Oklahoma City Urban Waters Report:

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Phase I–Mitigation of Impaired Beneficial Uses to Two Urban Oklahoma Reservoirs

State of Oklahoma
OWRB
WATER RESOURCES BOARD
the water agency

Environmental Protection Agency, Region 6

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FINAL REPORT

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Executive Summary

Both Lake Hefner and Lake Overholser are eutrophic urban drinking water resource reservoirs within Oklahoma City. This project was initiated to investigate the options for in-lake best management practices (BMPs) to improve lake water quality. When the project was proposed, there was a relatively low estimated external phosphorus (P) load and, since both lakes also manifest conditions suitable to the generation of internal P loading, it was assumed the internal load must be high in order to explain the continued water quality issues and blooms of blue-green algae. However, with recently available data illuminating a much greater external P loading from the North Canadian River watershed, it is apparent that internal loading is much less influential on water quality conditions in the lakes than previously assumed. Previous estimates of external load were based on a mean total phosphorus (TP) concentration of 0.157 mg L^{-1} at El Reno (based on roughly 4-8 measurements per year from 1998-2013). Current estimates are based on weekly measurements made at Yukon (closer to both lakes) over 2008-2011 with a mean concentration of 1.009 mg L^{-1}. In both lakes, external loading is by far the dominant source of P (more than 90%) despite implementation of watershed BMPs in an effort to tackle non-point sources. In Lake Hefner, an internal P load generated through annual hypolimnetic anoxia is responsible for a modest amount of P (4.7% of the load) and implementation of in-lake BMPs has been modeled using the BATHTUB model in order to assess the potential reduction of this load. Although, some of these BMPs can offer modest water quality gains, the overall impact on the lake is limited by the continued dominant nutrient loading from the North Canadian River. Of these BMPs, selective withdrawal of nutrient rich hypolimnetic waters is perhaps the simplest and most cost effective method for reducing overall P loading and is the only BMP recommended unless watershed BMPs are also implemented to reduce the external P load. In Lake Overholser, an internal P load may be present with the source being wind-induced resuspension of P containing sediment. However, due to the dominance of the external load and the limitations in using a model like BATHTUB, which is not fully suited to this purpose, an internal P load was not calculated for Lake Overholser. The potential implementation of in-lake BMPs has still been discussed but the impact they may have is unclear. As such, no in-lake BMP is recommended for Lake Overholser. Watershed management practices have been underway in the North Canadian River watershed in order to tackle non-point sources of nutrients and some improvements to water quality have been seen. However, recent data indicate point source contributions are important and, with continued urban development in the region, these are likely to increase in the future. Using BATHTUB, the potential water quality impacts of decreasing or increasing the external P load have been estimated. Significant improvements to both lake's water quality could be achieved if the loads are reduced, however, there is currently inadequate monitoring of this load as the most applicable monitoring effort (OCCs monitoring at Yukon, OK) has been discontinued. Any future improvements to lake water quality are dependent on increased awareness and management of watershed nutrient loads.

Background

The City of Oklahoma City, Oklahoma is heavily dependent on its urban water supply reservoirs, such as Lakes Hefner and Overholser, for drinking water, yet many of these resources have a long history of eutrophication with blooms of blue-green algae leading to poor potable water (Toetz 1982). Both of these lakes continue to experience excessive algal growth (OWRB 2013a) with Lake Overholser listed as a Nutrient Limited Watershed (NLW) and Lake Hefner with a Carlson's Trophic State Index (TSI) (using chlorophyll-a) of 62 or greater in some years, meeting the NLW listing requirement. Lake Overholser is also listed as impaired for turbidity, while Lake Hefner is listed as impaired for low dissolved oxygen. Lake Hefner lies within the Cimarron River watershed, but it receives nominal recharge from this basin as the bulk of recharge is diverted to Lake Hefner through Bluff Creek Canal from the North Canadian River. For this reason, the geological features of the North Canadian River basin are salient to the water chemistry of Lake Hefner. The North Canadian River drainage basin extends across northwestern Oklahoma and the Texas Panhandle and into northeastern New Mexico. From its headwaters to Lake Hefner, the entire watershed is 9,983 square miles. The Middle North Canadian watershed extends from Canton Reservoir to Lake Hefner, encompassing an area totaling 694 square miles and is the portion of greatest influence to lake recharge. This watershed includes portions of Blaine, Canadian, Oklahoma, and Dewey counties.

Control or reduction of excessive algae growth in Oklahoma's water supply reservoirs is critical for several reasons. Excessive algae impair drinking water supplies by causing taste and odor problems. Excessive algae levels are also linked to higher total organic carbon (TOC) within the reservoir (OWRB 2011). When disinfected through a typical chlorinated drinking water treatment train, this higher TOC causes a rise in carcinogenic trihalomethanes (THMs) and other disinfection by-products in finished drinking water (EPA 2014). Blue-green algae, common in eutrophic waters, have also been shown to produce cyanotoxins such as microcystins which have been recognized as a public health issue. Microcystins can cause liver damage; other cyanotoxins can be neurotoxic and cytotoxic (EPA 2012). Blue- green algae are also considered a major source of undesirable taste and odor compounds in drinking water from release of 2-Methylisoborneol (MIB) and Geosmin (Graham et. al. 2010). Excessive algae levels can impair the drinking water beneficial use such that the treatment costs skyrocket or the water supply is abandoned altogether.

While the City of Oklahoma City has overcome the problems presented by high TOC and blue-green algae in the drinking water pumped from Lake Hefner with the use of ozonation technology during drinking water treatment, this treatment comes at a high cost, and improvement of raw water should not be neglected, especially since the mean total phosphorus (TP) and total nitrogen (TN) concentrations in 2013 were greater than any time since 2004 and, at least, 2001, respectively. It should also be noted that ozonation is only available for the Lake Hefner drinking water; Lake Overholser, where water quality is more impaired, has a more typical treatment for drinking water. In recent years, regular treatments of the city's urban lakes with the algaecide copper sulfate has been well documented (OWRB 1999), highlighting the need for nutrient control measures in the watershed and reservoirs to maintain both their function as part of the city's primary water supply and the high recreational value the urban reservoirs serve.

The Oklahoma Conservation Commission has developed a watershed based plan (WBP) for the Central North Canadian Watershed aimed at identifying, monitoring and reducing nutrient loads in the watershed of both reservoirs (OCC, 2008). The Central North Canadian WBP has focused on implementing Best Management Practices (BMP) which target non-point sources, expanding on those BMPs already implemented under the Environmental Quality Incentives Program (EQIP). However, despite some evidence of decreasing nutrient loads, these are still relatively high and the water quality of both lakes continue to be an issue.

While there has been much research on the water and nutrient dynamics of both reservoirs over the years, the potential for internal phosphorus loading has been largely undocumented and neglected. A recent Total Maximum Daily Load (TMDL) study of Lake Thunderbird, a nearby reservoir, documented that over half of the phosphorus load came from in-lake sources and was a "significant controlling factor of eutrophication of the lake" (ODEQ 2013).

Cooperative work with the Tulsa District Corps of Engineers (COE) and the Poteau Valley Improvement Authority (PVIA) at Lake Wister, OK, and the Central Oklahoma Master Conservancy District (COMCD) at Lake Thunderbird, OK, has shown that in-lake modifications and BMPs can improve raw water quality and potentially reduce internal nutrient loads. Results of the studies with the Corps of Engineers and PVIA at Lake Wister have determined that modification of water releases can mitigate the rate of oxygen loss within a lake. Results of the study at Lake Thunderbird with COMCD have shown hypolimnetic oxygenation can be effective at oxygenating the hypolimnion, reducing anaerobically mediated sediment phosphorus (P) release and have a marked decrease in algal biomass, reducing peak chlorophyll-a (Chl-*a*) values by over 50% (OWRB, 2013). Increasing dissolved oxygen will increase the available habitat for fish species (volume of aerobic water), minimize the recycling of nutrients from the sediment and 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 of Oklahoma. In short, the work on Lake Wister and Lake Thunderbird has shown that in-lake management can be a necessary component of the recovery and enhancement of raw water supply.

This report highlights the value of understanding both the in-lake and watershed nutrient dynamics, and also the impact that in-lake BMPs can have on the water quality of the reservoirs. We accomplish this with a monitoring program designed to remedy data gaps coupled with a modeling effort using the BATHTUB model to simulate implementation of BMPs and potential varying nutrient loads from the watershed.

Lake Hefner

Lake Hefner is located in Oklahoma County eight miles northwest of downtown Oklahoma City, Oklahoma. It was impounded in 1943, and has a surface area of 2499 acres at a municipal pool elevation of 1999 feet. The natural flow originates from – Deer Creek and East and West Bluff Creeks in the Cimarron River watershed but a series of canals were built to divert most of this drainage around the lake to reduce the impact of urban land use on water quality. The major inflow to Lake Hefner is water diverted through Bluff Creek Canal from the North Canadian River downstream of Canton Reservoir and the cities of El Reno and Yukon. This inflow can either be the normal flow of the North Canadian or, alternatively, water released from Canton Reservoir with the intention of recharging Lake Hefner. The North Canadian also passes through the Stinchcomb Wildlife Refuge, a wetland habitat immediately upstream of the Bluff Creek Canal intake. The two sources of groundwater within this area are the sandstone of the Permian Age and the alluvial deposits along the North Canadian River. Lake Hefner serves as a public water supply reservoir for the northwest Oklahoma City area, and has a designed storage capacity of 75,000 acre-feet. As an offset reservoir, Lake Hefner has a relatively high residence time with a low sedimentation rate. Gross sedimentation for Lake Hefner since impoundment was estimated at 104 acre-feet per year by a bathymetric survey performed by the OWRB (2002). An aeration system was operated in the lake until 1995 but was discontinued due to poor system design, leading to significant sediment resuspension and to the use of the expensive ozonation technology during drinking water treatment, making the system temporarily unnecessary.

Lake Hefner is an aesthetic, urban locale providing the public with opportunities for recreational activities in the Oklahoma City metropolitan area including fishing, sailing, boating, windsurfing, jogging and cycling. Easy access to the entire lake shoreline, made possible by a paved multipurpose trail accompanied by its relatively high pool elevation and large size, make Lake Hefner a unique attraction in Oklahoma City.

Lake Overholser

Lake Overholser is located in Oklahoma County, 10 miles west of downtown Oklahoma City, Oklahoma. Lake Overholser was impounded in 1919, and has a surface area of 1567 acres at a municipal pool elevation of 1242 feet. Like Lake Hefner, Lake Overholser is an offset reservoir of the North Canadian River. Lake Overholser was set over the original riverbed, channeling the river along the lakes eastern side. Overtime, the lake has gained its characteristic morphology of a uniform shallow pool (mean depth 2.7 meters) with no channel (maximum depth 4.2 meters). Lake Overholser receives water through a coffer dam system sited immediately downstream of the Stinchcomb Wildlife Refuge and the Bluff Creek Canal intake for Lake Hefner. The inlet to the lake remains closed except during planned inflow events, giving some control of water inflow quantity and quality and increasing management options for the lake. The shallow nature of the lake allows for significant resuspension of sediment due to wind generated turbulence.

Lake Overholser serves as a public water supply reservoir for the southern portion of Oklahoma City during peak demand months of July, August and September. The lake has relatively low visitation when considering its location within the city, likely connected to its poor aesthetics stemming from the hypereutrophic, turbid conditions present year round. Popular recreational activities include bank fishing, cycling and paddle boarding.

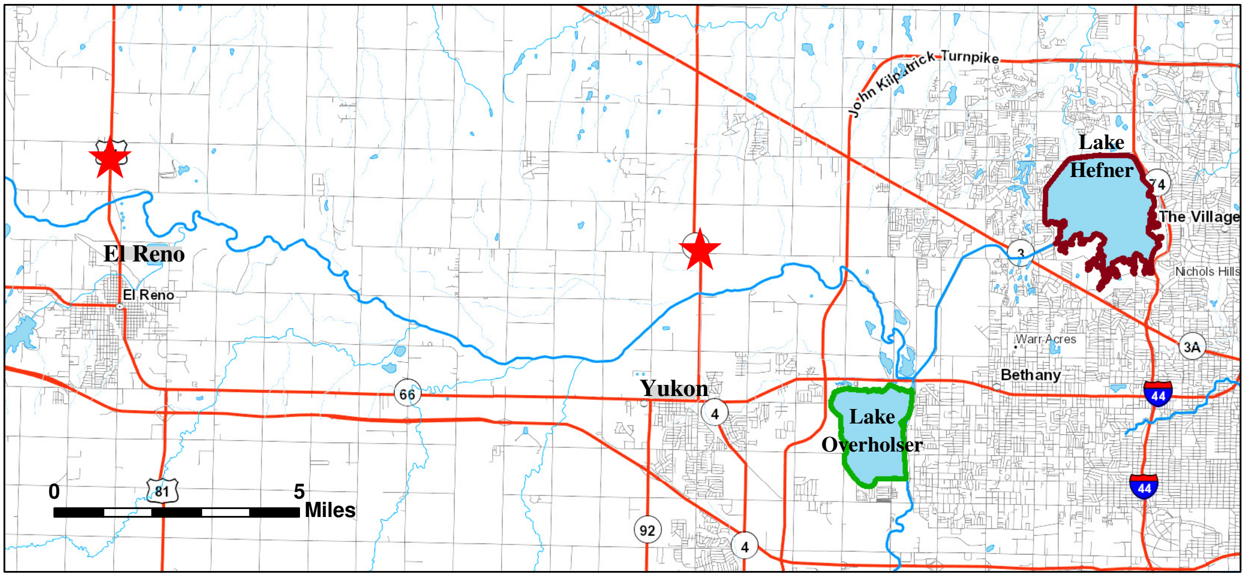

Figure 1 Map showing positions of Lakes Hefner and Overholser and North Canadian River sampling stations at El Reno and Yukon (red stars)

Methods

The evaluation scheme for this project is to amend existing data (2001 – 2013) with current water quality data. In short monitoring since the cessation of aeration fails to describe the extent or impact of stratification on overlying water quality. Sampling included multi-probe profiles, documentation of hypolimnetic nutrient accumulation and analysis of sediment nutrient content. The paragraphs below detail the sample design to fill information gaps and present a data set requisite for reservoir water quality modeling.

Sample Regime

In 2013, water quality sampling on Lakes Hefner and Overholser occurred from March 13th through September 17th (Table 1) at the sites indicated in Figures 1 and 2. All sites were sampled at each visit with the exception of Site 3 at Lake Overholser, which was too shallow to sample throughout much of the year.

On every visit, all sites had water quality profiles performed which included oxidation-reduction potential (ORP), dissolved oxygen (DO) saturation and concentration, temperature, specific conductance, total dissolved solids (TDS) and pH. Water quality profiles were measured in approximately one-meter vertical intervals from the lake surface to the sediment surface.

Nutrient samples were collected at the surface of Sites 1, 2 and 3 at each lake. In addition, nutrient samples were collected at Lake Hefner in 6 m depth intervals at Site 1 from the surface to 0.5 m off the bottom. In Lake Overholser, a bottom nutrient sample was also collected at Site 1. Analyses performed on these samples included phosphorus (P) and nitrogen (N) series. A water quality sample was also collected in the diversion canal for Lake Hefner during the only period of inflow during 2013.

On August 12th, 2013 an Ekman dredge sediment sample was collected for laboratory analysis from all lake sample sites and analyzed for TP. Sites were re-sampled in August 2014 for additional analysis of % solids.

