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American Recovery and Reinvestment Act of 2009 (ARRA)

CA # 2P-96690801, Project 4
Developing In-Lake BMPs to Enhance Raw Water Quality of Oklahoma's Sensitive Water Supply

Final Report

3800 N. Classen Boulevard
Oklahoma City, Oklahoma 73118

June 2011

Agency: Oklahoma Water Resources Board (OWRB)

Grant American Recovery and Reinvestment Act of 2009 (ARRA)
CA # 2P-96690801

Project: 4

Location: Lake Thunderbird, WBID OK 520810000020
Hydrologic Unit Code (HUC) 11090203

Lake New Spiro, WBID OK 220100010050
Hydrologic Unit Code (HUC) 11110105

Cooperators: Central Oklahoma Master Conservancy District (COMCD)
City of Norman
City of Spiro

Acknowledgements:

The U.S. Environmental Protection Agency funded 100% of this project, $56,801 allowing us to explore in-lake management practices to help reduce the problems created by excessive nutrient inputs into Lake Thunderbird and Lake New Spiro. Our appreciation to the Central Oklahoma Master Conservancy District, City of Norman and City of Spiro, for providing additional data, to the City of Norman for also providing additional funding, and their corporation with the OWRB on this project.

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Abstract:

From the summer of 2009 to spring of 2011, the Oklahoma Water Resource Board (OWRB) investigated in-lake best management practices (BMPs) at Lake Thunderbird and at Lake New Spiro. This report provides the Central Oklahoma Master Conservancy District (COMCD) and the City of Spiro with recommendations to implement the most cost-effective in-lake BMP options, mitigating excessive algae growth currently witnessed within these lakes achieved by reduction of phosphorous cycling.

> For Lake Thunderbird, the recommendation is for a layered oxygenation system that would reduce the largest area of anaerobic mediated sediment phosphorous release.
>
> For Lake New Spiro, a modified management scheme is recommended to reduce the effects of sediment phosphorous release by releasing hypolimnetic waters during flood pool conditions utilizing the emergency draw down pipe that currently exists in the dam structure.

These lakes were selected based on the growing drinking water impairments believed to be due to increasing algae levels within the reservoirs. At Lake Thunderbird this was witnessed by the presence of taste and odor compounds and increased drinking water treatment costs at recipient municipalities and at Lake New Spiro by disinfectant by-product formation and violations by the City of Spiro.

To investigate in-lake BMP options, a BATHTUB model was needed for each reservoir to establish the relationship between algae growth and nutrient input. To accomplish this a SWAT watershed model was produced for each watershed, as well as estimation of anaerobic mediated sediment phosphorous release to calculate nutrient inputs to the reservoir. Additionally, a bathymetric survey was produced within this project for Lake New Spiro to provide accurate morphometric data. Recent bathymetric survey data was available for Lake Thunderbird. Lastly, drinking water treatment data was analyzed to investigate any relationship it may have with raw water parameters.

For Lake Thunderbird it was determined that the combination of a relatively large nutrient input from the watershed with a high nutrient retention coefficient translates to a situation where the lake has persistent excessive algae growth. Anaerobic mediated phosphorous release from sediment compounds this issue by loading the anoxic hypolimnion with phosphorous throughout the hottest summer months. When thermal stratification deepens this mixes the nutrient rich hypolimnetic waters with epilimnetic waters fueling intense algae growth witnessed as a peak in chl-*a* in late summer/early fall.

For Lake New Spiro the combination of the SWAT and BATHTUB models indicate that the eutrophic situation stems from high nutrient input from its small watershed. Like Lake Thunderbird, Lake New Spiro's chl-*a* impairment is compounded by the addition of anaerobic mediated phosphorous release from the lake sediment in the late summer timeframe.

The BATHTUB model predictions indicate that reducing phosphorous loads by any means will result in a reduction in algae growth at either reservoir. Statistical regressions show a linear positive correlative relationship between organic enrichment through increased algae

growth and total organic carbon levels within the reservoir. Reducing sediment phosphorous load through recommended in-lake BMPs should provide immediate relief to the high levels of algae growth seen within each reservoir and is predicted to make reductions in total organic carbon levels, thereby reducing drinking water treatment costs and disinfectant by-product formation.

Integration with the Oklahoma Comprehensive Water Plan

Oklahoma's primary water initiative is to direct all of the state's water related project efforts toward its new guidance document, the Oklahoma Comprehensive Water Plan (OCWP), which is near finalization. The plan is concerned with both water quantity and water quality. Water quality directives of the OCWP will, at some level, search for innovative initiatives that improve water quality and thereby become additional options for the citizens of Oklahoma to protect their state's precious water resources.

The long-term objective of this project will provide viable cost-effective options for the COMCD and City of Spiro to improve the raw water quality of the water supplies of Lake Thunderbird and Lake New Spiro. While the problems at the lakes undoubtedly stem from excessive nutrient inputs from non-point sources (NPS) within the respective lake watersheds, watershed BMP impacts are slow to act. The in-lake BMP options recommended in this report will provide immediate relief to the reservoirs, and in the end allow for higher quality water to be provided the residents of the City's of Norman and Spiro, helping reach one of the OCWP goal's of providing higher quality water to the citizens of Oklahoma.

Background

Control or reduction of excessive algae growth in Oklahoma's water supply reservoirs is critical for several reasons. Organic enrichment caused by excessive algae levels impairs drinking water supplies by causing taste and odor problems. Excessive algae levels are also linked to disinfection byproducts (DBPs) such as carcinogenic trihalomethanes (THMs) and haloacetic acids (HAAs). Bluegreen algae, common in eutrophic waters, have been shown to produce toxins that have been recognized as an emerging public health issue. For example, microcystins can cause liver damage; with other toxins including neurotoxins, and cytotoxins. Blue green algae are also considered to be a major source of undesirable taste and odor compounds in drinking water.

Excessive algae levels can impair the Public and Private Water Supply designated beneficial use such that the treatment costs skyrocket or the water supply is abandoned altogether. This scenario has been demonstrated with the City of Tulsa and the water drawn from lakes Spavinaw and Eucha. The City of Tulsa has documented additional costs attributable to episodes of excessive algae in excess of $72.78/MG. When their current treatment system is unable to eliminate the taste and odor problems, Tulsa has the option to abandon Eucha/Spavinaw lakes. The additional cost of using Lake Hudson water exceeds $7,000 per day. The cost for developing a new water supply would be greater than $250,000,000.

A significant number of Oklahoma water systems are troubled by THM, total organic carbon (TOC), as well as taste and odor compounds. In 2008, 137 surface waterbodies were used as public water supplies, 82 of these waterbodies have systems with disinfection by-product violations, and 46 of these waterbodies are designated as Sensitive Water Supplies (SWS) in the Oklahoma Water Quality Standards (OWQS). Many of those violations may be attributed to organic enrichment by excessive algae growth. In short, a large portion of Oklahoma's water supply reservoirs are impacted by excessive algae growth requiring increased energy and materials cost for the municipalities. The City of Spiro has consistently exceeded TOC reduction rules, and DBP limits within the last four years. This has caused Spiro to add additional powdered activated carbon (PAC) into its treatment train. While helpful, PAC still does not avoid violations. The consistent summer spike of TOC seen by Spiro indicates algae growth at the root of the problem. Although continued investment in the treatment train will eventually yield drinking water within standards it is worthwhile to examine alternative avenues such as improving raw water quality through in-lake best management practices (BMPs). Both lakes are listed as impaired for low dissolved oxygen on the 303(d) list and are designated Nutrient Limited Watershed (NLW) and SWS lakes but fail to meet the 10 µg/mL chlorophyll-*a* (chl-*a*) criteria for SWS lakes.

Recent cooperative work with the Tulsa District Corps of Engineers and Poteau Valley Authority has shown how in-lake modifications can positively affect raw water quality. In these systems, the Corps of Engineers has determined that modification of water releases will increase the dissolved oxygen content of the lake. Increasing dissolved oxygen will increase the available habitat for fish (volume of aerobic water), minimize the recycling of nutrients from the sediment and ultimately reduce algae growth. This idea of maintaining an oxidized water column to increase habitable water volume and reduce algae growth shows promise for water supply reservoirs across the state. In short, the work on Lake Wister has shown that in-lake management can assist the recovery and enhancement of raw water supply. Both the

COMCD (Lake Thunderbird manager) and City of Spiro have requested the OWRB assist in developing management schemes to mitigate excessive algae growth. Both entities are willing to implement in-lake BMPs to improve raw water quality.

Outline of Events

The following outline is not meant to be an exhaustive list of events for the project but does help to give a picture of how the project proceeded.

2009

- August- December
    - QAPP written and approved.
    - Began communication with City of Spiro to collect and compile environmental data.

2010

- January-March
    - Statistical analysis of TOC, *chl-a*, and temperature data.
    - Collected bathymetric survey data of Lake New Spiro and edited for error.
    - Preliminary basins watershed model of both Lake New Spiro and Lake Thunderbird created.
- April- June
    - Collected water quality and sediment at Lake New Spiro.
    - Collected historical drinking water chemical usage and costs from the City of Norman.
    - Basins watershed model proved insufficient for our BATHTUB modeling needs; SWAT model set-up for both reservoirs began.
- July-September
    - Attended SWAT Model training. (Jody Cason)
    - Met with Rural Water Association (RWA) and discussed project, validated data.
    - SWAT model set-up began for both lake watersheds.
- October-December
    - SWAT models completed for each lakes' watershed.
    - BATHTUB models set-up for both lakes.
    - Completed analysis of in-lake BMP options and feasibility-Lake Thunderbird
- January- March
    - Completed analysis of in-lake BMP options and feasibility- Lake New Spiro
    - Water quality-drinking water cost analysis
    - Reporting

Project Tasks

1. Collect and Compile environmental data

A. Lake New Spiro

The goal of this task was to collect and compile available environmental data sufficient to fulfill as inputs for the BATHTUB water quality model, and allow for trend analysis for chlorophyll-*a* (chl-*a*) and total organic carbon (TOC). No locally funded water quality monitoring program exists at Lake New Spiro, therefore data was limited to that collected on a quarterly basis on a 4 year rotation by the state funded Beneficial Use Monitoring Program (BUMP). While this data is not as robust a set as desired, it proved sufficient for the needs of this project.

While sufficient water quality data for this project was available, bathymetric and sediment phosphorous data did not exist. In January 2010, a bathymetric survey was done at the lake. The report generated from this surveying is attached as **Appendix A**. The report was delivered to City of Spiro officials in the summer of 2010 to update their city records. In May of 2010, an Ekman dredge sediment sample was collected for laboratory analysis in order to estimate the phosphorous release rate, for input into the BATHTUB water quality model.

B. Lake Thunderbird

Water quality, bathymetric, and sediment phosphorous data for Lake Thunderbird were all readily available within the OWRB database from previous OWRB contractual work for the COMCD. The Lake Thunderbird bathymetric survey data can be found at **http://www.owrb.ok.gov/studies/reports/reports_pdf/thunderbird.pdf**

2. Data Processing

Lake New Spiro & Lake Thunderbird

Integrating the collected bathymetric data with dissolved oxygen profile data, water quality data and sediment phosphorous data allowed for the amount of anaerobic mediated sediment phosphorous release (internal phosphorous load) to be modeled.

To estimate the impact of anaerobic conditions to chl-*a*, a weight of evidence approach was developed using the results of several models. Inputs include historical water quality data, anaerobic mediated sediment load estimates and a watershed loading model - Soil and Water Assessment Tool (SWAT) and the lake water quality model BATHTUB. Each BATHTUB model was constructed with the current estimated anaerobic mediated sediment phosphorous release (sediment phosphorous release). The calculated sediment phosphorous release was then removed in portions from each BATHTUB model to determine its impact on chl-*a* values, and total phosphorous. The selected BMP option also was then evaluated for its reduction of internal phosphorous loading and resulting drop in chl-*a*.

3. Feasibility

Mitigation methods of whole lake mixing, selective aeration, selective withdrawal and selective oxidation were screened to provide oxidant to the lower lake layers at each reservoir. These methods represent a means to mitigate or negate the impact of phosphorous from anaerobic sediments. Construction along with operation and maintenance costs for the most feasible method, were estimated.

Section 1: Methods

1.1 Introduction

This section provides a synopsis of the modeling approach and methods applied to Lake New Spiro and Lake Thunderbird to achieve the goal of a high confidence estimate of anaerobic mediated sediment phosphorous release, and its impact on raw water quality at the respective reservoirs. While the same process was applied at each reservoir, gaps in data required notably different inputs for each models which will be discussed.

1.2 Watershed Model- Soil and Watershed Assessment Tool (SWAT)

Selection of the Soil and Water Assessment tool (SWAT) to model the watershed was based on its ability to model both a variety of land use types found in the watersheds of Lake New Spiro, and Lake Thunderbird, while incorporating external data sources, such as animal waste litter applied in the New Spiro watershed. The SWAT models also have a long history of use for watershed assessments and supporting Total Maximum Daily Load (TMDL) development within Oklahoma, which allows the model development within this project to be comparable to many others that have been executed.

The SWAT is a physically–based, continuous time watershed model that can be operated on a daily time step. It was developed by the United States Department of Agriculture - Agriculture Research Service (USDA-ARS). The SWAT model is designed to simulate and predict landscape processes and stream flow. The major components of the model include weather, hydrology, soil temperature and properties, plant growth, nutrients, land management and stream routing. In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into hydrologic response units (HRU). These HRUs consist of portions of a sub-watershed that possess unique land use, slope, and soil characteristics. The HRUs represent percentages of the sub-watershed area and are not identified spatially within a SWAT simulation. A detailed description of a SWAT model, its development and theoretical foundation can be found in Neitsch et al. (2005).

1.2.1 Watershed Model Spatial Constraints

The Lake Thunderbird modeled watershed was approximately 156,940 acres (245 sq miles). The main tributaries of Lake Thunderbird include Hog Creek on the North end, Clear Creek on the south and Dave Blue Creek on the south-west, and the Little River on the north-west end of the reservoir. See **Figure 1.**

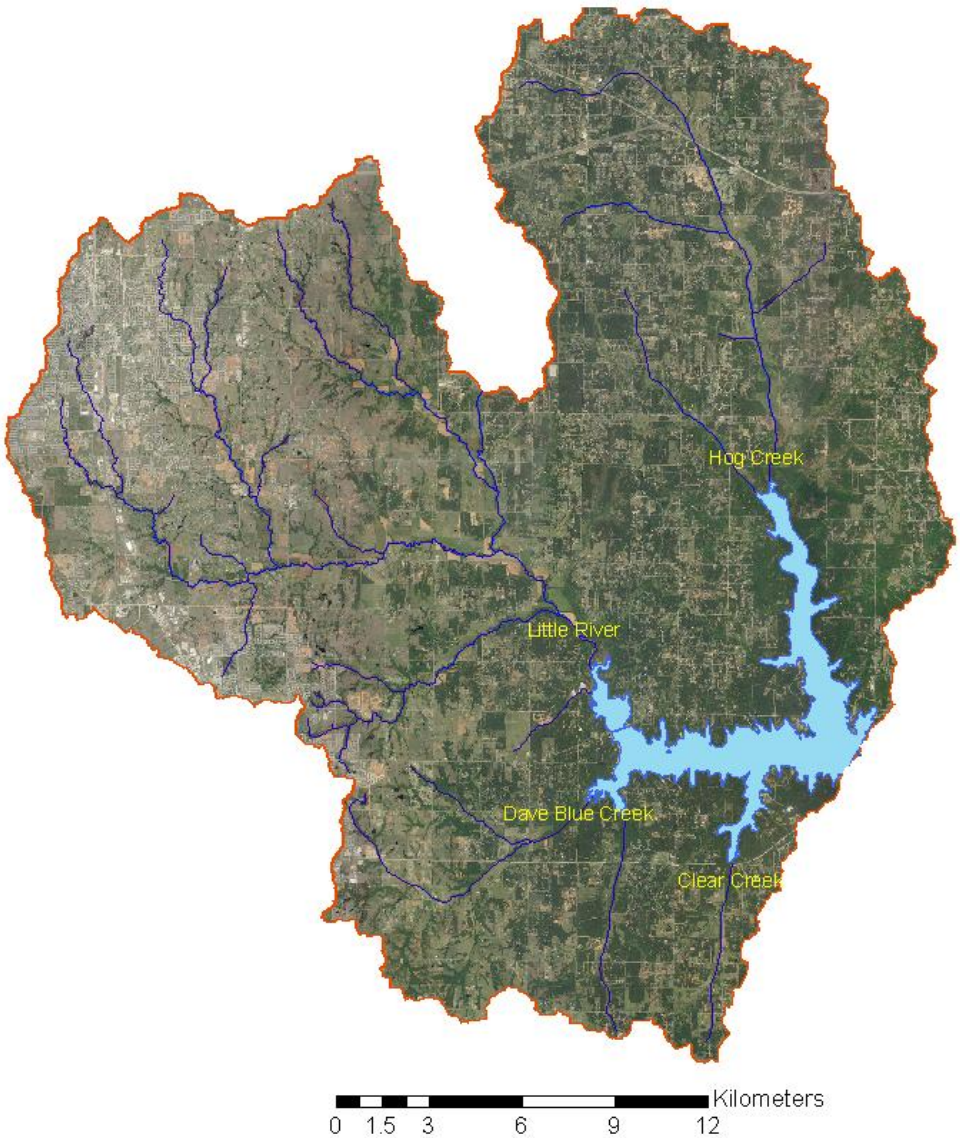

Figure 1: Lake Thunderbird Watershed with 2008 aerial imagery.

The Lake New Spiro modeled watershed was approximately 7950 acres (12.4 sq miles). The main tributary of Lake New Spiro is Holi-Tuska Creek. See **Figure 2.**

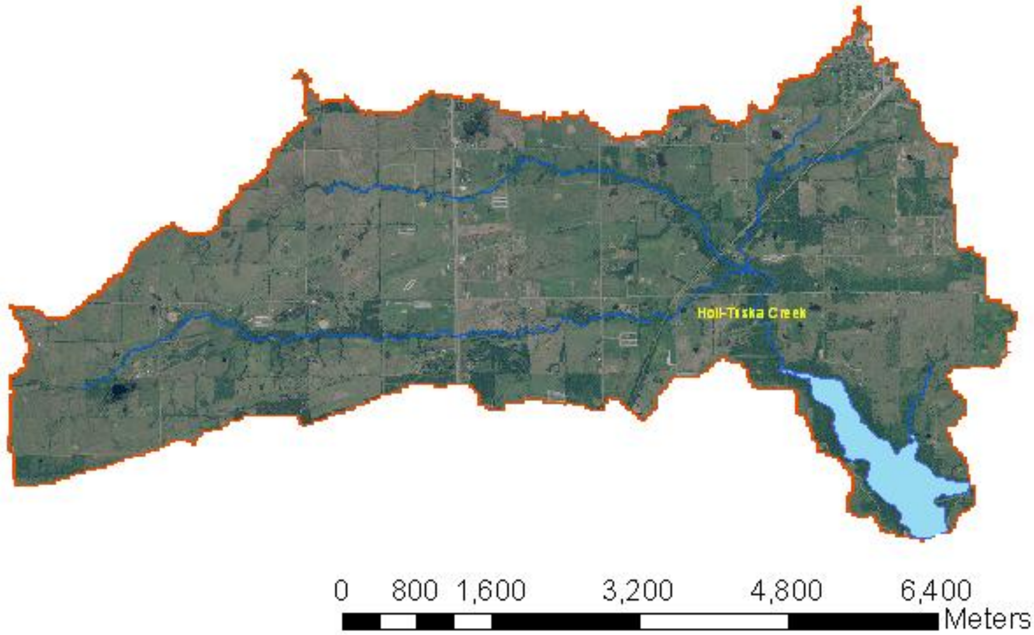

Figure 2: Lake New Spiro Watershed with 2008 aerial imagery

1.2.2 Time period and Time-step

For both lakes a daily time-step was employed with SWAT over the 9-year period modeled (2000-2009).

