Dr. Robert Knox, Dr. Robert Nairn, and rely heavily on coordination with COMCD. The Center for Restoration of Ecosystems and Watersheds (CREW) laboratories will be essential to performing sample analysis.

There are many potential constraints pertaining to sampling Lake Thunderbird water quality due to COVID-19 concerns. While sampling activities are planned to occur, it is likely that social distancing rules will still be active or that sampling and data collection will be unfeasible in those conditions. COVID-19 concerns could also limit the number of sampling events. Time is also a major constraint. The project must be completed in time to present findings to stakeholders in May 2021. To interpret data and design potential solutions, sampling and data analysis will need to be concluded at the latest by February 11, 2021.

Sampling is planned to occur during March 2021. Weather events such as snow or below freezing temperatures may impose constraints on sampling. Lake water samples will be taken from a boat rather than along the shoreline; therefore, equipment availability will be a concern as well. This could result in only one sampling trip, meaning the samples need to be taken accurately and stored and labeled properly to avoid contaminating and/or invalidating the samples and to maintain efficiency and organization for data analysis.

5.0 Project Timeline and Responsibilities

Figure 1 shows the primary responsibilities of each JAY team member. These roles were assigned based on the experience and skills of each team member. While each team member leads specific project areas, all team members will work on all parts of the project.

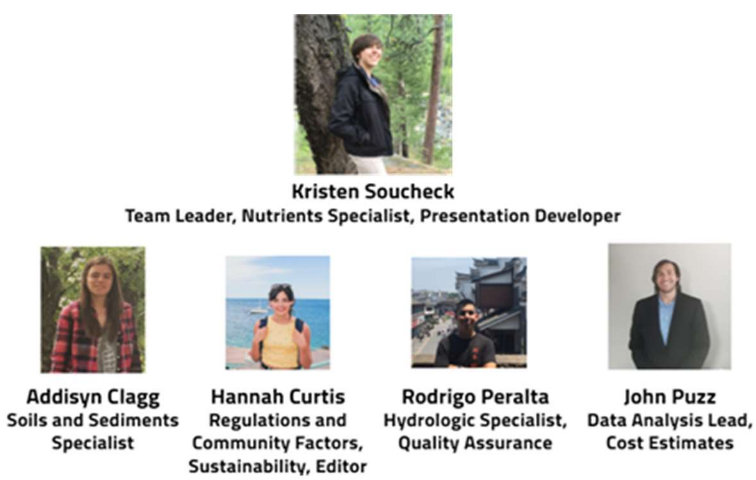

Figure 1: JAY Team Member Primary Responsibilities

5.1 Sampling

Depending on COVID-19 restrictions, as well as severe weather variability, sampling is planned to take place in March 2021. Water samples will be taken at four locations, with two additional locations if time permits. Due to COVID-19 restrictions, a maximum of 7 people will be allowed on the sampling boat at all times.

Figure 2 shows the sites sampled by the OWRB in 2019 (OWRB 2020). Sites 4, 1, and 5, representing two open water locations and a transition zone, respectively, will be sampled by JAY Personnel. To represent a tributary, samples will be taken at the bridge near site 6 (Figure 2). Site 6 cannot be sampled due to its inaccessibility. If time permits, sites 2 and 11, representing open water and a tributary, will also be sampled.

Figure 2: 2019 OWRB Sampling Locations; Red and Yellow Circles Represent Primary and Optional Sampling Locations (OWRB 2020)

5.2 Data Analysis

All group members will collaborate to perform laboratory analysis of the samples. As data analysis lead, John Puzz will oversee the overall data analysis to ensure efficiency and communication amongst the team.

5.3 Timeline

The timeline for when tasks are to be completed is outlined in Figure 3. The sampling event is shown to take place on January 30th, barring COVID-19 restrictions and weather delays, and the laboratory analyses are shown to take place in the time frame of January 31st – February 11th. The report should be completed by April 22nd, and the final oral presentation to COMCD and stakeholders will take place on May 4th.

Milestones include 33%, 66%, and 100% completion drafts, due February 16th, March 11th, and April 20th, respectively. A draft oral presentation will be prepared by April 22nd. These milestones will aid in the timely completion of project deliverables.

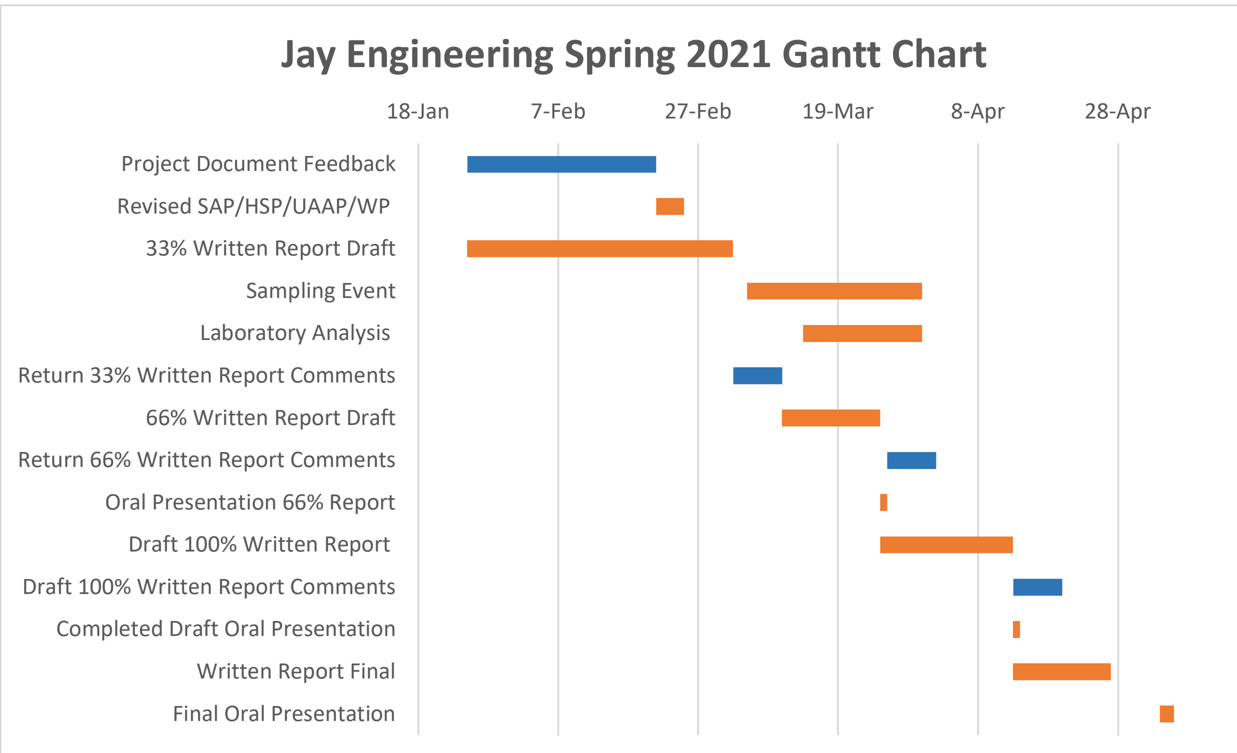

Figure 3: Gantt Chart Showing JAY Engineering Spring 2021 Timeline

6.0 Strategy

This project will be a collaborative effort between all JAY members, relying on effective communication and sharing work equitably. Work tasks are divided up throughout the Fall 2020 and Spring 2021 semesters, in which the Fall semester will be comprised of a majority of the research, community perception, and regulations, while the Spring semester will be comprised of sampling and data analysis, as well as preparing the final report to present to COMCD and stakeholders. Adhering to the procedures and requirements outlined in the HSP, SAP, QAPP is essential. Milestone drafts will serve to keep the project on schedule for a timely completion.

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QUALITY ASSURANCE PROJECT PLAN

Addressing Water Quality Issues of Lake Thunderbird

Prepared by:

JAY Engineering

202 W Boyd St, Norman, OK 73019

Prepared for:

Central Oklahoma Master Conservancy District

(COMCD)

February 23, 2021

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Approvals

Approved by: ______________________________________ ________________

Dr. Robert Knox, Project Advisor Date

Approved by: ______________________________________ ________________

Dr. Robert Nairn, Project Advisor Date

Approved by: ______________________________________ ________________

Kristen Soucheck, Team Leader Date

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1.0 Project Management

1.1 List of Personnel

Table 1 provides the names, primary roles, and contact information for all JAY Engineering personnel.

Table 1: List of JAY Engineering Personnel with Contact Information

Name	Position	Phone Number	E-mail
Robert Knox	Advisor	405-550-2355	rknox@ou.edu
Robert Nairn	Advisor	405-388-8819	nairn@ou.edu
Kristen Soucheck	Team Leader	732-570-0112	kristensoucheck@ou.edu
Addisyn Clagg	Sediments Specialist	405-593-6251	addisyn.c.clagg-1@ou.edu
Hannah Curtis	Chief Editor	405-816-1167	hannahcurtis@ou.edu
Rodrigo Peralta	Hydrologic Specialist	405-623-6193	rodrigo.peralta@ou.edu
John Puzz	Data Analysis Lead	713-715-9451	john.a.puzz-1@ou.edu

1.2 Project Organization

With the aid of Dr. Knox and Dr. Nairn as project advisors, the team of environmental scientists and engineers with JAY Engineering will evaluate existing water quality issues at Lake Thunderbird, with the end goal of designing a solution suite to address these issues. The organization of JAY Engineering is shown in Figure 1.