Table 1 Sampling Dates for Lake Hefner and Overholser in 2013

Year	**2013**									**2014**
Date	**3/13**	**4/25**	**5/9**	**6/12**	**6/19**	**7/12**	**8/12**	**8/30**	**9/17**	**8/07**
Profile	X	X	X	X	X	X	X	X	X	
Chl-*a*	X	X			X	X	X	X	X	
Secchi Depth	X	X	X	X	X	X	X	X	X	
Turbidity	X	X	X	X	X	X	X	X	X	
Nutrients	X	X			X	X	X	X	X	
Ekman Dredge							X			X

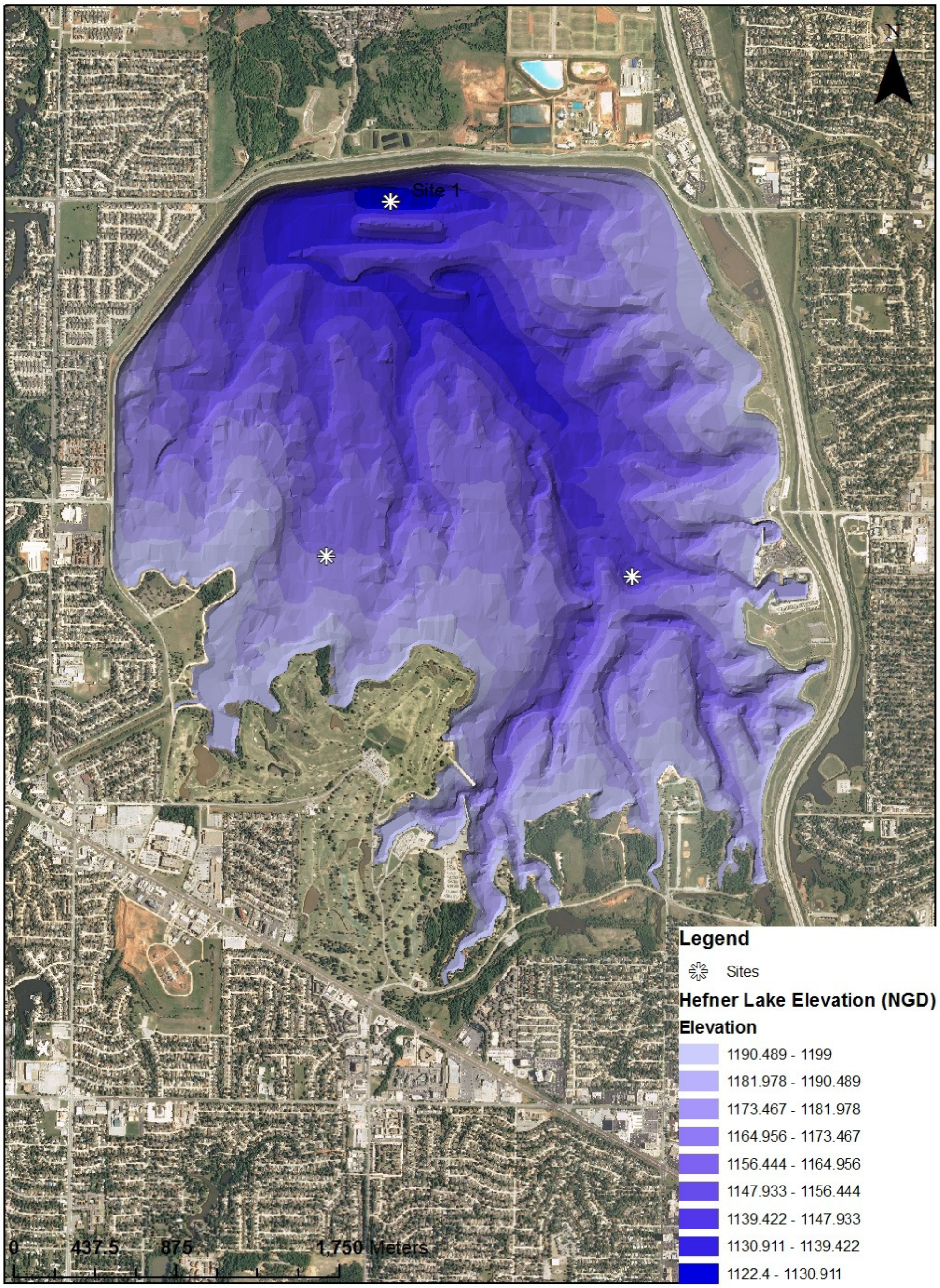

Figure 2 Lake Hefner sample sites.

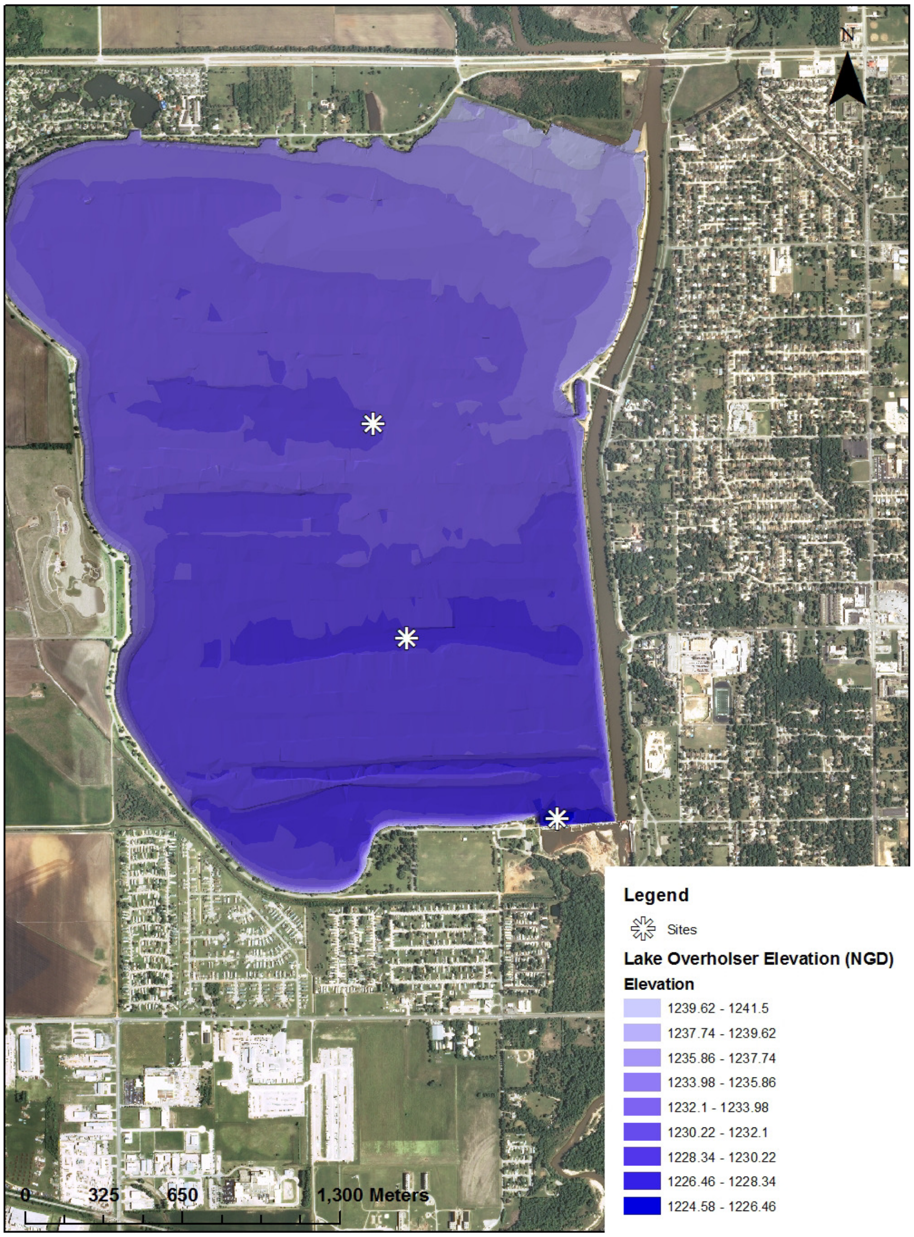

Figure 3 Lake Overholser sample sites

Quality Assurance and Quality Control (QA/QC)

Water quality and sediment sampling conducted in 2013 for this project followed the QA/QC procedures described in the EPA approved Quality Assurance Project Plan (QAPP) "Phase I - Mitigation of Impaired Beneficial Uses to Two Urban Oklahoma Reservoirs". No major failure occurred during the 2013 sampling season to compromise the integrity of the dataset. One observation worth noting was that ortho-phosphorus (Ortho-p) values for several samples were higher than that of total TP. Since TP is a measure of all phosphorus components, one of the two values was incorrect. This anomaly was reported to the lab of analysis. In this case, the TP method was taken as a more reliable measure than the Ortho-p method, due to both a greater control of variables and since Ortho-p can be subject to post sampling reactions with the potential to negatively impact the quality of results. Laboratory quality control samples included duplicates and replicates. Duplicate samples were taken at the surface of Site 1 for all laboratory analyzed samples and labeled "Site 1" and "Site 4", respectively, and delivered to the laboratory for analysis.

Duplicate and Replicate Samples

Duplicate samples yield an overall estimate of error either due to sampler or laboratory error. This paired data set yields a difference between the two "identical" samples. Site 4 is the duplicate sample label for Site 1 surface samples. The percent absolute difference (PAD) was used to describe the precision of each laboratory parameter based on the paired comparison of duplicate samples (Equation 1).

$$PAD = \left| x_{S1} - x_{S9} \right| / \ x * 100 \qquad \textit{(Equation 1)}$$

Results were tabulated and statistical summaries were generated for each parameter using the box and whisker plot function (Figure 3). All parameters showed relatively good precision with median PAD below 20%, with the exception of pheophytin-*a* (Pheo-a) which is a common degradation product of Chl-*a*. The Ekman dredge sediment sample for TP was only sampled a single time throughout the season, therefore a box and whisker plot was not appropriate. Sediment TP had a percent absolute difference of 1.74%, illustrating a good measure of precision.

The Kruskul-Wallis test, a non-parametric test for differences between medians, was applied to each depth category (Figures 4 and 5). Maximum depth and hypolimnetic ceiling were not significantly different between the two time periods. However, epilimnetic depth was significantly different (p=0.033) with a median depth of 4.0 meters while the aerator was on (before 1995) and 8.9 meters deep after (1995) the aeration system was discontinued. This difference is both statistically and physically significant indicating data collected prior to 1995 should not be used for the current investigation. These data have been excluded from all modeling efforts and analysis.

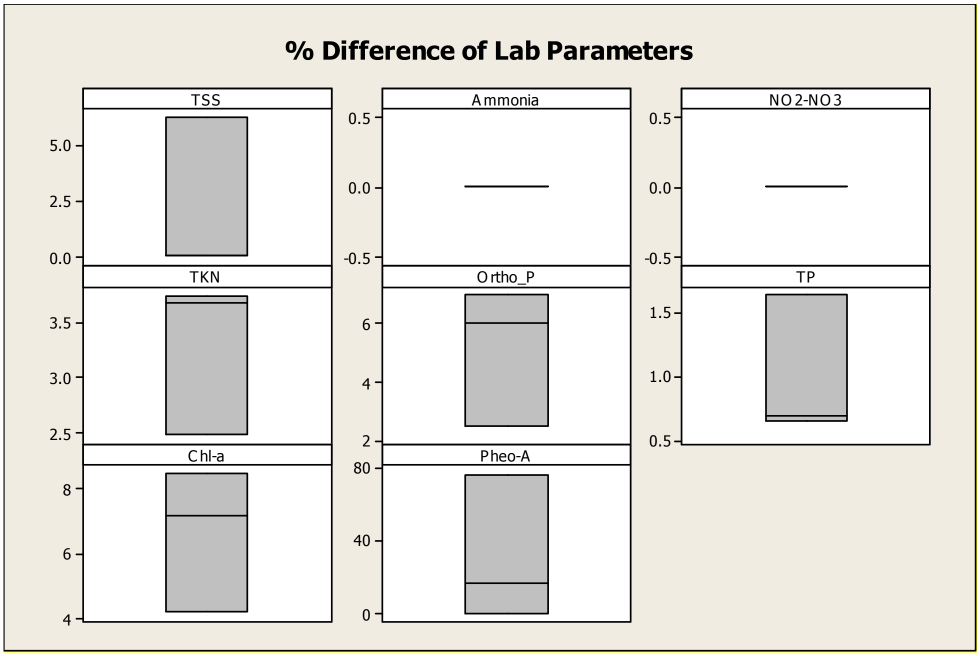

Figure 4 Percent Difference of Total Suspended Solids (TSS), Ammonia, Nitrate-nitrite (NO2-NO3), total Kjedahl nitrogen (TKN), Ortho-phosphate (Ortho-p), total phosphorous (TP), chlorophyll-*a* (Chl-*a*), and pheophytin-*a* (Pheo-a).

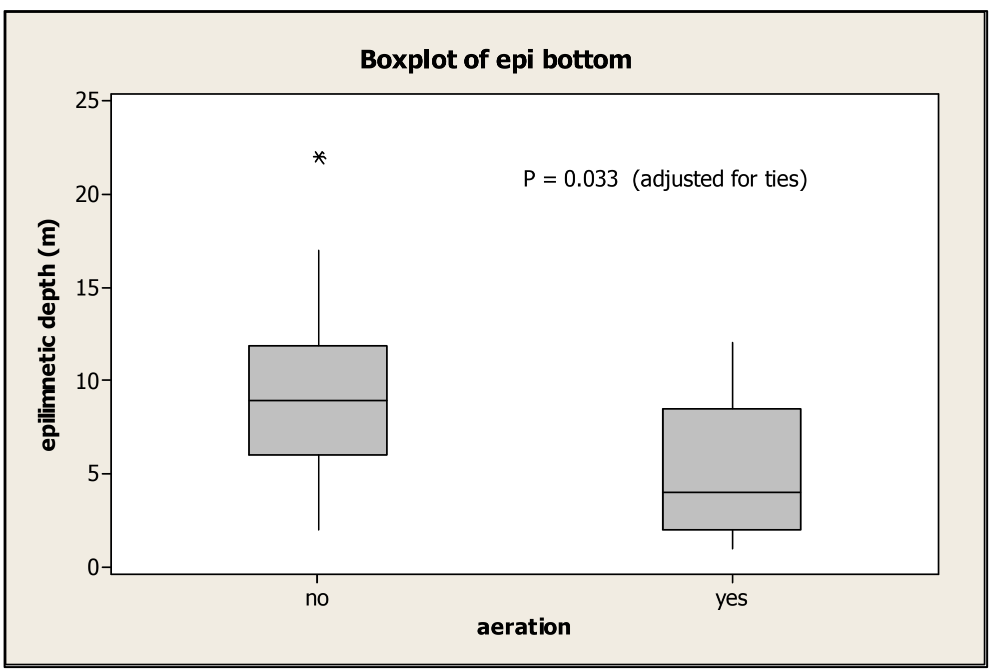

Figure 5 Box Plot of Depth to the Bottom of the Epilimnion During Periods of 'No' Aeration (post-1995) and 'Yes' Aeration (post-1995) for Lake Hefner

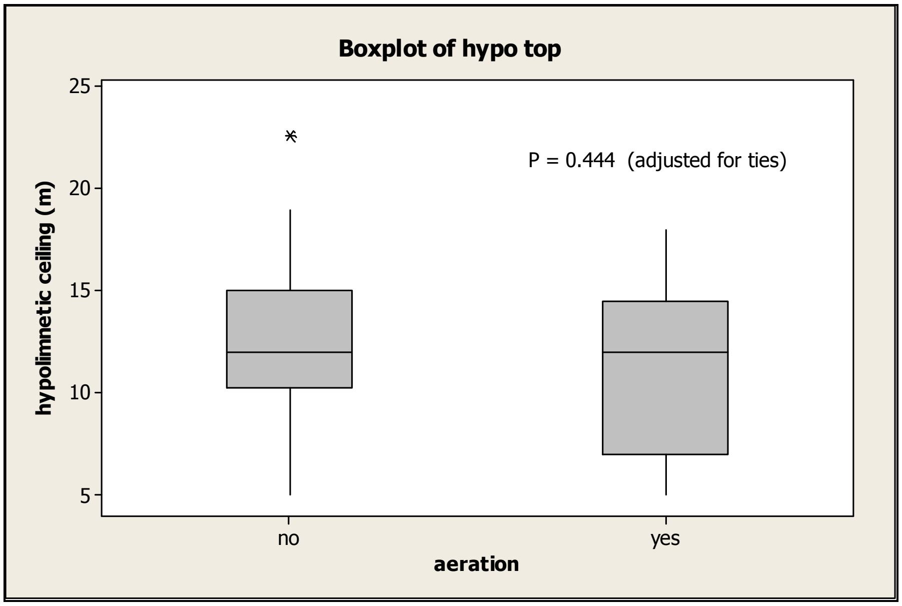

Figure 6 Box Plot of Depth to the Top of the Hypolimnion During Periods of 'No' Aeration (post-1995) and 'Yes' Aeration (post-1995) for Lake Hefner.

For Lake Hefner, surface water data from 2000-2013, statistical analysis of Secchi disk depth, turbidity, Chl-*a*, total phosphorus (TP), ortho-phosphate (Ortho-p), organic nitrogen, and sulfate showed no significant change over time. Non-parametric testing (Fishers and Tukey's) showed no significant difference between any site. Therefore, statistical summaries for BATHTUB input were run after aggregating all data from 2000-2013.

For Lake Overholser, data from 1994-2013 and encompassing 21 sample dates, were examined for trends and differences over time. Results of statistical analysis of surface values for Secchi disk depth, turbidity, Chl-*a*, TP, Ortho-p, organic nitrogen, and sulfate showed no significant change over time (1994-2013). Non-parametric testing (Fishers and Tukey's) showed no significant difference between any site. Therefore, statistical summaries for BATHUB input were run using all sites aggregated.

All data were considered for the purpose of this report but only data after January 1, 2000 were used for the BATHUB model.

