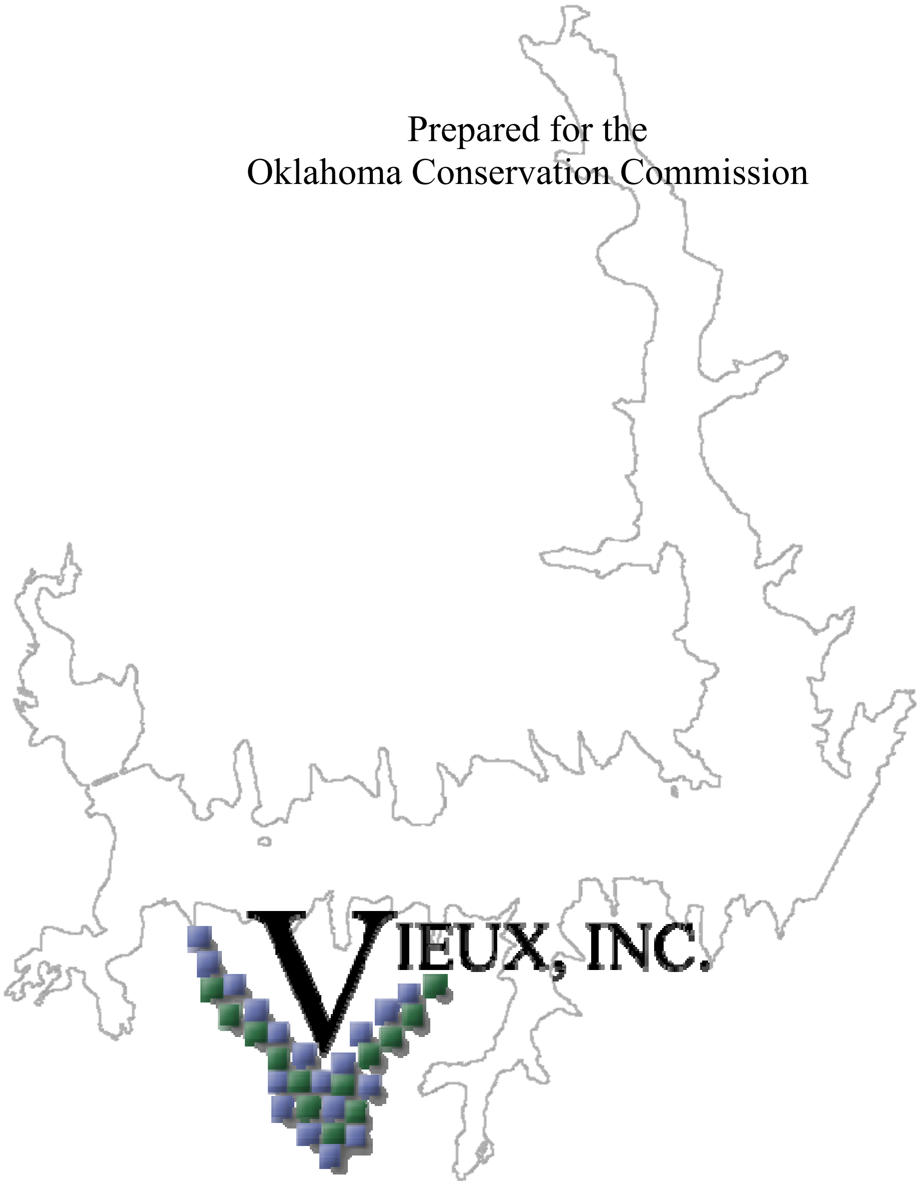
Lake Thunderbird Watershed Analysis and Water Quality Evaluation

319(h) fy 05 C9-996100-13

Project 2, Output 2.2.7



Prepared for the
Oklahoma Conservation Commission

Vieux & Associates, Inc.
350 David L. Boren Blvd., Suite 2500
Norman, OK 73072
www.vieuxinc.com
(405) 325-1818

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Lake Thunderbird was constructed by the Bureau of Reclamation with operations beginning in 1966. Designated uses of the impounded water are flood control, municipal water supply, recreation, and fish and wildlife propagation. The purpose of this study is to target management practices to address the impacts of urban development on nutrient and sediment loading to Lake Thunderbird. The Lake Thunderbird Watershed Analysis and Water Quality Evaluation is performed by Vieux & Associates, Inc. for the Oklahoma Conservation Commission (OCC).