1.2.3 Variable of Concern

The primary purpose of the SWAT model development for this project was to estimate an average yearly external nutrient load for the BATHTUB model. The output variables that were needed for the BATHTUB model include flow, organic and mineral phosphorous, organic nitrogen, ammonia, nitrate and nitrite, sediment, and soil nutrients.

1.2.4 SWAT Model Inputs

Because the SWAT model is not the focus of the project, each model input will not be discussed in detail. SWAT model inputs included elevation, soil data, land use data, meteorology, evaporation, point source, and fertilizer application.

1.2.5 SWAT model calibration

Hydrologic and nutrient calibration was performed unconventionally at Lake Thunderbird because insufficient flow gage data was available. Hydrologic calibration was done by calibrating SWAT model monthly flow outputs to the United States Army Corps of Engineers (USACE) monthly water budgets for Lake Thunderbird. Lake New Spiro had no USACE spillway gage data, evaporation, precipitation or water level gauging data available. To circumvent this, a dynamic water budget was set up with SWAT inflows and collected lake morphometrics. Precipitation data was compiled from the closest Mesonet station, located in Sallisaw, Oklahoma, approximately 18 miles from the Lake. Evaporation rates were assumed to match those found at a close USACE station at Lake Wister approximately twenty miles from New Spiro Lake.

1.3 Lake Water Quality Model - BATHTUB

BATHTUB is a steady-state modeling software package designed by USACE to facilitate application of empirical eutrophication models to reservoirs and lakes. Since its production, it has been trusted and applied to numerous lakes and reservoirs throughout the country (Kennedy 1995). BATHTUB has been shown as an effective tool for lake and reservoir water quality assessment and management, particularly when data, time, and monetary constraints exist. This modeling software formulates steady-state water and nutrient mass-balances in a spatially segmented hydraulic network that accounts for advective transport, diffusive transport, and nutrient sedimentation. Water quality conditions related to eutrophication are predicted within the model using empirical relationships previously developed and tested for reservoir application (Walker, 1985).

It should be noted that because BATHTUB is based on empirical equations derived from observed water quality relationships in USACE reservoirs within the United States, its ability to reliably predict are limited to reservoirs that fit the same profile as the reservoirs used in its development. This profile consists of relatively shallow lakes (less than 30 meters) with hydraulic residence times of less than two years. Both Lake Thunderbird and Lake New Spiro fit within these limits.

To model water quality conditions within each reservoir, BATHTUB requires inputs that describe both the physical and chemical characteristics of each reservoir. These include morphometric parameters of the lake, tributary flow rates and nutrient loading, and observed water quality concentrations to use as calibration targets. When warranted, BATHTUB also allows the user to segment a reservoir into a hydraulic network if warranted. This was done in some capacity for each reservoir, and will be discussed in **Section 1.3.2**.

1.3.1 BATHTUB Model Setup and Input Data

To setup each BATHTUB model four key inputs are required: lake morphometry, inflows, atmospheric loads, and weather data. For all numeric inputs, the model requires both a mean value and coefficient of variation.

1.3.2 Lake Morphometry

BATHTUB allows the user to segment the reservoir into a hydraulic network. Because bathymetric survey data existed for Lake Thunderbird and a new bathymetric survey was achieved within the project for Lake New Spiro, sufficient data existed to create a hydraulic network for each reservoir.

Based on water quality data, segmentation of the BATHTUB model was deemed necessary to separate the effects of mixing zones of the tributaries, and deeper lacustrine sites. Maps of the segmentation schemes can be seen in **Figure 3** and **Figure 4.** Morphometric characteristics for each lake and its corresponding segments are given in Figure 3**Table 1** and **Table 2**. These characteristics were derived from the bathymetric survey in 2001 for Lake Thunderbird, and the 2010 survey for Lake New Spiro. Lake segmentation at Lake Thunderbird allowed for separation of tributary zones (segments 1, 5 & 6), mixing zones (segments 4 & 2), and the lacustrine-like zone (segment 3) to be separated. At Lake New Spiro, water quality data justified segmentation to a mixing zone (segment 1) and lacustrine zone (segment 2).

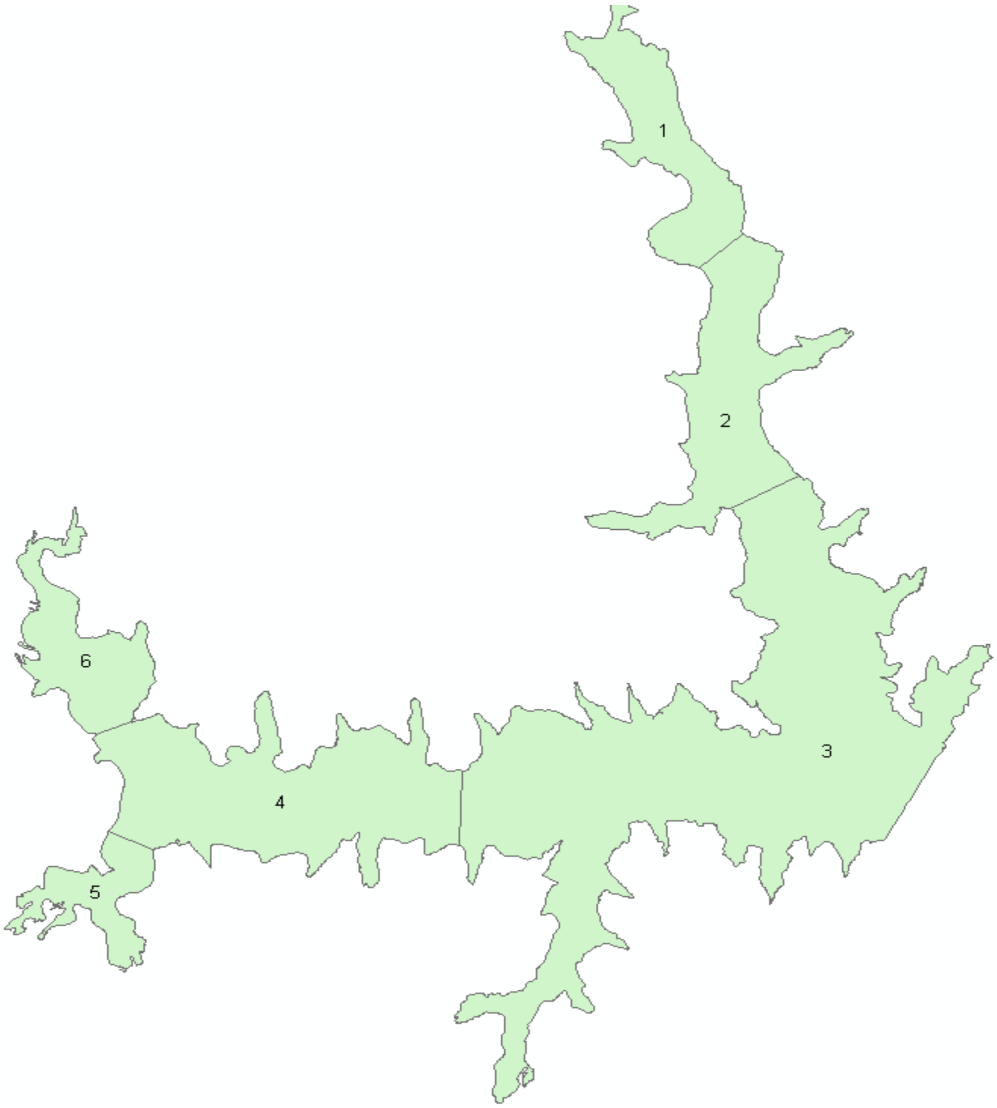

Figure 3: Thunderbird Lake segment network

Table 1: Morphometric Characteristics of Lake Thunderbird

Lake/Segment	Mean Depth (m)	Surface Area (km^2)	Volume (hm^3)
Thunderbird	5.92	21.953	130.27
Segment 1	2.40	1.695	4.03
Segment 2	4.98	2.529	12.61
Segment 3	8.30	11.011	91.42
Segment 4	4.65	4.152	19.33
Segment 5	1.22	.831	1.02
Segment 6	1.18	1.389	1.65

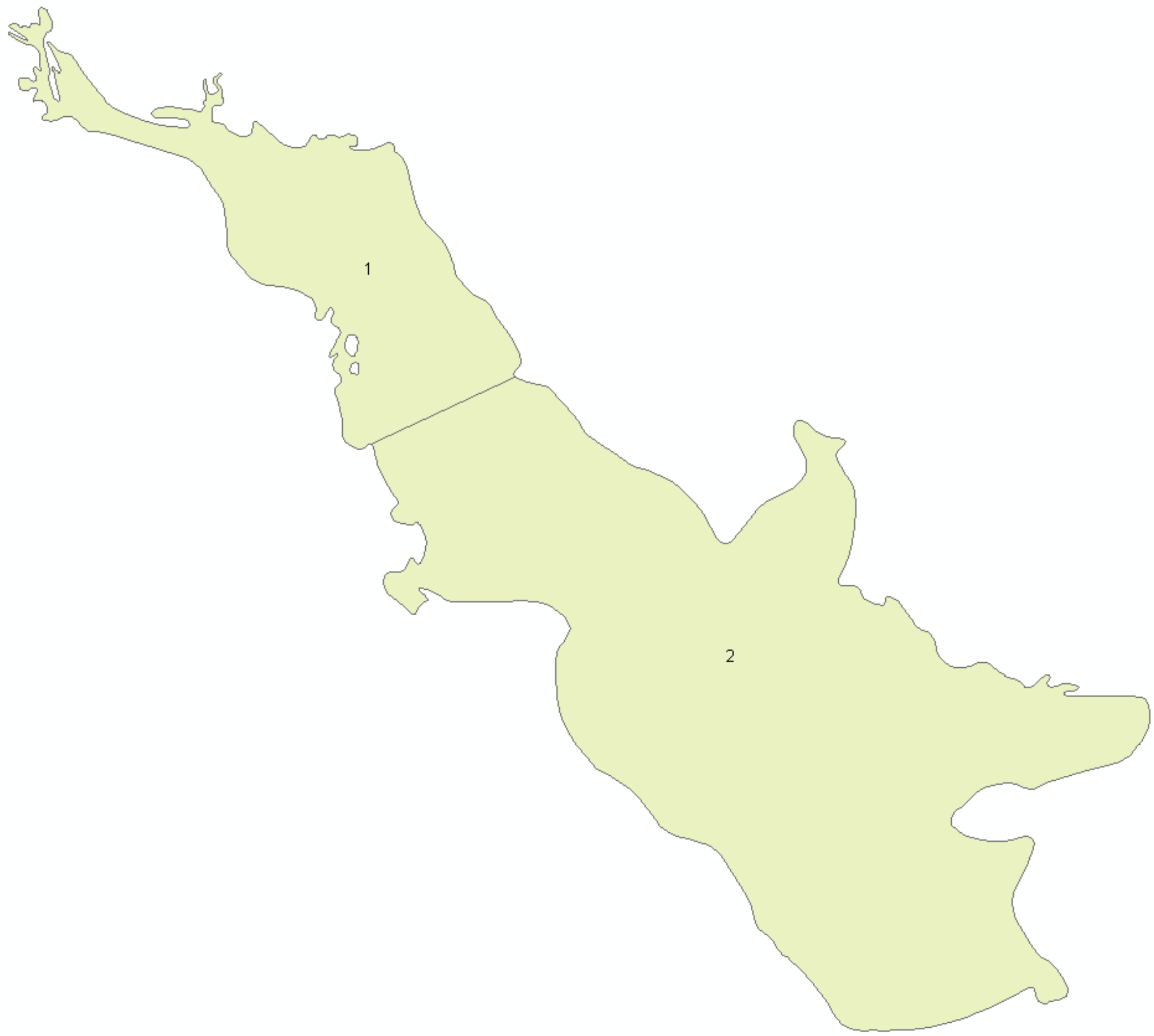

Figure 4: Lake New Spiro Segment Scheme

Table 2: Morphometric Characteristics of Lake New Spiro

Lake/Segment	Mean Depth (M)	Surface Area (km²)	Volume (hm³)
New Spiro	2.52	.99	2.5
Segment 1	1.19	.21	.3
Segment 2	2.85	.78	2.2

1.3.3 Weather Data

The BATHTUB model requires both precipitation and evaporation data. Precipitation data are available from the Oklahoma Mesonet system. For both reservoirs data from the closest Mesonet station was compiled. The average annual precipitation for the models' time frame was 0.98 meters at Lake Thunderbird and 1.087 meters at New Spiro Lake. Water surface evaporation rates were available from USACE for Lake Thunderbird. The average yearly water surface evaporation rate for Lake Thunderbird was 1.99 meters per year. New Spiro Lake is not a USACE reservoir, so a nearby USACE reservoir, Lake Wister's evaporation rate per unit area was used, and extrapolated to model Lake New Spiro's evaporation rate. This was found to be 1.32 meters per year. Lake Wister is located approximately 25 miles to the south of Lake New Spiro.

1.3.4 Inflow Estimates

The mass-balance concept is fundamental to reservoir and lake eutrophication modeling. BATHTUB formulates water and nutrient balances by establishing a control volume around each segment and evaluating the following terms:

Inflows=Outflows + Increase-in-Storage + Net Loss

Inflow Terms=External Inflow + Advective + Diffusive + Precipitation

Outflow Components=Discharge from Reservoir + Advective + Diffusive + Evaporation

The external, atmospheric, discharge, evaporation and increase-in-storage terms are calculated directly from information provided by the user.

For the BATHTUB models, for both lakes, constructed tributary inflow and constituent nutrient loads are provided by their respective SWAT models. For Lake Thunderbird the SWAT model has four resultant tributaries: Hog Creek, Little River, Dave Blue Creek, and Clear Creek (**Table 3, Table 4, Table 5, and Table 6**). For Lake New Spiro the SWAT model resulted in one tributary, Holi-Tuska Creek (**Table 7**). Because BATHTUB cannot differentiate where a tributary input is located within a given segment, lake watershed basins that feed directly into a segments waterbody are lumped into that segments tributary.

Lake Thunderbird SWAT Tributary Inflows

Table 3: Hog Creek

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	32.6	0.41
Total P (µg/L)	15.2	0.49
Ortho P (µg/L)	9.2	0.58
Total N (µg/L)	400	0.91
Inorganic N (µg/L)	292	0.56

Table 4: Little River

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	55.9	0.47
Total P (µg/L)	247.2	0.527
Ortho P (µg/L)	84.8	0.71
Total N (µg/L)	1582	0.42
Inorganic N (µg/L)	835	0.29

Table 5: Dave Blue Creek

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	14.83	0.49
Total P (µg/L)	102.0	1.54
Ortho P (µg/L)	78.5	0.013
Total N (µg/L)	735	0.36
Inorganic N (µg/L)	240	0.66

Table 6: Clear Creek

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	4.8	0.35
Total P (µg/L)	31.8	0.57
Ortho P (µg/L)	25.2	0.52
Total N (µg/L)	342	0.63
Inorganic N (µg/L)	206	1.01

Lake New Spiro BATHTUB Inflow Inputs

Table 7: Holi-Tuska Creek

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	12.2	0.54
Total P (µg/L)	239.7	0.28
Ortho P (µg/L)	107.7	0.53
Total N (µg/L)	2698	0.52
Inorganic N (µg/L)	1965	0.75

1.3.5 Outflows

In any mass-balance, outflows must be accounted for when possible. In BATHTUB this requires inputting them as outflow tributaries from segments with spillways and/or water withdraw.

At Lake Thunderbird there were two outflows defined. One is the USACE gated spillway that allows water to exit segment 1 in our model (**Table 8**). This data was compiled from the USACE database. The other is the raw water withdraw from segment 1, which serves as a municipal water supply for the cities of Norman, Midwest City and Del City (**Table 9**). Drinking water withdraw is depth variable but is generally taken from 4 meters. This data was obtained from the COMCD supplier of raw drinking water. Both outflows had nutrient parameters that matched the segment they were removed from, segment 1 epilimnion.

Table 8: Lake Thunderbird Spillway

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	56	0.614
Total P (µg/L)	48.15	0.33
Ortho P (µg/L)	21.2	0.37
Total N (µg/L)	931	0.21
Inorganic N (µg/L)	135	0.25

Table 9: COMCD Raw Water Withdrawal

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	22.35	0.05
Total P (µg/L)	48.15	0.33
Ortho P (µg/L)	21.2	0.37
Total N (µg/L)	931	0.21
Inorganic N (µg/L)	135	0.25

Similarly, Lake New Spiro has two output tributaries defined in our BATHTUB model: spillway and raw water withdrawal. The situation at Lake New Spiro was markedly different because the spillway is not gated; therefore no flow data was readily available. In this case, we created a dynamic water-budget then relied on combining the bathymetric data gathered in the project, with SWAT monthly inflows. Any volume of water that exceeded the height of the New Spiro Lake spillway was assumed overflow and nutrient losses were assumed to match epilimnetic values (**Table 10**).

The second outflow for Lake New Spiro is raw water withdrawal for drinking water. Raw water withdrawal was retrieved from City of Spiro water treatment plant records (**Table 11**). Outflows also require nutrient load for nutrient mass-balance calculations. These nutrient loads were assumed to match the corresponding segment's epilimnetic data, since both spillway discharge and water withdrawals come directly from segment 2.

Table 10: Lake New Spiro Spillway

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	10.5	0.096
Total P (µg/L)	110.3	0.306
Ortho P (µg/L)	34.9	0.92
Total N (µg/L)	1202	0.12
Inorganic N (µg/L)	74.06	1.61

Table 11: City of Spiro Water Withdrawal

Parameter	Mean	Coefficient of Variation
Flow (hm^3/yr)	0.36	0.029
Total P (µg/L)	110.273	0.306
Ortho P (µg/L)	34.9	0.92
Total N (µg/L)	1202	0.12
Inorganic N (µg/L)	74.06	1.61

1.3.6 Atmospheric Loads

An atmospheric load is the atmospheric deposition of nutrients directly to a lake surface. While these are generally small when compared to the watershed and internal nutrient load for eutrophic waterbodies, they should be accounted for when possible. The BATHTUB model allows for the input of total phosphorous (Total P), ortho-phosphorous (Ortho P), total nitrogen (Total N) and inorganic nitrogen (Inorganic N). The National Atmospheric Deposition Program (NADP) stations has several stations within Oklahoma, unfortunately data only exists to calculate inorganic nitrogen from this data source, therefore default values provided by the program have been used. These values are given in **Table 12.**

Table 12: BATHTUB Default Atmospheric Loads

Parameter	Mean (mg/m^2-yr)	Coefficient of Variation
Total Phosphorous	30	0.5
Ortho Phosphorous	15	0.5
Total Nitrogen	1000	0.5
Inorganic Nitrogen	1000	0.5

1.3.7 Observed Water Quality

BATHTUB also allows for the input of observed water quality for each hydraulic segment. These input values are extremely important while they do not serve as inputs into the empirical models; they provide a valuable tool to assess error once initial setup is achieved. They give the user valuable feedback, which qualifies if the correct empirical equation and/or calibration factors have been selected. Observed water quality input criteria for our models included Total P, Total N, chl-*a*, Secchi depth, organic nitrogen, and Total P minus Ortho P.