Additional Watershed Water Quality Data

Watershed nutrient data were supplied by the Oklahoma Conservation Commission (OCC) for three of their monitoring stations on the North Canadian River at Yukon, El Reno and from below Canton Lake. Data was available from June 2008 until December 2011 for Yukon and from June 2008 until February 2013 for El Reno and Canton Lake. Additional data were available from the states BUMP station at El Reno from November 1998 until July 2013.

Lake Water Quality Model-BATHTUB

BATHTUB is a steady-state modeling software package designed by the United States Army Corps of Engineers (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) including Oklahoma for both diagnostic (OWRB 2011) and TMDL purposes (DEQ 2013). BATHTUB modeling 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).

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. Some of these data were obtained via a monitoring effort as part of this project (**Sample Regime**) while the remainder is compiled from existing state, federal and private sources (**Additional Lake Water Quality Data**, **Additional Watershed Water Quality Data** and **BATHTUB Input Data**).

Input Data

Averaging Period

BATHTUB allows the user to choose the period of time over which water and mass balance calculations will be carried out, usually a season or a year. Several factors should be considered when setting the averaging period but most importantly, hydraulic residence time and the nutrient turnover ratio. Both Lakes Hefner and Overholser have relatively long hydraulic residence times which suggests a one year averaging period is appropriate to incorporate loading that occurs prior to the period of concern. The phosphorus turnover ratios in both reservoirs are relatively low; at 6.1 for Lake Overholser, and 7.4 for Lake Hefner, which signifies that a yearlong averaging period is appropriate as a shorter modeling period would further shrink the turnover ratio. BATHTUB warns that turnover ratios below 2 should be cause of concern as pool and outflow water quality measurements would reflect loading conditions experienced prior to the start of the averaging period.

Lake Morphometrics

BATHTUB requires morphometric inputs for any reservoir modeling exercise including surface area, mean depth, and length of the reservoir. When appropriate, BATHTUB allows the user to segment the reservoir into a hydraulic network. For both of the offset reservoirs modeled, the reservoirs are physically isolated from their gated canal inflows, and so no true riverine zone exists for both reservoirs. As can be seen in Figure 1 and 2, both reservoirs are also very circular with no isolated waters; therefore no segmentation was warranted for either of the model set-ups. Statistical analysis presented earlier supports this assumption. Model inputs for morphometry were derived from the OWRB bathymetric survey.

Table 2 Morphometric Parameters for Lake Hefner and Lake Overholser (OWRB 2002).

Lake Hefner	
Surface Area (km^2)	10.11
Mean Depth (m)	8.84
Length (km)	3.43
Lake Overholser	
Surface Area (km^2)	6.44
Mean Depth (m)	2.70
Length (km)	3.14

Weather Data

The BATHTUB model requires both precipitation and evaporation data. Precipitation data were available from the Oklahoma Mesonet system. For both reservoirs' data from the closest Mesonet station (OKC WEST) were compiled. Water evaporation rates were calculated off of the closest USACE lakes (Lake Thunderbird) daily open water evaporation rate. Inputs for both reservoirs BATHTUB models can be found on Table 3.

Table 3 Precipitation and Evaporation Data for Lake Hefner and Lake Overholser.

Lake Hefner	
Precipitation ($m\ m^{-2}$)	0.83 (0.26 CV)
Evaporation ($m\ m^{-2}$)	2.02 (0.10 CV)
Lake Overholser	
Precipitation ($m\ m^{-2}$)	0.83 (0.26 CV)
Evaporation ($m\ m^{-2}$)	2.02 (0.10 CV)

Watershed

As mentioned in the background section, both Lakes Hefner and Overholser are offset reservoirs, which allows for selection of inflow events and largely disconnects the reservoirs from their watersheds. Because the inflow water can also come from different sources, Canton Lake and/or the North Canadian River, it makes watershed models an unreliable predictor of inflow water quality measures. Therefore, we make use of a mass balance approach to estimate both inflows and outflows.

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 + Change-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 change-in-storage terms are calculated directly from information provided by the user.

Inflow Estimates

For the BATHTUB model differing methods were used to calculate inflow rates for the two lakes due to gauge data availability. For Lake Hefner, inflow was estimated using the USGS gauge on the Bluff Creek Canal directly above Lake Hefner (Table 4). For Lake Overholser, no tributary gauge exists due to its unique coffer dam system and so inflow rates were provided by the City of Oklahoma City (Table 5).

Due to the limitations in inflow rates mentioned above, the inflow nutrient concentrations were also calculated in two different ways. For Lake Hefner the FLUX program was used to estimate inflow nutrient concentrations and loads. This program is able to map the flow/concentration relationship developed from the sample record onto the entire flow record to calculate total mass discharge and mean concentrations over the flow period (Walker 1996). Data can be stratified by flow to better represent all flow conditions. Flux was first used to combine North Canadian River nutrient concentrations from Yukon, provided by OCC, with discharge measured at the USGS gauge at Yukon to test the validity of the chosen stratification scheme. Of the flow based stratification schemes suggested by the program, we chose to split the data at 50%, 200% and 800% of mean flow to give four groups. This same scheme was then used with Yukon nutrient data and flow data from the Bluff Creek gauge to give inflow nutrient concentrations and loads to Lake Hefner (Table 4). For Lake Overholser the nutrient concentrations calculated with the Yukon nutrient and flow data were used (Table 5). The nutrient concentration data from Yukon were used since it is the closest point to either lake that has a comprehensive sampling record (weekly) and, out of the options available, best represents the inflow concentrations to both Lakes Hefner and Overholser. These current estimates gave a mean concentration of 1.009 mg L^{-1} at Yukon over 2008-2011. In comparison, previous estimates of TP load in the North Canadian River were made using the BUMP data set with a mean concentration of 0.157 mg L^{-1} at El Reno (based on roughly 4-8 measurements per year from 1998-2013).

Table 4 Lake Hefner Tributary Inflows - Bluff Creek Canal Values Calculated by the FLUX Program Using Bluff Creek Flow Data and North Canadian River Nutrient Concentration Data from Yukon.

Parameter	Mean	Coefficient of Variation
Flow ($hm^3\ yr^{-1}$)	56.86	0.24
Total P ($\mu g\ L^{-1}$)	873	0.10
Ortho-p ($\mu g\ L^{-1}$)	442	0.12
Total N ($\mu g\ L^{-1}$)	3450	0.10
Inorganic N ($\mu g\ L^{-1}$)	502	0.15
Chloride ($\mu g\ L^{-1}$)	120295	0.46

Table 5 Lake Overholser Tributary Inputs - Coffer Dam Inflow Values. Flow Data Provided by Oklahoma City. Nutrient Concentrations Calculated by the FLUX Program Using North Canadian River Flow and Nutrient Concentration Data from Yukon.

Parameter	Mean	Coefficient of Variation
Flow ($hm^3\ yr^{-1}$)	20.6	0.65
Total P ($\mu g\ L^{-1}$)	1190	0.99
Ortho-p ($\mu g\ L^{-1}$)	596	0.09
Total N ($\mu g\ L^{-1}$)	4510	0.16
Inorganic N ($\mu g\ L^{-1}$)	502	0.11
Chloride ($\mu g\ L^{-1}$)	118000	0.15

Outflow Estimates

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

For Lake Hefner, no traditional spillway exists. The only significant exits of water from the reservoir for the period of record are through evaporation from the surface and drinking water withdraws from the north side of the reservoir. The City of Oklahoma City provided monthly drinking water withdrawal records for the modeling period. Drinking water withdrawal nutrient concentrations were set to average observed surface water values for the modeling period.

Like Lake Hefner, Lake Overholser has a unique outflow pattern as inflow patterns are regulated by the city. Unlike Lake Hefner, Lake Overholser does have a traditional dam spillway, and did operate throughout the modeling period. Lake Overholser is also used as an auxiliary water supply for the city during peak use. Outflow model inputs for both reservoirs can be found in Tables 6 and 7.

Table 6 Lake Hefner Water Withdrawal

Parameter	Mean	Coefficient of Variation
Flow ($hm^3\ yr^{-1}$)	53.99	0.19
Total P ($\mu g\ L^{-1}$)	79.3	0.30
Ortho-p ($\mu g\ L^{-1}$)	35.7	0.71
Total N ($\mu g\ L^{-1}$)	976	0.22
Inorganic N ($\mu g\ L^{-1}$)	144	0.75
Chloride ($\mu g\ L^{-1}$)	143689	0.11

Table 7 Lake Overholser Water Withdrawal (WD) and Spillway Overflow (SW)

Parameter	Mean	Coefficient of Variation
Flow WD ($hm^3\ yr^{-1}$)	9.04	0.48
Flow SW ($hm^3\ yr^{-1}$)	7.40	
Total P ($\mu g\ L^{-1}$)	233.3	0.48
Ortho-p ($\mu g\ L^{-1}$)	144.3	0.74
Total N ($\mu g\ L^{-1}$)	1351.2	0.49
Inorganic N ($\mu g\ L^{-1}$)	237.6	1.14
Chloride ($\mu g\ L^{-1}$)	130720	0.51

Change in Storage

The change in storage term required by BATHTUB was calculated for Lake Hefner, using USGS gauge data, as the mean annual lake level change over the period 2000-2013. This gave a change in storage of -0.065 m. For Lake Overholser, input data provided by the City of Oklahoma City were used (as used by Storm *et al*, 2007).

Atmospheric Loads

An atmospheric nutrient load is the deposition of wet (precipitation) and dry (dust and aerosols) nutrients directly to a lake surface. While these inputs are generally small when compared to the watershed and internal nutrient loads for eutrophic waterbodies, they are increasingly recognized as significantly impacting surface waters and should be accounted for when possible. The BATHTUB model allows for the input of TP, ortho-phosphorous (Ortho-p), TN 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 BATHTUB program have been used. These values are given in Table 8.

Table 8 BATHTUB Default Atmospheric Loads

Parameter	Mean ($mg\ m^{-2}\ yr^{-1}$)	Coefficient of Variation
Total Phosphorous	30	0.5
Ortho Phosphorous	15	0.5
Total Nitrogen	1000	0.5
Inorganic Nitrogen	1000	0.5

Observed Water Quality

BATHTUB also requires 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 TP, TN, Chl-*a*, Secchi disk depth, organic nitrogen, TP minus Ortho-p, and chloride (conservative substance).

Data included for the observed water quality dataset for both lakes are described previously in Methods section. The means and coefficient of variation that went into the two BATHTUB models are given in Table 9 and Table 10.

Table 9   Lake Hefner Observed Surface Water Quality 2000-2013.

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	0.82	0.63
Total P ($\mu g\ L^{-1}$)	79.3	0.30
Total N ($\mu g\ L^{-1}$)	976	0.22
Chlorophyll-a ($\mu g\ L^{-1}$)	19.1	0.61
Secchi Depth (m)	0.77	0.33
Organic Nitrogen ($\mu g\ L^{-1}$)	787	0.22
Total P - Ortho-p ($\mu g\ L^{-1}$)	43.7	0.46
Chloride ($\mu g\ L^{-1}$)	143689	0.11

Table 10   Lake Overholser Observed Surface Water Quality 2000-2013.

Parameter	Mean	Coefficient of Variation
Non-algal Turbidity (1/m)	4.93	0.84
Total P (μg L^{-1})	233.3	0.48
Total N (μg L^{-1})	1351.2	0.49
Chlorophyll-a (μg L^{-1})	35.1	0.77
Secchi Depth (m)	0.28	0.47
Organic Nitrogen (μg L^{-1})	1218.9	0.51
Total P - Ortho-p (μg L^{-1})	81.59	0.65
Chloride (μg L^{-1})	130720	0.51

Sediment Phosphorous

Sediment phosphorus dynamics operate in two separate schemas for the reservoirs modeled. Lake Hefner is generally a stratified monomictic system with a well defined anoxic hypolimnion throughout much of the summer (Figure 6), while Lake Overholser is a shallow polymictic wind-mixed system that would only stratify under unusually calm hot conditions (Figure 7). This has implications both for sedimentation of P and the potential for P release from sediments. Variations in sedimentation can be handled with appropriate choices for model equations and variation of sedimentation terms. In addition, BATHTUB provides an avenue to incorporate an internal P load if one is measured or, as in the case for this study, is calculated.

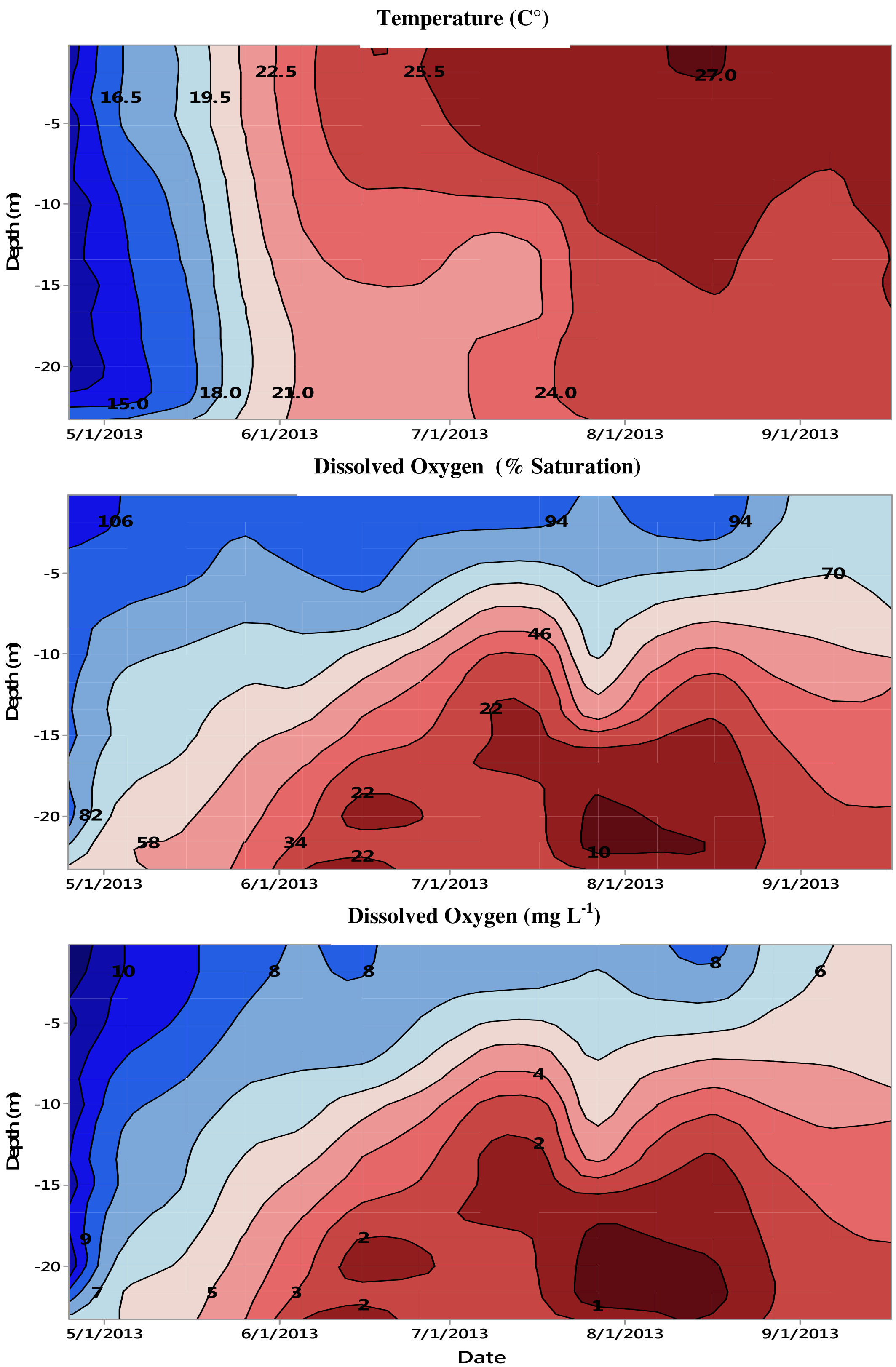

Figure 7 Lake Hefner Isopleths Plots Showing Temperature (C°), Dissolved Oxygen (% Saturation) & Dissolved Oxygen (mg L^{-1}).