Lake Thunderbird is a sensitive water supply lake, serving the City of Norman, Midwest City and Del City in central Oklahoma. Excessive algal growth in the Lake leads to water quality degradation that includes periodic undesirable taste and odor of the finished drinking water product, and potential ecological and recreational impairment. Growth of algae accelerated by nutrients transported by runoff to the lake has caused the lake to exceed the set water quality goal for chlorophyll-a under existing conditions. Both rural and urban areas contribute runoff in the watershed that drains to the Lake. Nutrient and sediment transport is affected by both flow rates and concentration in runoff from diffuse or non-point sources in the watershed. Areas in the watershed that contribute the most nutrients to the lake are identified through watershed modeling. High levels of chlorophyll-a, an accepted measure of algal content, caused non-attainment of designated uses in the lake resulting in Lake Thunderbird being added to the 303(d) list as an impaired water body in the State of Oklahoma.

As urban development occurs under build-out scenarios, nutrient loading is projected to increase causing further deterioration of in-lake water quality. Each year, an average of 20 tons of phosphorus is transported to the lake from non-point sources in the watershed. Shallow areas of the lake in the Little River Arm of the lake are demonstrated to reduce the nutrient loading to the main body of the lake by sedimentation processes. Phosphorus-sediment resuspension/deposition upstream of Alameda Street on the Little River Arm of Lake Thunderbird is modeled as a source/sink for nutrients that enter the main body of the lake. The effect of this area in the Little River Arm is to reduce the phosphorus load to the main body of lake by 36% annually.

Effects of management practices in the watershed are evaluated in terms of the in-lake concentration of chlorophyll-a, which is a primary indicator of excessive algal growth. Improvements in water quality achieved through application of fertilizer reduction, wetlands, and structural measures are evaluated under baseline and build-out scenarios. Targeted management practices that will reduce chlorophyll-a concentrations are considered individually and as aggregated practices. Achieving the 20μg/L chlorophyll-a concentration in the lake will require broad application and maintenance of management practices throughout the watershed. Application of management practices in the City of Norman alone would not be sufficient to meet the water quality goals set for the lake under existing or build-out scenarios.

1.0 Introduction

This study evaluates the effect of projected conversion from agricultural to urban land use on the water quality in the watershed that is tributary to Lake Thunderbird. The primary objectives of this study are to evaluate existing land use patterns and to project the future impact of land use change on non-point source nutrient and sediment load from stormwater runoff to Lake Thunderbird, and target management practices to improve water quality in the lake. The watershed analysis and water quality evaluation is performed by Vieux and Associates, Inc. for the Oklahoma Conservation Commission (OCC).

Lake Thunderbird is designated as a sensitive water supply lake by the State of Oklahoma (ODEQ, 2002). Accelerated eutrophication and annual nutrient load to Lake Thunderbird has become a concern, and is accompanied by taste and odor complaints by water consumers. Annual load is the product of flow rate and concentration of nutrients, and is a key factor in understanding the impact of nutrients on receiving water quality. Increased urban development (build-out) results in greater runoff volume and higher concentrations of nitrogen and phosphorus delivered to the receiving waters. As nutrients increase, algal growth accelerates and the chlorophyll-a concentration increases (Thomann, 1987). During water treatment algal by-products (generally measured by chlorophyll-a) result in undesirable taste and odor. Undesirable algae blooms in the lake can lead to decreased recreational uses and other intended uses of the water in the reservoir.

1.1 Study Area

The 256 mi^2 (664 km^2) Lake Thunderbird watershed is located in Oklahoma and Cleveland County. The municipalities of Moore, Midwest City, Noble, Norman, Oklahoma City, and Slaughterville have land areas within the Lake Thunderbird watershed. While most of Moore lies within the watershed, it comprises only about 8% of the watershed. The communities of Norman and Oklahoma City contribute 89% of the drainage area. The municipalities of Midwest City, Noble, and Slaughterville contribute less than 2% of the drainage area. The contributing area from each municipality in the watershed is presented in Table 1. The spatial distribution of municipalities in the watershed is illustrated in Figure 1. Lake Stanley Draper and associated drainage are not included in the study as described in Section 2.3.