For Lake Thunderbird, an abundance of observed water quality data was available from OWRB contract work with the COMCD. Observed water quality data input values were derived from yearly growing-season averages of available water quality data from 2003-2009. The final observed water quality inputs for each segment are listed in **Table 13** through **Table 18.**

For Lake New Spiro, water quality data was limited to OWRB BUMP data which occurs on a quarterly basis on a 5 year rotation. Because of the data limitation all available data within the growing season were averaged for each segment. The New Spiro final observed water quality inputs for each segment are listed in **Table 19** and **Table 20.**

Lake Thunderbird BATHTUB Water Quality Inputs by Segment

Table 13: Segment 1

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	2.42	0.22
Total P (µg/L)	50.15	0.277
Total N (µg/L)	931	0.21
Chlorophyll-a (µg/L)	36.25	0.357
Secchi Depth (m)	0.332	0.19
Organic Nitrogen (µg/L)	865	0.25
Total P- Ortho P (µg/L)	29.7	0.21

Table 14: Segment 2

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	1.03	0.424
Total P (µg/L)	38.9	0.27
Total N (µg/L)	782	0.22
Chlorophyll-a (µg/L)	31.3	0.55
Secchi Depth (m)	0.61	0.312
Organic Nitrogen (µg/L)	760	0.25
Total P- Ortho P (µg/L)	35.5	0.3

Table 15: Segment 3

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	0.8	0.483
Total P (µg/L)	33.76	0.24
Total N (µg/L)	847	0.177
Chlorophyll-a (µg/L)	29.53	0.49
Secchi Depth (m)	0.76	0.25
Organic Nitrogen (µg/L)	726.8	0.212
Total P- Ortho P (µg/L)	23.6	0.3

Table 16: Segment 4

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	1.38	0.295
Total P (μg/L)	45	0.367
Total N (μg/L)	824	0.19
Chlorophyll-a (μg/L)	32.4	0.531
Secchi Depth (m)	0.483	0.325
Organic Nitrogen (μg/L)	778	0.26
Total P- Ortho P (μg/L)	32.4	0.504

Table 17: Segment 5

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	2.32	0.25
Total P (μg/L)	69.26	0.25
Total N (μg/L)	939	0.23
Chlorophyll-a (μg/L)	41.7	0.36
Secchi Depth (m)	0.29	0.41
Organic Nitrogen (μg/L)	906	0.24
Total P- Ortho P (μg/L)	45.75	0.19

Table 18: Segment 6

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	4.89	0.32
Total P (μg/L)	92.8	0.23
Total N (μg/L)	1048	0.098
Chlorophyll-a (μg/L)	37	0.49
Secchi Depth (m)	0.163	0.39
Organic Nitrogen (μg/L)	952	0.15
Total P- Ortho P (μg/L)	54.5	0.244

Lake New Spiro BATHTUB Water Quality Inputs by Segment

Table 19: Segment 1

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	2.35	0.48
Total P (µg/L)	118.2	0.14
Total N (µg/L)	1296	0.15
Chlorophyll-a (µg/L)	37.4	0.23
Secchi Depth (m)	0.40	0.16
Organic Nitrogen (µg/L)	1103	0.08
Total P- Ortho P (µg/L)	90.12	0.174

Table 20: Segment 2

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	1.76	0.42
Total P (µg/L)	110.3	0.36
Total N (µg/L)	1202	0.12
Chlorophyll-a (µg/L)	36.7	0.32
Secchi Depth (m)	0.51	0.12
Organic Nitrogen (µg/L)	1116	0.10
Total P- Ortho P (µg/L)	82.79	0.11

1.3.8 Anaerobic Mediated Phosphorous Release

Phosphorous (P) loading resulting from anoxic sediment surfaces often represents a significant portion of summer P load to lakes and reservoirs (Nurnberg 1994). BATHTUB allows for anaerobic mediated phosphorous release values to be input. Incorporating this feature into the model allowed the model to simulate in-lake BMPs conditions. These in-lake BMP BATHTUB models were then used to estimate the lake response in terms of Total P, Ortho-P loads and chl-*a*.

There are many methods to calculate anaerobic mediated phosphorous release depending on the amounts and type of data available. For our study, we used a procedure which requires calculating the size of anoxic area and areal extent of anoxia called the Anoxic Factor (AF) and the rate with which P is released from the anoxic sediment surface (release rate) (Nurnberg 2005). This method was selected based on the fact that water quality profile data were not sufficient at Lake New Spiro to come up with the actual AF number.

0

Where AF = (duration of anoxia ( ) x anoxic sediment area ( )/lake surface area (Ao)

The procedure centralizes around the calculation:

Anaerobic Mediate Phosphorous Release = Predicted Anoxic Factor (AFpred) x Release Rate (RR).

AFpred is shown by:
AFpred = -35.4 + 44.2 LOG (TP) + 0.95z/√A
Where: **TP** is yearly average water column total phosphorous in µg/L,
z is the mean depth in meters, and,
A is lake surface area in km^2.

RR is shown by:
Log (RR) = 0.8 + 0.76log(TPsed)
Where: **TPsed** is the total phosphorous in the sediment given in g/kg.

To validate this procedure, an empirical AF was averaged over a three year period of Lake Thunderbird data in which bi-weekly oxygen profiles allowed for duration of anoxia and area of anoxic sediment to be estimated. The result was an AF calculation at Lake Thunderbird with an average of 55 days with predicted AF calculation (AFpred) of 76 days. Results of these calculations are listed in **Table 21** and **Table 22**.

Table 21: Anoxic Factor, Release Rate, and Annualized Sediment Phosphorous Load for Lake Thunderbird

Calculation	Value
AF (days)	47
AFpred (days)	55
Release Rate (mg/m²/day)	4.88
Annualized Areal Phosphorous Load (mg/m²/year)	270

Table 22: Anoxic Factor, Release Rate, and Annualized Sediment Phosphorous Load for Lake New Spiro

Calculation	Value
AFpred (days)	59
Release Rate (mg/m²/day)	11.85
Annualized Areal Phosphorous Load (mg/m²/year)	695

1.3.9 Selection of Empirical Equations and Calibration

The foundation of BATHTUB revolves around a series of empirical equations that have been calibrated and tested for reservoir application. These empirical relationships are used to calculate steady-state concentrations of TP, TN, chl-*a*, and transparency based on the inputs and forcing functions. To predict each output, one of several built-in empirical equations must be selected.

Based on previous experience of team members and the application designations given in the BATHTUB User's Manual, empirical equations were selected based on each reservoirs situation.

After the model was set up with selected empirical equations, BATHTUB water quality predictions were within 10% of observed values for both Lake Thunderbird and Lake New Spiro. In order to bring the predicted conditions even closer to actual in-lake conditions, BATHTUB allows the user to modify a set of calibration factors. This was done for the chief parameters of concern TP, TN, and chl-*a*.

Section 2: Results and Discussion

2.1 SWAT Model Results

The objective of the SWAT model was to serve as nutrient and flow input loads for the respective reservoirs.

2.1.1 Lake Thunderbird SWAT Model Results

As seen in **Figure 5,** Lake Thunderbird watershed is dominated by grasslands and deciduous forest which are low in terms of exportation of nutrients. However, the Little River watershed located in the northwest corner of the map is dominated by developed land within the cities of Norman and Moore, which results in a situation where the Little River is responsible for 86% of the watershed phosphorous load to the lake while only accounting for 52% of the watershed area. Nutrient and flow values for each tributary can be found within **Table 3, Table 4, Table 5,** and **Table 6**.

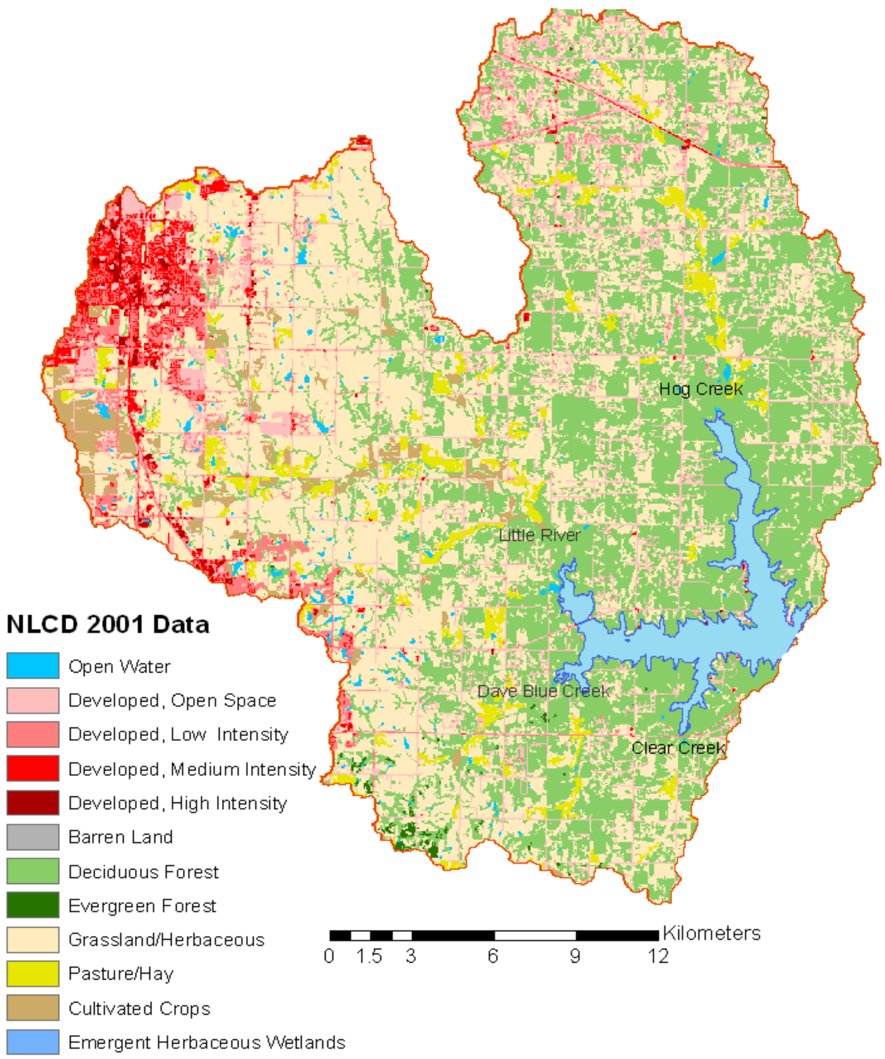

Figure 5: Lake Thunderbird SWAT Model NCLD Map.

Table 23: Lake Thunderbird Land Use Breakdown

	Land Cover Classification Legend	Area (km²)	%
11	Open Water	27.4	4%
21	Developed Open Space	59.6	9%
22	Developed Low Intensity	28.3	4%
23	Developed Medium Intensity	12.9	2%
24	Developed High Intensity	2.8	<1%
31	Barren Land	0.1	<1%
41	Deciduous Forest	222.7	35%
42	Evergreen Forest	1.4	<1%
71	Grassland/Herbaceous	242.9	38%
81	Pasture Hay	22.3	4%
82	Cultivated Crops	14.5	2%
95	Emergent Herbaceous Wetlands	0.03	<1%

2.1.2 Lake New Spiro SWAT Model Results

As seen in **Figure 6** and **Table 24 ,** Lake New Spiro watershed is dominated by pasture land. In addition to the nutrient load roughly 31,000 kg of animal litter is applied to the watershed basin each year. This data taken from the Oklahoma Department of Agriculture, Food and Forestry poultry litter land application map layer released September of 2010.

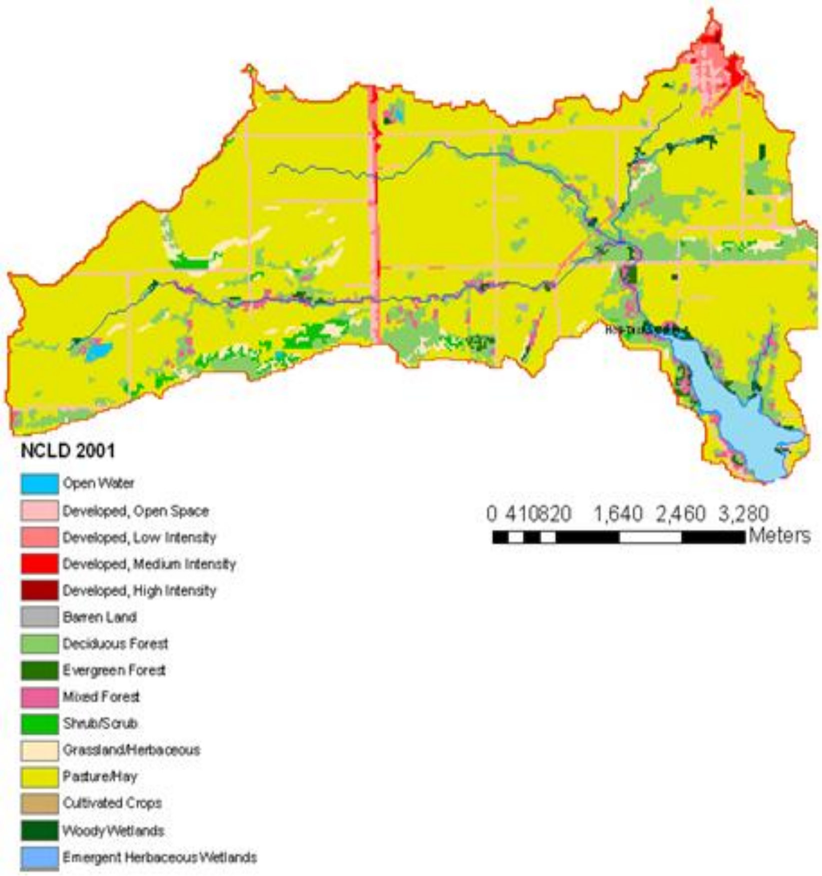

Figure 6: Lake New Spiro SWAT NCLD Map

Table 24: Lake New Spiro Land Use Breakdown

NLCD Code	Land Cover Classification Legend	Area (Acres)	%
11	Open Water	251.6	3%
21	Developed Open Space	354.8	4%
22	Developed Low Intensity	133.7	1%
23	Developed Medium Intensity	34.6	<1%
24	Developed High Intensity	4.0	<1%
31	Barren Land	4.6	<1%
41	Deciduous Forest	991.2	12%
42	Evergreen Forest	38.0	<1%
43	Mixed Forest	170.9	2%
52	Shrub/Scrub	112.3	1%
71	Grassland/Herbaceous	175.1	2 %
81	Pasture Hay	5599.7	70 %
82	Cultivated Crops	3.2	<1%
90	Woody Wetlands	69.4	<1%
95	Emergent Herbaceous Wetlands	1.5	<1%

2.2 BATHTUB Model Results

The objective of the BATHTUB model was to establish the impact that anaerobic mediated sediment phosphorous release had on the two eutrophic waterbodies. Then the reductions of sediment phosphorous loads were simulated to see the effect in-lake BMPs can have on chl-*a* reduction.

2.2.1 Lake Thunderbird BATHTUB Model Results

The BATHTUB model was used to predict average water quality in Lake Thunderbird with the purpose of isolating the effects of anaerobic mediated sediment phosphorous release on the waterbody. After calibrating the model with adjustment to the empirical formulas of the model as mentioned in section **1.3.9**, the BATHTUB model predictions of in-lake nutrients were closely associated with the observed water quality data.

The physical side of the model was also validated with observed data. As seen in **Table 25,** only 6% of water entering the reservoir was unaccounted for; this could be explained for by other potential water outflows not accounted for by the BATHTUB model such as groundwater loss and seepage through the dam. Hydraulic residence time was estimated to be 1.5 years (18 months) with a phosphorous nutrient residence time of 0.28 years and a retention coefficient of 0.85 (**Table 26**). Phosphorous retention coefficient is defined as the fraction of the external P loading retained with the waterbody. According to the BATHTUB model, Lake Thunderbird retains about 85% of the phosphorous loaded into the lake.

Table 25: Lake Thunderbird BATHTUB Hydraulic Mass-Balance Outputs

Overall Water Balance						Averaging Period =	1.00	years
				Area	Flow	Variance	CV	Runoff
Trb	Type	Seg	Name	km^2	hm^3/yr	$(hm3/yr)^2$	-	m/yr
1	1	1	Hog Creek	152.0	32.6	1.79E+02	0.41	0.21
2	1	5	Dave Blue Creek	82.7	14.8	5.19E+01	0.49	0.18
3	1	6	Little River	282.0	55.9	6.90E+02	0.47	0.20
4	4	3	COMCD Uptake		22.4	1.25E+00	0.05	
5	4	3	Releases		56.0	1.18E+03	0.61	
6	1	3	Clear Creek	27.9	4.8	2.82E+00	0.35	0.17
			PRECIPITATION	21.6	21.2	1.29E+01	0.17	0.98
			TRIBUTARY INFLOW	544.6	108.2	9.24E+02	0.28	0.20
			*****TOTAL INFLOW**	566.2	129.3	9.37E+02	0.24	0.23
			GAUGED OUTFLOW		78.3	1.18E+03	0.44	
			ADVECTIVE OUTFLOW	566.2	8.0	2.14E+03	5.80	0.01
			*****TOTAL OUTFLOW**	566.2	86.3	9.59E+02	0.36	0.15
			*****EVAPORATION**		43.0	2.24E+01	0.11	

Table 26: Lake Thunderbird BATHTUB Phosphorous Mass-Balance Outputs

Overall Mass Balance Based Upon				Observed		Outflow & Reservoir Concentrations			
Component:				TOTAL P					
				Load		Load Variance			Conc
Trb	Type	Seg	Name	kg/yr	%Total	$(kg/yr)^2$	%Total	CV	mg/m^3
1	1	1	Hog Creek	497.1	2.5%	1.01E+05	0.1%	0.64	15.2
2	1	5	Dave Blue Creek	1512.8	7.6%	5.97E+06	3.7%	1.61	102.0
3	1	6	Little River	13815.7	69.3%	9.52E+07	59.0%	0.71	247.1
4	4	3	COMCD Uptake	754.5		3.21E+05		0.75	33.8
5	4	3	Releases	1890.6		3.35E+06		0.97	33.8
6	1	3	Clear Creek	152.8	0.8%	1.04E+04	0.0%	0.67	31.8
			PRECIPITATION	648.0	3.3%	1.05E+05	0.1%	0.50	30.6
			SEDIMENT P RELEASE	3297.6	16.6%	6.01E+07	37.2%	2.35	
			TRIBUTARY INFLOW	15978.4	80.2%	1.01E+08	62.7%	0.63	147.7
			*****TOTAL INFLOW**	19923.9	100.0%	1.61E+08	100.0%	0.64	154.1
			GAUGED OUTFLOW	2645.1	13.3%	1.75E+06		0.50	33.8
			ADVECTIVE OUTFLOW	269.6	1.4%	2.45E+06		5.80	33.8
			*****TOTAL OUTFLOW**	2914.7	14.6%	1.58E+06		0.43	33.8
			*****RETENTION**	17009.3	85.4%	1.51E+08		0.72	
	Overflow Rate (m/yr)			4.0		Nutrient Resid. Time (yrs)			0.2804
	Hydraulic Resid. Time (yrs)			1.5060		Turnover Ratio			3.6
	Reservoir Conc (mg/m3)			43		Retention Coef.			0.854

Close nutrient concentration model predictions translated to a closely modeled chl-*a* response in both the un-calibrated and calibrated model. Based on Carlson Trophic State Index (TSI) within the calibrated model, both predicted and observed results classified Lake Thunderbird as eutrophic with a predicted Carlson TSI for chl-*a* of 61.2

The strong agreement on all aspects of the model: physical, chemical, and biological response; allowed us to feel confident that altering internal phosphorous load characteristics of the BATHTUB model would garner a realistic chl-*a* response. The total phosphorous concentrations in the lake had a somewhat linear response to linear changes in the internal phosphorous load to the lake (**Figure 6**), and this translated into a linear chl-*a* response (**Figure 7**). However while this linear relationship exists, percent reduction of internal load resulted in much smaller changes in total phosphorous concentrations than the load reduction. For example the internal phosphorous load at Lake Thunderbird represents 16% of the entire phosphorous load of the lake, when this internal load was completely removed (-100% reduction), only a 8.3 % reduction of total phosphorous concentration was achieved (**Table 27**). This translated into a 12.3% reduction in mean chl-*a* for the growing season.