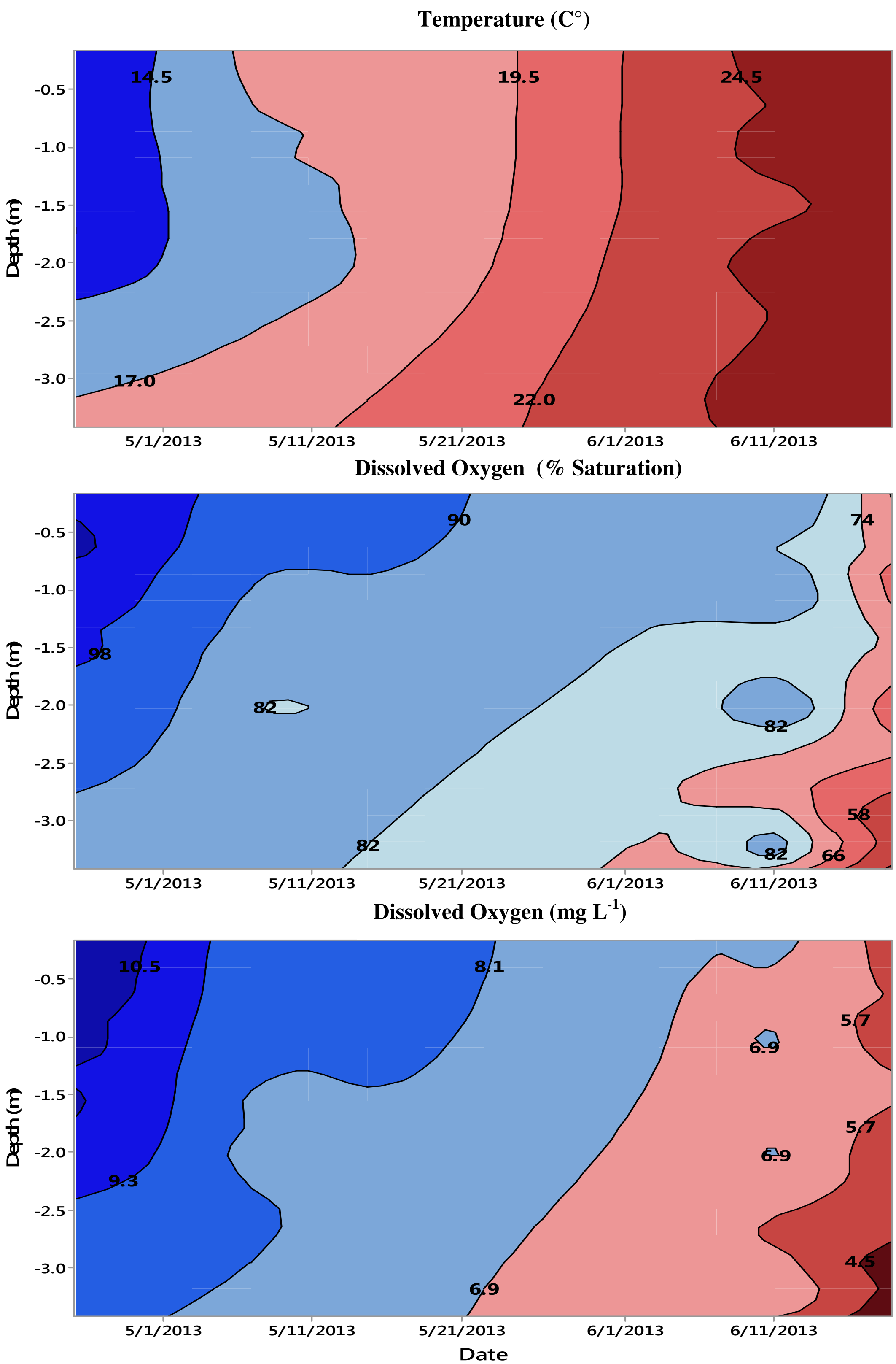

Figure 8 Lake Overholser Isopleths Plots Showing Temperature (C°), Dissolved Oxygen (% Saturation , and Dissolved Oxygen (mg L^{-1}).

Lake Hefner Sediment Phosphorus Release

In stratified systems that develop an anoxic hypolimnion, P loading resulting from anoxic sediment surfaces often represents a significant portion of summer P load to lakes and reservoirs (Nurnberg 1994). Anaerobic mediated sediment phosphorus releases can be modeled by combining estimates of anoxic phosphorus release rates (***RR***) with an estimate of the spatial and temporal extent of anoxia, expressed as an Anoxic Factor (***AF***) giving an internal phosphorus load (***IntP***) (Nurnberg 2009) following Equation 2.

$$IntP = RR \times AF \qquad \textit{(Equation 2)}$$

The ***RR*** of phosphorus is expressed as:

$$Log\,(RR) = 0.8 + 0.76\,log\,(TPsed) \qquad \textit{(Equation 3)}$$

Where: ***TPsed*** is the sediment total phosphorous content in g kg^{-1} (dry weight). The mean ***RR*** from all the sampling sites was then used. The sediment TP content was 654, 297 and 535 g kg^{-1} at sites 1, 2 and 3 respectively. This distribution may be caused by preferential transport of smaller particles to the deeper area of the lake giving a greater sediment particle surface area for P adsorption. The mean ***RR*** of all sites was 3.66 mg m^{-2} d^{-1}.

The ***AF*** (d yr^{-1}) can either be computed from dissolved oxygen profiles (Equation 4) (Nurnberg 2009) or calculated from the summer epilimnetic total phosphorus concentration (Equation 5).

$$\boldsymbol{AF1} = \sum_{i=1}^{n} \frac{ti \cdot ai}{A0i} \qquad \textit{(Equation 4)}$$

Where: ***n*** is the total number of periods when dissolved oxygen concentrations fall below 1 mg L^{-1}, ***ti*** is the duration of each period in days, ***ai*** is the sediment area in the anoxic region and ***A0i*** is the total lake area.

$$\boldsymbol{AF2 = -36.2 + 50.1LOG(TPsummer) + 0.762Z} \div \sqrt{\boldsymbol{A}} \qquad \textit{(Equation 5)}$$

Where: ***TPsummer*** is the mean summer epilimnetic total phosphorus concentration (µg L^{-1}), ***Z*** is the mean depth (m) and ***A*** is the surface area of the lake (km).

In this study, both methods were used to separately estimate ***AF***, giving values of ***AF1*** = 16.6 d yr^{-1} and ***AF2*** = 66.0 d yr^{-1}. Using Equation 2, these correspond to internal phosphorus loads of 0.17 mg m^{-2} d^{-1} and 0.66 mg m^{-2} d^{-1} respectively. It was decided to use the greater value of 0.66 mg m^{-2} d^{-1} as the more conservative value when considering possible scenarios of reductions in P loading to Lake Hefner. Significant internal P release is clearly indicated by increasing hypolimnetic TP and Ortho-p as the seasons progresses from spring to summer (Figure 8) and hypolimnetic dissolved oxygen decreases (Figure 6). The shallow, windswept polymictic Lake Overholser does not show the same clear signal of sediment nutrient release with stratification and anoxia as Lake Hefner (Figure 9).

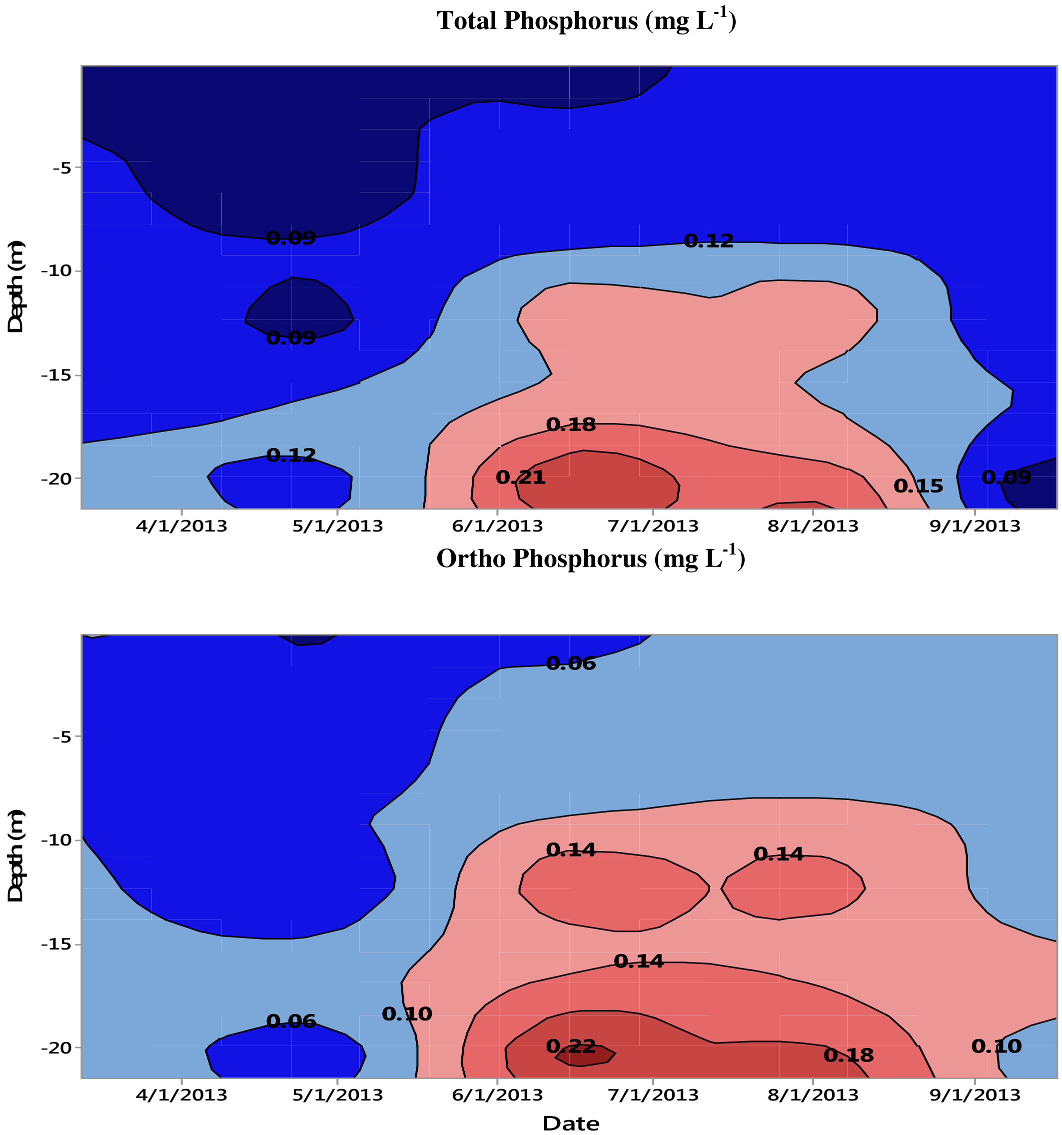

Figure 9 Lake Hefner Isopleths Plots Showing Total Phosphorus (mg L^{-1}) and Ortho-phosphorus (mg L^{-1}).

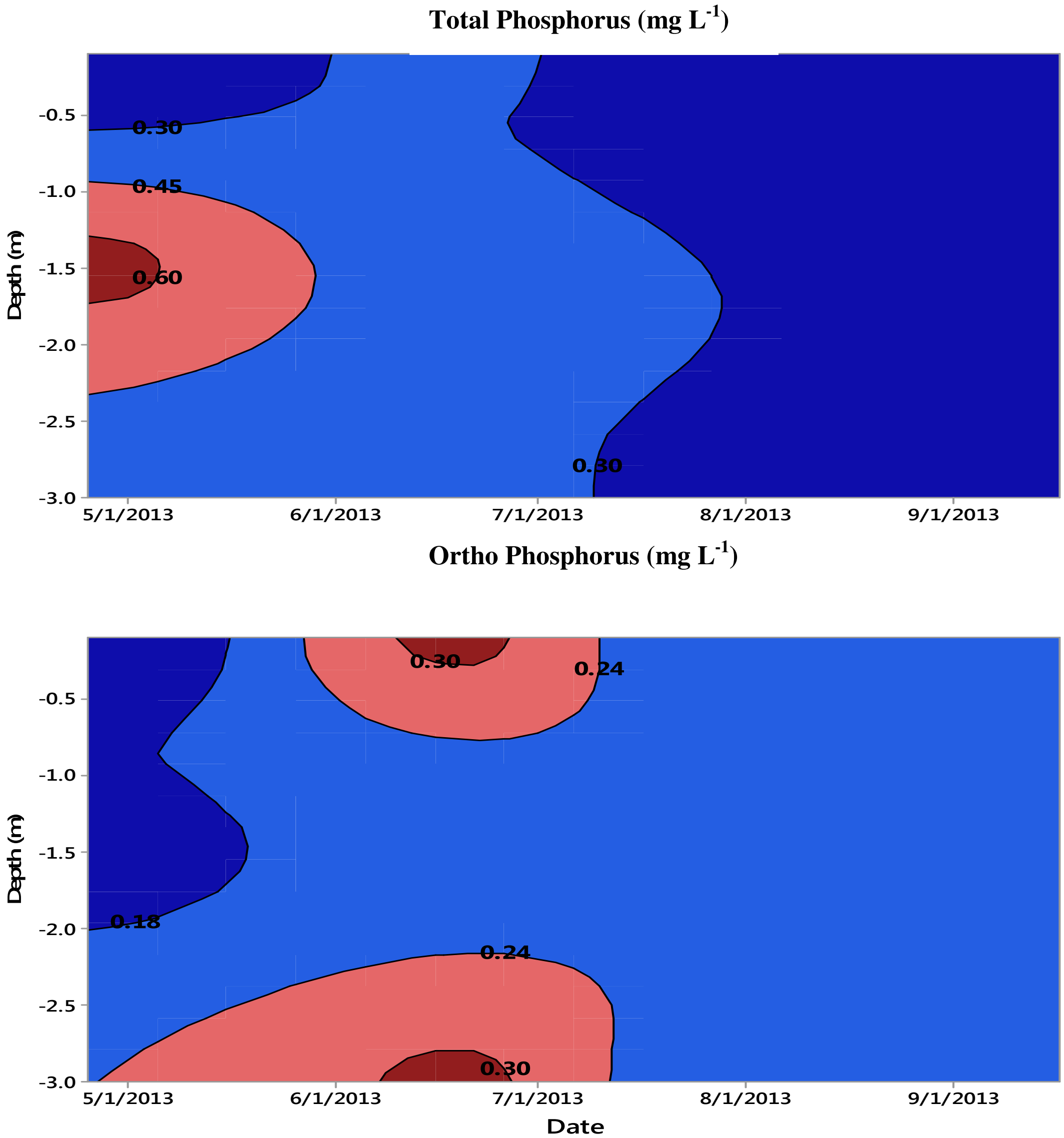

Figure 10 Lake Overholser Isopleths Plots Showing Total Phosphorus (mg L^{-1}) and Ortho-phosphorus (mg L^{-1}). Note that due to the shallow depth of Lake Overholser these isopleths are based on limited vertical measurements (0.5, 1.5 and 3 m) and due to analysis constraints the 1.5 m depth was only sampled at site 1 once during 2013.

Lake Overholser Sediment Phosphorus Release

Lake Overholser is generally a wind-mixed system that does not stratify under normal conditions. Anaerobic mediated sediment phosphorous release should be generally low as the hypolimnion usually remains oxic throughout the year. The surface sediment layer should also remain oxic due to both passive oxygen diffusion and wind-induced surface wave action which mixes oxic waters into the surface sediment layer. While not mediated by hypolimnetic anoxia, sediment P release should not be considered insignificant, as the same wind-induced surface waves which maintain polymixis also cause significant amounts of sediment resuspension, driving the low water clarity present throughout the system. Niemistö *et al*, 2011, found significant increases in soluble reactive phosphorus during sediment resuspension events in the shallow Kirkkojärvi basin (mean depth 1.1 m, max. depth 3.5 m) of Lake Hiidenvesi, Finland, predominantly due to aerobic release of P via ligand exchange reactions of P bound to iron and aluminum oxides. During sediment resuspension there is also the potential for the surface oxic sediment layers to be breached allowing Ortho-p release from any anoxic sub-surface layers. Sediment TP in Lake Overholser ranged from 223 mg kg^{-1} dry weight in the deepest area (~3 meters), to 179 mg kg^{-1} in the shallower areas of the lake. We do not have data showing the distribution of P phases or grain size distributions in the Lake Overholser sediments so it is impossible say whether this distribution is caused by grain size effects, preferential P release in shallow areas with increased sediment resuspension or from still other mechanisms. Moreover, the sediment TP samples were collected using an Ekman grab which provides bulk sediment samples suitable for estimating anoxic sediment P release (as in Lake Hefner). These samples may not accurately represent the TP concentrations in surface sediments (1-2 cm), which are most susceptible to wind-mediated resuspension, since surface sediments can be enriched in P due to migration of Ortho-p from anoxic sub-surface layers.

Studies on P release from resuspension are extremely limited and empirical methods for calculating release from resuspended sediment are not available. The method originally proposed to estimate sediment P release in Lake Overholser was by comparing the difference in expected P levels from inflow concentrations and hydrodynamics to what has been observed at the reservoir.