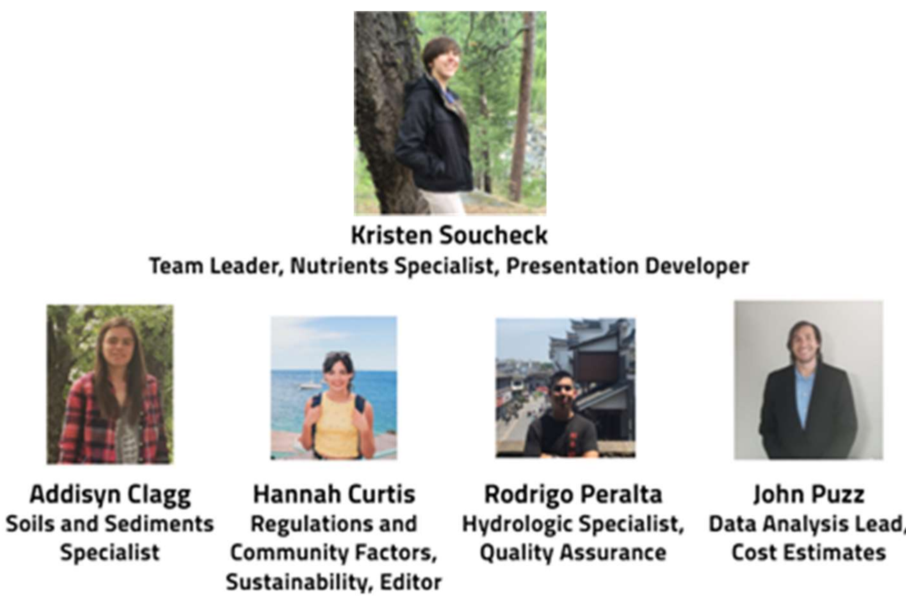

Figure 1: Organizational Structure of JAY Engineering

Kristen Soucheck, as team leader, is responsible for overseeing all aspects of the project. This includes reviewing all project documents and developing all presentations related to the project. She will serve as the point of communication between the JAY Engineering team and the project advisors, Dr. Knox and Dr. Nairn. She has focused her literature review on nutrients and will lead sampling and analysis related to this topic. Along with overseeing other documents, Soucheck was also the primary author on the HSP.

Addisyn Clagg is serving as the soil and sediments expert. She will be responsible for field and laboratory analysis relating to this subject. Additionally, she has focused her literature review on this topic. For Fall 2020, Clagg has served as the Project Documents Leader. Thus, in addition to being the primary author of the PWP, she has overseen the completion of the HSP, SAP, and QAPP.

Hannah Curtis, as Chief Editor, is responsible for reviewing all project documents and presentations to ensure they are accurate and easily understandable. Her literature review focuses on regulations, community acceptance, and sustainability; she will advise solution designs so that they adhere to these factors.

Rodrigo Peralta, as the Hydrologic Specialist, has focused his literature review on watershed-level impairment and best management practices. He will also be responsible for the analysis of hydraulic data and will be leading the assessment of in-lake technologies, especially regarding their efficiencies. Peralta has also focused on developing the SAP.

John Puzz, in the role of Data Analysis Lead, will oversee the analysis of both existing data and those generated from sampling events. His literature review focused on in-lake improvement technologies. During solution suite design, he will focus on economic factors, as well as operation and maintenance. Puzz has also worked on developing the QAPP.

2.0 Project Background

2.1 Site Description

Located 13 miles east of Norman, Lake Thunderbird is a reservoir created by the impoundment of the Little River, a tributary of the Canadian River that runs through central Oklahoma. The lake has 86 miles of shoreline and a surface area of roughly 6,070 acres (USBR 2009). The reservoir was constructed to provide flood control and to serve as a water supply for Norman, Del City, and Midwest City and was completed in 1965 (Simonds 1999). Lake Thunderbird continues to supply raw municipal and industrial water for these communities. The reservoir and surrounding state park also serve as recreational facilities and habitat for fish and wildlife. Recreational resources have included hunting, fishing, swimming, and boating (Simonds 1999). The Lake Thunderbird watershed encompasses 257 square miles, with agriculture and forest as the primary land uses (Julian et al. 2015). The lake does not have any point sources of pollution but receives drainage from three cities: Norman, Moore, and Oklahoma City.

Lake Thunderbird is considered an impaired body of water for public/private water supply and warm water aquatic community (Dynamic Solutions, LLC 2013). Water quality issues include high turbidity, low dissolved oxygen (DO), and high chlorophyll-a (Julian et al. 2015). High turbidity is due in part to shoreline erosion, which has been an ongoing problem. Shoreline soils at Lake Thunderbird are generally acidic, non-cohesive, and nutrient-deficient, facilitating erosion and preventing natural revegetation (Allen 2001).

Chlorophyll-ais produced by many photosynthetic organisms and used as a measure of algal biomass; thus, high chlorophyll-a levels are indicative of eutrophication and excessive nutrient loads. Lake Thunderbird has recently been classified as either eutrophic or hypereutrophic (OWRB 2020). Excessive algal growth can create objectionable tastes and odors, impairing use as a water supply. Eutrophication also contributes to low DO, as the decomposition of dead algal biomass exerts a significant oxygen demand. The hypolimnion of Lake Thunderbird routinely experiences anoxic conditions in the summer (OWRB 2020). Anoxic conditions are harmful to aerobic biota and impair the lake's designated use for fish and wildlife propagation. Additionally, anaerobic conditions can lead to release of phosphorus form lake sediments, increasing in-lake phosphorus concentrations, and contributing to algal growth.

There have been ongoing efforts to improve the water quality of Lake Thunderbird, utilizing both in-lake technologies and watershed-level control. In 2011, the SDOX system was installed to increase DO in the hypolimnion; however, it has been determined that the system is undersized and does not affect lake water quality (OWRB 2020). Erosion control efforts have included installing riprap and vegetation (USBR 2009). The Oklahoma Department of Environmental Quality has established total maximum daily loads for sediments, nutrients, and organic matter in order to achieve adequate DO, turbidity, and chlorophyll-a (2013). However, management measures to achieve these goals were not defined. Further action is needed to improve water quality and remove Lake Thunderbird from the list of impaired water bodies. Water sampling will be conducted to measure DO, turbidity, and other parameters and to identify existing water-quality issues.

2.2 Project Goals

Lake Thunderbird is subject to ongoing water quality issues, including erosion and eutrophication, that lead to its status as an impaired body of water. The aim of this project is to develop enduring and sustainable solutions that will address these concerns. This project will evaluate existing data collected by the Oklahoma Water Resources Board to identify the extent of Lake Thunderbird's water quality issues and determine areas for improvement. These data will be supplemented by field sampling. In-lake and watershed-level technologies will be identified and compared, leading to the design of a solution suite. Final deliverables for this project include a written document presenting the proposed solution suite design and an oral presentation to the Central Oklahoma Master Conservancy District board and stakeholders.

2.3 Data Quality Objectives

Data collected for chemical parameters from sampling of Lake Thunderbird will be of sufficient precision to incorporate into analysis of lake water quality. Following the procedures outlined in the SAP will help ensure precise and organized sample collection and analysis. Quality assurance (QA) and quality control (QC) measures will be taken to ensure acceptable precision, accuracy, and overall validity of the data produced. QA measures such as decontamination, labeling, recording, chain-of-custody, and transport are discussed in section 3.3. QC methods such as field and equipment blanks, field duplicates, laboratory replicates (split samples), spiked samples, and calibrations blanks will all be used, and their purpose and method are discussed in section 3.4. All data obtained will be used in combination with data provided by the Oklahoma Water Resources Board (OWRB) to determine the best management practices and technologies to resolve Lake Thunderbird's issues with eutrophication, more specifically dissolved oxygen levels, turbidity, and chlorophyl-a, which all fail to meet USBR and OAC standards.

2.4 Project Timeline

Project efforts began in September 2020, and the project is expected to be completed and findings communicated to stakeholders in May 2021. Fall 2020 focused on background research, literature reviews, and completion of project documents (Figure 2). The second phase of the project will begin in January 2021 and will consist of sampling, data analysis, and solution design. Sampling is scheduled to take place in March of 2021 and will be followed by laboratory analysis (Figure 3). Using the data generated from sampling, as well as water quality data provided by the OWRB, potential in-lake technologies and water-shed level management practices will be assessed. The project will conclude with a presentation of a finalized solution suite design to the Central Oklahoma Master Conservancy District board and stakeholders.