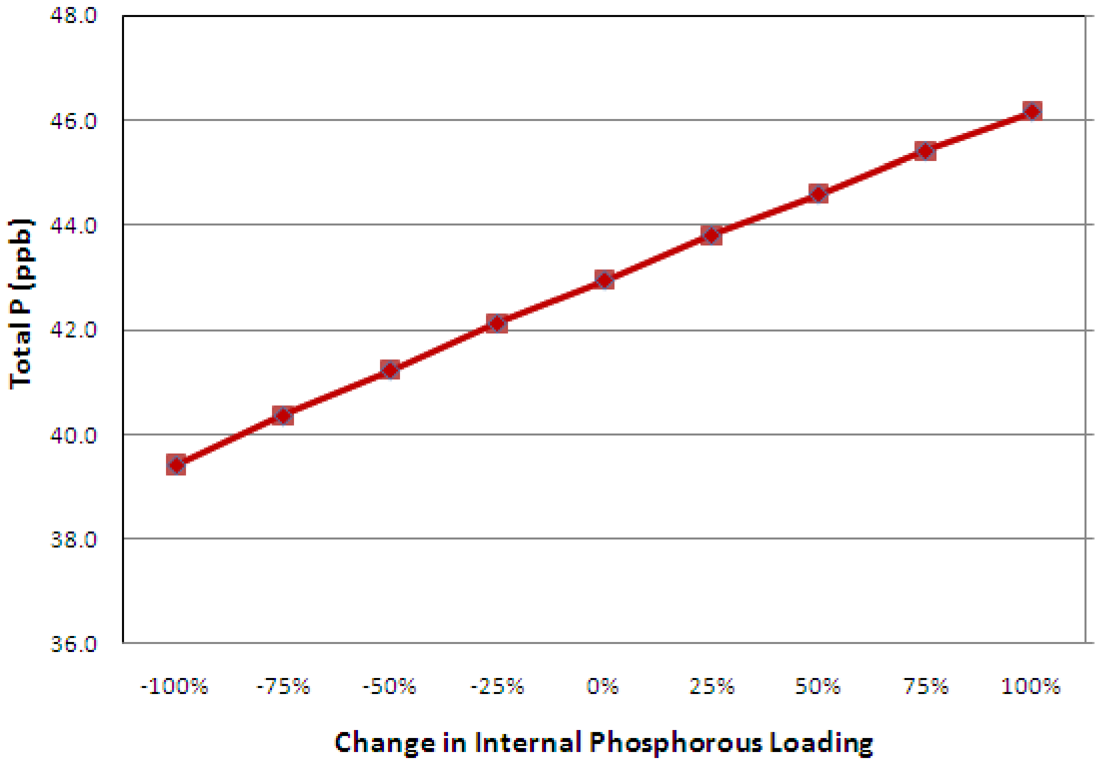

Figure 7: BATHTUB simulated changes in the values of area weighted mean Total P concentrations for Lake Thunderbird in response to changes in sediment phosphorous loading.

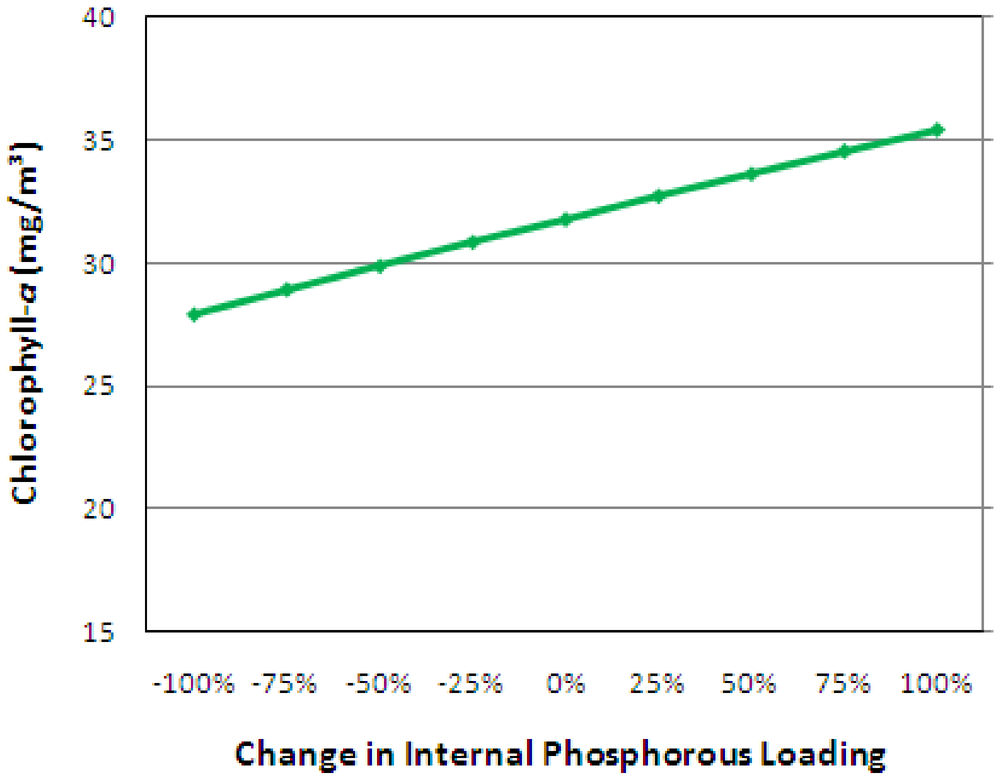

Figure 8: BATHTUB simulated changes in the values of area-weighted mean chl-*a* concentrations for Lake Thunderbird in response to changes in sediment phosphorous loading.

Table 27: Lake Thunderbird BATHTUB outputs Total P and chl-*a* for changes in internal phosphorous load concentrations.

Change in Sediment Phosphorous Load (%)	Total Phosphorous Conc. Area Weighted Mean (µg/L)	Chlorophyll-*a* Area Weighted Mean (mg/m^3)
+100%	46.2	35.4
+75%	45.4	34.5
+50%	44.6	33.6
+25%	43.8	32.7
0%	43.0	31.8
-25%	42.1	30.8
-50%	41.2	29.9
-75%	40.4	28.9
-100%	39.4	27.9

2.2.2 Lake New Spiro BATHTUB Model Results

Like the Lake Thunderbird BATHTUB model, the Lake New Spiro BATHTUB model was used to predict average water quality with the purpose of isolating the effects of anaerobic mediated sediment phosphorous release. After calibrating the model with adjustment to the empirical formulas as mentioned in section **1.3.8**, the BATHTUB model predictions were closely associated with the observed water quality data. The hydraulic mass balance of the New Spiro BATHTUB model was not able to account for 1.2% of the water entering the reservoir (**Table 28)**; this was witnessed as advective outflow. Hydraulic residence time was estimated to be 0.21 years with a phosphorous nutrient residence time of 0.1 years, and a phosphorous retention coefficient of 0.63 (**Table 29**). Close nutrient concentration model predictions translated to a closely modeled chl-*a* response in the model. The generated Carson TSI value was 64.5 for observed and predicted chl-*a*. This classifies Lake New Spiro as hyper-eutrophic.

Table 28: Lake New Spiro BATHTUB Hydraulic Mass-Balance Outputs

Overall Water Balance						Averaging Period =	1.00	years
				Area	Flow	Variance	CV	Runoff
Trb	Type	Seg	Name	km^2	hm^3/yr	$(hm3/yr)^2$	-	m/yr
1	1	1	Trib 1	93.2	12.2	4.33E+01	0.54	0.13
2	4	2	City of Spiro Raw water Uptake		0.4	1.09E-04	0.03	
3	4	2	Overflow		10.5	1.02E+00	0.10	
			PRECIPITATION	1.0	1.1	2.86E-02	0.16	1.09
			TRIBUTARY INFLOW	93.2	12.2	4.33E+01	0.54	0.13
			***TOTAL INFLOW	94.2	13.3	4.33E+01	0.50	0.14
			GAUGED OUTFLOW		10.9	1.02E+00	0.09	
			ADVECTIVE OUTFLOW	94.2	1.1	4.43E+01	6.24	0.01
			***TOTAL OUTFLOW	94.2	11.9	4.33E+01	0.55	0.13
			***EVAPORATION		1.3	7.12E-03	0.06	

Table 29: New Spiro BATHTUB Phosphorous Mass-Balance Output

Overall Mass Balance Based Upon				Predicted		Outflow & Reservoir Concentrations			
Component:				TOTAL P					
				Load		Load Variance			Conc
Trb	Type	Seg	Name	kg/yr	%Total	$(kg/yr)^2$	%Total	CV	mg/m^3
1	1	1	Trib 1	2919.1	83.3%	3.15E+06	66.9%	0.61	239.7
2	4	2	City of Spiro Raw water Uptake	39.0		2.43E+02		0.40	107.9
3	4	2	Overflow	1135.6		2.16E+05		0.41	107.9
PRECIPITATION				29.9	0.9%	2.24E+02	0.0%	0.50	27.6
SEDIMENT P RELEASE				555.3	15.8%	1.56E+06	33.1%	2.25	
TRIBUTARY INFLOW				2919.1	83.3%	3.15E+06	66.9%	0.61	239.7
*****TOTAL INFLOW**				3504.3	100.0%	4.71E+06	100.0%	0.62	264.2
GAUGED OUTFLOW				1174.6	33.5%	2.30E+05		0.41	107.9
ADVECTIVE OUTFLOW				115.1	3.3%	5.36E+05		6.36	107.9
*****TOTAL OUTFLOW**				1289.7	36.8%	9.19E+05		0.74	107.9
*****RETENTION**				2214.6	63.2%	2.03E+06		0.64	
	Overflow Rate (m/yr)			12.0		Nutrient Resid. Time (yrs)			0.1
	Hydraulic Resid. Time (yrs)			0.21		Turnover Ratio			12
	Reservoir Conc (mg/m3)			110		Retention Coef.			0.632

The agreement between the physical, chemical and biological response predictions and observed data, gave confidence that the Lake New Spiro BATHTUB model could give close approximations of chl-*a* and total phosphorous load changes when altering internal phosphorous load values. Like the Lake Thunderbird BATHTUB model, the total phosphorous concentrations in the lake had a somewhat linear response to linear changes in the internal phosphorous load to the lake (**Figure 9**) and this translated into a linear chl-*a* response (**Figure 10).** However while this linear relationship exists, percent reduction of internal load resulted in much smaller changes in total phosphorous concentrations than the load reduction. Internal loading represents 16% of the entire phosphorous load of the lake, when this internal load was completely removed only a 9% reduction in total phosphorous was realized (**Table 30**). This translated into a 6% reduction in mean chl-*a* for the year.

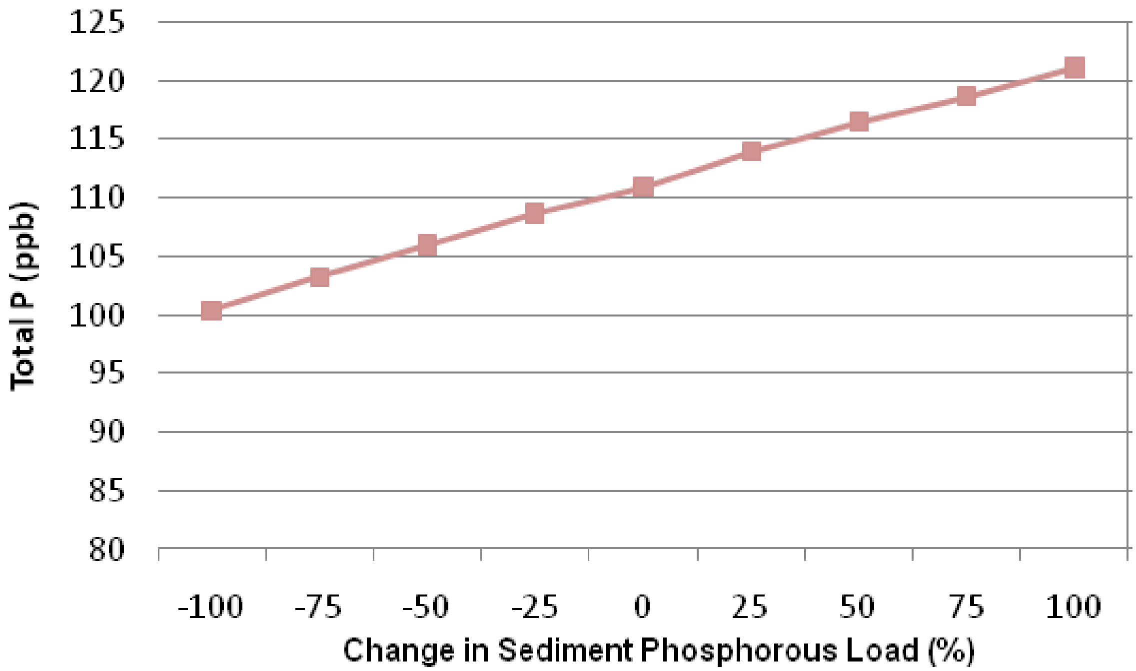

Figure 9: BATHTUB simulated changes in the values of area-weighted mean Total P concentrations for Lake New Spiro in response to change in internal phosphorous loading.

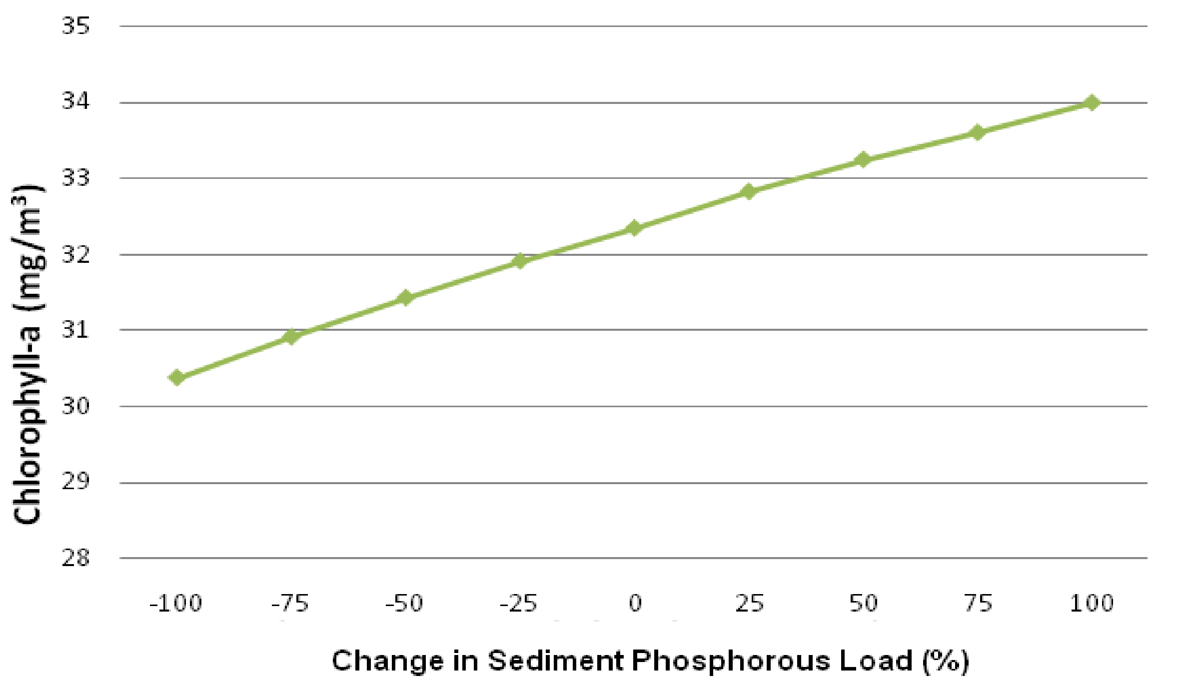

Figure 10: BATHTUB simulated changes in the values of area-weighted mean chl-*a* concentrations for Lake New Spiro in response to change in internal phosphorous loading.

Table 30: New Spiro BATHTUB area weighted mean Total P and chl-a for changes in internal phosphorous load concentrations.

Change in Internal Phosphorous Load (%)	Total Phosphorous Conc. (µg/L)	Chlorophyll-*a* (mg/m^3)
+100%	121.1	34.0
+75%	118.6	33.5
+50%	116.4	33.2
+25%	113.9	32.8
0%	110.9	32.3
-25%	108.6	31.9
-50%	106.0	31.4
-75%	103.2	30.9
-100%	100.4	30.4

2.2.3 Error Analysis

BATHTUB offers the user the option of comparing observed and predicted concentrations with Student's T Tests. These are computed using three alternative measures of error: observed error only (T1); error typical of model development data set (T2); and observed and predicted error (T3). Tests of model applicability are normally based upon T2 and T3. If their values exceed an absolute value of 2 for the comparison of area-weighted mean concentrations the applicability of the models would be questionable in this case.

As seen in **Table 31**, all of Lake Thunderbird's T2 and T3 statistics are well below the 2 threshold, with the exception of Secchi disk depth. This study is primarily concerned with TP and chl-*a* response to changing internal load, Secchi disk error will have no bearing on this study. This suggests that BATHTUB model is applicable to the conditions at Lake Thunderbird and error is low enough that it can be trusted with confidence for the purposes of this report.

Table 31: T Statistics for Lake Thunderbird BATHTUB Model

Segment:	Area-Wtd Mean							
	Observed		Predicted		Obs/Pred	T-Statistics ---->		
Variable	Mean	CV	Mean	CV	Ratio	T1	T2	T3
TOTAL P MG/M3	43.0	0.27	43.0	0.54	1.00	0.00	0.00	0.00
TOTAL N MG/M3	858.0	0.18	857.9	0.64	1.00	0.00	0.00	0.00
C.NUTRIENT MG/M3	34.0	0.23	34.0	0.44	1.00	0.00	0.00	0.00
CHL-A MG/M3	31.8	0.49	31.8	0.83	1.00	0.00	0.00	0.00
SECCHI M	0.6	0.27	1.1	0.42	0.56	-2.16	-2.10	-1.18
ORGANIC N MG/M3	772.7	0.23	897.3	0.63	0.86	-0.66	-0.60	-0.22
TP-ORTHO-P MG/M3	30.0	0.32	33.2	0.58	0.90	-0.32	-0.28	-0.15
ANTILOG PC-1	824.8	0.16	606.8	1.09	1.36	1.94	0.87	0.28
ANTILOG PC-2	10.7	0.24	16.6	0.36	0.65	-1.79	-1.41	-1.00
(N - 150) / P	17.6	0.21	17.6	0.94	1.00	0.00	0.00	0.00

As seen in **Table 32**, T2 and T3 statistics are well below the 2 threshold for model applicability. This suggests that the BATHTUB model is also applicable to the conditions at Lake New Spiro and error is low enough that confidence can be placed in predictions.

Table 32: T Statistics for Lake New Spiro BATHTUB Model

Segment:		Area-Wtd Mean						
	Observed		Predicted		Obs/Pred	T-Statistics ---->		
Variable	Mean	CV	Mean	CV	Ratio	T1	T2	T3
TOTAL P MG/M3	112.0	0.31	110.0	0.30	1.02	0.06	0.07	0.04
TOTAL N MG/M3	1222.6	0.13	1222.6	0.10	1.00			
C.NUTRIENT MG/M3	69.9	0.21	69.4	0.14	1.01	0.03	0.03	0.03
CHL-A MG/M3	36.9	0.30	33.0	0.36	1.12	0.38	0.32	0.24
SECCHI M	0.5	0.13	0.4	0.25	1.28	1.97	0.88	0.88
ORGANIC N MG/M3	1113.2	0.10	1051.2	0.27	1.06	0.59	0.23	0.20
TP-ORTHO-P MG/M3	84.3	0.12	99.3	0.26	0.85	-1.38	-0.45	-0.58

2.2.4 Model Verification

The last step in validating a BATHTUB model is verifying the model with an independent data set derived from a different monitoring period. For the Lake Thunderbird BATHTUB model, a verification model was set up with all model options and calibration factors held constant. A dataset taken from the 2010 calendar year was used for verification because it was the most complete of datasets not included in the BATHTUB dataset. In **Table 33**, observed and predicted concentrations were given for the models. This table shows that the observed concentrations for the verification data set are closely approximated by the model. This demonstrates that the model has been appropriately set up and is robust enough to closely model lake response. In **Table 34**, the T-statistics are given for the verification data set predicted and observed values. Here we see that in general, error is relatively low with the exception of Secchi depth. Secchi depth error is still below the 2 threshold for T-values that BATHTUB recommends, Secchi depth has little bearing on this study since chl-*a* and TP are the focus.