As will be further discussed in **Results and Discussion**, the external load to both lakes is much greater than previously thought due to a previous underestimation of the P loads in the North Canadian River. This increased external load (as measured at Yukon) masks any signal in the BATHTUB model which might allow quantification of an internal load. Without a study investigating P release from Lake Overholser sediments under varying sediment resuspension and water quality conditions (pH, DO etc.), an estimate of internal P load is not possible. However, the BATHTUB model does under predict the Ortho-p concentrations in the lake suggesting that a mechanism is operating which is not fully represented by the equations modeling P dynamics in BATHTUB. The Ortho-p concentrations can be seen to increase between June and July (Figure 9) at the surface (0.1 m) and bottom (3 m) of the lake and, since the 1.5 m depth was not sampled during that period, it possibly represents a whole water column increase. In addition, there are almost certainly processes affecting the P load occurring between Yukon and the intakes to both lakes and the current external P load could be an overestimate.

While we cannot fully calculate the internal load we can still use equation 3 to calculate a ***RR*** for Lake Overholser based on the sediment TP contents for comparative purposes and for use if any periods of hypolimnetic anoxia were to occur. This gave a mean ***RR*** of 1.86 mg m^{-2} d^{-1}, much lower than that found in Lake Hefner (3.66 mg m^{-2} d^{-1}). Since this represents an anoxic ***RR***, any aerobic P release is likely to be smaller. However, since hypolimnetic anoxia is not required for this mechanism to occur and since wind induced sediment resuspension can occur year round, the internal source has the potential to be much greater than if predicted by equation 2 as the product of ***RR*** and ***AF***. Since we cannot estimate the Lake Overholser internal load, and since BATHTUB predicts the observed water quality without an internal load, we will not include one in the model. BATHTUB can still be used to estimate impacts of decreasing external load.

Selection of Empirical Equations, Error Analysis 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 (Appendix: Tables A1-A2). After the model was set up with the selected empirical equations for each lake, BATHTUB water quality predictions were within 10% of observed values (Appendix: Tables A3-A4).

BATHTUB offers the user the option of comparing observed and predicted concentrations with T Statistics. 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 (Walker 1996). BATHTUB offers a suggested cutoff value for model applicability at an absolute value of 2, as this would indicate that it is highly unlikely (less than a 5% chance) that the area-weighted mean concentrations of the modeled reservoir are typical of those in the model development dataset (Walker, 1996). Nutrient estimates for Lake Hefner had good measures of error for the T2 and T3 statistics (Appendix: Tables A5-A6). This suggests that the BATHTUB model and model selections are applicable to the conditions at Lake Hefner and Overholser and error is low enough that it can be trusted with confidence for the purposes of preliminary BMP development. 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, Organic N and TP - Ortho-p, followed by calibration of Chl-*a* (Appendix: Tables A7-A8). For Lake Overholser, only calibration of the TN sub-model was actually needed to adequately predict Chl-*a* , with before and after calibration Chl-*a* concentrations of 33.7 and 35.1 µg L^{-1} respectively. However, calibration of the remaining chief parameters was still carried out so that the model would represent the data as well as possible and to correct an overestimation of TP - Ortho-p. Interestingly, Storm *et al*, 2007 found a similar underestimation of TP – Ortho-p during their BATHTUB modeling effort of Lake Overholser. As part of this process water balances were calculated in BATHTUB using the water balance terms previously described (inflow, outflow, evaporation, precipitation and change in storage) (Appendix: Tables A9-A10).

Results and Discussion

The objective of the BATHTUB model was to establish the impact that internal loading had on the two eutrophic waterbodies. The first step of this process was to calculate nutrient mass balances as predicted by each of the calibrated BATHTUB models for Lake Hefner (Tables 11 & 12) and Lake Overholser (Tables 13 & 14) and to assess the current influence of any internal P loads on Chl-*a*. Reductions of internal and external phosphorous loads were simulated to see the effect in-lake BMPs can have on Chl-*a* reduction.

Lake Hefner

The hydraulic residence time of Lake Hefner was estimated to be 1.97 years with a phosphorous residence time of 0.14 years (1.7 months) and a retention coefficient of 0.93 (Table 11). Phosphorous retention coefficient is defined as the fraction of the external P loading retained within the waterbody. According to the BATHTUB model, Lake Hefner retains about 93% of the phosphorous loaded into the lake, either in the water column or stored within the lake sediments. The only P exiting the reservoir does so in the form of drinking water withdrawal, or through the food web. There is a large internal P load, as calculated using equation 2 (Nurnberg, 2009), of 2437.2 kg P yr^{-1}. However, despite its size, this only accounts for 4.7% of the entire load and is dominated by the external P load from Bluff Creek Canal (4.96 x 10^4 kg P yr^{-1}), which accounts for 94.8% of the annual load. As mentioned earlier, this is a much greater external load than previously thought and likely represents a combination of issues. Firstly, previous estimates of P loads in the North Canadian River watershed have either concentrated modeling efforts in the region of El Reno and Calumet (Storm *et al*, 2007) and/or they have made use of BUMP data collected at El Reno. The more recently available data from Yukon, made available by OCC, shows P concentrations generally significantly higher than at either of these locations, indicating additional point or non-point sources downstream of El Reno (Figures 10-12). In addition, due to the necessity of sampling a very large number of waterbodies in the state, the BUMP sampling at El Reno is limited to 6-8 times annually. Estimates of P loads based on this quantity of data has the potential to significantly underestimate loads (Johnes, 2007) since it is impossible to sample representative flows across the entire flow record, especially if strong seasonal or flow influences exist.

Nitrogen loads were also dominated by Bluff Creek inputs which supplied 95.1% of the modeled N inputs (1.96 x 10^5 kg N yr^{-1}). The nitrogen residence time was slightly longer than that of phosphorus at 0.42 years (Table 11) and 78% of the nitrogen was either retained in the sediment and water column or lost through denitrification. Denitrification was not explicitly modeled but is likely to be partially accounted for in the nitrogen sedimentation model chosen in BATHTUB and cannot be distinguished from sedimentation using this method. Both observed and predicted results classified Lake Hefner as eutrophic with a TSI for Chl-*a* of 59.5; below the limit of 62 for Oklahoma's NLW listing.

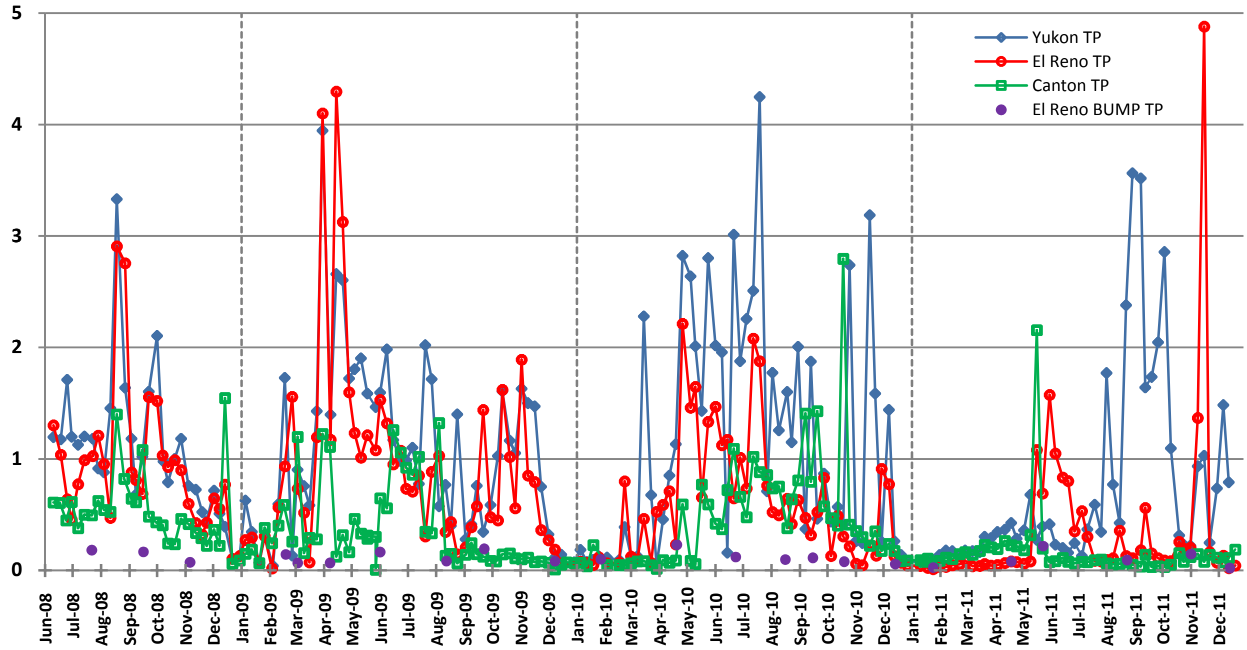

Figure 11 North Canadian River Total Phosphorus Concentrations (mg L^{-1}) at Yukon (hollow diamonds), El Reno (hollow circles = OCC data; solid circles= BUMP data) and Canton Lake (hollow squares).

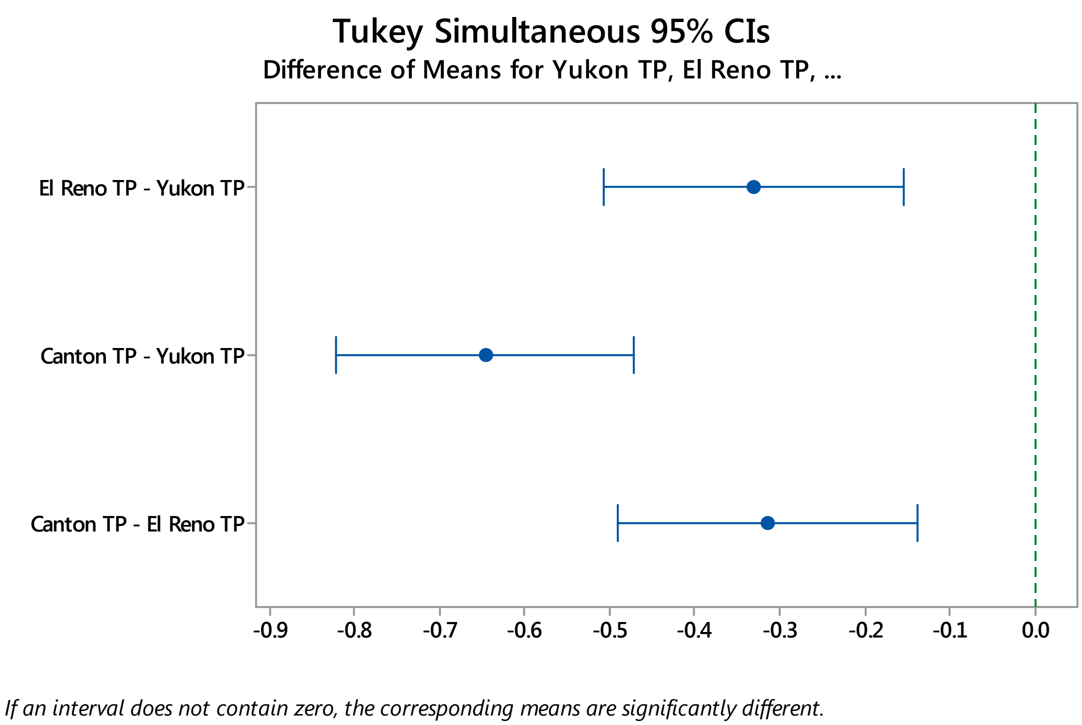

Figure 12 Results of a One Way ANOVA using Tukey's Simultaneous 95% Confidence Interval for the All Year Means (2008-2013) of Total Phosphorus Concentrations in the North Canadian River Measured at Yukon, El Reno and Canton Lake. Means are Statistically Different.

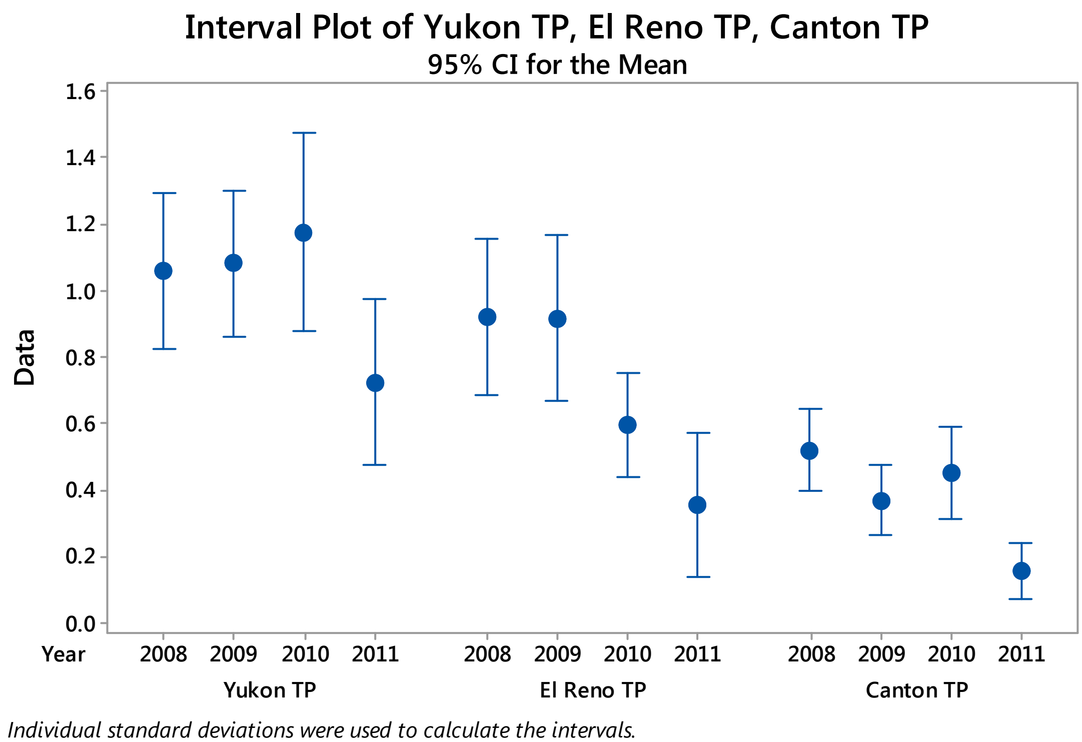

Figure 13 Interval Plot of North Canadian River Mean TP Concentrations (mg L^{-1}) at Yukon, El Reno and below Canton Lake.

Table 11 Lake Hefner Total Phosphorus Mass Balance Based Upon Predicted Outflow and Reservoir Concentrations.

TOTAL P	Load (kg yr^{-1})	%Total	Load Variance (kg $yr^{-1})^2$	%Total	CV	Conc. (mg m^{-3})	Export (kg km^{-2} yr^{-1})
PRECIPITATION	303.3	0.6%	2.30E+04	0.0	0.50	34.0	30.0
INTERNAL LOAD	2437.2	4.7%	0.00E+00		0.00		
TRIBUTARY INFLOW: Bluff Creek Canal	49638.8	94.8%	1.69E+08	100.0	0.26	873.0	
***TOTAL INFLOW	52379.3	100.0%	1.69E+08	100.0	0.25	796.1	5180.9
GAUGED OUTFLOW: Drinking Water Withdrawal	4281.4	8.2%	1.74E+06		0.31	79.3	
ADVECTIVE OUTFLOW	-625.7		1.80E+06		2.15	79.3	
***TOTAL OUTFLOW	3655.7	7.0%	2.90E+06		0.47	79.3	361.6
***STORAGE INCREASE	-52.6		2.52E+02		0.30	79.3	
***RETENTION	48776.2	93.1%	1.35E+08		0.24		
Overflow Rate (m yr^{-1})	4.5		Nutrient Resid. Time (yrs)			0.1353	
Hydraulic Resid. Time (yrs)	1.9670		Turnover Ratio			7.4	
Reservoir Conc. (mg m^{-3})	79		Retention Coef.			0.931	

Table 12 Lake Hefner Total Nitrogen Mass Balance Based Upon Predicted Outflow and Reservoir Concentrations

TOTAL N	Load (kg yr^{-1})	%Total	Load Variance (kg yr^{-1})^2	%Total	CV	Conc. (mg m^{-3})	Export (kg km^{-2} yr^{-1})
PRECIPITATION	10110.0	4.9%	2.56E+07	1.0%	0.50	1132.0	1000.0
TRIBUTARY INFLOW: Bluff Creek Canal	196167.0	95.1%	2.57E+09	99.0%	0.26	3450.0	
***TOTAL INFLOW	206277.0	100.0%	2.59E+09	100.0%	0.25	3135.3	20403.3
GAUGED OUTFLOW: Drinking Water Withdrawal	52694.2	25.5%	2.73E+08		0.31	976.0	
ADVECTIVE OUTFLOW	-7701.2		2.94E+08		2.23	976.0	
***TOTAL OUTFLOW	44993.0	21.8%	2.89E+08		0.38	976.0	4450.3
***STORAGE INCREASE	-647.3		2.03E+04		0.22	976.0	
***RETENTION	161931.3	78.5%	1.59E+09		0.25		
Overflow Rate (m yr^{-1})	4.5		Nutrient Resid. Time (yrs)			0.4229	
Hydraulic Resid. Time (yrs)	1.9670		Turnover Ratio			2.4	
Reservoir Conc. (mg m^{-3})	976		Retention Coef.			0.785	

Lake Overholser

The hydraulic residence time of Lake Overholser was estimated to be 1.31 years with a phosphorous residence time of 0.16 years (1.9 months) and a retention coefficient of 0.87 (Table 13). The P turnover ratio was 6.1. Like in Lake Hefner, the P load was dominated by tributary inputs from the North Canadian River which supplied 99.2% of the modeled P inputs (2.45 x 10^4 kg P yr^{-1}.). The only P exiting the reservoir does so in the form of drinking water withdrawal (2109.0 kg P yr^{-1}), through the spillway when it is operational (1726.4 kg P yr^{-1}), or through the food web. The N loads were also dominated by tributary inputs from the North Canadian River which supplied 93.5% of the modeled N inputs (9.29 x 10^5 kg N yr^{-1}) (Table 14). Both in this study and in the study by Storm et al, 2006, N inputs were dominated by Organic N with very low levels of nitrate in tributary waters. Both observed and predicted results classified Lake Overholser as eutrophic with a TSI for Chl-*a* of 65.5; sufficient for the lake to remain on Oklahoma's list of NLWs.