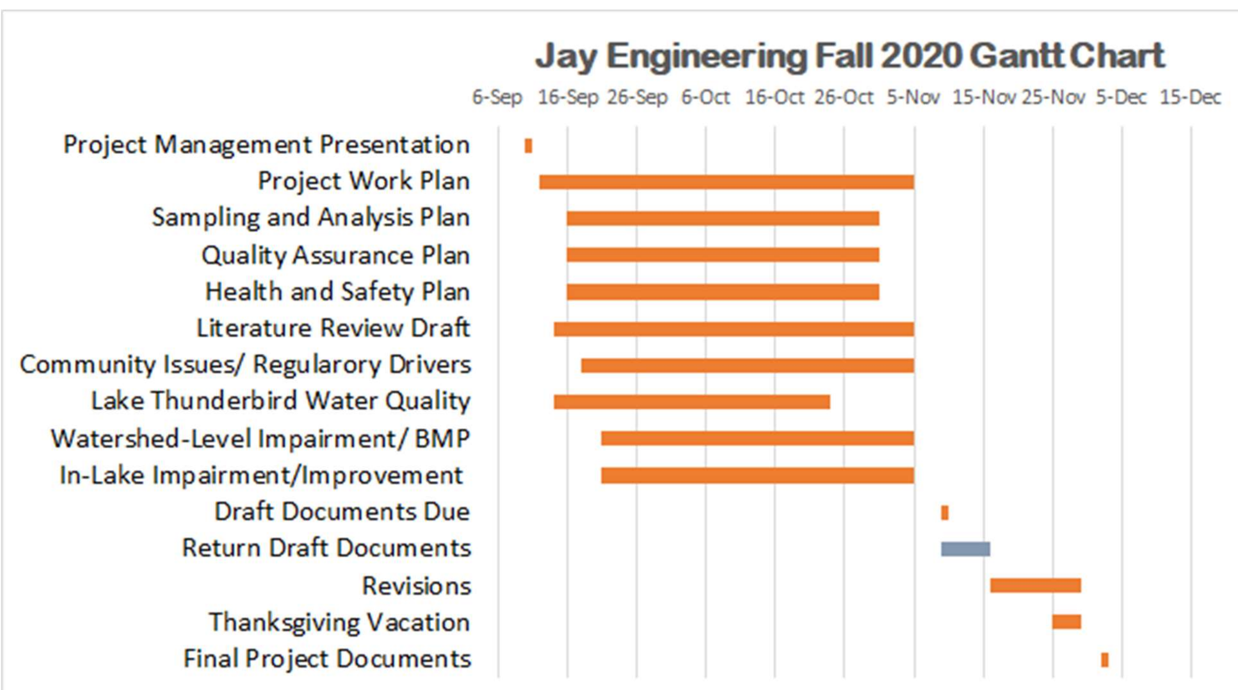

Figure 2: JAY Engineering Fall 2020 Project Schedule

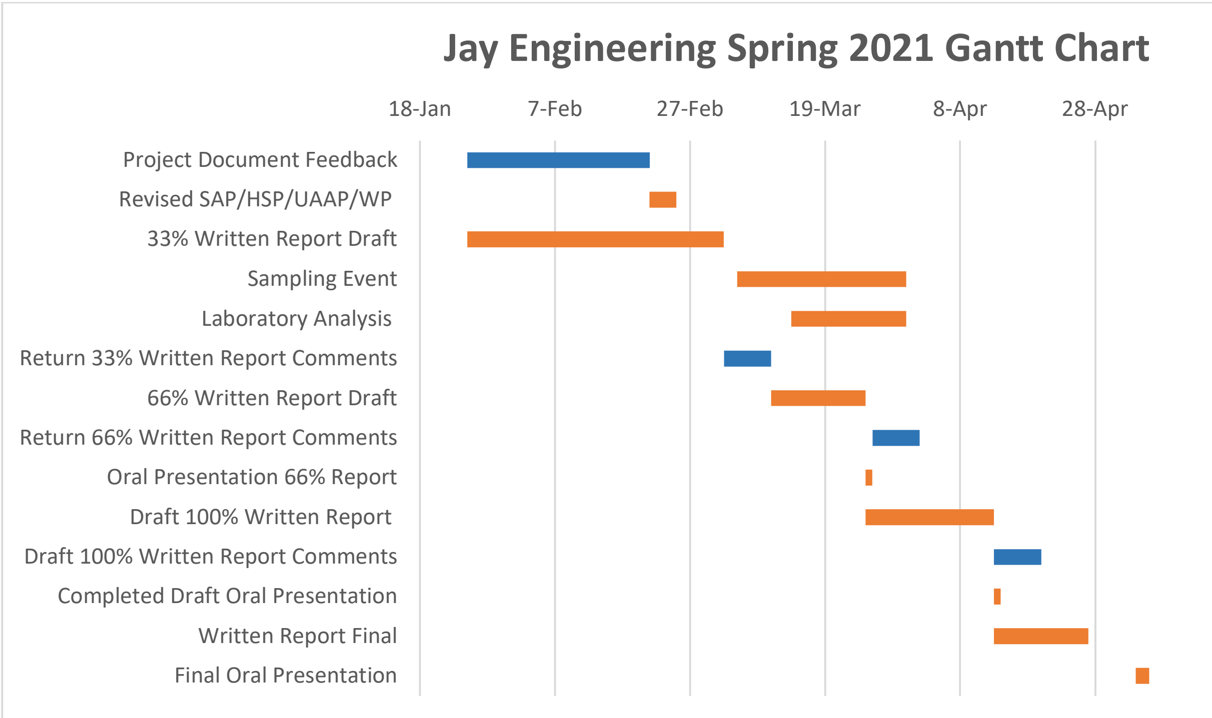

Figure 3: JAY Engineering Spring 2021 Project Schedule

3.0 Data Sampling and Analysis

3.1 Project Design

Jay Engineering will analyze samples taken from Lake Thunderbird at several locations for various parameters that may contribute to the poor water quality and poor community outlook of the lake. Field samples will be analyzed for nitrate, nitrite, organophosphate, sulfate, chloride, total phosphorus, and total nitrogen concentrations. Field measurements performed by JAY Engineering will include turbidity, Secchi disk depth, alkalinity, hardness, temperature, dissolved oxygen (DO), pH, oxidation-reduction potential (ORP), specific conductance (SC), and chlorophyll-a. Nitrite, nitrate, total nitrogen, organophosphate, total phosphorus, and chlorophyll-a data will provide more information on limiting nutrients of the lake. Alkalinity, pH, and specific conductance of the lake are important parameters for predicting the chemical reactivity of the lake to many different compounds and will also be tested in each sample. Clarity, measured as Secchi disk depth, and turbidity will be analyzed to assess the level of suspended solids of the lake.

Figure 4 provides an aerial view of Lake Thunderbird and its surroundings. Figure 5 shows the 4 sampling locations at sites 4, 1, and 5, representing two open water locations and a transition zone, respectively. To represent a tributary, samples will be taken at the bridge near site 6 (Figure 4). Site 6 cannot be sampled due to its inaccessibility; however, water will be sampled below the bridge near site 6. If time permits, sites 2 and 11, representing open water and a tributary, will also be sampled. Samples from a tributary, intermediate zone, and open water will help produce a more expansive set of data for the condition of the lake and the non-point sources of nutrient loading.

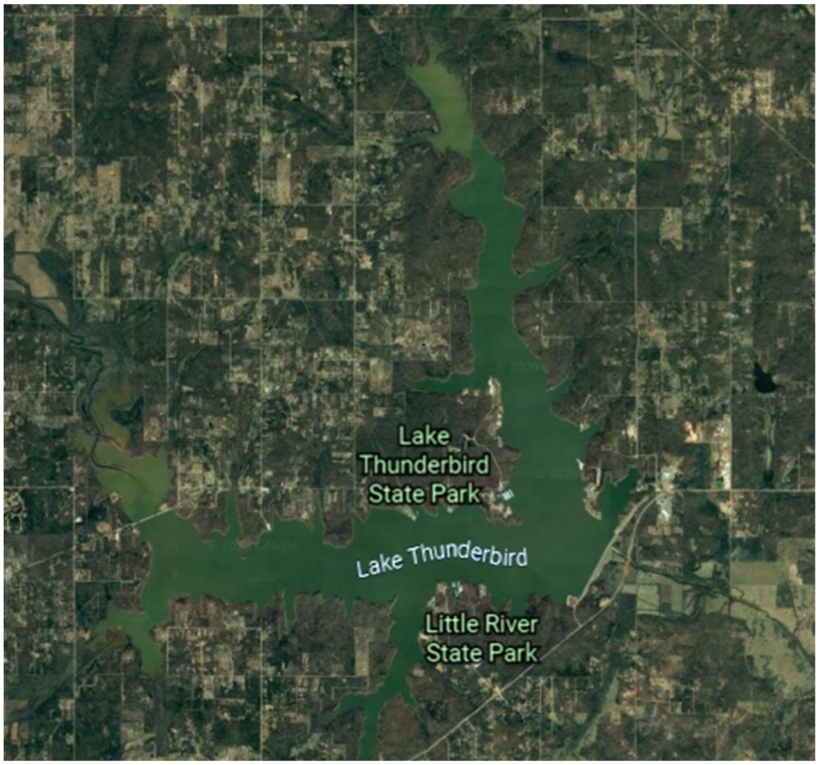

Figure 4: Satellite Image of Lake Thunderbird (Google Earth)

Figure 5: 2019 OWRB Sampling Locations; Red and Yellow Circles Represent Primary and Optional Sampling Locations (OWRB 2020)

3.2 Sampling Methods

Water samples will be taken by boat from each of these sites. Water samples will be collected at each of these sites through dipping and discrete depth sampling. Reference the Sampling and Analysis Plan (SAP) for further detail on these procedures. These procedures will allow for collection of water samples at the surface and other specific depths for data analysis.