Table 1 Municipalities contributing drainage to Lake Thunderbird (excluding Lake Thunderbird)

City	Area (mi^2)	Watershed %
Midwest City	0.20	0.08
Moore	20.46	7.99
Noble	1.85	0.72
Norman (not including Lake Thunderbird)	122.98	47.99
Lake Thunderbird	8.70	3.40
Oklahoma City	96.60	37.70
Slaughterville	1.57	0.61
Unincorporated	3.86	1.51

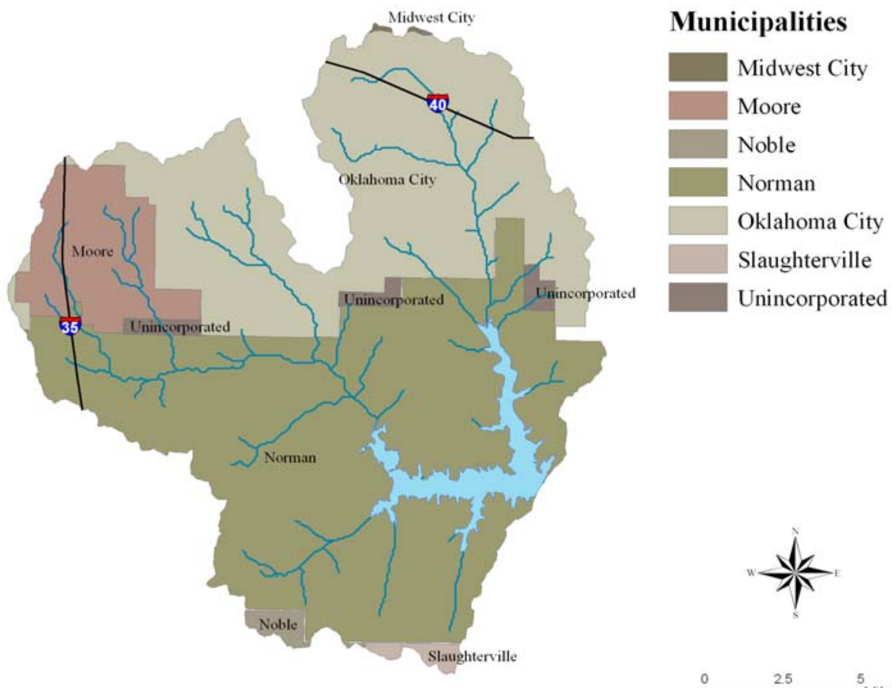


Figure 1 Municipalities within the Lake Thunderbird watershed

Lake Thunderbird was created by the construction of the Norman Dam, which was completed in 1965. The surface area of Lake Thunderbird is 8.7 mi^2. The OWRB conducted a bathymetric survey of the reservoir in 2001 (OWRB, 2002). From this bathymetric survey, Lake Thunderbird has a maximum depth of 58 feet, mean depth of 15.4 feet, surface area of 5,439 acres and volume of 105,838 acre-feet. The dam is located at the confluence of Hog Creek and Little River about 13 miles east of Norman, and about 30 miles southeast of Oklahoma City, Oklahoma. The headwaters of the Little River drain to the Southern branch of Lake Thunderbird. The Little River continues downstream to the Canadian River, in Hughes County, Oklahoma. The northern branch of Lake Thunderbird is fed by Willow Branch and Hog creeks. The Norman dam and Lake Thunderbird reservoir are operated by the Central Oklahoma Master Conservancy District (COMCD) for multiple purposes including water supply and recreation. COMCD supplies drinking water derived from the reservoir to Norman and two other municipalities, Del City and Midwest City.

1.2 Study Goals and Tasks

Understanding the impact of land use changes on non-point source nutrient and sediment load from stormwater runoff to Lake Thunderbird is accomplished by watershed modeling. The Soil & Water Assessment Tool (SWAT) by Srinivasan and Arnold (1994) is used to model the watershed. Targeted management practices are selected by modeling the nutrient loads to the lake by subbasin. Those practices that result in improvement in chlorophyll-a concentrations are targeted in areas that produce the greatest load.

The study consists of the following tasks:

- Assess impact of urban development in the Lake Thunderbird watershed using the distributed water quality model SWAT for continuous simulation of surface runoff and nutrient load.
- Assess watershed load of nutrients and sediment under baseline and build-out conditions. Identify areas for application of targeted management practices to control nutrient load to Lake Thunderbird.
- Develop climatological water balance for Lake Thunderbird under baseline landuse conditions.
- Evaluate total phosphorus and chlorophyll-a model of lake water quality.
- Evaluate nutrients and sediment concentrations for Lake Thunderbird under baseline and build-out conditions, with focus on the in-lake relationship between phosphorous and chlorophyll-a.
- Evaluate the effect of nutrients from the Little River Arm of Lake Thunderbird above Alameda on the main body of the lake.
- Assess relative improvement of lake water quality through application of targeted management practices.