Unfortunately Lake New Spiro had insufficient data to run a verification model.

Table 33: Predicted and Observed Values for Lake Thunderbird BATHTUB Verification model.

Segment:	7	Area-Wtd Mean				
	Predicted Values--->			Observed Values--->		
Variable	Mean	CV	Rank	Mean	CV	Rank
TOTAL P MG/M3	43.7	0.54	45.9%	39.4	0.23	41.4%
TOTAL N MG/M3	907.2	0.64	43.8%	931.5	0.26	45.5%
C.NUTRIENT MG/M3	35.1	0.44	49.2%	32.0	0.23	44.6%
CHL-A MG/M3	32.6	0.83	94.7%	34.0	0.60	95.3%
SECCHI M	1.1	0.42	49.3%	0.7	0.22	26.3%
ORGANIC N MG/M3	903.1	0.65	89.7%	781.6	0.31	83.7%
TP-ORTHO-P MG/M3	29.6	0.66	49.5%	25.9	0.32	43.8%

Table 34: T-Statistics of 2010 Verification Dataset

Segment:	Area-Wtd Mean							
	Observed		Predicted		Obs/Pred	T-Statistics --->		
Variable	Mean	CV	Mean	CV	Ratio	T1	T2	T3
TOTAL P MG/M3	39.4	0.23	43.7	0.54	0.90	-0.45	-0.39	-0.18
TOTAL N MG/M3	931.5	0.26	907.2	0.64	1.03	0.10	0.12	0.04
C.NUTRIENT MG/M3	32.0	0.23	35.1	0.44	0.91	-0.41	-0.47	-0.19
CHL-A MG/M3	34.0	0.60	32.6	0.83	1.04	0.07	0.12	0.04
SECCHI M	0.7	0.22	1.1	0.42	0.63	-2.09	-1.67	-0.99
ORGANIC N MG/M3	781.6	0.31	903.1	0.65	0.87	-0.47	-0.58	-0.20
TP-ORTHO-P MG/M3	25.9	0.32	29.6	0.66	0.87	-0.42	-0.37	-0.18

2.3 Raw Water and Drinking Water Regression Analysis

With the passage of the U.S. Safe Drinking Water Act in 1974, TOC analysis has emerged as a recognized analytical technique to measure water quality and the amount of natural organic matter (NOM) during the drinking water purification process. In water treatment facilities, source water is subject to reaction with some form of chlorine in order to disinfect. When finished water containing NOM is treated, chlorinated disinfection byproducts (DBPs) such as trihalomethanes (THM) and haloacetic acids (HAA5) are produced. These compounds have been shown to be carcinogenic in laboratory animals. Since 2003, the EPA has regulated the amount of DBPs allowed in treated drinking water, and requires that a percentage of TOC in raw drinking water be removed to prevent DBP formation. While TOC is regulated by the EPA as a percentage removed, DBPs are regulated as an absolute threshold with the maximum amount of THM allowed in drinking water is 80 µg/L, as an annual average, and the maximum amount of HAA5 allowed is 60 µg/L, as an annual average. This sets up a situation where it is possible to meet TOC reduction standards, but fails to reduce TOC, and therefore NOM, enough to prevent excessive DBP formation. When this occurs the need for immediate relief becomes necessary and in-lake BMPs need to be evaluated.

According to the Safe Drinking Water Information System (SDWIS) operated by the ODEQ, the City of Spiro has violated the maximum allowable amount of THM at some point annually from 2004 through 2009, with consistent violations of HAA5 as well. The City of Norman has not violated DBP regulations according the records provided by SDWIS.

Since algae is largely composed of organic carbon, and one of the goals of in-lake BMPs is to improve water quality through reduction of algae growth measured by chl-*a*, it is possible that a relationship exists between chl-*a* and TOC. In this section we discuss the possible link between chl-*a* and TOC at Lake Thunderbird, and its potential impact on drinking water treatment costs for raw water recipients. Insufficient data was available for the City of Spiro to do any in-depth analysis.

On Lake Thunderbird a positive correlation relationship existed between surface chl-*a* values and total organic carbon (TOC) data, where waters with greater chl-*a* concentrations were more likely to exhibit higher TOC concentrations (**Figure 11**).

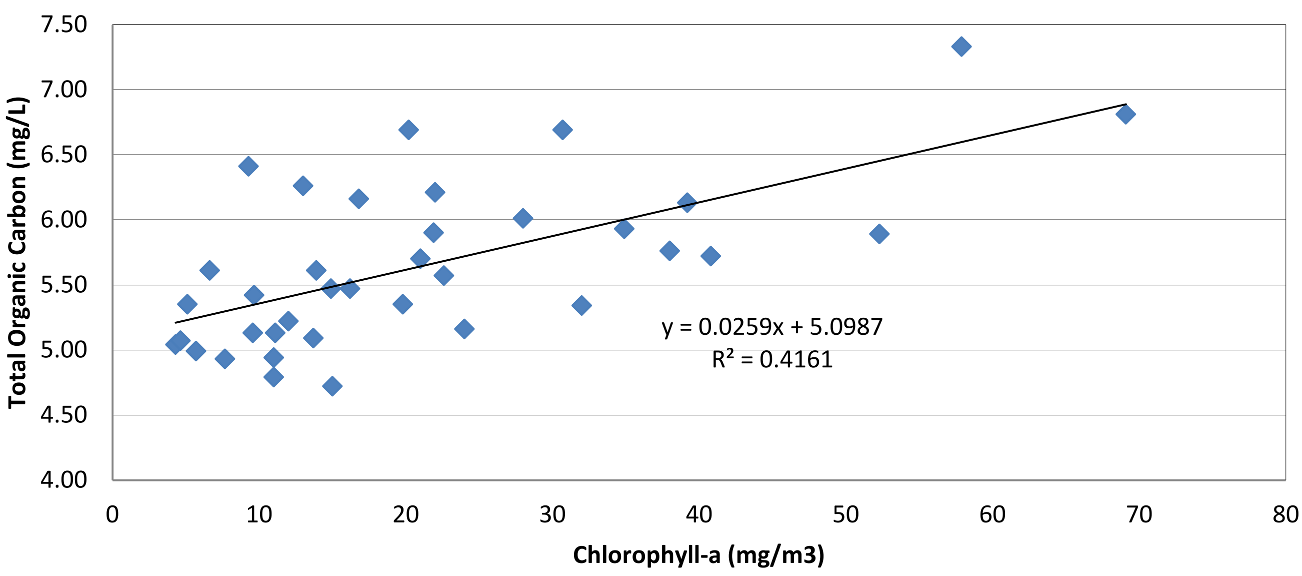

Figure 11: Lake Thunderbird TOC vs Chlorophyll-*a* for raw water samples.

The positive correlation between Lake Thunderbird surface TOC and chl-*a*, established that a relationship exists between chl-*a* and TOC formation at Lake Thunderbird. To see if TOC in Lake Thunderbird had any bearing on the raw water received by raw drinking water recipients, Lake Thunderbird TOC data was paired with data taken from the raw water received by the City of Norman on dates within 5 days of each other. A linear regression was then performed on this paired dataset. A strong correlation was found where surface TOC values at Lake Thunderbird closely approximated raw water received by the City of Norman drinking water treatment plant (**Figure 12**). The R^2 indicates significance with approximately 64% of the variability explained by the in-lake TOC values. Perhaps more importantly is the fact that the slope is very close to a 1 to 1 ratio and the y intercept is very close to zero.

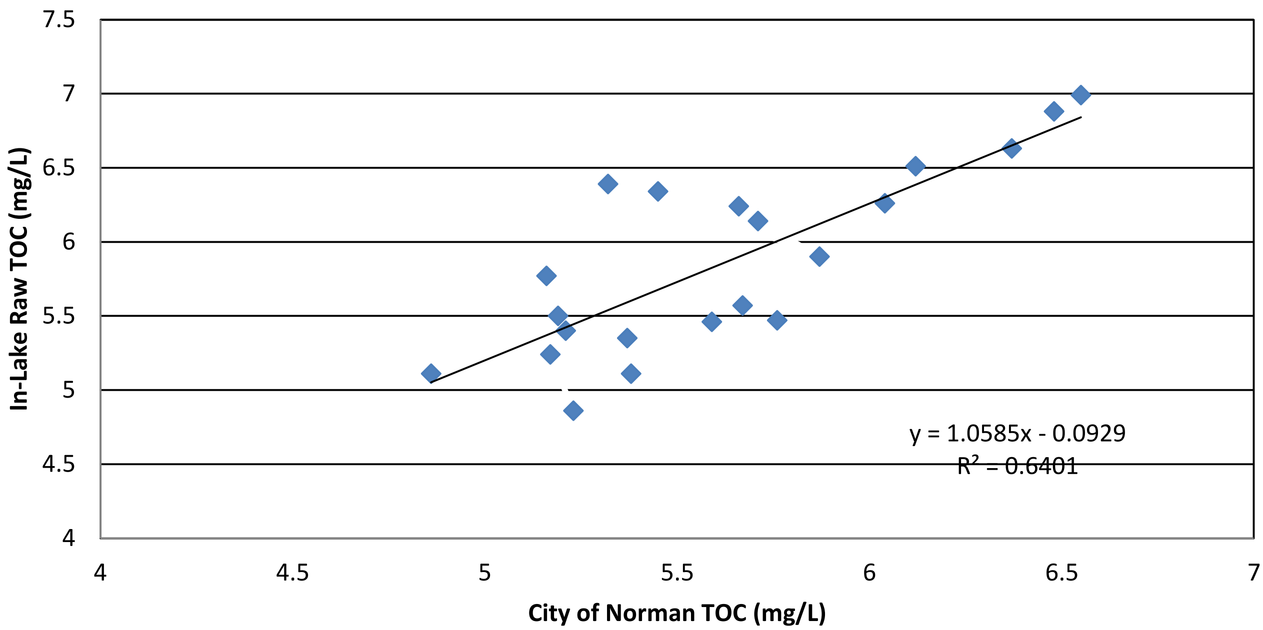

Figure 12: Lake Thunderbird TOC vs City of Norman Raw TOC from corresponding dates.

In the EPA's Stage 1 DBP rule, drinking water utilities must measure TOC to serve as an indicator of DBP formation potential. Drinking water utilities are also required to remove a percentage of this TOC based on both the amount of TOC in the raw water and the alkalinity to help prevent DBP formation. In short, the more TOC present and the lower the alkalinity, the greater the amount of TOC that must be removed (EPA 2003).

In **Figure 11** and **Figure 12,** a relationship was displayed in which increasing chl-*a* led to increasing TOC in waters received by the drinking water treatment plant. Since the EPA requires greater TOC removal when more TOC is present, and this is achieved by increased expenditure of treatment materials, a linear regression was performed to look at the relationship between TOC and drinking water treatment costs per unit volume at the City of Norman drinking water treatment plant. The result was a positive correlation where greater TOC equaled greater drinking water treatment costs and predicts a $8.46/mg change in treatment costs per mg/l TOC per 1,000,000 gallons (**Figure 13**).

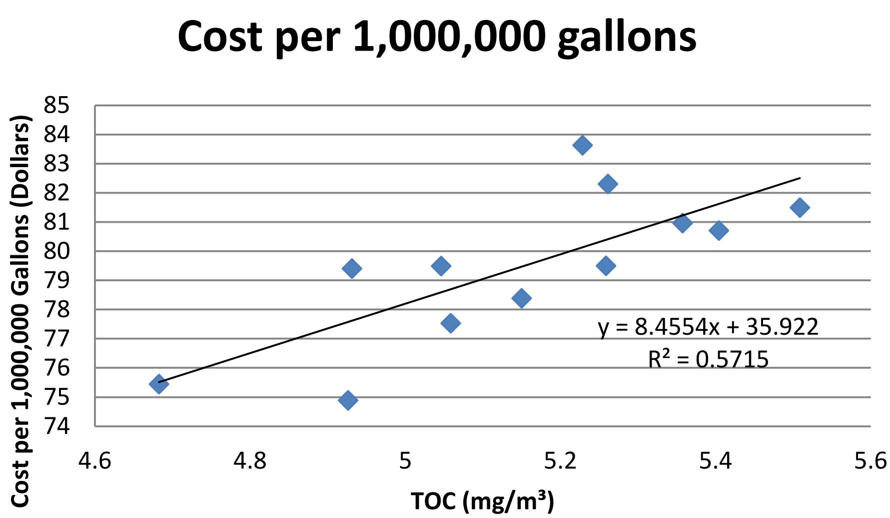

Figure 13: City of Norman treatment costs vs raw TOC. Dataset 2002-2009

Lastly because our data set shows that average monthly TOC varies seasonally, we have graphed the average monthly drinking water treatment costs of the City of Norman per unit volume with the corresponding raw water TOC by month. The figure shows that in general, average monthly TOC and drinking water treatment costs from 2002 through 2009 drop in early spring and then greatly rise through the summer through the end of the year (**Figure 14**).

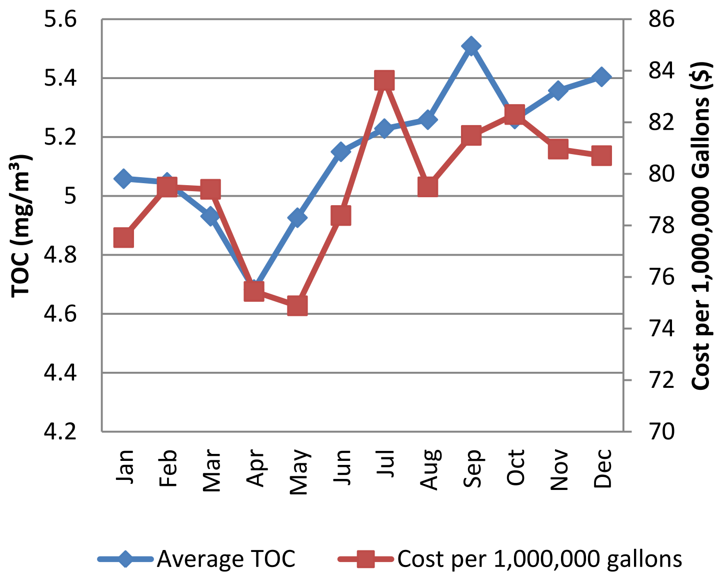

Figure 14: Average TOC and Cost per 1,000,000 gallons by month. Dataset 2002-2009

The culmination of the preceding drinking water treatment data, and the BATHTUB model led us to believe that reduction of phosphorous will reduce algae growth in the discussed lakes. With reduction of algae growth, organic carbon should be reduced along with drinking water treatment costs and DBPs in finished drinking water. All of the preceding analysis was taken from the City of Norman water treatment plant, which receives roughly 50% of the water from Lake Thunderbird, it is likely the other water recipients of Lake Thunderbird, Midwest City and Del City would have raw water quality trends and costs that should be similar to the City of Norman. Thus, potential savings documented could be expanded when accounting for all of the raw water recipients.

2.4 In-Lake BMP Options and Feasibility

2.4.1 Introduction

The primary purposes of the proposed in-lake BMPs are to treat anoxic conditions in the hypolimnion without disrupting natural stratification. The result should be a reduction of anaerobically mediated phosphorous sediment load thereby reducing the water column Total P, algae, and subsequently total organic carbon, and taste and odor compounds. A reduction of TOC is predicted to equate to a reduction of drinking water treatment costs for the respective municipalities and higher confidence of meeting DBP regulations.

2.4.2 Lake Thunderbird BMP Options and Feasibility

Three methods for managing the anoxic hypolimnion of Lake Thunderbird are discussed. They include artificial (whole lake) circulation, also known as fine-bubble diffusion, depth-selective flow routing, and Supersaturated Dissolved Oxygen Injection System (SDOX), which is a type of layer oxidation. Each action alternative has a different implementation requirement, cost, and likelihood of success.

Artificial Circulation (Fine Bubble Diffusion)
Artificial Circulation was evaluated for use in Lake Thunderbird in 2002 and 2005. This method disrupts thermal stratification within the lake; increasing dissolving oxygen (DO) in the deep areas of the lake while eliminating stagnant zones which may be subject to sediment accumulation and algal blooms. Artificial circulation is best accomplished in deeper lakes through fine bubble diffusion. This is done through installation of an on-shore air compressor that delivers atmospheric air through lines connected to perforated pipes that run through the bottom of the lake. The bubble plume created by the fine bubble diffuser is sufficient in creating convectional forces in the lake which are strong enough to mix the entire lake.

While this system could eliminate the DO problem at Lake Thunderbird, this option was rejected. Rejection was based on the fact that mixing the entire water column could cause secondary problems that may outweigh the benefits mitigation of sediment phosphorous release. These problems include decreased water clarity caused by the stirring of the lake bottom, and increase in algal biomass as phytoplankton sedimentation is decreased (Toetz 2003). This system would cost a minimum of $250,000 for the apparatus plus installation construction and yearly operational (electricity) and maintenance costs.

Depth Selective Flow Routing
This method would involve placing a barrier in front of the spillway intake to force siphoning of anoxic sediment pool waters from the hypolimnion. Curtains and pile sheets could be used to minimize movement of epilimnetic water to the intake. Net oxygenation occurs due to the fact that anoxic waters are removed instead of traditional epilimnetic overflows. Extensive and expensive modifications to the spillway would be required. This option was rejected at Lake Thunderbird primarily because historical hydraulic mass-balance data indicates that there is insufficient overflow to run a flow routing system out of the reservoir on an average meteorological year.

Preferred Alternative – Supersaturated Dissolved Oxygen Injection - SDOX
Implementation of SDOX is the preferred alternative. It is a layer aeration technique which would withdraw water from the hypolimnion, supersaturate it with oxygen to about 300% concentration, and inject the water back into the hypolimnion. The SDOX differs from typical hypolimnetic aeration techniques, in that pure oxygen is dissolved in withdrawn hypolimnetic waters before reinjection, preventing bubble formation. This means no oxygen is lost to the atmosphere or to the naturally oxygenated epilimnetic layer. This method also maintains natural stratification in the lake. In **Table 35**, estimation of reduction of internal phosphorous load is displayed.

During the life of this project a unique situation arose when the American Recovery and Reinvestment Act (ARRA) was passed. The operator of Lake Thunderbird, the COMCD, was able to implement the preferred in-lake BMP with funding through an ARRA loan. Designating it as a "Green Project" the EPA agreed to fund construction, start-up and monitoring of the system for 2 years. SDOX construction has been completed and is set to go online in the summer of 2011; a generalized schematic can be seen in **Figure 15**, with a map of system location in **Figure 16.**

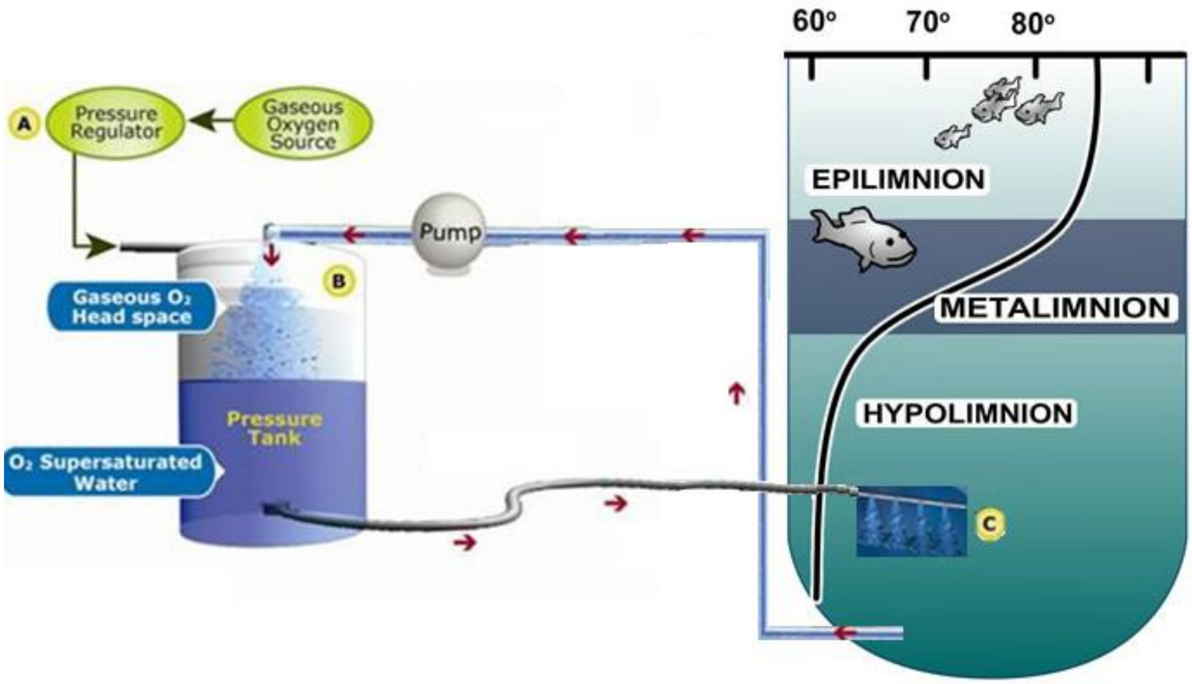

Figure 15: Conceptual Illustration of the SDOX System at Lake Thunderbird.