Table 13 Lake Overholser Total Phosphorus Mass Balance Based Upon Predicted Outflow and Reservoir Concentrations with an Internal Load of 0 mg m^2 d^{-1} (no internal load).

TOTAL P	Load (kg yr^{-1})	%Total	Load Variance (kg yr^{-1})^2	%Total	CV	Conc. (mg m^{-3})	Export (kg km^{-2} yr^{-1})
PRECIPITATION	192.9	0.8	9.30E+03	0.0	0.50	33.7	30.0
INTERNAL LOAD	-	-	-	-	-	-	-
TRIBUTARY INFLOW: North Canadian River	24514.0	99.2	8.51E+08	100.0	1.19	1190.0	
***TOTAL INFLOW	24706.9	100.0	8.51E+08	100.0	1.18	938.7	3843.3
GAUGED OUTFLOW: Drinking Water Withdrawal and spillway	3835.5	15.5	2.27E+06		0.67	233.3	
ADVECTIVE OUTFLOW	-686.7	4.6	1.02E+07		2.81	233.3	177.3
***TOTAL OUTFLOW	3148.7	12.7	1.06E+07		1.03	233.3	489.8
***STORAGE INCREASE	-60.0		8.35E+02		0.48	233.3	
***RETENTION	21618.1	87.5	6.95E+08		1.22		
Overflow Rate (m yr^{-1})	2.1		Nutrient Resid. Time (yrs)			0.1639	
Hydraulic Resid. Time (yrs)	1.3110		Turnover Ratio			6.1	
Reservoir Conc. (mg m^{-3})	233		Retention Coef.			0.875	

Table 14 Lake Overholser Total Nitrogen Mass Balance Based Upon Predicted Outflow and Reservoir Concentrations.

TOTAL N	Load (kg yr^{-1})	%Total	Load Variance (kg yr^{-1})^2	%Total	CV	Conc. (mg m^{-3})	Export (kg km^{-2} yr^{-1})
PRECIPITATION	6428.5	6.5	1.03E+07	0.3%	0.50	1123.6	1000.0
TRIBUTARY INFLOW: North Canadian River	92906.0	93.5	3.85E+09	99.7%	0.67	4510.0	
***TOTAL INFLOW	99334.5	100.0	3.87E+09	100.0%	0.63	3773.9	15452.2
GAUGED OUTFLOW: Drinking Water Withdrawal and spillway	22213.7	22.4	1.11E+08		0.59	1351.2	
ADVECTIVE OUTFLOW	-3977.2		3.62E+08		4.78	1351.2	
***TOTAL OUTFLOW	18236.5	18.4	5.34E+08		1.27	1351.2	2836.8
***STORAGE INCREASE	-347.4		2.84E+04		0.49	1351.2	
***RETENTION	81445.5	82.0	1.64E+09		0.50		
Overflow Rate (m yr^{-1})	2.1		Nutrient Resid. Time (yrs)			0.236	
Hydraulic Resid. Time (yrs)	1.31		Turnover Ratio			4.2	
Reservoir Conc. (mg m^{-3})	1351		Retention Coef.			0.820	

In-Lake BMP Options and Feasibility

Introduction

While in general, most 'internal' phosphorous loading in Oklahoma is generated through the result of a phosphorus rich sediment bed exposed to anoxic conditions, this was not the case for Lake Overholser. Two different schema's must be taken to properly evaluate potential BMPs for Lake Hefner and Lake Overholser. In both cases, since the external load is so dominant, any potential gains are limited. However, in the case of Lake Hefner, these gains still offer appreciable reductions in the total load and could be useful as an overall strategy to reduce both external and internal loads. Predicted water quality responses to BMP implementation maintain the same assumptions as when modeled without BMP implementation.

Lake Hefner

At Lake Hefner, the second greatest load of phosphorus to the lake is generated through sediment phosphorous release under strong reducing conditions due to the anoxia that develops under summer stratification. The primary purpose of the proposed in-lake BMPs are to treat anoxic conditions in the hypolimnion minimizing or eliminating sediment phosphorous release generated under anoxic conditions. Elimination of sediment phosphorous release in the reservoir should push the system towards phosphorous limitation reducing algal biomass in the reservoir particularly during the summer period and further drive the system to the desirable phosphorous limited conditions.

Methods of managing anoxic/hypoxic conditions usually include artificial circulation/fine bubble diffusion, direct oxygenation of the hypolimnion, and depth selective withdrawal. Due to the lack of releases at Lake Hefner and lack of a conventional spillway system, traditional depth selective withdrawal is not a viable option. However, preferential drinking water withdrawal from deeper, nutrient rich waters is an option. Included is an analysis of the effect that reducing external phosphorus load can have on lake P and Chl-*a* concentrations. Each action alternative has different benefits and risks along with a recommendation. These are summarized in Table 15. Only depth selective drinking water withdrawal is recommended unless reductions in the external loading of P is also considered.

Table 15 Lake Hefner BMP Recommendation Summary

Option	Benefit	Risk	Recommendation
Depth selective drinking water withdrawal	Direct reduction in P via removal of P rich waters & reduced chance of summer/autumn algal blooms. Minimal costs.	Possibility of destratification	Yes
Artificial circulation	Potential decreased internal P load and reduced hypolimnic anoxia while system operates	Potential increase in internal P loading and transport of nutrients to the epilimnion	No
Hypolimnetic oxygenation	Decreased internal P load and reduced hypolimnic anoxia while system operates	None	Not unless as part of a strategy that also targets external loads
Aluminum Sulfate Treatment	Decreased internal P load (estimated 1-7 years)	Potential risks to aquatic life	Not unless as part of a strategy that also targets external loads

Depth Selective Withdrawal

Depth selective withdrawal is perhaps both the easiest and cheapest option for reducing the phosphorus levels in the Lake Hefner. Selective withdrawal in this case would entail pulling raw drinking water from the deepest layers of the lake during the summer; removing nutrient rich hypolimnetic water from resuspension at fall turnover. During the summer months phosphorus (both TP and Ortho-p) accumulates in the hypolimnion, in concentrations as high as 393 µg L^{-1} (measured at 22 m depth, August 2013). The April-September 2013 mean TP concentrations in the 12-22 m and 20-22 m depth zones were 172.7 and 240.5 µg L^{-1}, respectively. Preferential withdrawal of this nutrient rich water could reduce the overall phosphorus loads in the lake. Although, this would not directly impact the available phosphorus in the photo-active summer epilimnion, it would lead to a much reduced phosphorus input to the epilimnion when the lake de-stratifies in the autumn. In addition, the annual phosphorus removal via drinking water extraction could increase from 4281 kg yr^{-1} to either 7280 kg yr^{-1} (withdrawal of water from 12-22 m) or 9459 kg yr^{-1} (withdrawal of water from 20-22 m), based on the historic drinking water usage (2000-2012) from Lake Hefner, the 2013 phosphorus concentrations and assuming preferential withdrawal from deeper waters during the April-September period. An additional benefit may be the drawdown of more oxic waters which may reduce some of the anoxic phosphorus release. In this manner drawdown is likely to reduce the duration of stratification. These loads would vary annually depending on drinking water usage, phosphorus loads and the extent of summer hypolimnion anoxia. In addition, the withdrawal of this nutrient rich water through the season would tend to limit the buildup to the very high peak concentrations seen in mid- to late-summer. Although, it is not possible to model the reduction in phosphorus loads using BATHTUB, it would help move the system towards a phosphorous limited state with a potential reduction in the likelihood of, late summer and autumn, blue-green algae blooms. Use of this phosphorus rich water may require treatment to reduce phosphorus levels before distribution to public or commercial users. However, such considerations are beyond the scope of this report which is primarily concerned with the water quality of the lakes. It should also be noted that these concentrations are below those found in Lake Overholser surface waters (mean 233.3 $\mu g\ L^{-1}$) which are often used for water supply to Oklahoma City. Costs for this option would depend on the exact set up of the current withdrawal system but are likely minimal. Overall, this BMP is recommended for the reduction of the internal, and overall, load of P in Lake Hefner.

Artificial Circulation (Fine Bubble Diffusion)

Artificial Circulation is a method of aeration that disrupts thermal stratification within the lake generally through the use of fine bubble diffusers bringing atmospheric oxygen throughout the entire water column. The result, if done properly, is sufficient distribution of oxygen to satisfy sediment oxygen demand in the deep areas of the lake with elimination of stagnant zones subject to algal blooms. While oxygen is provided through the gas air bubbles, a larger mass of oxygen is transferred downward through increased availability of atmospheric oxygen to the bottom of the reservoir.

Fine bubble diffusion is achieved 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 needs to be sufficient in creating convectional forces in the lake strong enough to break density differences in the water column but not so strong that strong upwelling currents are induced.

The problem with artificial circulation in reservoirs is that if undersized or oversized, the very problems it sets to fix are exacerbated. When artificial circulation is undersized, anoxic zones form and sediment phosphorous release still occurs. The artificial currents in the reservoir upwell these released nutrients, increasing their availability in the photic zone further fueling algal growth. When oversized, a large current is generated in the reservoir that sweeps water along the sediment surface stirring the lake bottom, increasing availability of sediment bound nutrient to the surface (OWRB 1999). Lastly, artificial circulation has the ability to increase heat to the bottom of the reservoir through the elimination of the natural strata's that form in reservoirs, eliminating the cold water refuge needed for some fish species known to reside in the reservoir.

Oklahoma City has attempted whole lake aeration from the 1980's through the late 1990's. This system was diagnosed as overpowered by a factor of 2.8 (Lorenzen and Fast 1977). The additional power was cited as entraining nutrients from the sediment to the surface, also potentially decreasing phytoplankton sedimentation rates.

For the ecological reasons stated above artificial circulation would not be recommended for use in Lake Hefner based on its history of use in Oklahoma and the potential to cause more harm if done improperly.

Hypolimnetic Oxygenation

Hypolimnetic oxygenation involves providing oxygen directly to the hypolimnion without mixing or disruption of the lakes natural stratification pattern. When done properly the systems offer only positive impacts on the ecology of the system, with none of the negative side effects that whole lake aeration can cause because stratification is not broken and upwelling currents are not generated. This is in effect a no-harm BMP in that, if hypolimnetic oxygen demand is greater than expected and sediment phosphorous release is generated there will be no increased availability of these nutrients in the epilimnion, and the addition of oxygen will only decrease the amount of sediment P release that is generated in the system through a summer season.

There are many methods to deliver oxygen for hypolimnetic oxygenation, the most well known methods include using a contact chamber, a shore based super-saturated deliver system (SDOX), or linear diffuser system.

Contact chamber oxygenation uses a Speece Cone system where pure oxygen is injected into the top of a submerged cone with bottom waters which is pumped into a cone with a submerged pump. Highly oxygenated water is discharged out the bottom of the cone. The advantage of this system is that it can be scaled to any size, and meet any hypolimnetic oxygen demand. Rate of oxygen addition can be easily controlled and oxygen can be distributed at the sediment-water interface. The disadvantage of the system is that it relies on a submersible pump and requires submerged electrical lines to power the chamber.

A shore based super-saturated dissolved oxygen system is another method of hypolimnetic oxygenation. It is a layer oxygenation technique which withdraws water from the hypolimnion, supersaturates it with oxygen to about 300% concentration, and reinjects the water back into the hypolimnion (Figure 13). The SDOX differs from hypolimnetic aeration techniques, in that pure oxygen is dissolved in withdrawn hypolimnetic waters before reinjection. With oxygen in solution, no bubbles are formed, and hence no mixing or upwelling will occur, and no oxygen is lost to the atmosphere or to the oxygenated epilimnetic layer under stratified conditions. This technology was implemented at Lake Thunderbird in 2010, and has been operating in the reservoir for the past 4 years. The system appears to be undersized for the reservoir with anoxic conditions developing under peak hypolimnetic oxygen demand conditions, nonetheless, the system has been very successful in reducing sediment phosphorous release and late summer algal blooms. Peak Chl-*a* has been reduced by over half since operation of the unit has begun (OWRB 2013). The disadvantage of this technology is that it is relatively new to the industry with the unit at Lake Thunderbird being the first permanently installed system in the United States for limnological application. With its novel application, mechanical failures have occurred and frequent downtime has been experienced, limiting its ability to treat hypolimnetic waters during the period of need.

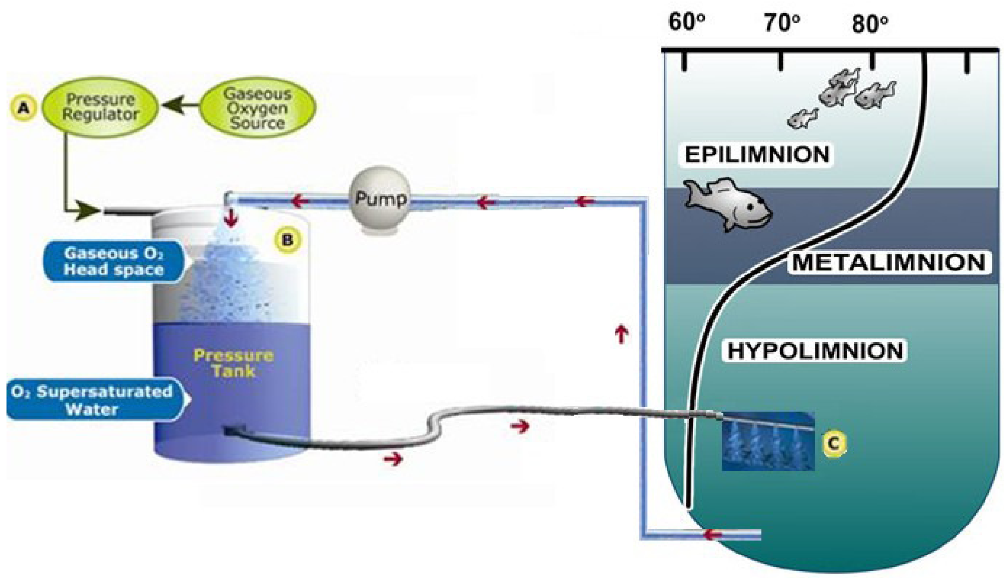

Figure 14 Conceptual Illustration of the SDOX System at Lake Thunderbird.

The last method of hypolimnetic oxygenation discussed is through linear diffuser systems. In this method direct oxygen is slowly discharged through a linear diffuser system. Large-scale systems (>100 tons per day of oxygen) are in operation by Tennessee Valley Authority and US Army COE in large power generation reservoirs in the southern United States. With linear diffuser systems efficiency, some upwelling currents are generated but in general are small and do not break stratification. These systems are best suited for very deep reservoirs where increased contact time with oxygen bubbles occur in the hypolimnion. Because the bubbles ascend vertically upon diffusion of oxygen, the efficiency of the system is substantially less than the contact chamber or super-saturation injection technologies which approach 100%. Use of bubbles also reduces its ability to oxygenate sediment; particularly those with high oxygen demand such as exist at Lake Hefner.

Because of these reasons contact chamber technology or super-saturated delivery systems would be the most desirable of the hypolimnetic oxygenation BMPs for internal phosphorous reduction in Lake Hefner. However, these should only be considered alongside the need to reduce external phosphorus loading to both lakes. Estimated costs for this option would be $267,000 for the actual system and $350,000 for installation and engineering. Additionally, oxygen for the system would cost \$40,000 per year, giving a final cost of \$1,017,000 over 10 years or \$1,417,000 over 20 years. This would not include all operational costs such as electricity and maintenance.