1.3 Previous Studies

Beginning in 2000, the Oklahoma Water Resources Board (OWRB) began sampling Lake Thunderbird for the COMCD to evaluate nutrients on water quality in Lake Thunderbird (OWRB, 2004a). Goal setting in 2000 by the COMCD, the OWRB, and the three municipalities receiving water from Lake Thunderbird (Norman, Midwest City, and Del City) resulted in an upper limit of 20 μg/L of chlorophyll-a for open water sites during the growing season (OWRB, 2001). chlorophyll-a, the molecule or pigment common to all algae for growth is a commonly accepted measure of algae content. This upper limit represents a commonly accepted boundary between high (eutrophic) and excessive (hypereutrophic) algae growth. The OWRB found that for chlorophyll-a to remain under 20 μg/L, epilimnetic (surface) nutrients would need to decrease (OWRB, 2004a). Achieving this reduction must occur by reducing the nutrients in runoff from the watershed.

In 2006, the OWRB water quality standards (WQS) designated Lake Thunderbird as a Sensitive Water Supply (SWS) Nutrient Limited Watershed (NLW) (OWRB, 2006). This status was determined based on exceedance of the OWRB WQS 785:45-5-10 (7) “chlorophyll-a long-term average concentration at 0.5 meters below lake surface shall not exceed 10μg/l”. Excessive nutrients are limiting one or more of the designated uses of this lake.

The OWRB defines a NLW as a “watershed of a waterbody with a designated beneficial use which is adversely affected by excess nutrients as determined by Carlson’s (1977) Trophic State Index (TSI) using chlorophyll-a of 62 or greater” (OWRB, 2006). Carlson’s TSI uses algal biomass as the basis for trophic state classification. Three variables, chlorophyll pigments (from measurement of chlorophyll-a), secchi depth, and total phosphorus, are used to independently estimate algal biomass for calculation of Carlson’s TSI. From the 2005 Beneficial Use Monitoring Program (BUMP) report for Lake Thunderbird, the TSI ranged from 41 to 67 with an average TSI of 58 based on samples collected in 2003 and 2004 (OWRB 2005). With an average TSI of 58, the lake is classified as eutrophic, indicative of high levels of productivity and nutrient rich conditions. At TSI greater than 60, blue-green algae dominate with episodes of severe taste and odor problems (Carlson, 1996).

A water quality report summarizing water quality sampling found Lake Thunderbird to be eutrophic with periods of hypereutrophic growth (OWRB, 2004a). Total phosphorus was the single most important variable in predicting chlorophyll-a. The OWRB determined that for chlorophyll-a to remain under 20ug/L the nutrients in the top layer of the lake (epilimnion) need to decrease.

The OWRB sampled algae from Lake Thunderbird from 2001 through 2003 (OWRB, 2004b). The study found that Lake Thunderbird contains taste and odor producing species of algae, some of which are capable of producing nuisance blooms, as well as species that can potentially produce toxins. A direct relationship was identified between nuisance algae and nutrient concentrations in the lake. The preliminary testing did not suggest an immediate concern for algae toxins, but recommended maintenance of lower nutrient levels in the lake to minimize risk from nuisance algae.

Runoff in the watershed tributary to Lake Thunderbird is a major source of nutrient load to the lake. Vieux and Associates performed a study on the Rock Creek watershed for the COMCD (COMCD, 2006). The study focused on the impact of urbanization in the Rock Creek tributary on Lake Thunderbird water quality, and relied on tributary sampling during storm events from 2005-2006 for analysis in this watershed. Stormwater samples collected during four storm events was used to characterize existing conditions within the basin and to compare with published values for estimation of total phosphorus load to the lake due to urbanization of the land area. The study found that as urbanization increases, i.e., imperviousness, so does nutrient load. The increase in runoff caused by increased impervious area of developed land partially accounts for the increased load of nutrients in the runoff water. The remainder of the increase in projected load is explained by increased fertilization in urban areas compared to undeveloped land in the Rock Creek watershed.