3.3 Quality Assurance

Decontamination, labeling, and chain of custody will be used to ensure all equipment is free of contamination, and that all samples are properly labeled, handled, and stored. These processes are also outlined in the SAP.

Sample bottles will be rinsed in triplicate with deionized (DI) water between each sampling site. Alkalinity and hardness kit flasks will be rinsed in triplicate with DI water before each test. Turbidity kit vials will be rinsed in triplicate with DI water and the outside wiped before each reading.

During the collection of each sample, the following information will be recorded in the field book:

- Sample date and time
- Sample location (latitude and longitude)
- Names of team members collecting the sample
- Analytical parameter being measured
- Chain-of-custody form number

At the end of the sampling event, the following information will be recorded in the field book:

- Sampling start and end time
- Specific locations sampled and description of overall weather and environment
- Team members present and their individual responsibilities
- Any additional personnel present
- Calibration numbers for equipment used
- Any changes in assigned responsibilities or sampling procedures

Additionally, chain-of-custody forms will be used to determine whose custody each sample is in at any given time. The forms will accompany the sample to the laboratory for further analysis. A sample is considered to be in someone's custody if it is in the possession of the person or locked up or secured in a place restricted to authorized personnel. In this case, the sampling leader will write their initials in the "released by" column on the sampling date. The full example of the chain-of-custody form is shown in Table 2 below.

Table 2: Example Chain-of-Custody Form

Item #	Date & Time	Location	Released by:	Received by:	Comments

All water samples will be transported and stored on ice in large ice coolers with the lids on. Ice coolers will be used in order to keep the temperature relatively constant and the environment dark. Refer to the SAP for more information on sample preservation and hold times. Chain-of-custody forms will be transported and stored with the samples.

All laboratory analyses will be conducted in The University of Oklahoma's Carson Engineering Center, room 328/330.

Instrument/equipment testing, inspection, maintenance, and calibration is discussed in further detail in section 3.5.

3.4 Quality Control

The Quality Control procedures will follow the EPA's "Quality Assurance, Quality Control, and Quality Assessment Measures" (EPA 2012) for water monitoring and assessments.

EPA Internal Quality Control may involve:

- Field blanks/equipment blanks
- Negative and positive plates
- Field duplicates
- Laboratory replicates (split samples)
- Spike samples
- Calibration blanks

Field blanks are samples of deionized water filled in-situ like other field samples, then treated and analyzed as a regular sample. The EPA suggests at least 10 percent of samples to be field blank samples. This will help identify any possible systematic error or contamination of samples.

If there are any levels of analytes detectable in the field blanks that exceed the quantitation limit (QL), the samples for the analyte of concern likely have some level of contamination and should be either rejected or considered an estimate if the level of contamination is small relative to the actual concentration of the analyte of concern.

Equipment blanks may also be used. Equipment blanks will follow the same guidelines as field blanks, but the deionized water is first obtained after rinsing decontaminated measuring equipment. If some level of contamination is quantified, all equipment used to obtain the data will be decontaminated.

Field duplicates will be lake samples taken from the same location by the same team. This will the sampling and laboratory analysis precision. Relative percent difference between field and duplicate samples will determine if the data is useable. The percent difference of concentrations between the duplicate and original samples will be determined by Equation 1. A standard rule of thumb is that all values that fall under less than a 20 percent difference will be acceptable (EPA n.d.).

$$\%\,difference = \frac{|X_1 - X_2|}{(X_1 + X_2)/2} * 100 \quad \textbf{(1)}$$

Where X_1 is the original sample concentration and X_2 is the duplicate sample concentration. All data sets that exceed a 20 percent difference will be rejected.

Laboratory replicates will be samples split into subsamples. This will test the analytical precision of the procedures and equipment used. The samples' results will be compared to detect and correct for possible error. At least 2 laboratory replicates will be tested for each analyte following the same procedure. Sample variation will be calculated using Equation 1. The same standards for field duplicate samples will be used for laboratory replicate samples. Less than a 20 percent difference will be considered acceptable.

If data for an analyte of concern is rejected, a second sample may be retrieved and retested using the same or different method.

Spike samples will have a known concentration of analyte added to a test sample and will be tested with the same procedure as the original sample. Spike samples will be performed at least once for every analyte that is measured ex-situ. This will provide more information on the accuracy of ex-situ sample testing. The response of the added analyte to the spiked sample will be measured and compared to the original sample for inconsistencies. Unless specified by the analyte of interest's standard procedure, the spiked sample will have twice the concentration of the original sample. The concentration of the added analyte will be 50-100 times the concentration of the original sample so as to limit the increase in the sample volume. The sample volume should not increase by more than 5 percent. The amount of the spike added will be determined by Equation 2.

$$\text{Volume of spike added} = \frac{\text{desired concentration} * \text{sample volume}}{\text{concentration of spike solution}} \quad \textbf{(2)}$$

Once the spiked sample is analyzed, percent recovery (%R) will be calculated to check the accuracy of the procedure. If the %R is below 30 percent, the sample will be rejected. Samples with %R between 30-74 percent will be considered an estimate, and samples between 75-125 percent will be considered accurate (EPA, 2005). %R will be calculated by Equation 3.

$$\%R = \frac{(\text{Spike sample concentration} - \text{original sample concentration}) * 100}{Spike\ solution\ concentration} \quad \textbf{(3)}$$

Calibration blanks will be used for all in-situ equipment to ensure proper calibration of all equipment. The blanks will have no analyte added. The blank may only contain deionized water if no reagent is required. If a reagent is required, the appropriate amount of reagent will be added with no analyte. When treated as a sample, the blanks should have no detectable level of analyte.

If analyte is detected, the equipment may be contaminated and must be decontaminated again and recalibrated. If the analyte reaches the quantitation limit of the device, a different procedure may be required for the analyte being detected, or the piece of equipment may be faulty and must be replaced.

All laboratory analyses will be conducted in The University of Oklahoma's Carson Engineering Center, room 328/330.

3.5 Instruments and Equipment

All equipment used for analyses will be obtained from the Center for Restoration of Ecosystems and Watersheds (CREW) laboratory facilities, 18 of which are located inside the Carson Engineering Center. All CREW work and instrumentation that has been used has fallen under the EPA's QAPPs and QMPs.

Tables 3 lists in-situ measurement equipment that will be borrowed from the CREW laboratory with equipment detection range and accuracy. All YSI 6920v2 specifications are taken from the user manual (YSI Inc. 2012) Other equipment to be borrowed from CREW is listed in Table 4.

Table 3: In-situ Measurement Equipment to be Obtained from CREW, with Detection Range and Accuracy

Analytical Parameter	Equipment Required	Detection Range	Accuracy
Chlorophyll-a	YSI 6920v2 Datasonde	0.1 to 400 µg/L	N/A
Dissolved Oxygen	YSI 6920v2 Datasonde	0 to 50 mg/L	0 to 20 mg/L: greater of +/- 1 % of reading or 0.1 mg/L 20 to 50 mg/L: +/- 15 % of reading
Oxidation Reduction Potential	YSI 6920v2 Datasonde	-999 to +999 mV	+/- 20 mV
pH	YSI 6920v2 Datasonde	0 to 14 units	+/- 0.2 units
Specific Conductance	YSI 6920v2 Datasonde	0 to 100 mS/cm	+/- [0.5% reading + 0.001] mS/cm
Temperature	YSI 6920v2 Datasonde	-5 to 50°C	+/- 0.15°C
Transparency of water	Secchi disk	N/A	N/A

Table 4: Other Required In-Situ Measurement Equipment to be Acquired from CREW

Equipment Name	Description
250mL Bottles	Plastic and glass sampling containers
Cooler	Stores samples on ice
Handheld GPS device	Record geographic location of samples

Table 5 presents laboratory test methods with detection limits, along with the equipment that will be required to perform each method. Methods and detection limits for anions are taken from SEAL Analytical (2019).