The affect of any of the BMPs designed to reduce internal P loads on lake phosphorus and Chl-*a* concentrations can be seen in Figures 14 & 15**.** If the BMP is 100% successful then a 100% reduction in internal load could be expected with a reduction in the Chl-*a* and TP concentrations to 18.7 µg L^{-1} and 77.3 µg L^{-1}, respectively. These figures also demonstrate implications under situations of increasing internal load, for instance, if increased hypolimnetic anoxia were to occur.

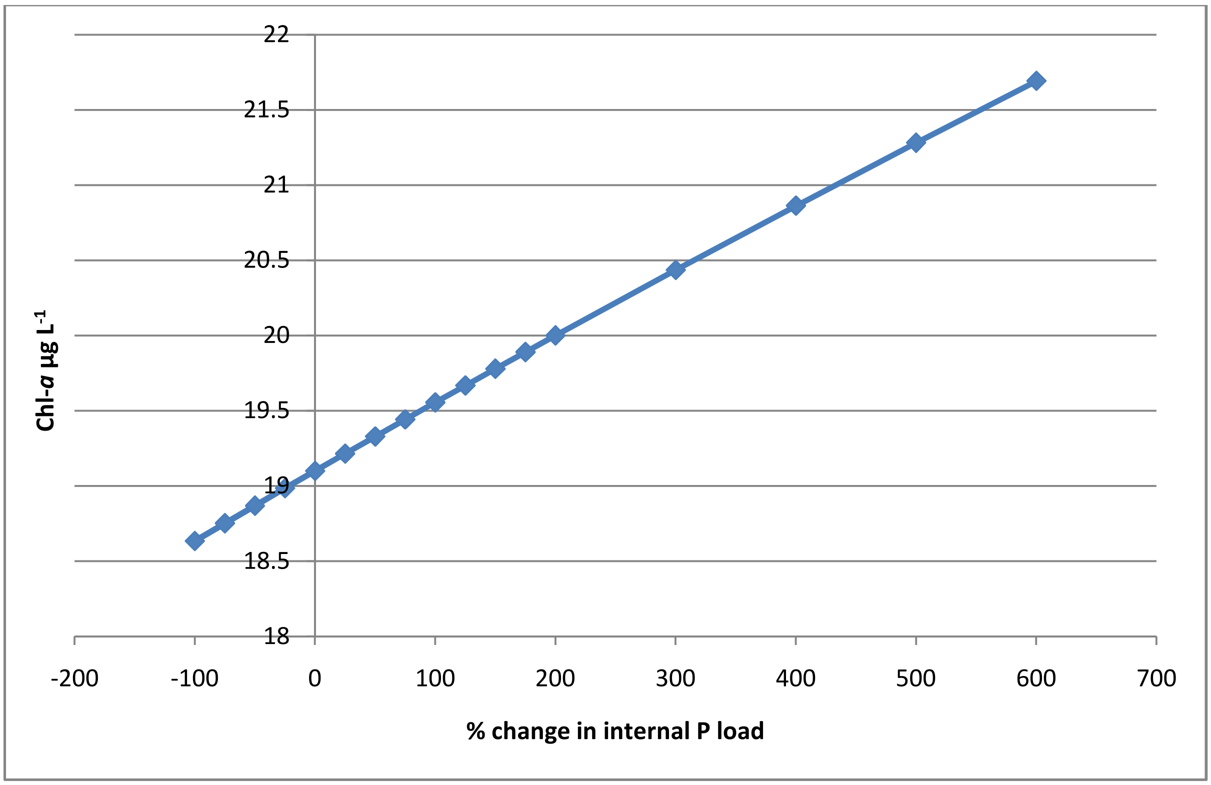

Figure 15 Lake Hefner % Change in Internal P Load and Effect on Lake Chl-a Concentrations (µg L^{-1}).

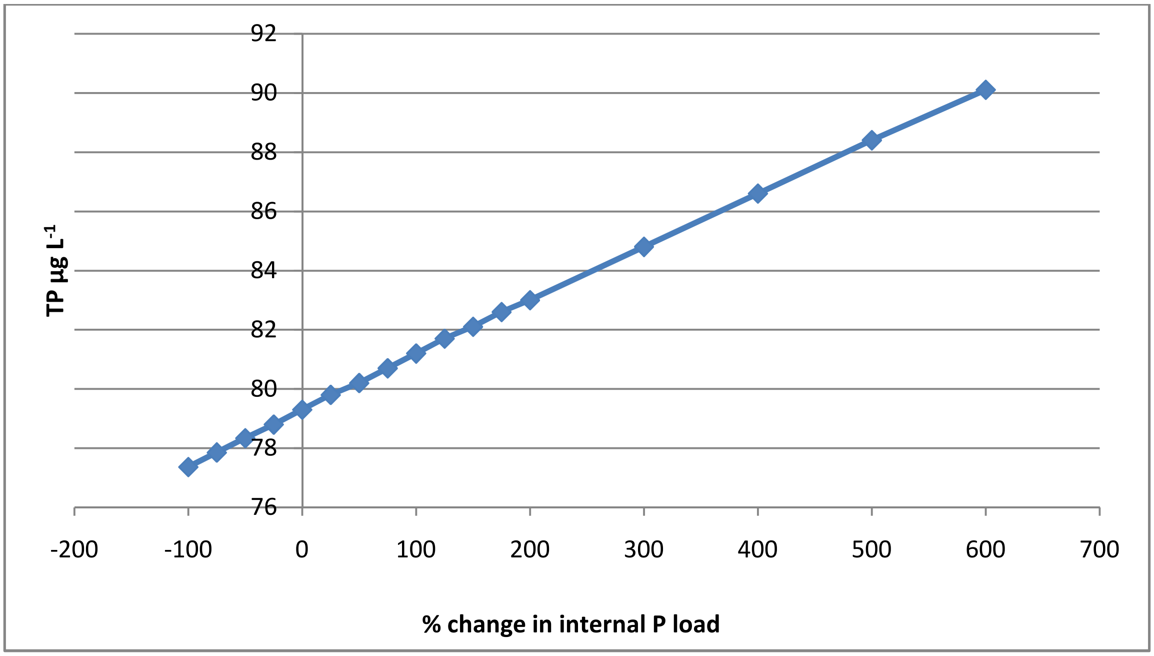

Figure 16 Lake Hefner % Change in Internal P Load and Effect of Lake TP Concentrations (µg L^{-1}).

Nutrient Inactivation by Aluminum Sulfate Treatment

Nutrient inactivation by application of a compound such as aluminum sulfate (alum) is also a restorative alternative which does offer relief to the internal loading observed. As a rule of thumb, this method is not recommended to mainstream reservoirs without pristine watersheds. As an off-channel reservoir, this method has merit, and would present as a treatment to permanently bind sediment phosphorous.

Application of this method to the nutrient rich sediment in the 15 m to 23 m depth zone would produce benefits. A prescription for alum treatment in this zone of the lake has been developed following a protocol given in Cooke *et al.* (1993) and examined in phase 1 work for Lake Hefner (OWRB 1999).

In general, alum applications yield effective phosphorous control for 1-5 years in mainstream reservoirs. In a reservoir like Lake Hefner, where no water is released and a very low sedimentation rate is observed, this may allow for a slightly longer effective timeframe to be achieved. Lake water quality impacts would be expected to be similar to those represented in Figures 14 & 15. However, sedimentation of dead algae, and other organic sources, would undoubtedly recharge the lake with organic rich sediment over time. Furthermore, in light of the large external phosphorus load, this BMP should only be considered as part of a watershed based strategy to reduce phosphorus loading. Dosage assumptions were based on water quality alkalinity and pH, morphometry, and an alum composition of eighteen molecules water per one aluminum molecule. All calculations were conservative to allow for a maximum estimate of cost to be made. Wet dosage was based on a 48.5% alum by weight and 600 pounds per 55 gallons drum as per the manufacturer.

An additional benefit of alum is the precipitation of nutrients from the water column at the time of treatment. This would result in exceptional short term water quality.

Lake Overholser BMP Options and Feasibility

At Lake Overholser, the greatest potential, but undetected source of, internal phosphorous load comes from resuspension of nutrient rich sediment. Due to the extremely shallow and wind mixed nature of the system, stratification rarely develops and rates of anaerobically mediated sediment phosphorous release are low and so a separate set of in-lake BMPs must be evaluated for reduction of internal nutrient loads to Lake Overholser. Three methods to achieve this are discussed. Each action alternative has different benefits and risks along with a recommendation and are summarized in Table 16. No in-lake BMP is recommended for Lake Overholser unless reductions in the external loading of P are also considered.

Table 16 Lake Overholser BMP Recommendation Summary

Option	Benefit	Risk	Recommendation
Dredging	Removal of P containing sediments and reservoir deepening leading to less resuspension	Temporary increase in internal load during dredging activities	Not unless as part of a strategy that also targets external loads
Aluminum Sulfate Treatment	Decreased internal P load (estimated 1-7 years)	Potential risks to aquatic life	Not unless as part of a strategy that also targets external loads
Revegetation/Floating Wetlands	Biotic uptake of available P, reduction in sediment resuspension	Potential increase in sediment P release	Not unless as part of a strategy that also targets external loads

Dredging

Dredging in Lake Overholser could achieve reduction in internally loaded phosphorous by two means; reduction of wind resuspension through deepening of the reservoir, and removal of nutrient rich deposited sediment in the reservoir deep enough to expose less nutrient rich parent material sediment. However, due to the urban location of Lake Overholser, there is no suitable dewatering pond location nearby and dredged material would have to be transported offsite, increasing the cost of this already expensive mitigation option. Although this BMP has the potential to improve water quality in the long term, a short term increase in internal P loading and turbidity would be expected. Also, with a continued large external phosphorus load, water quality improvements could be minimal. Therefore, this BMP is not recommended without an effort to also reduce the external P load. Additionally, this option is not favored by the City of Oklahoma City (pers. comm. OKC 2014).

Aluminum Sulfate Treatment

The costs for alum treatment in Lake Overholser would be similar to those in Lake Hefner. Reductions in any internal load would be expected along with continued stripping of P from the water column until any resuspended alum reaches its P binding capacity. However, due to the limitations in detecting any internal P load in Lake Overholser during this project, the impact on water quality that this BMP might have cannot be modeled here and so cannot be recommended.

Revegetation and/or Floating Wetlands to Reduce Hydrodynamic Disturbance

Wu and Hua (2014) have shown wetland vegetation is able to reduce sediment resuspension and phosphorus release in shallow lakes. This BMP could involve both planting native wetland species on the shoreline and/or the creation and planting of floating wetlands. Oklahoma experience has shown floating wetlands to be a practicable application. Conclusions from one application in Oklahoma have shown this action will provide multiple benefits: fish & wildlife habitat, direct water quality improvement while also serving as a breakwater facility (OWRB 2013b). Strategic placement of the wetlands may reduce wind-induced sediment resuspension by reducing fetch length. However, assessment of such would require a specific modeling effort coupled with knowledge of sediment P release which was beyond the scope of this report. One acre of floating wetlands could be deployed at a cost of $1,020,938. Although, this is a relatively small area, these wetlands can act as founder colonies, supplying seeds and propagules to other areas around the shore and increasing the effectiveness of this BMP in successive years. Due to the large monetary costs of this BMP and lack of modeling to support theorized water quality improvements, this BMP is not recommended without an effort to also reduce the external P load which would continue to have a dominate influence on Lake Overholser water quality.

Watershed Management: Impacts of External Nutrient Loads

As discussed throughout this report, the external nutrient loads to both lakes are much higher than previously thought. This is apparent in the weekly water quality data from Yukon and El Reno as provided by OCC (Figures 10-12). Storm *et al*, (2013) describe watershed management efforts designed to reduce the impact of non-point (mainly agricultural) sources on the water quality of the middle North Canadian basin. There is some evidence that these efforts have had an impact on the TP loads (Figure 12), especially as measured below Canton Lake and at El Reno. However, the loads at Yukon showed less of a response and OCC discontinued monitoring there at the end of 2011 in order to concentrate their efforts at El Reno and Canton Lake (pers. comm. OCC 2014). Urban growth, with an associated growth in point sources, is high in the area with continual development in the cities of El Reno and Yukon. It is unlikely that nutrient loads will further decrease without an effort to tackle both urban and rural point sources within the watershed. Furthermore, with the discontinuation of the OCC monitoring effort at Yukon there is no direct way to gauge potential decreases (or increases) in nutrient loads to either lake, and modeling efforts would be hampered by lack of supporting water quality and discharge information. Despite this, the potential improvements to lake water quality from reducing catchment nutrient loads are great. Using BATHTUB to model these load reductions, we see a decrease of Chl-*a* in Lake Hefner from 19.1 to 5 mg L^{-1} following a 90% reduction in external nutrient loads (TP = 87.3 µg L^{-1}, TN = 345 µg $L^{-1}$and inorganic N = 50.2 µg L^{-1}) (Figure 16). With just a reduction in TP (87.3 µg L^{-1}) we see a Chl-*a* decrease from 19.1 to 11.4 mg L^{-1}. In Lake Overholser, a similar 90% nutrient load reduction (TP= 119 µg L^{-1}, TN= 451 µg $L^{-1}$and inorganic N= 50.2 µg L^{-1}) would give a decrease of Chl-*a* from 35.1 to 8.1 mg L^{-1} (Figure 17).

However, the reverse of this is also true in that BATHTUB indicates an increase of Chl-*a* with increasing nutrient loads. With a 200% increase in nutrient loads to Lake Hefner (TP=2619 µg L^{-1}, TN= 10350 µg $L^{-1}$and inorganic N=1506 µg L^{-1}) the Chl-*a* levels climb to 25.6 mg L^{-1}. In Lake Overholser a similar load increase could give Chl-*a* levels of 57.0 mg L^{-1}.

Such an increase in nutrient loading is not improbable considering the increasing urban development in the watershed and the lack of requirement for discharger monitoring of nutrients.

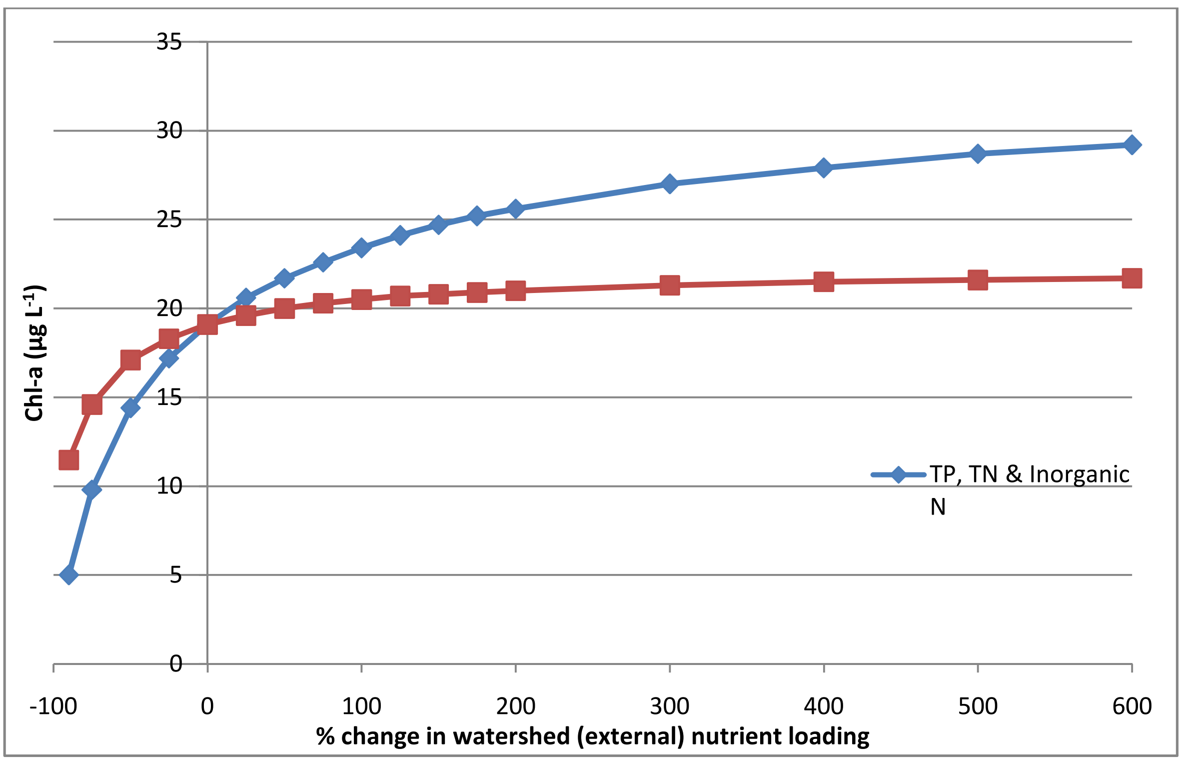

Figure 17 Lake Hefner Chl-*a* Response to % Changes in Watershed Nutrient Loads.
Red squares = change in TP load only, blue diamonds = change in TP, TN and inorganic N loads