Table 35: Estimated reduction of anoxic sediment area and resulting internal phosphorous load.

Total Lake Contour Areas			
Depth	Area (m2)	Sediment P Load (kg/year)	
12	960261.4	262.3	
13	958204.7	261.7	
14	580264	158.5	
15	179277.8	48.9	
16	191041.2	52.2	
17	33047.03	9.1	
18	643.33	0.2	
Total	2902739	792.9	
Area Treated By SDOX			
Depth	Area (m2)	Sediment P Load Reduced (kg/year)	% of this layer
12	944967.2	258.1	98%
13	952903.1	260.3	99%
14	580264	158.5	100%
15	179277.8	48.9	100%
16	191041.2	52.2	100%
17	33047.03	9.1	100%
18	643.33	0.2	100%
Total	2882144	787.2	
Percent Reduction	99%	99%	

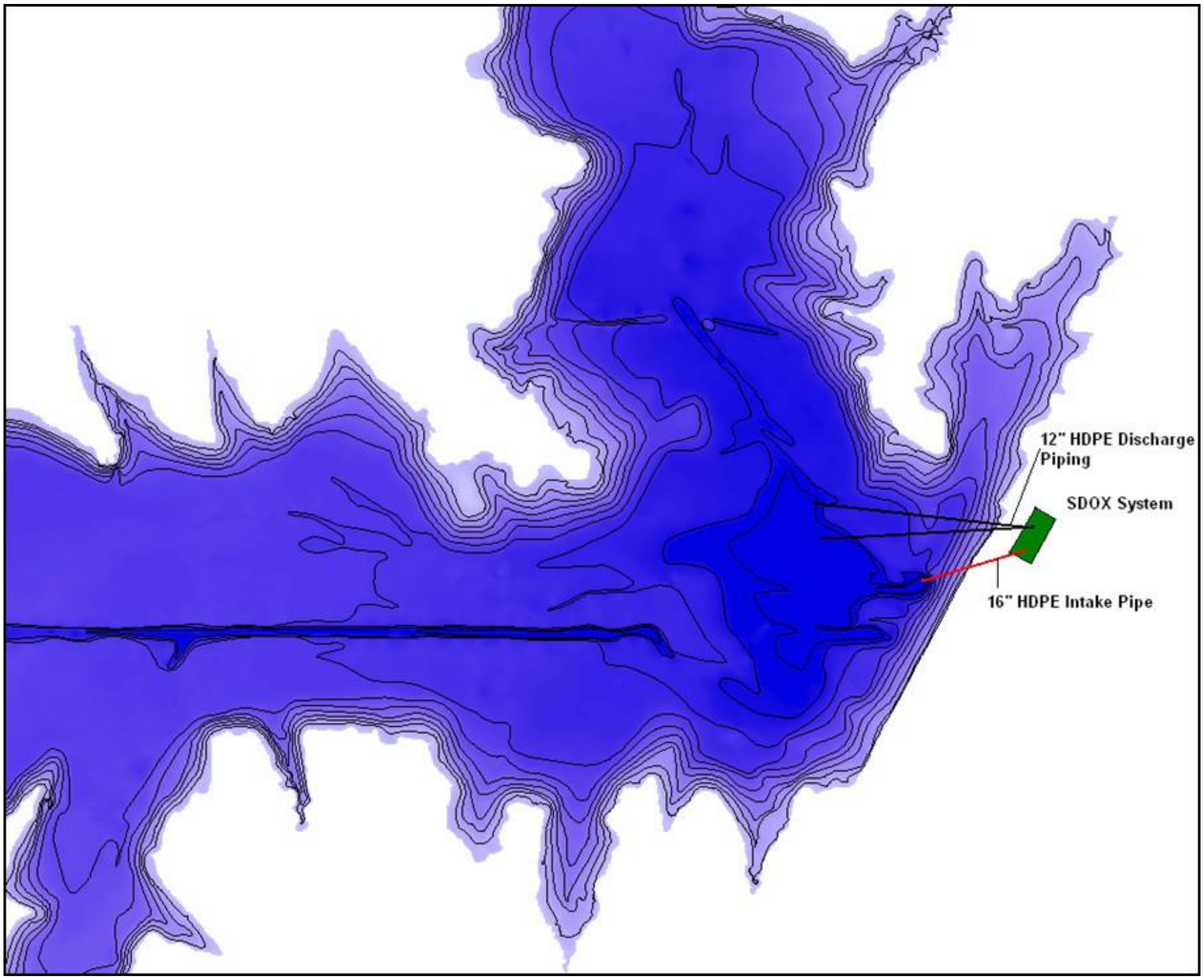

Figure 16: Map of SDOX BMP area

2.4.3 Lake New Spiro BMP Options and Feasibility

Three methods for managing the anoxic hypolimnion of Lake New Spiro are discussed. As discussed in section **2.5.2**, the three in-lake BMPs evaluated include artificial (whole lake) circulation, also known as fine-bubble diffusion, depth-selective flow routing, Supersaturated Dissolved Oxygen Injection System (SDOX), which is a type of layer oxidation, and also No Action which would not address the anoxia problem. Lake New Spiro is a distinctly different situation than Lake Thunderbird because it provides water for a much smaller municipality, where funds for implementation are not readily available.

Artificial Circulation (Fine Bubble Diffusion)

Artificial Circulation was evaluated for use in Lake New Spiro, this method disrupts thermal stratification within the lake; increasing dissolving oxygen (DO) in the deep areas of the lake while eliminating stagnant zones which may be subject to sediment accumulation and algal blooms. Artificial circulation is best accomplished in lakes through fine bubble diffusion.

This is done through installation of an on-shore air compressor that delivers atmospheric air through lines connected to perforated pipes that run through the bottom of the lake. The bubble plume created by the fine bubble diffuser is sufficient in creating convectional forces in the lake which are strong enough to mix the entire lake.

While this system could eliminate the DO problem at Lake New Spiro; this option was rejected on the fact that with mixing it could also increase turbidity as sediment from the bottom is mixed into the water column by the convectional forces that also destratify the lake. This can actually result in an increase in phosphorous in the water column, because while the system would shunt anaerobic mediated phosphorous release, the potential to mix nutrient loaded sediment into the water column could increase the nutrient load to the lake. This system would cost a minimum of $75,000 plus construction and yearly operational and maintenance costs; making the system expensive for a water body serving 2200 citizens.

SDOX

Implementation of SDOX was evaluated for Lake New Spiro. It is a layer aeration technique which would withdraw water from the hypolimnion, supersaturate it with oxygen to about 300% concentration, and inject the water back into the hypolimnion. The SDOX differs from typical hypolimnion (layer) aeration in that pure oxygen is injected rather than compressed air. Initial design, oversight and construction costs, startup and operation for a year are estimated to cost $300,000. Annual O&M costs thereafter (based on a 130-day summer pumping season) are estimated to be about $25,000. The technique of this system would preserve ecological integrity in-tact by preserving the cool hypolimnetic waters, but would eliminate the internal phosphorous flux mediated by the anaerobic conditions that currently exist within the reservoir in the summer months.

This In-Lake BMP has been rejected on the fact that the start-up and annual costs would likely overwhelm the small municipality but if funding sources become available, this BMP has the potential to provide the most relief from anaerobically mediated sediment phosphorous release.

Preferred Alternative- Depth Selective Flow Routing

Traditionally, epilimnetic water is lost from the reservoir during times when excessive inflow causes the lake level to exceed spillway height. At Lake New Spiro, the epilimnetic water is saturated with oxygen and has significantly lower nutrient levels than seen the hypolimnetic layer, where the water is nutrient rich and anoxic. Depth selective flow routing operates on the idea that a release of hypolimnetic waters saturated with nutrients from sediment phosphorus flux, instead of epilimnetic waters during overflow events, will reduce the internal load to the reservoir. Traditionally, flow routing requires significant alteration of the spillway structure at the lake to allow for the depth of water that exits the lake to be altered. At Lake New Spiro a unique situation exists where a draw-down pipe in the spillway could be opened during overflow events, which would reduce the hypolimnetic waters of the lake (**Figure 17**). The drawn-down pipe's intake elevation is 416' National Geodetic Vertical Datum (NGVD) and the lake's conservation pool elevation is 426.5' NGVD giving the pipe access to water at roughly 3.2 meters in depth. The 10 years BUMP data available shows that stratification exists from mid-May through mid-September, at 3 meters and above. All available data suggests that throughout the summer stratification period the emergency release pipe intake would remain within the hypolimnion for releasing. This BMP has been selected as the preferred option because it costs nothing for the municipality to implement, but provides a real means for hypolimnetic nutrient reduction.

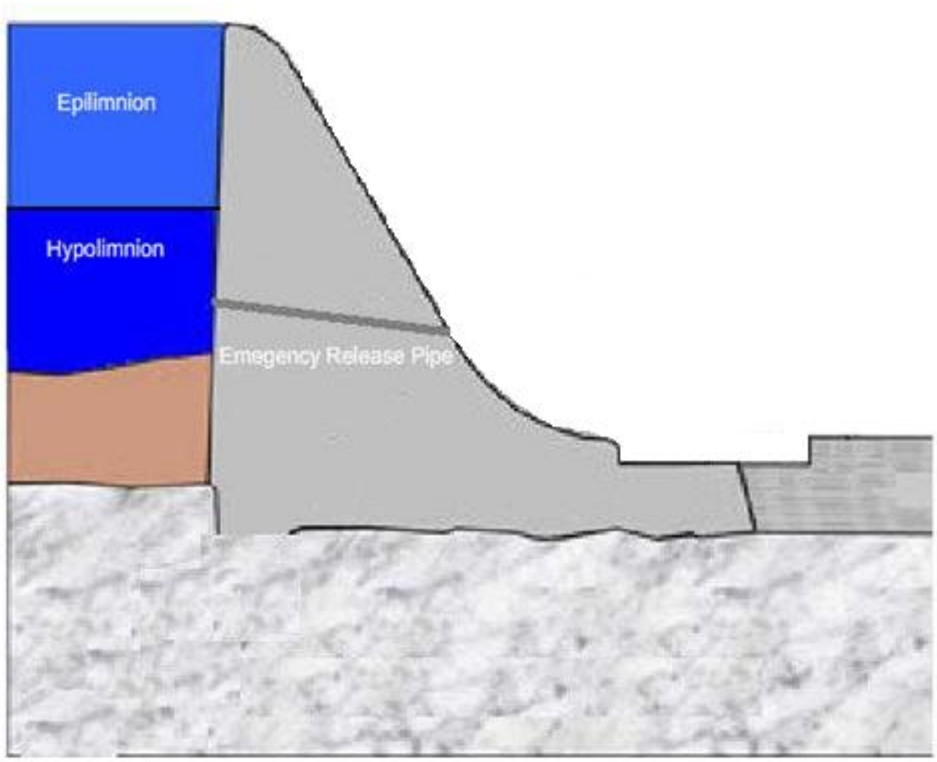

Figure 17: Conceptual schematic of the emergency release structure at Lake New Spiro.

To evaluate this in-lake BMP the number of days that overflow occurs within the stratification time window had to be estimated, as well as the flow rate of the pipe, and the difference in nutrient concentrations between the surface and hypolimnetic waters. Based on the water budget created for this project there is on average of 88 days during the stratification window in which overflow occurs and the pipe could be operated. To estimate the flow rate of the pipe the Darcy-Weisbach equation was rearranged to calculate for flow rate Q. Some assumptions were made to make pipe flow calculations possible for this projects framework. One necessary assumption was that the height of water in the lake stayed constant during the time draw down pipe was open. The height selected for this assumption was the lake spillway elevation height 426.5’ NGVD**.** This assumption is valid because the proposed BMP would only be operated during times of overflow, to protect against loss of potential drinking water and to allow for the anoxic flow routing waters to mix with oxygenated epilimnetic spillway waters. The flow of the pipe was found to be 29,030 cubic meters per day of operation (**Table 36**).

The Darcy-Weisbach equation that was used to calculate flow is given below:

where:

Δ p - pressure drop due to friction in the pipe
– density at intake
f - friction coefficient
L - pipe length
v - velocity
D - internal pipe diameter
Q - volumetric flow rate

Table 36: Input values for pipeflow calculations

Parameter	Value	Units	Description
L	53.6448	meters	Length of discharge pipe
D	0.3048	meters	Discharge Pipe Diameter
f	0.012	cm	Estimated Roughness coefficient for concrete pipe
	998.2	kg/m^3	Density of water at pipe intake depth
v	1E-06	m^2/sec	Calculated velocity of water
p1	19.1449	psi	Pressure at discharge pipe intake
p2	14.4799	psi	Pressure at discharge pipe outlet

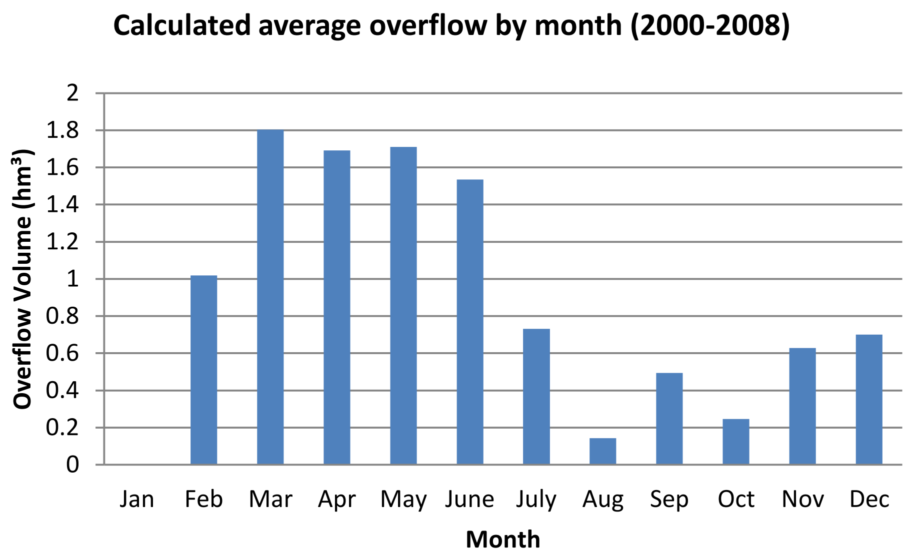

Figure 18: Calculated average monthly overflow volumes for years 2000-2008.

When this estimated pipe flow is combined with the average hypolimnetic Total P values of 0.19 mg/L you get a release of 5.4 kg of Total P per day. When one combines this same volume of water with the epilimnetic Total P value of .11 mg/L you get a release of 3.2 kg a day by traditional overflow; meaning every day the pipe is operated, on average 2.2 kg of Total P will be shunted from the system that would normally be kept in the system. When you combine these values with the estimated summer operating timeframe of 88 days, 195 kg of Total P can be removed from the system (**Figure 18** and **Table 37**). This translates to a 28% reduction of anaerobic mediated sediment phosphorous load. On any given year true reduction of sediment phosphorous load could be more or less given the hydraulic conditions witnessed. Within our data time frame of 2000 to 2008, there was great variation in the number of days that the system could be operated. The driest year on record 2006 the system could only have been run for a maximum of 26 days, representing a reduction of internal P load of 60 kg or 8% of the total sediment P load (**Figure 19**). The wettest year on record had an estimated 125 days of operation during the stratification window; this represents a reduction of 275 kg of Total P or 39% of the Total Sediment P load.

Table 37: Average, minimum and maximum estimated reduction of internal P load during evaluation period.

	Average from 2000-2008	2006	2007	
Maximum number of days pipe could be operated	88.6	28.3	125	days
Average epilimnetic total P	0.1	0.1	0.1	mg/L
Average hypolimnetic total P	0.2	0.2	0.2	mg/L
Total P lost by pipe flow per day	5.4	5.4	5.4	kg
Total P lost by pipe flow per year	478	152	675	kg
Total P lost by overflow per day	3.2	3.2	3.2	kg
Total P lost by overflow per year	283.5	91.8	400	kg
Calculated Total P reduction	195	60.9	275	kg
BATHTUB predicted Sediment P Load	706.8	706.8	706.8	kg
Sediment P Load reduction	27.6%	8.6%	38.9%	%

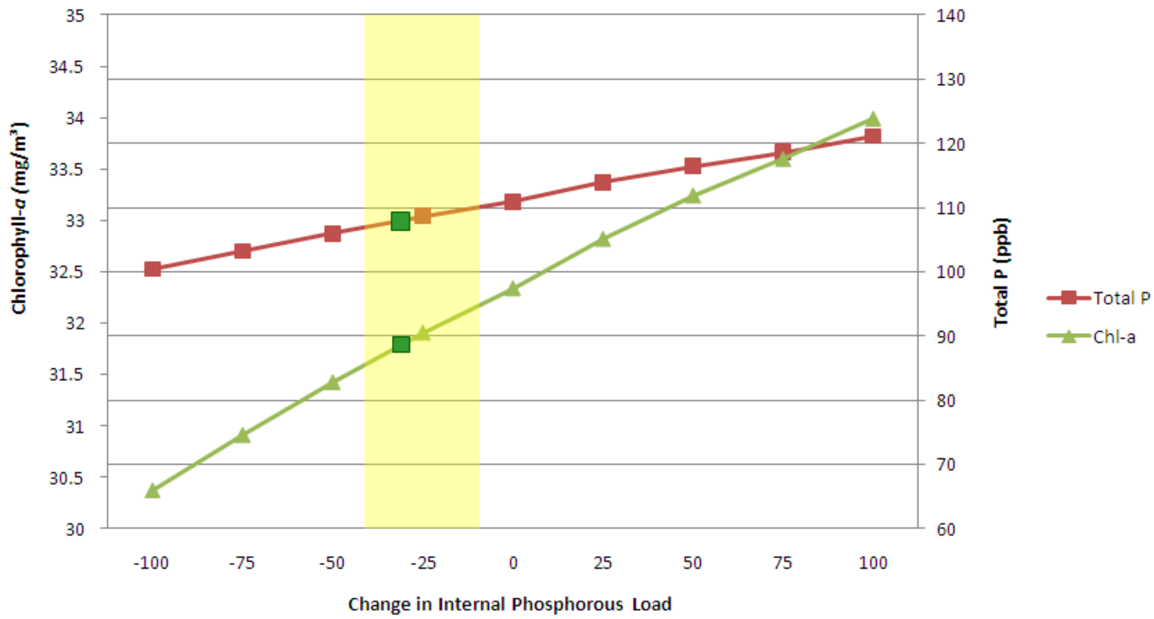

Figure 19: Change in Internal Phosphorous Load with minimum and maximum reductions highlighted in yellow and average reductions marked with dark green markers.