Table 5: Parameters analyzed in the Carson Engineering Center laboratory with their respective analytical method, analytical equipment and detection limit

Analytical Parameter	Method	Equipment Required	Detection Limit (DL)
Alkalinity	HACH Method 8203	Alkalinity Kit, Digital Titrator	10 mg/L
Chloride	Std. Method 4500-Cl- E	SEAL AQ400 Discrete Analyzer	0.3 mg/L
Hardness	HACH Method 8213	Hardness Kit	1 mg/L (low-range) 17 mg/L (high range)
Nitrate	EPA Method 353.2	SEAL AQ400 Discrete Analyzer	0.03 mg/L
Nitrite	EPA Method 353.2	SEAL AQ400 Discrete Analyzer	0.0008 mg/L
Organophosphate	EPA Method 365.1	SEAL AQ400 Discrete Analyzer	0.005 mg/L
Sulfate	ASTM D516-90	SEAL AQ400 Discrete Analyzer	1 mg/L
Total Nitrogen	HACH Method 10208	HACH TNT826 and DR3800 Spectrophotometer	5 mg/L
Total Phosphorous	HACH Method 10209/10210	HACH TNT843 and DR3800 Spectrophotometer	0.01 mg/L
Turbidity	N/A	HACH 2100P Turbidimeter	0.01 NTU

Calibration and maintenance measures for all equipment will be followed in accordance with their operating manuals.

3.6 Sample Recording

On-site data will be recorded by at least two team members to correct for possible human error and prevent loss of data. Data will be transferred as soon as possible to an online file. A duplicate file will be uploaded to a USB drive so that there will be one physical copy of the project data.

3.7 Secondary Data

Secondary data from the OWRB water quality report will be used to compare results. The report will provide data on all analytes that Jay Engineering will be examining in 2021 for previous years since 2000. These data also provide field observations at the time the samples were taken. The secondary data will provide a more extensive understanding of how certain analytes may vary based on time, weather, temperature, and seasonal variation. Jay Engineering will provide an updated data set of the analytes of concern to provide a better understanding on Lake Thunderbird's eutrophication issues over the previous years. Jay Engineering will be limited on the number of sites and samples taken over time but will base produced data off similar conditions as specific data obtained by the OWRB water quality report.

4.0 Assessment and Oversight

4.1 Data Review, Verification, and Validation Requirements

Each sample that is taken will be labeled correctly as described in the SAP to include the team name, date and time the sample was taken, the sample identification number, the analytical parameter that is being testing, and the initials of the sampler. Field data will be recorded in weather resistant field books by two personnel to avoid data loss and ensure accuracy. Data will then be compiled onto an online document accessible by all personnel. All parameters that can be measured in the field should be done so in order to eliminate error or contamination through transport. Replicate samples will be taken to examine the variability of the data and ensure the data is accurate. Replicate samples that produce a large amount of error in the data will be deemed invalid due to potential contamination or poor handling and preservation.

Due to Covid-19, sample retrieval may only be conducted by one or two team members per sampling location. Any possible error from this scenario will be reduced by cross examination of other team samples from identical sites discussed in section 3.4 of quality control procedures.

4.2 Oversight

The project will be conducted by JAY Engineering under the supervision of Dr. Robert Knox and Dr. Robert Nairn to ensure all sample retrieval and data analysis is valid. Group work will be cross checked by all group members, and any inconsistencies will be reported by the group leader Kristen Soucheck. Weekly meetings will be held to provide input by other team members, encourage cross examination, and correct any initially overlooked errors. Quality control procedures will be followed throughout the project to reduce any possible error and optimize the accuracy of all data obtained for the project. The PWP, SAP, and HSP will also be followed on-site and in the laboratory to ensure a clear direction of goals, proper sample procurement and analysis, and minimized risk to all member of JAY Engineering. EPA procedures will be implemented when necessary for the QAPP, PWP, SAP, and HSP to ensure every plan is as effective as possible. Dr. Robert Knox and Dr. Robert Nairn will review the draft of every plan and give advice to JAY Engineering on where to correct and improve each plan. Communication with all members of JAY Engineering will be maintained to optimize coordination and remove any inconsistencies or gaps between each plan. To ensure that the project is completed on time, the schedule outlined in the Gannt charts will be followed.

5.0 References:

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JAY
ENGINEERING

SAMPLING AND ANALYSIS PLAN

Addressing Water Quality Issues of Lake Thunderbird

Prepared by:

JAY Engineering

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Prepared for:

Central Oklahoma Master Conservancy District

(COMCD)

February 23, 2021

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Approvals

Approved by: ______________________________________ ________________

Dr. Robert Knox, Project Advisor Date

Approved by: ______________________________________ ________________

Dr. Robert Nairn, Project Advisor Date

Approved by: ______________________________________ ________________

Kristen Soucheck, Team Leader Date

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1.0 Background

Located 13 miles east of Norman, Lake Thunderbird is a reservoir created by the impoundment of the Little River, a tributary of the Canadian River that runs through central Oklahoma. The lake has 86 miles of shoreline and a surface area of roughly 6,070 acres (USBR 2009). The reservoir was constructed to provide flood control and to serve as a water supply for Norman, Del City, and Midwest City and was completed in 1965 (Simmonds 1999). Lake Thunderbird continues to supply raw municipal water for these communities. The reservoir and surrounding state park also serve as recreational facilities and habitat for fish and wildlife. Recreational resources have included hunting, fishing, swimming, and boating (Simmonds 1999). The Lake Thunderbird watershed encompasses 257 square miles, with agriculture and forest as the primary land uses (Julian et al. 2015). The lake does not have any point sources of pollution but receives drainage from three cities: Norman, Moore, and Oklahoma City.

Lake Thunderbird is considered an impaired body of water for public/private water supply and warm water aquatic community (Dynamic Solutions, LLC 2013). Water quality issues include high turbidity, low dissolved oxygen (DO), and high chlorophyll-a (Julian et al. 2015). High turbidity is due in part to shoreline erosion, which has been an ongoing problem. Shoreline soils at Lake Thunderbird are generally acidic, non-cohesive, and nutrient-deficient, facilitating erosion and preventing natural revegetation (Allen 2001). Chlorophyll-a is produced by many photosynthetic organisms and used as a measure of algal biomass; thus, high chlorophyll-a levels are indicative of eutrophication and excessive nutrient loads. Lake Thunderbird has recently been classified as either eutrophic or hypereutrophic (OWRB 2020). Excessive algal growth can create objectionable tastes and odors, impairing use as a water supply. Eutrophication also contributes to low DO, as the decomposition of dead algal biomass exerts a significant oxygen demand. The hypolimnion of Lake Thunderbird routinely experiences anoxic conditions in the summer (OWRB 2020). Anoxic conditions are harmful to aerobic biota and impair the lake's designated use for fish and wildlife propagation.

2.0 Objective

There have been ongoing efforts to improve the water quality of Lake Thunderbird, utilizing both in-lake technologies and watershed-level practices. In 2011, the SDOX system was installed to increase DO in the hypolimnion; however, it has been determined that the system is undersized and does not affect lake water quality (OWRB 2020). Erosion control efforts have included installing riprap and vegetation (USBR 2009). The Oklahoma Department of Environmental Quality has established total maximum daily loads for sediments, nutrients, and organic matter in order to achieve adequate DO, turbidity, and chlorophyll-a (Dynamic Solutions, LLC 2013). However, management measures to achieve these goals were not defined. Further action is needed to improve water quality and remove Lake Thunderbird from the list of impaired water bodies. The aim of this project is to develop enduring and sustainable solutions that will address these concerns. This project will evaluate existing data collected by the Oklahoma Water Resources Board to identify the extent of Lake Thunderbird's water quality issues and determine areas for improvement. Water sampling will also be conducted to measure DO, turbidity, and other parameters and to identify existing water-quality issues.

3.0 Sampling Approach

3.1 Site Description

Figure 1 shows the sites sampled by the Oklahoma Water Resources Board in 2019 (OWRB 2020). Sites 4, 1, and 5, representing two open water locations and a transition zone, respectively, will be sampled. To represent a tributary, samples will be taken at the bridge near site 6 (Figure 1). Site 6 cannot be sampled due to its inaccessibility. If time permits, sites 2 and 11, representing open water and a tributary, will also be sampled.

Figure 1: 2019 OWRB Sampling Locations; Red and Yellow Circles Represent Primary and Optional Sampling Locations (OWRB 2020)

3.2 Sampling Rationale

Water quality samples will be taken at the four sites outlined in section 3.1, with two additional sites if time permits. These sites were chosen because they represent the riverine, lacustrine, and transition environments of Lake Thunderbird. Taken together, the water quality data from these three sites should be characteristic of Lake Thunderbird as a whole. The bridge near site 6 represents a tributary, or a small offshoot that feeds into Lake Thunderbird. Samples will be taken from the bridge. Site 5 represents an intermediate zone between the tributary and open water of Lake Thunderbird. Site 4 and 1 represent open water of Lake Thunderbird. These sampling sites, as well as sites 2 and 11, will have to be accessed by boat. Supplementary samples may be taken on the sampling day if JAY Engineering deems this necessary. All subsequent sampling will be properly documented, including justification.

Surface samples will be taken at all sites. Using the YSI 6920v2 data probe, temperature measurements will be taken at 1 m intervals Site 1 to determine whether the lake is stratified. If unstratified, surface samples will be taken as representative of the entire water column. Otherwise, samples will be taken at additional depths at Site 1. Site 1 was chosen to determine stratification as it is the deepest of the sites being sampled.