The nutrient that has the most control over the amount of plant biomass is the nutrient with the lowest concentration, or the nutrient that "runs out" before other nutrients (Thoman and Mueller, 1987 p. 398). Looking at the amount of nutrients in the water body one can arrive at the N/p ratio. Simplistically, based on cell stoichiometry, when the ratio of N/p is less than 10, nitrogen controls and for N/p >10, phosphorus controls. Evaluation of OWRB BUMP surface water samples from 2001-2003 resulted in an N/p ratio of 38, indicating that the lake is phosphorus limited. The minimum N/p was 9.58, the maximum N/p was 179.6. Separate analysis by the OWRB also suggested that phosphorus was a limiting nutrient (OWRB, 2004a). Once the N/p ratio was determined, evaluation of the lake using a simple phosphorus model is possible. However, with phosphorus concentrations greater than 24 ug/L the lake may become nitrogen limited, which can affect the number and types of algae present (OWRB, 2004b). Using this same model the effects on the main body of the lake of the Little River Arm of Lake Thunderbird above Alameda Street could be evaluated as well as the effects of urban development on water quality in the lake. Further study would be required to identify the combined effect of increased

N and P nutrients affecting phyto-plankton growth kinetics and biomass production. In summary, the Lake Thunderbird water supply lake has excessive nutrient and algae growth with concentrations of chlorophyll-a that exceed set water quality goals for the designated Sensitive Water Supply lake.

1.4 Report Organization

The report is organized in the following sections.

Section 1 – Introduction: summarizes why the study has been undertaken, the goals and tasks associated with the project and previous studies in the basin.
Section 2 – Watershed Analysis: presents a discussion of the watershed characterization, evaluation of other pollutant sources and setup of the watershed model.
Section 3 – In-lake Modeling: describes water balance computations, evaluation of the upper arm of the Little River branch of Lake Thunderbird, and the in-lake water quality evaluation.
Section 4 – Results of the calibration and projections of the total phosphorus, nitrate, and sediment results of SWAT modeling for baseline and build-out scenarios and evaluation of chlorophyll-a with both scenarios.
Section 5 – Targeted Management Practices: presents targeted management practices to attain in-lake water quality goals.
Section 6 – Summary and Conclusions
Section 7 – Appendices

2.0 Watershed Analysis

The characteristics of the Lake Thunderbird watershed are important for identifying where nutrient load is coming from under existing or baseline conditions, and in the build-out scenario. The targeting of management practices also relies on knowing where urbanization has and will occur. Quantification of the surface runoff to the lake from the contributing drainage area is needed to estimate nutrient load to the lake. This section describes the methodology used to characterize the watershed landuse for the baseline condition and build-out scenario including collection of spatial data utilized for modeling the watershed with SWAT (Arnold, 1998). Lake Stanley Draper was evaluated for inclusion/exclusion in the basin modeling. Because Lake Stanley Draper is a pooling reservoir for a pipeline conveying water to Oklahoma City, it rarely discharges. Therefore, its drainage area is removed from consideration. Point source discharges and bypass-discharge to Lake Thunderbird were evaluated and summarized with discussion of their relative impacts on lake water quality. SWAT model setup is discussed. SWAT model calibration to the water budget and known nutrient levels for the build-out scenario is discussed in Section 4.1.

2.1 Watershed Characterization

Landuse in the Lake Thunderbird watershed was provided by the Association of Central Oklahoma Governments (ACOG) Water Services Division. ACOG assembled and analyzed landuse trends and future landuse plans provided by the municipalities within the watershed. The geospatial data provided guidance and digital landuse for the baseline landuse scenario, current as of 2000, and for the build-out scenario, which was projected for the year 2030. The ACOG landuse maps provide a consistent landuse classification scheme over the watershed governed by multiple municipalities.

GIS data was assembled for modeling the watershed with SWAT. Spatial data was selected based on currency, resolution, industry standards, accuracy, and consistency for use within the SWAT modeling environment. Data was preprocessed and projected to Albers Equal Area projection and resampled to 100m x 100m resolution. The landuse, soils and topography data sets are utilized for analysis in SWAT. The watershed topography is shown in Figure 2.

Landuse & Zoning –	Association of Central Oklahoma Governments landuse categories as of July 16, 2003.
Soils- STATSGO –	Soils data compiled by the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA).
Topography –	National Elevation Dataset (NED) obtained from the United States Geological Survey (USGS) at a resolution of 30 meters.