Since the proposed BMP at Lake New Spiro discharges nutrient rich anoxic waters, it is necessary to examine potential negative impacts that flow-routing could have downstream. The modified release would discharge in an ephemeral streambed that connects to the Pouteau River 0.95 miles downstream (**Figure 20**). A historical compilation of phosphorous data for the Pouteau River gives an average concentration of 0.16 mg/L, the average hypolimnetic total phosphorous value for Lake New Spiro is 0.2 mg/L. The hypolimnetic withdrawal is only proposed to operate during periods of spillway overflow; this means that the anoxic nutrient rich water will always be mixed with the oxygenated, less nutrient rich epilimnetic waters. This combined with the 0.95 miles that the discharge water will travel should provide ample time for the discharge waters to reoxygenate and attenuate any of the additional phosphorous that it may contain. It is also worthwhile to note that the streambed that Lake New Spiro would discharge to is seasonally dry therefore, no negative impacts to aquatic wildlife will occur.

While no negative impacts are expected downstream from Lake New Spiro should lake managers decide to implement the proposed BMP, it is recommended that follow up testing be done to both quantify the success of the BMP and insure negative impacts downstream are avoided.

Figure 20: Lake New Spiro Spillway with ephemeral streambed highlighted in blue.

3. Conclusion

Lake Thunderbird and Lake New Spiro are both sensitive water supply lakes that are impaired for chl-*a* and dissolved oxygen. The result of the models detailed in this report indicates that the annual sediment phosphorous flux via anaerobic mediated release is a significant portion of both reservoirs total annual phosphorous load. This indicates that the dissolved oxygen impairment is exacerbating the chl-a impairment. The increased phosphorous load fuels increased algal biomass, organically enriching the waters of each reservoir witnessed as increased total organic carbon (TOC). The result is a situation where drinking water treatment plants have to increase chemical usage to meet EPA guidelines on reductions of TOC, increasing their treatment costs. In some cases, organic enrichment exceeds the treatment plants ability to reduce total organic carbon levels, and EPA maximum allowable disinfectant by-products rule is exceeded by the municipality. Targeting in-lake BMPs that mitigate the low dissolved oxygen are predicted to not only reduce chl-*a* but raw water treatment costs as well.

At Lake Thunderbird, the models indicate that approximately 16% of the annual total phosphorous load to the lake originates from the sediment via anaerobic mediated release. While the reservoir's organic enrichment is primarily caused from the excessive nutrient load from its watershed, reducing the in-lake phosphorous release provides a method of immediately reducing a portion of the phosphorous load to the lake, while nonpoint source work within the watershed brings the watershed situation under control. Regression analysis with the Lake Thunderbird water quality data and the City of Norman drinking water treatment data, indicates that organic enrichment through increase algal biomass is increasing TOC within the reservoir. This increase in TOC is linked to an increase in drinking water treatment cost of $8.46/mg per mg/L TOC per 1,000,000 gallons. Implementing the supersaturated dissolved oxygen system recommended for Lake Thunderbird is predicted to reduce algal biomass by 10%, this correlates to a reduction in total organic carbon and drinking water treatment costs for recipient municipalities.

At Lake New Spiro, a similar situation exists where nearly 16% of the total phosphorous load to the lake comes from the sediment via anaerobic mediated release. While the majority of the nutrients come from the watershed, reducing phosphorous through in-lake best management practices should provide relief to the intense algal growth witnessed in the reservoir throughout the growing season. Implementing a depth selected water withdrawal with the emergency draw-down pipe already installed in the dam is calculated to reduce the sediment phosphorous load by 8 to 39% depending on the weather that particular year. This will result in reductions in the water column phosphorous and algal biomass. If drinking water treatment trends from Lake Thunderbird hold true for Lake New Spiro, this should reduce the TOC received in the raw drinking water with the potential of reducing the DBPs witnessed in finished drinking water and drinking water treatment costs.

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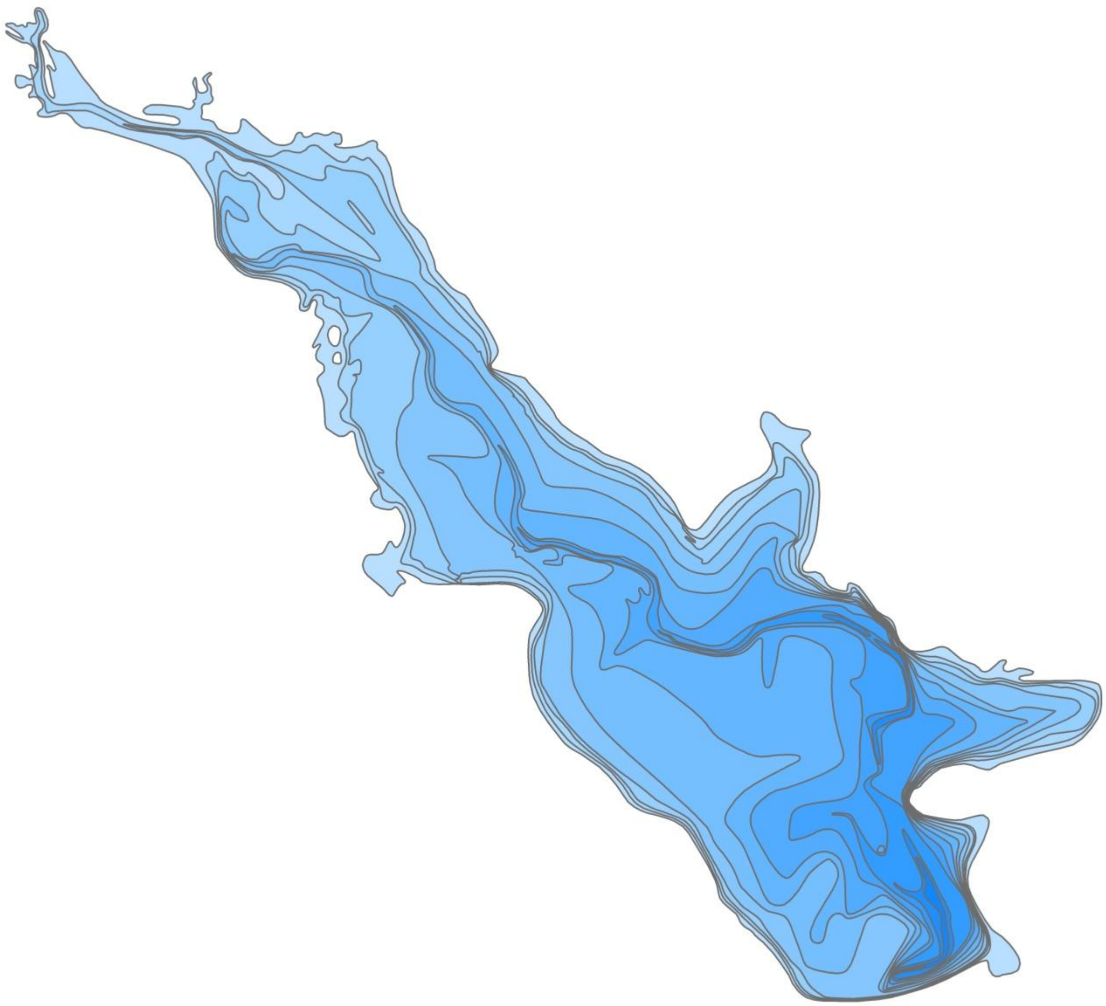
Appendix A:
HYDROGRAPHIC SURVEY of
NEW SPIRO LAKE



Final Report

October 8, 2010

Prepared by:

State of Oklahoma
OWRB
WATER RESOURCES BOARD
the water agency

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NEW SPIRO LAKE
HYDROGRAPHIC SURVEY REPORT

INTRODUCTION

The Oklahoma Water Resources Board (OWRB) conducted a hydrographic survey of New Spiro Lake in February of 2010. The purpose of this survey was to produce a new elevation-area-capacity table for New Spiro Lake that would aid in limnological studies

LAKE BACKGROUND

New Spiro Lake is located on Holi-Tuska Creek in Le Flore County (**Figure 1**). It was built in 1963. Its original purposes were water supply, flood control, and recreation. The dam is located in Sec. 01-T08N-R25E.

Figure 1: Location map for New Spiro Lake.

HYDROGRAPHIC SURVEYING PROCEDURES

The process of surveying a reservoir uses a combination of Geographic Positioning System (GPS) and acoustic depth sounding technologies that are incorporated into a hydrographic survey vessel. As the survey vessel travels across the lake's surface, the echosounder gathers multiple depth readings every second. The depth readings are stored on the survey vessel's on-board computer along with the positional data generated from the vessel's GPS receiver. The collected data files are downloaded daily from the computer and brought to the office for editing. During editing, data "noise" is removed or corrected, and average depths are converted to elevation readings based on the daily-recorded lake level elevation on the day the survey was performed. Accurate estimates of area-capacity can then be determined for the lake by building a 3-D model of the reservoir from the corrected data. The process of completing a hydrographic survey includes four steps: pre-survey planning, field survey, data processing, and GIS application.

Pre-survey Planning

Boundary File

The boundary file for New Spiro Lake was on-screen digitized from the 2006 color digital orthoimagery quarter quadrangle (DOQQ) mosaic of Le Flore County, Oklahoma. The screen scale was set to 1:1,500. A line was to represent the shoreline as closely as possible. Due to the photography being a summer photo, it was difficult to determine the actual shoreline when there are trees and other vegetation hanging over the lake. The 2008 and 2003 DOQQs of the lakes were used as back ground reference. The reservoir boundaries were digitized in NAD 1983 State Plane Coordinates (Oklahoma South-3501).

Set-up

HYPACK software from Hypack, Inc. was used to assign geodetic parameters, import background files, and create virtual track lines (transects). The geodetic parameters assigned were State Plane NAD 83 Zone OK-3501 Oklahoma South with distance units and depth as US Survey Feet. The survey transects were spaced according to the accuracy required for the project. The survey transects within the digitized reservoir boundary were at 300 ft increments and ran perpendicular to the original stream channels and tributaries. Approximately 26 virtual transects were created for New Spiro Lake.

Field Survey

Lake Elevation Acquisition

The lake elevation for Lake Ponca was obtained by collecting positional data over a period of 2 hours and 40 minutes with a survey-grade Global Positioning System (GPS) receiver. The receiver was placed over the water's surface. A measurement was taken from the antenna to the surface of the water. The collected data and antenna height was then uploaded to the On-line Positioning Users Service (OPUS) website. The National Geodetic Survey (NGS) operates OPUS as a means to provide GPS users easier access to the National Spatial Reference System (NSRS). OPUS allows users to submit their GPS data files to NGS, where the data is processed to determine a position using NGS computers and software. Calculated coordinates are averaged from three independent single-baseline solutions computed by double-differenced, carrier-phase measurements between the collected data file and 3 surrounding Continuously Operating Reference Stations (CORS). Under ideal conditions, OPUS can easily resolve most positions to within centimeter accuracy. A report containing the newly calculated positional data was electronically returned via email. This report contained the elevation of the surface of the water corrected for the antenna height.

Method

The procedures followed by the OWRB during the hydrographic survey adhere to U.S. Army Corps of Engineers (USACE) standards (USACE, 2002). The quality control and quality assurance procedures for equipment calibration and operation, field survey, data processing, and accuracy standards are presented in the following sections.

Technology

The Hydro-survey vessel is an 18-ft aluminum Silverstreak hull with cabin, powered by a single 115-Horsepower Mercury outboard motor. Equipment used to conduct the survey included: a ruggedized notebook computer; Syqwest Bathy 1500 Echo Sounder, with a depth resolution of 0.1 ft; Trimble Navigation, Inc. Pro XR GPS receiver with differential global positioning system (DGPS) correction; and an Odom Hydrographics, Inc, DIGIBAR-Pro Profiling Sound Velocimeter. The software used was HYPACK.

Survey

A three-man survey crew was used during the project. Data collection for New Spiro Lake occurred in February of 2010. The water level elevation for New Spiro Lake was 426.5 ft NGVD. Data collection began at the dam and moved upstream. The survey crew followed the parallel transects created during the pre-survey planning while collecting depth soundings and positional data. Data was also collected along a path parallel to the shoreline at a distance that was determined by the depth of the water and the draft of the boat – generally, two to three feet deep. Areas with depths less than this were avoided.

Quality Control/Quality Assurance

While on board the Hydro-survey vessel, the Syqwest Bathy 1500 Echo Sounder was calibrated using A DIGIBAR-Pro Profiling Sound Velocimeter, by Odom Hydrographics. The sound velocimeter measures the speed of sound at incremental depths throughout the water column. The factors that influence the speed of sound—depth, temperature, and salinity—are all taken into account. Deploying the unit involved lowering the probe, which measures the speed of sound, into the water to the calibration depth mark to allow for acclimation and calibration of the depth sensor. The unit was then gradually lowered at a controlled speed to a depth just above the lake bottom, and then was raised to the surface. The unit collected sound velocity measurements in feet/seconds (ft/sec) at 1 ft increments on both the deployment and retrieval phases. The data was then reviewed for any erroneous readings, which were then edited out of the sample. The sound velocity corrections were then applied to the to the raw depth readings. The average speed of sound in the water column was 4660 ft/sec during the New Spiro Lake survey.

A quality assurance cross-line check was performed on intersecting transect lines and channel track lines to assess the estimated accuracy of the survey measurements. The overall accuracy of an observed bottom elevation or depth reading is dependent on random and systematic errors that are present in the measurement process. Depth measurements contain both random errors and systematic bias. Biases are often referred to as systematic errors and are often due to observational errors. Examples of bias include a bar check calibration error, tidal errors, or incorrect squat corrections. Bias, however, does not affect the repeatability, or precision, of results. The precision of depth readings is affected by random errors. These are errors present in the measurement system that cannot be easily reduced by further calibration. Examples of random error include uneven bottom topography, bottom vegetation, positioning error, extreme listing of survey vessel, and speed of sound variation in the water column. An assessment of the accuracy of an individual depth or bottom elevation must fully consider all the error components contained in the observations that were used to determine that measurement. Therefore, the ultimate accuracy must be estimated (thus the use of the term "estimated accuracy") using statistical estimating measures (USACE, 2002).

The depth accuracy estimate is determined by comparing depth readings taken at the intersection of two lines and computing the difference. This is done on multiple intersections. The mean difference of all intersection points is used to calculate the mean difference (MD). The mean difference represents the bias present in the survey. The standard deviation (SD), representing the random error in the survey, is also calculated. The mean difference and the standard deviation are then used to calculate the Root Mean Square (RMS) error. The RMS error estimate is used to compare relative accuracies of estimates that differ substantially in bias and precision (USACE, 2002). According the USACE standards, the RMS at the 95% confidence level should not exceed a tolerance of ± 2.0 ft for this type of survey. This simply means that on average, 19 of every 20 observed depths will fall within the specified accuracy tolerance.

HYPACK Cross Statistics program was used to assess vertical accuracy and confidence measures of acoustically recorded depths. The program computes the sounding difference between intersecting lines of single beam data. The program provides a report that shows the standard deviation and mean difference. A total of 36 cross-sections points at New Spiro Lake were used to compute error estimates. A mean difference of 0.025 ft and a standard deviation of 0.106 ft were computed from intersections. The following formulas were used to determine the depth accuracy at the 95% confidence level.

$$RMS = \sqrt{\sigma^2{}_{Randomerror} + \sigma^2{}_{Bias}}$$

where:

Random error = Standard deviation
Bias = Mean difference
RMS = root mean square error (68% confidence level)

and:

$$RMS\ (95\%)\ depth\ accuracy = 1.96 \times RMS(68\%)$$

An RMS of ± 0.21 ft with a 95% confidence level is less than the USACE's minimum performance standard of ± 2.0 ft for this type of survey. A mean difference, or bias, of 0.025 ft is well below the USACE's standard maximum allowable bias of ± 0.5 ft for this type of survey.

The GPS system is an advanced high performance geographic data-acquisition tool that uses DGPS to provide sub-meter positional accuracy on a second-by-second basis. Potential errors are reduced with differential GPS because additional data from a reference GPS receiver at a known position are used to correct positions obtained during the survey. Before the survey, Trimble's Pathfinder Controller software was used to configure the GPS receiver. To maximize the accuracy of the horizontal positioning, the horizontal mask setting was set to 15 degrees and the Position Dilution of Precision (PDOP) limit was set to 6. The position interval was set to 1 second and the Signal to Noise Ratio (SNR) mask was set to 4. The United States Coast Guard reference station used in the survey is located near Sallisaw, Oklahoma.

A latency test was performed to determine the fixed delay time between the GPS and single beam echo sounder. The timing delay was determined by running reciprocal survey lines over a channel bank. The raw data files were downloaded into HYPACK - LATENCY TEST program. The program varies the time delay to determine the "best fit" setting. A position latency of 0.4 seconds was produced and adjustments were applied to the raw data in the EDIT program.

Data Processing

The collected data was transferred from the field computer onto an OWRB desktop computer. After downloading the data, each raw data file was reviewed using the EDIT program within HYPACK. The EDIT program allowed the user to assign transducer offsets, latency corrections, tide corrections, display the raw data profile, and review/edit all raw depth information. Raw data files are checked for gross inaccuracies that occur during data collection.

Offset correction values of 3.2 ft. starboard, 6.6 ft. forward, and -1.1 ft. vertical were applied to all raw data along with a latency correction factor of 0.4 seconds. The speed of sound corrections were applied during editing of raw data.

A correction file was produced using the HYPACK TIDES program to account for the variance in lake elevation at the time of data collection. Within the EDIT program, the corrected depths were subtracted from the elevation reading to convert the depth in feet to an elevation. The average elevation of the lake during the survey was 426.5 ft (NGVD).

After editing the data for errors and correcting the spatial attributes (offsets and tide corrections), a data reduction scheme was needed due to the large quantity of collected data. To accomplish this, the corrected data was resampled spatially at a 5 ft interval using the Sounding Selection program in HYPACK. The resultant data was saved and exported out as a xyz.txt file. The HYPACK raw and corrected data files for New Spiro Lake are located on the DVD entitled *New Spiro HYPACK/GIS Metadata.*

GIS Application

Geographic Information System (GIS) software was used to process the edited XYZ data collected from the survey. The GIS software used was ArcGIS Desktop and ArcMap, version

9.3.1, from Environmental System Research Institute (ESRI). All of the GIS datasets created are in Oklahoma State Plane South Coordinate System referenced to the North American Datum 1983. Horizontal and vertical units are in feet. The edited data points in XYZ text file format were converted into ArcMap point coverage format. The point coverage contains the X and Y horizontal coordinates and the elevation and depth values associated with each collected point.

Volumetric and area calculations were derived using a Triangulated Irregular Network (TIN) surface model. The TIN model was created in ArcMap, using the collected survey data points and the lake boundary inputs. The TIN consists of connected data points that form a network of triangles representing the bottom surface of the lake. The lake volume was calculated by slicing the TIN horizontally into planes 0.1 ft thick. The cumulative volume and area of each slice are shown in **Appendix A.**

Contours, depth ranges, and the shaded relief map were derived from a constructed digital elevation model grid. This grid was created using the ArcMap Topo to Raster Tool and had a spatial resolution of five feet. A low pass 3x3 filter was run to lightly smooth the grid to improve contour generation. The contours were created at a 2-ft interval using the ArcMap Contour Tool. The contour lines were edited to allow for polygon topology and to improve accuracy and general smoothness of the lines. The contours were then converted to a polygon coverage and attributed to show 2-ft depth ranges across the lake. The bathymetric maps of the lakes are shown with 2-ft contour intervals in **Appendix B**.

All geographic datasets derived from the survey contain Federal Geographic Data Committee (FGDC) compliant metadata documentation. The metadata describes the procedures and commands used to create the datasets. The GIS metadata file for both lakes is located at on the DVD entitled *New Spiro HYPACK/GIS Metadata.*

RESULTS

Results from the 2010 OWRB survey indicate that New Spiro Lake encompasses 249 acres and contains a cumulative capacity of 2,023 ac-ft at the normal pool elevation (426.5 ft National Geodetic Vertical Datum (NGVD). The average depth for New Spiro Lake was 8.1 ft.