3.3 Field Equipment

The equipment required for sampling and field analyses is listed in Table 1. All equipment will be obtained and tested the week before the sampling date. Additionally, the equipment will be retested and calibrated on the sampling date.

Table 1: Equipment and Reagents for Sampling and Field Analyses

Equipment Name	**Description**
250mL Bottles	Plastic and glass sampling containers
Hach 2100P Turbidimeter	Measures turbidity
Hach Digital Titrator	Measures alkalinity
Hardness Kit	Measures hardness
Cooler	Stores samples on ice
YSI 6920v2 Datasonde and YSI 650 MDS Controller	In-situ measurement of temperature, pH, DO, ORP, specific conductance, and chlorophyll-a
Secchi disk	Gauges transparency of water
Handheld GPS device	Record geographic location of samples

3.4 Sampling Methods

Two methods will be utilized to collect samples. Surface samples will be collected by dipping using a sample container. A sampling pole will be used to collect surface samples if necessary. Discrete depth samples will be collected using a Van Dorn sampler. The sampler is lowered horizontally to the designated depth; a messenger is then sent down to close the cylinder, which is then raised. Sample bottles can then be filled by opening the valves on the sampler (USEPA 2013).

Sampling will likely be conducted by boat. Safety measures are described in the HSP. The boat will be anchored during sampling. Grab samples will be taken over the side of the boat while remaining seated. Samples will be preserved while onboard and transferred to a cooler once ashore.

The latitude and longitude of each sample location will be determined using a handheld GPS device and will be recorded in a waterproof field notebook.

3.5 Quality Assurance

The following quality assurance measures are based on the EPA's *Sampling and Analysis Plan Guidance and Template* (2014). Quality assurance measures are described in further detail in the Quality Assurance Project Plan (QAPP). Field blanks will be used to evaluate any contamination of samples in the field from the sampling equipment or the environment. These blanks will be collected by filling the sampling container with deionized (DI) water. The field blanks will then be preserved, transported, and analyzed following the same procedures as the field samples. A field blank will be collected for every 10 samples. Initial calibration of instruments such as the pH meter must be conducted in a controlled environment before field testing.

Replicate samples will be collected and analyzed to evaluate variability in sampling. Duplicates and field samples will be collected simultaneously under identical conditions. At least 10% of samples collected should be duplicates. Duplicates will be analyzed for all analytes for which standard samples are analyzed. Laboratory quality control samples will also be analyzed. These consist of matrix spike and matrix spike duplicates for organics and matrix spike and duplicate samples for inorganics.

3.6 Sample Labeling

All water samples will be labeled clearly and uniformly. This labeling format will allow for quick and easy identification after the sampling event. The labels will be written beforehand and will contain the following information:

- Team name
- Date and time
- Sample identification number
- Analytical parameter being sampled
- Initials of the sampler

3.7 Sampling Documentation

During the collection of each sample, the following information will be recorded in the field book:

- Sample date and time
- Sample location - geographic data (latitude, longitude)
- Names of team members collecting the sample
- Analytical parameter being measured
- Chain-of-custody form number

At the end of the sampling event, the following information will be recorded in the field book:

- Sampling start and end time
- Specific locations sampled and description of overall weather and environment
- Team members present and their individual responsibilities
- Any additional personnel present

- Calibration numbers for equipment used
- Any changes in assigned responsibilities or sampling procedures

Additionally, chain-of-custody forms will be used to determine whose custody each sample is in at any given time. The forms will accompany the sample to the laboratory for further analysis. A sample is considered to be in someone's custody if it is in the possession of the person or locked up or secured in a place restricted to authorized personnel. In this case, the sampling leader will write their initials in the "released by" column on the sampling date. The full example of the chain-of-custody form is shown in Table 2.

Table 2: Example Chain-of-Custody Form

Item #	Date & Time	Location	Released by:	Received by:	Comments

3.8 Decontamination Procedures

Sample bottles will be rinsed in triplicate with DI water between each sampling site. Alkalinity and hardness kit flasks will be rinsed in triplicate with DI water before each test. Turbidity kit vials will be rinsed in triplicate with DI water and the outside wiped before each reading.

3.9 Water Quality Parameters

Specific conductivity, pH, DO, ORP, chlorophyll-a, and temperature will be measured in-situ. Turbidity, alkalinity, and hardness will also be determined in the field.

The water quality parameter form shown in Figure 2 will be followed to document parameter results in each sampling location.

General Information	
Site Name or ID:	**Date:**
Site Address:	**Sample Collection Time:**
Team Members:	**Report Form ID:**
Designated Contact (Name, Title, and Phone Number):	

Meter/Kit IDs

Field Point of Use QC					
Parameter	**Blank or Background Result**	**QC Lot Number**	**QC True Value**	**QC Result**	**Acceptance Range**
****STOP and REPORT**** *If a field point-of-use QC result is outside of acceptance range, report the result to the Designated Contact before proceeding.*					

Sample Results				
Parameter	**Units**	**Sample Result**	**Duplicate Result**	**Expected Range**
*****STOP and REPORT**** *Verbally report results to Designated Contact.*				

Deviations from SOP(s) and Other Notes

Submitted By	
Report Submitted By (PRINT):	
Report Submitted By (Signature):	
Date:	

Figure 2: Water Quality Parameter Report Form (US EPA 2017)

3.10 Sample Transport and Storage

All water samples will be transported and stored in large ice coolers with the lids on. Ice coolers will be used in order to keep the temperature relatively constant and the environment dark. Chain-of-custody forms will be transported and stored with the samples. Table 3 lists the sample preservation requirements and hold times as outlined by Eurofins Spectrum Analytical, Inc. (2016).

Table 3: Parameters of Interest, with Preservation Requirements

Analytical Parameter	Method	Container Type	Preservation Requirements	Analysis Holding Time
Chloride	Std. Method 4500-Cl- E	Plastic or Glass	None	28 days
Nitrate	EPA Method 353.2	Plastic or Glass	Cool ≤6°C	48 hours
Nitrite	EPA Method 353.2	Plastic or Glass	Cool ≤6° C	48 hours
Orthophosphate	EPA Method 365.1	Plastic or Glass	Cool ≤6° C	48 hours
Sulfate	ASTM D516-90	Plastic or Glass	Cool ≤6°C	28 days
Total Nitrogen	HACH Method 10208	Plastic or Glass	N/A	24 hours
Total Phosphorous	HACH Method 10209/10210	Plastic or Glass	N/A	24 hours

4.0 Analytical Approach

4.1 Field Measurements and Analyses

Temperature, pH, specific conductance, DO, ORP, and chlorophyll-a will be measured in the field using the YSI 6920v2 probe. Turbidity will be measured in the field using the Hach 2100P Turbidimeter. A Hach Digital Titrator will be used to measure alkalinity and hardness in the field following HACH methods 8203 and 8213, respectively. Turbidity, alkalinity, and hardness will be measured in triplicate for each site.

Water clarity will be measured using a Secchi Disk. Lower the disk into the water until no longer visible and record this depth. Depths are recorded at the water line using the depth markings on the rope. Raise the disk until it becomes visible again and record this depth. The average of the two depths is the Secchi reading (U.S. Sailing 2018). Repeat this process twice for each sampling site.

4.2 Laboratory Analytical Methods

Chloride, sulfate, nitrate, nitrite, nitrate, and orthophosphate will be measured using the SEAL AQ400 Discrete Analyzer. The equivalent methods for each analyte are as follows (SEAL Analytical 2019):

- Chloride— Std. Method 4500-Cl-E
- Nitrate and Nitrite—EPA Method 353.2
- Sulfate—ASTM D516-90
- Orthophosphate—EPA Method 365.1

Total nitrogen will be measured following HACH Method 10208 using a HACH TNT826 test and DR3800 Spectrophotometer. Total phosphorus will be measured using HACH Method 10209/10210 using a HACH TNT843 test DR3800 Spectrophotometer.

4.3 Disposal of Residual Materials

Disposal of residual materials will be completed according to Table 5 below, adapted from the EPA Management of Investigation Derived Waste (IDW) (2020).

Materials which may become IDW include, but are not limited to:

- Personal protective equipment (PPE) - This includes gloves, masks, etc.
- Disposable equipment and items - This includes plastic equipment covers, broken or unused sample containers, sample container boxes, tape, etc.
- Cleaning fluids such as wash water.
- Packing and shipping materials.

Table 5: Management of Investigation Derived Waste (USEPA 2020)

Type	Non-Hazardous Disposal
PPE-Disposable	Place waste in trash bag. Dispose in dumpster.
Decontamination Water	Containerize in an appropriate container with tight-fitting lid. Leave on-site with permission of site operator. Decontamination water may also be disposed in a sanitary sewer system if doing so does not endanger human health or the environment or violate federal or state regulations.
Disposable Equipment	Containerize in an appropriate container with tight-fitting lid. Leave on-site with permission of site operator, otherwise arrange with program site manager for testing and disposal.
Trash	Place waste in trash bag. Dispose in dumpster.