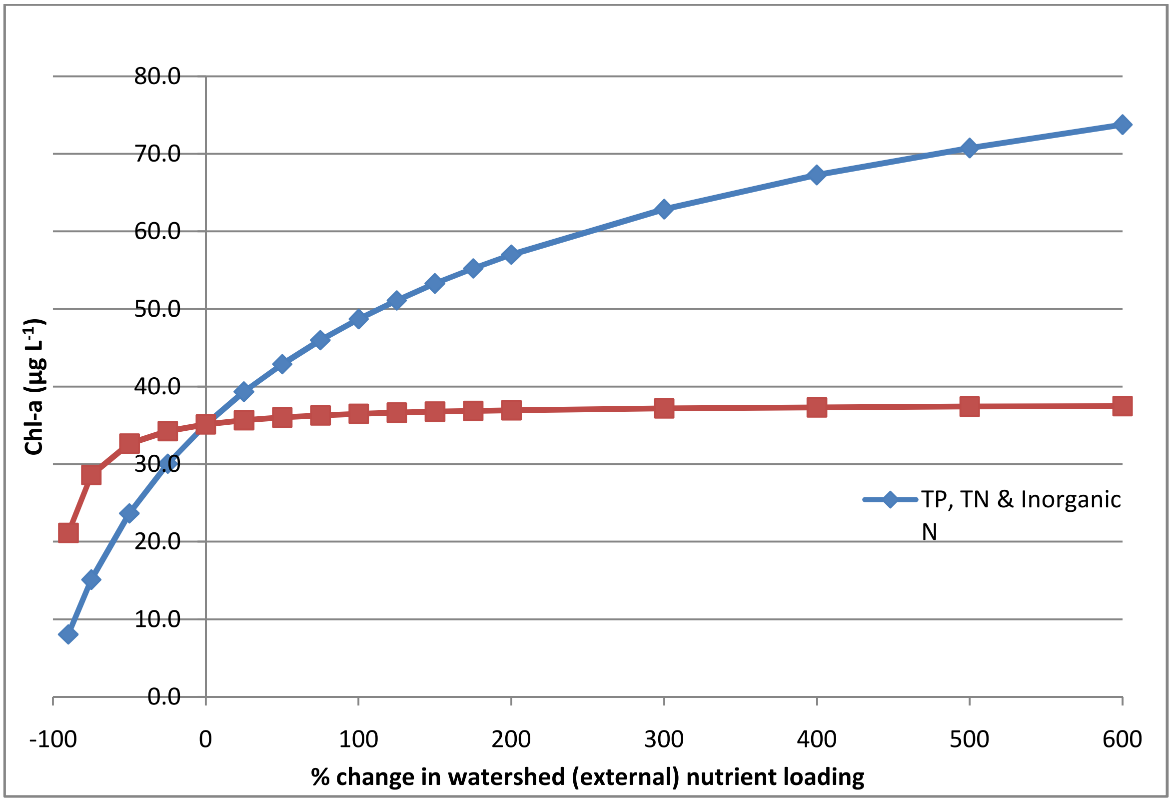

Figure 18 Lake Overholser Chl-a Response to % Changes in Watershed Nutrient Loads. Red squares = change in TP load only, blue diamonds = change in TP, TN and inorganic N loads

Conclusion

This project determined the greatest impact on water quality in both Lakes Hefner and Overholser is the nutrient loads in the North Canadian River, outweighing internal sediment sourced nutrients. In-lake BMP implementation may reduce internal P loading and improve water quality in both lakes, but these effects will be relatively moderate considering the extent of external P sources. This was shown for Lake Hefner using the BATHTUB model to simulate a reduction in internal loading. Significant improvements to both lake's water quality could be achieved if the external loads are reduced, however, there is currently inadequate monitoring of this load as the most applicable monitoring effort (OCCs monitoring at Yukon, OK) has been discontinued. Any future improvements to lake water quality are dependent on increased awareness and management of watershed nutrient loads and so, all in-lake BMPs should only be considered alongside watershed based BMPs.

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Appendix A:

Table A1: Description of BATHTUB Model Equations for Lake Hefner.

Model Options	Code	Description
Conservative Substance	1	COMPUTED
Phosphorus Balance	3	2ND ORDER, FIXED
Nitrogen Balance	2	2ND ORDER, DECAY
Chlorophyll-a	1	P, N, LIGHT & T
Secchi Depth	1	VS. CHLA & TURBIDITY
Dispersion	1	FISCHER-NUMERIC
Phosphorus Calibration	1	DECAY RATES
Nitrogen Calibration	1	DECAY RATES
Error Analysis	1	MODEL & DATA
Availability Factors	0	IGNORE
Mass-Balance Tables	1	USE ESTIMATED CONCS
Output Destination	2	EXCEL WORKSHEET

Table A2: Description of BATHTUB Model Equations for Lake Overholser.

Model Options	Code	Description
Conservative Substance	1	COMPUTED
Phosphorus Balance	1	2ND ORDER, FIXED
Nitrogen Balance	3	2ND ORDER, DECAY
Chlorophyll-a	1	P, N, LIGHT & T
Secchi Depth	1	VS. CHLA & TURBIDITY
Dispersion	1	FISCHER-NUMERIC
Phosphorus Calibration	1	DECAY RATES
Nitrogen Calibration	1	DECAY RATES
Error Analysis	1	MODEL & DATA
Availability Factors	0	IGNORE
Mass-Balance Tables	1	USE ESTIMATED CONCS
Output Destination	2	EXCEL WORKSHEET

Table A3: Initial (uncalibrated) Predicted and Observed Nutrient Values for Lake Hefner Ranked against BATHTUB's CE Model Development Dataset.

	Predicted Values			Observed Values		
Variable	**Mean**	**CV**	**Rank**	**Mean**	**CV**	**Rank**
CONSERVATIVE SUB	150540.3	0.47		143689.0	0.11	
TOTAL P MG/M3	74.1	0.24	68.6%	79.3	0.30	71.2%
TOTAL N MG/M3	906.0	0.25	43.8%	992.0	0.22	49.4%
C.NUTRIENT MG/M3	48.0	0.20	64.4%	52.5	0.26	68.6%
CHL-a MG/M3	10.3	0.66	55.0%	19.1	0.61	82.2%
SECCHI M	0.9	0.44	42.0%	0.8	0.33	32.7%
ORGANIC N MG/M3	454.7	0.34	46.7%	787.0	0.22	84.0%
TP - ORTHO-p MG/M3	33.8	0.41	54.9%	43.7	0.46	65.3%
HOD-V MG/M3-DAY	59.7	0.48	36.6%			
MOD-V MG/M3-DAY	63.1	0.47	45.8%			
ANTILOG PC-1	325.1	0.55	58.5%	640.9	0.41	76.9%
ANTILOG PC-2	5.8	0.60	42.1%	8.3	0.48	69.0%
(N - 150) / P	10.2	0.39	22.7%	10.6	0.39	24.5%
INORGANIC N / P	11.2	0.74	16.3%	5.8	1.61	4.9%
TURBIDITY 1/M	0.8	0.63	63.2%	0.8	0.63	63.2%
ZMIX * TURBIDITY	6.1	0.83	80.5%	6.1	0.83	80.5%
ZMIX / SECCHI	8.1	0.59	81.7%	9.8	0.62	89.0%
CHL-a * SECCHI	9.6	0.83	46.5%	14.7	0.69	69.6%
CHL-a / TOTAL P	0.1	0.68	29.7%	0.2	0.68	62.7%
FREQ(CHL-a>10) %	39.9	1.03	55.0%	76.8	0.38	82.2%
FREQ(CHL-a>20) %	8.5	1.92	55.0%	35.0	1.03	82.2%
FREQ(CHL-a>30) %	2.1	2.50	55.0%	15.0	1.55	82.2%
FREQ(CHL-a>40) %	0.6	2.92	55.0%	6.7	1.95	82.2%
FREQ(CHL-a>50) %	0.2	3.24	55.0%	3.1	2.28	82.2%
FREQ(CHL-a>60) %	0.1	3.51	55.0%	1.6	2.56	82.2%
CARLSON TSI-P	66.2	0.05	68.6%	67.2	0.06	71.2%
CARLSON TSI-CHL-a	53.5	0.12	55.0%	59.5	0.10	82.2%
CARLSON TSI-SEC	61.1	0.10	58.0%	63.8	0.07	67.3%

Table A4: Initial (uncalibrated) Predicted and Observed Nutrient Values for Lake Overholser Ranked against BATHTUB's CE Model Development Dataset.

	Predicted Values			Observed Values		
Variable	Mean	CV	Rank	Mean	CV	Rank
CONSERVATIVE SUB	183603.9	0.40		130720.0	0.51	
TOTAL P MG/M3	233.7	0.58	96.1%	233.3	0.48	96.1%
TOTAL N MG/M3	1232.3	0.35	62.7%	1351.2	0.49	68.0%
C.NUTRIENT MG/M3	84.1	0.35	85.8%	92.0	0.48	88.2%
CHL-a MG/M3	31.0	0.66	94.0%	35.1	0.77	95.7%
SECCHI M	0.2	0.67	0.8%	0.3	0.47	3.8%
ORGANIC N MG/M3	1235.1	0.32	97.0%	1218.9	0.51	96.8%
TP - ORTHO-p MG/M3	167.9	0.51	96.5%	81.6	0.65	85.4%
HOD-V MG/M3-DAY	675.1	0.46	99.8%			
MOD-V MG/M3-DAY	350.1	0.46	98.9%			
ANTILOG PC-1	2611.5	0.59	96.5%	2345.7	0.58	95.8%
ANTILOG PC-2	4.2	0.79	20.9%	6.2	0.62	46.8%
(N - 150) / P	4.6	0.75	2.8%	5.1	0.72	4.0%
INORGANIC N / P	0.0	190.57	0.0%	0.9	6.85	0.0%
TURBIDITY 1/M	4.9	0.84	99.1%	4.9	0.84	99.1%
ZMIX * TURBIDITY	6.6	0.94	82.8%	6.6	0.94	82.8%
ZMIX / SECCHI	7.6	0.78	78.8%	4.7	0.63	49.6%
CHL-a * SECCHI	5.4	1.15	18.7%	9.9	0.90	48.2%
CHL-a / TOTAL P	0.1	0.86	27.0%	0.2	0.90	33.9%
FREQ(CHL-a>10) %	93.5	0.15	94.0%	95.7	0.11	95.7%
FREQ(CHL-a>20) %	65.5	0.60	94.0%	72.5	0.55	95.7%
FREQ(CHL-a>30) %	39.9	1.03	94.0%	47.8	1.02	95.7%
FREQ(CHL-a>40) %	23.6	1.39	94.0%	30.2	1.42	95.7%
FREQ(CHL-a>50) %	14.0	1.69	94.0%	19.0	1.78	95.7%
FREQ(CHL-a>60) %	8.5	1.94	94.0%	12.0	2.09	95.7%
CARLSON TSI-P	82.8	0.10	96.1%	82.8	0.08	96.1%
CARLSON TSI-CHL-a	64.3	0.10	94.0%	65.5	0.11	95.7%
CARLSON TSI-SEC	85.1	0.11	99.2%	78.3	0.08	96.2%

Table A5: T Statistics Comparing Observed and Predicted Means for Lake Hefner Using the Following Error Terms: T1 = Observed water quality; T2 = Error typical of model development dataset; T3 = Observed and predicted error.

	Observed		Predicted		Obs/Pred	T-Statistics		
Variable	Mean	CV	Mean	CV	Ratio	T1	T2	T3
CONSERVATIVE SUB	143689.0	0.11	150540.3	0.47	0.95	-0.42		-0.10
TOTAL P MG/M3	79.3	0.30	74.1	0.24	1.07	0.23	0.25	0.18
TOTAL N MG/M3	976.0	0.22	906.0	0.25	1.08	0.34	0.34	0.22
C.NUTRIENT MG/M3	52.0	0.26	48.0	0.20	1.08	0.31	0.40	0.24
CHL-a MG/M3	19.1	0.61	10.3	0.66	1.85	1.00	1.77	0.68
SECCHI M	0.8	0.33	0.9	0.44	0.83	-0.57	-0.67	-0.34
ORGANIC N MG/M3	787.0	0.22	454.7	0.34	1.73	2.50	2.19	1.37
TP - ORTHO-p MG/M3	43.7	0.46	33.8	0.41	1.29	0.56	0.70	0.42
ANTILOG PC-1	636.8	0.41	325.1	0.55	1.96	1.66	1.92	0.99
ANTILOG PC-2	8.4	0.48	5.8	0.60	1.44	0.77	1.19	0.48
(N - 150) / P	10.4	0.39	10.2	0.39	1.02	0.05	0.06	0.04

Table A6: T Statistics Comparing Observed and Predicted Means for Lake Overholser (no internal load) using the following error terms: T1 = Observed water quality; T2 = Error typical of model development dataset; T3 = Observed and predicted error.

	Observed		Predicted		Obs/Pred	T-Statistics		
Variable	Mean	CV	Mean	CV	Ratio	T1	T2	T3
CONSERVATIVE SUB	130720.0	0.51	183603.9	0.40	0.71	-0.67		-0.52
TOTAL P MG/M3	233.3	0.48	233.7	0.58	1.00	0.00	-0.01	0.00
TOTAL N MG/M3	1351.2	0.49	1232.3	0.35	1.10	0.19	0.42	0.15
C.NUTRIENT MG/M3	92.0	0.48	84.1	0.35	1.09	0.18	0.44	0.15
CHL-a MG/M3	35.1	0.77	31.0	0.66	1.13	0.16	0.36	0.12
SECCHI M	0.3	0.47	0.2	0.67	1.60	1.01	1.68	0.58
ORGANIC N MG/M3	1218.9	0.51	1235.1	0.32	0.99	-0.03	-0.05	-0.02
TP - ORTHO-p MG/M3	81.6	0.65	167.9	0.51	0.49	-1.11	-1.97	-0.87
ANTILOG PC-1	2345.7	0.58	2611.5	0.59	0.90	-0.19	-0.31	-0.13
ANTILOG PC-2	6.2	0.62	4.2	0.79	1.47	0.61	1.24	0.38
(N - 150) / P	5.1	0.72	4.6	0.75	1.11	0.15	0.33	0.10

Table A7: **Model Coefficients for Lake Hefner Following Calibration.**

Variable	**Mean**	**CV**
Total Phosphorus	0.87	0.45
Total Nitrogen	0.85	0.55
Organic Nitrogen	1.20	0.12
TP - Ortho-p	0.9	0.15
Chlorophyll-*a*	1.75	0.26

Table A8: **Model Coefficients for Lake Overholser Following Calibration (no internal load).**

Variable	**Mean**	**CV**
Total Phosphorus	1.004	0.45
Total Nitrogen	0.82	0.55
Organic Nitrogen	0.94	0.12
TP - Ortho-p	0.48	0.15
Chlorophyll-*a*	1.04	0.26

Table A9: Lake Hefner Water Balance

	Area (km^2)	Flow ($hm^3\ yr^{-1}$)	Variance ($hm^3\ yr^{-1})^2$	CV	Runoff ($m\ yr^{-1}$)
PRECIPITATION	10.1	8.9	5.21E+00	0.26	0.88
TRIBUTARY INFLOW		56.9	1.86E+02	0.24	
***TOTAL INFLOW	10.1	65.8	1.91E+02	0.21	6.51
GAUGED OUTFLOW		54.0	1.05E+02	0.19	
ADVECTIVE OUTFLOW	10.1	-7.9	3.01E+02	2.20	
***TOTAL OUTFLOW	10.1	46.1	1.96E+02	0.30	4.56
***EVAPORATION		20.4	4.27E+00	0.10	
***STORAGE INCREASE		-0.7	0.00E+00	0.00	

Table A10: Lake Overholser Water Balance

	Area (km^2)	Flow ($hm^3\ yr^{-1}$)	Variance ($hm^3\ yr^{-1})^2$	CV	Runoff ($m\ yr^{-1}$)
PRECIPITATION	6.4	5.7	2.21E+00	0.26	0.89
TRIBUTARY INFLOW		20.6	1.79E+02	0.65	
***TOTAL INFLOW	6.4	26.3	1.82E+02	0.51	4.09
GAUGED OUTFLOW		8.6	1.68E+01	0.48	
ADVECTIVE OUTFLOW	6.4	4.9	2.00E+02	2.89	0.76
***TOTAL OUTFLOW	6.4	13.5	1.83E+02	1.00	2.10
***EVAPORATION		13.1	1.39E+00	0.09	
***STORAGE INCREASE		-0.3	0.00E+00	0.00	