SUMMARY and COMPARISON

Table 1 is comparison of area and volume changes of New Spiro Lake at the normal pool elevation. Based on the design specifications, New Spiro Lake had an area of 329 acres and cumulative volume of 2,200 acre-feet of water at normal pool elevation (426.5 ft NGVD). The surface area of the lake has had a decrease of 80 acres or approximately 24%. The 2010 survey shows that New Spiro Lake has an apparent decrease in capacity of 8.0% or approximately 177 acre-feet. Caution should be used when directly comparing between the design specifications and the 2010 survey conducted by the OWRB because different methods were used to collect the data and extrapolate capacity and area figures. It is the recommendation of the OWRB that another survey using the same method used in the 2010 survey be conducted in 10-15 years. By using the 2010 survey figures as a baseline, a future survey would allow an accurate sedimentation rate to be obtained.

Table 1: Area and Volume Comparisons of New Spiro Lake at normal pool (426.5 ft NGVD).

Feature	*Survey Year*	
	1963 Design Specifications	2010
Area (acres)	329	249
Cumulative Volume (acre-feet)	2,200	2,023
Mean depth (ft)	6.7	8.1
Maximum Depth (ft)	--	22.73

REFERENCES

U.S. Army Corps of Engineers (USACE). 2002. Engineering and Design - Hydrographic Surveying, Publication EM 1110-2-1003, 3rd version.

Oklahoma Water Resources Board (OWRB). 1970. Oklahoma Water Atlas.

Oklahoma Water Resources Board (OWRB). 2000. OWRB Dam Record Inspection Report. New Spiro Dam.

Hudgins, Thompson, Ball and Associates, Inc. 1963. Construction Plans for Holi-Tuska Creek Dam and Reservoir.

APPENDIX A: Area-Capacity Data

Table A. 1: New Spiro Lake Capacity/Area by 0.1-ft Increments.

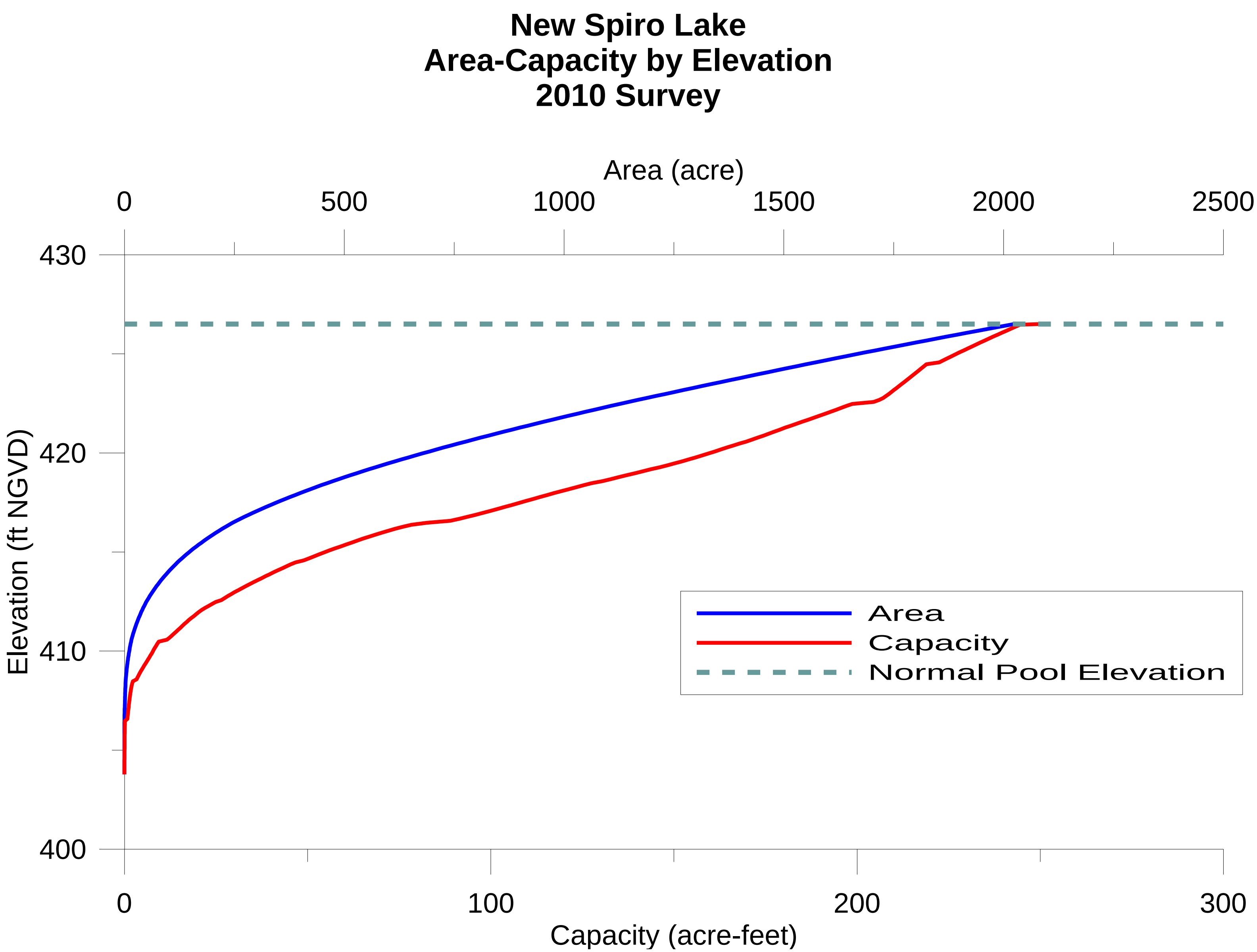
NEW SPIRO LAKE AREA-CAPACITY TABLE
OKLAHOMA WATER RESOURCES BOARD
2010 Survey
Capacity in acre-feet by tenth foot elevation increments
Area in acres by tenth foot elevation increments

Elevation (ft NGVD)		0.07	0.17	0.27	0.37	0.47	0.57	0.67	0.77	0.87	0.97
403	Area								0	0.0001	0.0003
	Capacity								0	0	0
404	Area	0.0006	0.0011	0.0016	0.0024	0.0035	0.0374	0.0405	0.0437	0.0469	0.0502
	Capacity	0.0001	0.0002	0.0003	0.0005	0.0008	0.0034	0.0073	0.0115	0.0161	0.0209
405	Area	0.0536	0.0572	0.061	0.0649	0.069	0.0735	0.0787	0.0845	0.0908	0.0976
	Capacity	0.0261	0.0316	0.0376	0.0438	0.0505	0.0577	0.0653	0.0734	0.0822	0.0916
406	Area	0.1056	0.1153	0.1266	0.1394	0.1538	0.8215	0.876	0.9313	0.9875	1.0446
	Capacity	0.1017	0.1128	0.1249	0.1381	0.1528	0.2137	0.2986	0.3889	0.4849	0.5865
407	Area	1.1029	1.1623	1.2228	1.2839	1.3465	1.4112	1.481	1.5597	1.6404	1.7235
	Capacity	0.6939	0.8071	0.9264	1.0517	1.1832	1.3211	1.4657	1.6177	1.7777	1.9459
408	Area	1.8122	1.9083	2.0174	2.1501	2.3227	3.3341	3.5967	3.8744	4.1671	4.4711
	Capacity	2.1227	2.3086	2.5047	2.713	2.936	3.2339	3.5804	3.9538	4.3558	4.7877
409	Area	4.7841	5.1166	5.4546	5.7862	6.121	6.4581	6.7886	7.1156	7.4347	7.7453
	Capacity	5.2505	5.7455	6.274	6.8362	7.4316	8.0607	8.7233	9.4183	10.146	10.905
410	Area	8.0551	8.3666	8.6802	9.0225	9.4017	11.627	12.316	12.93	13.521	14.105
	Capacity	11.695	12.517	13.369	14.254	15.175	16.249	17.448	18.71	20.033	21.414
411	Area	14.694	15.264	15.834	16.423	17.032	17.647	18.314	19.007	19.691	20.36
	Capacity	22.855	24.353	25.908	27.521	29.193	30.928	32.725	34.591	36.527	38.529
412	Area	21.107	21.988	22.919	23.89	24.957	26.486	27.358	28.241	29.166	30.118
	Capacity	40.602	42.757	45.001	47.342	49.783	52.371	55.064	57.843	60.713	63.678
413	Area	31.108	32.127	33.151	34.169	35.234	36.348	37.444	38.509	39.594	40.722
	Capacity	66.74	69.902	73.165	76.532	80.002	83.582	87.272	91.069	94.975	98.991
414	Area	41.895	43.063	44.22	45.396	46.693	48.956	50.316	51.684	53.065	54.452
	Capacity	103.12	107.37	111.74	116.22	120.82	125.62	130.59	135.68	140.92	146.3
415	Area	55.896	57.401	58.956	60.503	62.034	63.593	65.14	66.81	68.532	70.289
	Capacity	151.82	157.48	163.3	169.27	175.4	181.68	188.12	194.72	201.49	208.43
416	Area	72.1	74.007	76.017	78.337	82.59	88.948	91.463	93.675	95.813	97.9
	Capacity	215.55	222.85	230.35	238.07	246.09	254.73	263.76	273.01	282.49	292.18
417	Area	99.928	101.91	103.87	105.81	107.71	109.63	111.55	113.48	115.37	117.28
	Capacity	302.07	312.17	322.45	332.94	343.62	354.49	365.55	376.8	388.25	399.88
418	Area	119.35	121.4	123.48	125.51	127.54	130.49	132.68	134.87	137.09	139.3
	Capacity	411.71	423.76	436	448.45	461.1	474.02	487.18	500.56	514.16	527.98
419	Area	141.52	143.72	146.06	148.25	150.27	152.22	154.1	155.94	157.75	159.5
	Capacity	542.03	556.29	570.78	585.5	600.43	615.56	630.88	646.38	662.07	677.94
420	Area	161.18	162.85	164.54	166.24	167.96	169.77	171.36	172.96	174.49	175.97
	Capacity	693.97	710.18	726.54	743.09	759.8	776.69	793.75	810.97	828.35	845.87
421	Area	177.46	178.91	180.37	181.91	183.49	185.05	186.65	188.21	189.75	191.26
	Capacity	863.55	881.37	899.33	917.45	935.72	954.15	972.74	991.48	1010.4	1029.4
422	Area	192.75	194.24	195.7	197.18	198.72	204.51	206.06	207.15	207.96	208.67
	Capacity	1048.6	1068	1087.5	1107.1	1126.9	1147.2	1167.7	1188.4	1209.1	1230
423	Area	209.37	210.07	210.77	211.47	212.17	212.86	213.54	214.23	214.91	215.59
	Capacity	1250.9	1271.9	1292.9	1314	1335.2	1356.5	1377.8	1399.2	1420.6	1442.2

Table A. 2: New Spiro Lake Capacity/Area by 0.1-ft Increments (cont).

NEW SPIRO LAKE AREA-CAPACITY TABLE OKLAHOMA WATER RESOURCES BOARD 2010 Survey Capacity in acre-feet by tenth foot elevation increments Area in acres by tenth foot elevation increments											
Elevation (ft NGVD)		0.07	0.17	0.27	0.37	0.47	0.57	0.67	0.77	0.87	0.97
424	Area	216.27	216.94	217.61	218.28	218.94	222.45	223.54	224.64	225.74	226.85
	Capacity	1463.7	1485.4	1507.1	1528.9	1550.8	1572.9	1595.2	1617.6	1640.2	1662.8
425	Area	227.98	229.10	230.24	231.39	232.54	233.70	234.87	236.05	237.24	238.43
	Capacity	1685.5	1708.4	1731.4	1754.4	1777.6	1801.0	1824.4	1847.9	1871.6	1895.4
426	Area	239.64	240.85	242.06	243.29	244.53	*249.9	* Actually 426.5			
	Capacity	1919.3	1943.3	1967.5	1991.8	2016.1	*2023				

Figure A. 1. Area-Capacity Curve for New Spiro Lake



APPENDIX B: New Spiro Lake Maps

Figure B. 1: New Spiro Lake Bathymetric Map with 2-foot Contour Intervals.

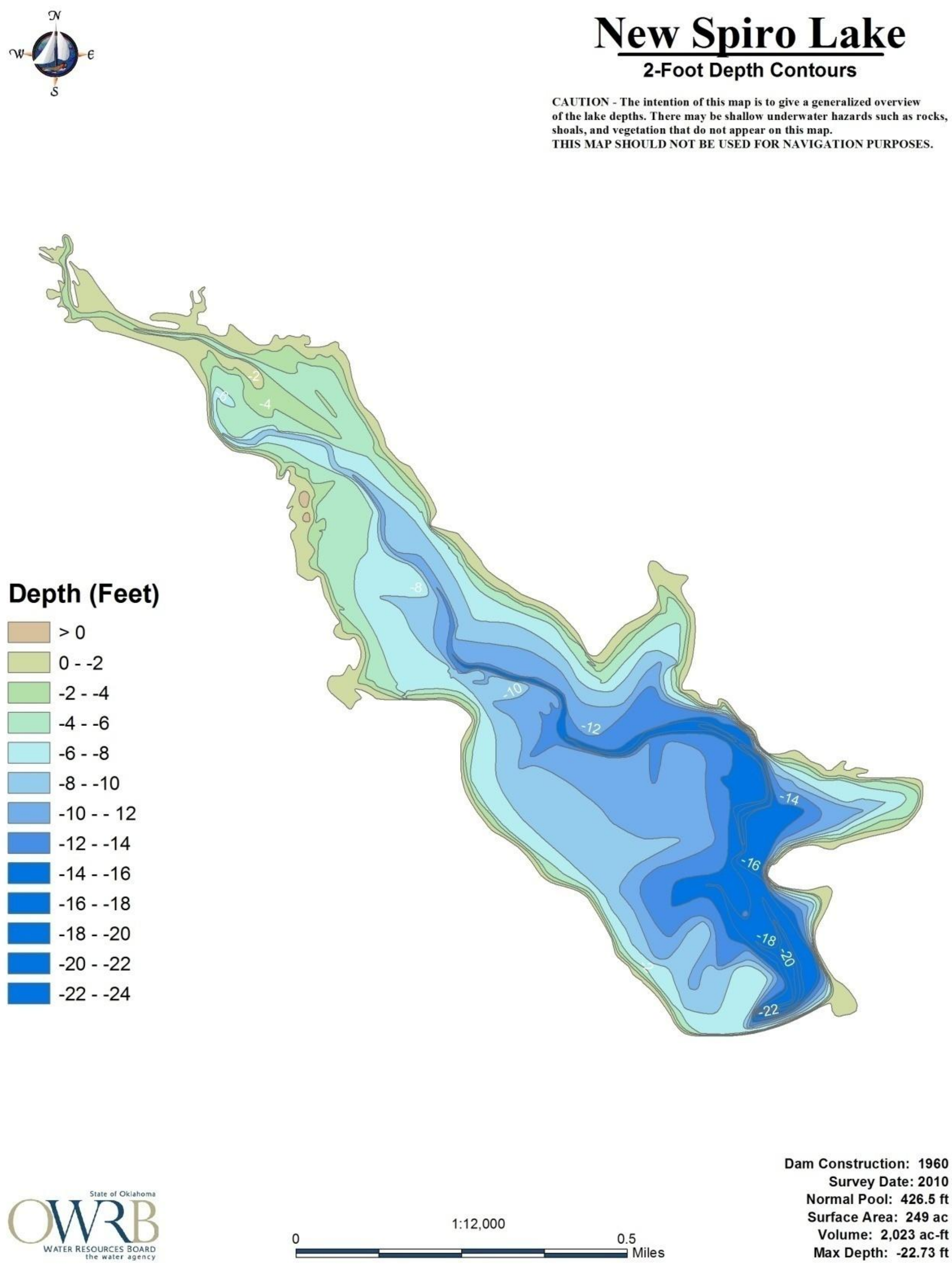


Figure B. 2: New Spiro Lake Shaded Relief Bathymetric Map.

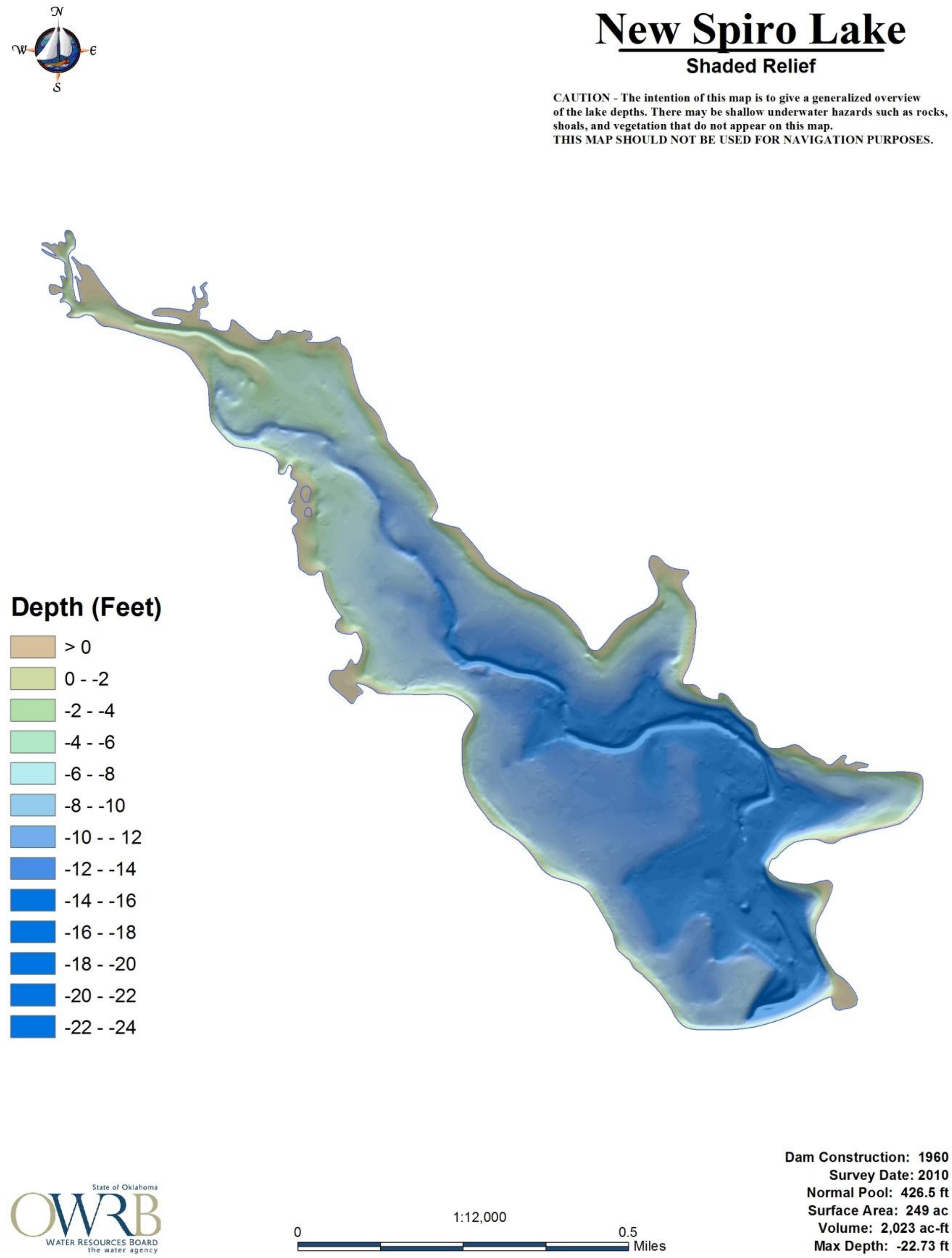


Figure B. 3: New Spiro Lake Collected Data Points.