5.0 Health and Safety

During field and laboratory work, JAY Engineering will follow the health and safety measures outlined in the HSP. In the event of an emergency, the information provided in Table 6 can be used to reach the personnel's emergency contact.

Table 6: Individual Emergency Contact Information

Name	Address	Phone Number	Emergency Contact Name	Emergency Contact Number
Addisyn Clagg	1351 Edgewood Terrace Norman, OK 73026	405-593-6251	Kaleigh Clagg	405-618-8899
Hannah Curtis	1306 Cherry Stone St. Norman, OK 73072	405-816-1167	Terri Curtis	405-514-5841
Rodrigo Peralta	101 South 5th St. Noble, OK 73068	405-623-6193	Leslie Leigh	405-397-3615
John Puzz	722 Mossy Rd Norman, OK 73069	713-715-9451	David Puzz	405-227-5303
Kristen Soucheck	1800 Beaumont Dr Apt 1223 Norman, OK 73071	732-570-0112	John Soucheck	732-933-9574
Robert Knox	824 South Flood St. Norman, OK 73069	405-550-2355	Linda Georinger	405-249-8893
Robert Nairn	1629 Wilderness Drive, Norman, OK 73071	405-388-8819	Kathryn Amanda Nairn	405-664-0989

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Appendix B: Water Quality Data and Analysis

Table 27: Ten-year averages of water quality parameters at various sites on Lake Thunderbird plus/minus standard deviation

Site	TSS mg/L	Chlorophyll-a µg/L	Turbidity NTU	NO_2+NO_3 mg/L	TP mg/L	Ortho-P mg/L	DO mg/L
1	12.48 ±12.17	19.19 ±15.22	10.56 ±7.30	0.17 ±0.34	0.08 ±0.13	0.05 ±0.12	7.96 ±1.78
2	13.88 ±25.00	22.14 ±13.28	10.74 ±8.01	0.31	0.02 ±0.01	0.05 ±0.02	
3		24.42 ±15.25	13.95 ±6.34				8.76 ±1.42
4	14.09 ±3.47	22.08 ±14.99	31.34 ±29.0	0.37 ±0.13	0.12 ±0.01	0.14 ±0.21	5.61 ±3.06
5		25.61 ±14.99	18.23 ±13.44				6.79 ±3.16
6	50.16 ±26.42	6.75 ±14.22	47.37 ±44.04	0.14 ±0.39	0.10 ±0.09	0.03 ±0.03	7.94 ±1.68
8	28.20 ±12.41	5.30 ±11.97	27.32 ±23.49	0.14 ±0.39	0.05 ±0.03	0.01 ±0.01	0.56 ±1.25
11	43.3 ±27.61	28.85 ±18.73	46.23 ±29.66	0.14 ±0.49	0.08 ±0.09	0.02 ±0.02	8.18 ±1.70
12			7.74 ±3.93				5.02 ±3.64

Table 28: p-Values returned from SKT for Surface Water Quality; Italics indicates statistically significant trend

	Site								
Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**11**	**12**
DO	*0.005673*	*3.993e-06*	*5.76e-10*	*0.03962*	*0.003024*	0.1219	0.9495	0.4101	0.03959
Chlorophyll-a	*0.00834*	*0.003927*	0.05554	0.07021	*0.005539*	*4.93E-05*	*1.86E-07*	*0.000613*	-
Turbidity	*0.02163*	0.49419	0.3772	*2.67E-14*	0.5587	*0.001229*	*4.09E-09*	0.1813	-
Secchi Depth	*0.003433*	0.1235	0.05554	*1.47E-14*	*0.007255*	*0.000887*	0.2152	0.5505	-
TP	0.1614	0.4205	-	0.1526	-	0.2599	0.2405	0.2929	-
Ortho-P	*1.14E-05*	0.6119	-	1	-	*1.91E-07*	*1.04E-10*	*9.39E-11*	-
TSS	*1.09E-06*	*3.56E-06*	-	*1.93E-05*	-	*0.008826*	0.07021	-	-
NO_2+NO_3	*8.27E-08*	0.1351	-	0.8509	-	*7.88E-11*	*1.74E-15*	*5.01E-15*	-
Kjeldahl N	0.7752	0.4166	-	0.2928	-	0.6816	0.09715	0.273	-

Table 29: p-Values returned from SKT for Bottom Water Quality; Italics indicates statistically significant trend

	Site				
Parameter	**1**	**2**	**4**	**5**	**12**
DO	*0.01009*	*0.0001067*	*0.003138*	0.74347	*0.02161*
TP	0.14253	0.5696	0.8249	-	-
Ortho-P	*0.04377*	0.2057	0.06162	-	-
TSS	0.3403	0.324	0.8249	-	-
NO_2+NO_3	*5.81E-09*	0.2133	0.2128	-	-
Kjeldahl N	0.7869	0.8333	*0.02333*	-	-

Table 30: Total nitrogen and phosphorus concentrations of samples collected during March 2021 sampling event; italics indicate concentrations outside of the measurement range of 1-16 mg/L for TN or BDL of 1.5 mg/L for TP

Sample	TN (mg/L)	TP (mg/L)
Laboratory Blank	14.5	*-0.016*
Field Blank	*24.4*	*-0.027*
Site 1	*26.8*	*0.027*
Site 2	10	*0.022*
Site 2 Laboratory Duplicate	*43.9*	*-0.016*
Site 4	12.4	*0.021*
Site 4 Field Duplicate	*16.1*	*0.013*
Site 5	7.45	*0.015*
Site 6	7.74	*0.026*
Site 6 Field Duplicate	*22.5*	*0.017*
Site 11	14.7	*0.030*

Table 31: Total suspended solids concentrations for samples collected from Lake Thunderbird during March 2021 sampling event

Sample	TSS (mg/L)
Site 1	137
Site 2	450.2
Site 4	0
Site 4 Field Duplicate	32.6
Site 5	118.6
Site 6 Team A	135
Site 6 Team A Duplicate	356.8
Site 6 Team B	263.6
Site 11	121.8
Field Blank	309.4
Laboratory Blank	322.4

Table 32: Turbidity, Secchi Disk depth, alkalinity, hardness, and parameters measured by YSI during March 2021 Lake Thunderbird sampling event

Site Name	Secchi Disk Depth (ft)	Turbidity (NTU)	Alkalinity (mg/L)	Hardness (mg/L)	Temp (°C)	SC (mS)	DO (mg/L)	pH	ORP (mV)	Chl-a (µg/L)
1	3	12	130	320	11.19	0.531		8.16	741.3	
		12	141	340						
		11	159	340						
3	3	10	171	320	11.52	0.429		8.23	741.4	
		11	162	300						
		11	169	300						
4	2.75	10	175	240	11.77	0.423	10.95	8.45	254.2	8.8
	2.33	12	193	220						
		10	200	220						
5	1.58	14	195	220	12.09	0.44	11.02	8.56	244.4	13.5
	2.16	13	203	200						
		13	177	200						
6 - West Bridge		23.9	198	300	11.74	0.481	10.52	8.47	219	19.7
		24.2	192	260						
		23.8	197	260						
6 - East Bridge		20.8	187	280	11.67	0.483		8.24	740.5	
		21.6	189	280						
		20.6	185	280						
11	1	23	227	220	12.54	0.449	11.1	8.6	253.2	14.1
	1.16	23	197	240						
		23	200	240						

Appendix C: Primary Screening of Alternatives

Table 33: Possible in-lake treatment technologies for Lake Thunderbird

Solution	Description	Benefits	Limitations	Source
Algicides	Application of algicide to lake surface to kill algae and prevent bloom formation	Controls algal growth; some algicides allow for selective treatment of cyanobacteria	New blooms may arise if nutrient concentrations not addressed; repeated use may result in elevated toxin concentrations in lake bottom	SAWPA n.d.
Artificial Circulation	Installation of onshore air compressor to bubble air out of perforated pipes on lake bottom, creating convection that mixes the lake; disruption of thermal stratification to increase DO in deep areas	May solve low DO issues as well as eliminate stagnant zones where sediment accumulation and algal blooms can occur	Mixing water column may decrease water clarity due to lifting of sediment; potential increase in algal biomass due to reduced settling	OWRB 2011
Biomanipulation	Reducing planktivorous fish population through encouraging fishing or introducing piscivorous species to allow for increased zooplankton predation on phytoplankton	Reduction in algal biomass leads to reductions in turbidity and chlorophyll-a[1]; may indirectly increase DO; lower cost than chemical P inactivation.	Typically temporary solution unless combined with control of nutrient inputs[2]; ineffective if less than 50% reduction of planktivorous fish population[1]	[1]Hansson and Brönmark 2009 [2]Wetzel 2001

Table 34: Possible in-lake treatment technologies for Lake Thunderbird (continued)

Solution	Description	Benefits	Limitations	Source
Floating Treatment Wetlands	Small islands made of either synthetic or natural buoyant material with vegetation on top that act as both breakwater systems and sources for biological uptake in lakes and ponds	No additional land use, low cost, design flexibility, enhanced pollutant-removal effectiveness, sustainable wildlife habitats, and improved aesthetics	Challenging to anchor, the need for harvesting, the potential for blocking access to the lake and reducing lake recreation, and the potential for lake contaminants that could damage the plants	Sample et al. 2013
Harvesting Algal Biomass	Physical removal of algae using screens, filters, flotation, or sedimentation	Removes N and P from system; harvested algae may be used as biofuel or in compost	Time-consuming due to large lake surface area; continuous removal of algae necessary; harvested algae may be considered hazardous if toxin concentrations high	SAWPA n.d.
Hypolimnetic Oxygenation	Injection of water supersaturated with oxygen into hypolimnion to increase DO and ORP, reducing internal phosphorus loading from sediment	Increases DO in lake bottom and reduces internal nutrient loading from sediments; maintains lake stratification[1]	High capital cost; may be ineffective if undersized[2]	[1]OWRB 2011 [2]OWRB 2020
Sediment Dredging	Removal of sediments that contain nutrients such as P and N	Reduction of internal nutrient loading; increases flood storage capacity of reservoir	High cost; must dispose of waste sediments; limited to reducing internal P loading	SAWPA n.d.

Table 35: Possible in-lake treatment technologies for Lake Thunderbird (continued)

Solution	Description	Benefits	Limitations	Source
Sediment Oxidation	Direct injection of oxidizers with a higher redox potential than Fe into lake sediment to inactivate P	Reduces internal nutrient loading due from sediment P	Limited to shallow lakes; Relatively high cost per unit area; Internal P loading must be controlled by Fe redox reactions to be effective	Lewtas et al. 2015
Shoreline Revegetation	Planting of native vegetation along the shoreline and littoral zone to reestablish plant communities to prevent soil erosion and sequester excess nutrients	Decreases in soil erosion reduce loading of sediments and attached nutrients; provides wildlife habitat and improves lake aesthetics	Multiple plantings required; successful plant establishment depends upon weather conditions	Allen 2001
Ultrasonic Irradiation	Disruption of air vesicles through use of ultrasonic radiation to sink cyanobacteria to sediments and reduce photosynthesis	Shown to potentially be effective through successful disruption of cyanobacteria production in laboratory tests	Application of ultrasound has yet to produce satisfactory results in large lakes; requires multiple devices to cover large surface area	Ahn et al. 2003

Table 36: Possible watershed-level treatment techniques and BMPs for Lake Thunderbird

Solution	Description	Benefits	Limitations	Source
Bioretention Cell	Vegetated trench to retain and filter stormwater	Reduces loadings of sediments, nutrients, and other pollutants such as metals	System can clog; media may need to be replaced periodically	Vogel and Moore 2016
Cistern	Capture and store rainfall to reduce runoff volume	Removal of sediments and sediment-bound pollutants; harvested rainwater may be suitable for other uses	Requires periodic dewatering and sediment removal; only removes pollutants bound to sediments	Winston et al. 2020
Constructed Wetlands	Filters out pollutants and suspended solids from runoff using microorganism uptake/transformation and filtration techniques.	Efficiently removes excess metals, TSS, and nutrients such as phosphorous and nitrogen, and in turn increases DO levels[1]	Requires a large amount of land[2]; Some invasive plant species e.g. cattails can decrease biodiversity[3]	[1]Tyndall and Bowman 2016 [2]Halverson 2004 [3]USDA 2009
Conventional Stormwater Management	Collection of runoff water in detention or retention basins, allowing for settling of suspended solids before discharge	Removes sediments contributing to turbidity; Can achieve 35-50% phosphorus removal efficiency. Improve outflow water quality.	Not aesthetically pleasing; Can raise water table/impact hydrology	OCC 2008
Grassed Swale	Area with dense vegetation to collect and filter first flush of runoff	Reduces nutrient loads by slowing and filtering runoff; cost-effective[1]	Maintenance includes mowing and removing debris; low nutrient removal[2]	[1]OCC 2008 [2]Martin-Mikle et al. 2015

Table 36: Possible watershed-level treatment techniques and BMPs for Lake Thunderbird (continued)

Solution	Description	Benefits	Limitations	Source
Green Channel Cover	Grass or infiltrating media that covers existing concrete open channels	Promotes infiltration, lowers peak flow, and lowers nutrient/ metal loads	Construction may be time-consuming, costly	Palanisami and Chui, 2015
Green Roofs	Capture precipitation falling on impervious area	Reduce runoff volume and peak flows	Localized treatment; may act as net exporter of nutrients	Vogel and Moore 2016
Infiltration Trench	Stone-filled excavation that intercepts and stores runoff	Reduce peak flows of runoff, effective nutrient removal	Require pretreatment to remove suspended solids; may become clogged; potential for groundwater contamination	Barr Engineering 2001
Nutrient Management	Reduce fertilizer inputs to agricultural and urban areas through public education and awareness or ordinances	Reduces nutrient loadings from runoff; encourages community involvement	Voluntary reductions requires community buy-in and annual soil testing[3]; difficulty of ordinance institution	OCC 2008
Permeable Pavement	Porous surface replaces impervious areas to increase infiltration, and filters first flush	Ideal for highly developed areas; reduce runoff volume	Marginal nutrient removal	Vogel and Moore 2016
Rain Barrel	Placed at roof downspouts to collect for lawn watering	Collects rooftop runoff to reduce peak flows	Maintenance to empty barrels; does not treat stormwater	Martin-Mikle et al. 2015
Riparian Buffer Zone Establishment	Establishment of natural vegetation/un-mowed areas in zone around stream banks to prevent soil erosion and filter pollutants from runoff	Acts as buffer to reduce nutrient loading to influent streams[1]; wider buffer zones provide habitat for wildlife	Requires cooperation from individual landowners; challenging to place riparian buffers in urbanized areas[2]	[1]Prepas and Charette 2003 [2]SWRPC 2010

Table 36: Possible watershed-level treatment techniques and BMPs for Lake Thunderbird (continued)

Solution	Description	Benefits	Limitations	Source

Sand Filter	Runoff accumulates in pretreatment basin, water is infiltrated by sand bed	Requires little space, high sediment removal efficiency	Filter can become clogged during rainy season or areas with high sediment loads, relatively high cost	Barr Engineering 2001
Streambank Stabilization	Placement of coir/geotextile mats/logs to encourage vegetative growth and prevent soil erosion	Reduce sediment transport downstream to Lake Thunderbird	Requires cooperation of landowners along streambanks; Slopes steeper than 3:1 H:V must be regraded	Kalibová et al. 2016

Table 37: Summary of primary screening of Lake Thunderbird remediation alternatives

Solution	Retained for Further Analysis?	Explanation
Algicides	No	Can be toxic to other aquatic organisms including zooplankton and fish; would require repeated applications
Artificial Circulation	No	Disruption of stratification may harm aquatic organisms and increase turbidity
Biomanipulation	No	In lake phosphorous level exceed effective range
Bioretention Cells	Yes	Provides reduction in peak flows and filters pollutants including nutrients
Chemical Coagulation	No	High chemical costs make alternative unsuitable for large lakes; multiple applications may be necessary
Cisterns	Yes	Potential for high sediment and phosphorus removal
Constructed Wetlands	Yes	Has the potential to effectively remove excess levels of nutrients and increase DO levels; cost efficient
Conventional Storm Water Management	No	Potential for poor public acceptance due to being aesthetically unpleasing; potential to alter site hydrology
Grassed Swales	No	No room for implementation in already-developed areas
Green Channel Covers	No	Construction potentially costly and time-consuming
Green Roofs	No	Potential to be net exporter of nutrients
Floating Treatment Wetlands	No	Would require large percentage lake coverage, interfering with recreation; requires frequent maintenance
Harvesting Algal Biomass	No	Time consuming due to continuous removal; may interfere with recreation; potential for harvested algae to be toxic

Table 37: Summary of primary screening of Lake Thunderbird remediation alternatives (continued)

Solution	Retained for Further Analysis?	Explanation
Hypolimnetic Oxygenation	No	Multiple devices required due to limited zone of influence; cost-prohibitive
Infiltration Trenches	No	Less aesthetically pleasing than bioretention cells
Nutrient Management	No	Difficulty in implementation of ordinances or resident buy-in
Permeable Pavement	Yes	Reduction in urban runoff; can be implemented in highly-developed areas
Rain Barrels	No	Does not improve stormwater quality
Riparian Buffer Zone Establishment	No	Difficulty in securing cooperation from individual landowners in the area
Sand Filter	Yes	High sediment and phosphorus removal with small footprint
Sediment Dredging	No	Relatively low P reduction for lakes with small internal loading relative to non-point source loading; high cost
Sediment Oxidation	No	Limited to only shallow lakes; high cost
Shoreline Revegetation	Yes	Potential to improve lake aesthetics and provide wildlife habitat; reduction in sediment loading may reduce in-lake turbidity
Streambank Stabilization	No	Difficulty in assessing upstream banks throughout watershed; potentially high cost due to long streambank length and need for regrading
Ultrasonic Irradiation	No	Has only been implemented in small waterbodies; further research is needed on the technology