Additional shapefiles are used, to improve the accuracy of the watershed delineation, and to verify landuse classifications including the Hydrologic Unit Code (HUC-12) watersheds, National Hydrology Dataset (NHD) Streams, municipality borders, and aerial photography.

Streams Network –	NHD United States Geologic Survey (USGS) in cooperation with the United States Environmental Protection Agency (EPA), 1999.
Watersheds –	Boundaries from USGS 12-digit Hydrologic Unit Code (HUC 12)

Municipalities – Boundaries from University of Oklahoma Geo-Information Systems, August 2006.

Aerial Imagery – National Agricultural Imagery Program (NAIP) 2003 complied by the USDA, Farm Services Agency, Aerial Photography Field Office.

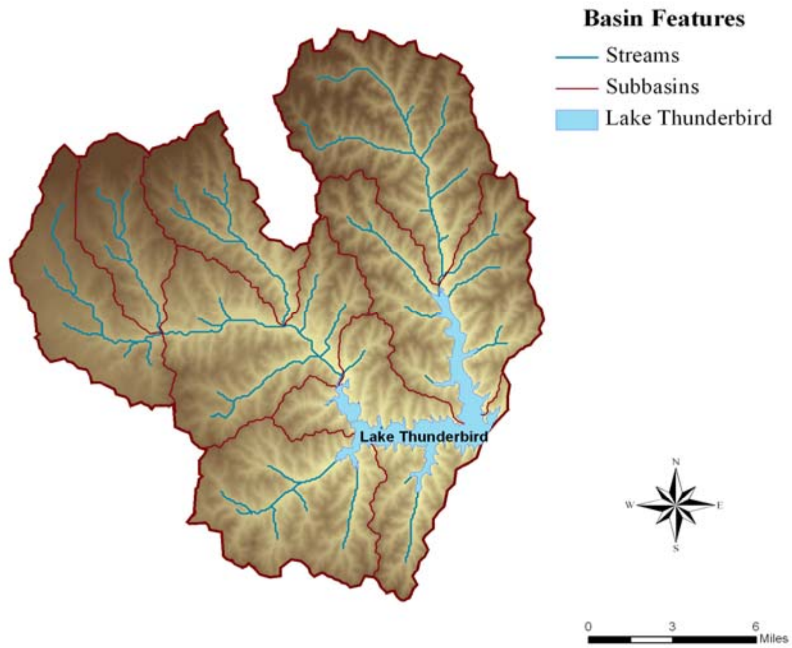


Figure 2 Lake Thunderbird entire watershed basin boundary, streams, lakes, and elevation

Landuse data from ACOG was provided as a single layer with numeric codes for baseline landuse scenarios and alphabetic codes for projected build-out by 2030. The projected build-out landuse scenario converted baseline landuse classified as *Vacant* (active/passive agriculture, vacant, and farmsteads) into developed areas of residential, commercial, industrial, institutional, and transportation categories. The ACOG build-out scenario created two new residential categories; agricultural residential and suburban residential. ACOG landuse categories were aligned with SWAT landuse categories for analysis as shown in Table 2.

Table 2 ACOG to SWAT landuse category mapping

ACOG Landuse Categories	SWAT Landuse Category
Single Family Residential	Residential Medium Density (URMD)
Multi-Family Residential	Residential High Density (URHD)
Suburban Residential	Residential Medium Low Density (URML)
Agricultural Residential	Residential Low Density (URLD)
Vacant	Agricultural-Pasture (PAST)
Parks and Open Spaces	Agricultural-Generic (AGRL)
Suburban Residential	Residential Med/Low Density
Agricultural Residential	Residential-Low/Density

ACOG Landuse Categories	SWAT Landuse Category
Commercial/Mixed Use	Commercial (UCOM)
Industrial	Industrial (UNID)
Transportation Corridors	Transportation (UTRN)
Institutional	Institutional (UNIS)
Reservoirs	Open Water (WATR)

According to the ACOG landuse classifications, only one type of agricultural land is identified in the basin. This classification is further refined through supplemental information on the distribution of agricultural lands obtained from the 2002 Agricultural Census from the National Agricultural Statistics Service for Oklahoma and Cleveland counties (USDA, 2002). The type of agriculture landuse that is dominant in the basin is used to assign model parameters in SWAT. The agricultural survey includes the total land in farms, land in cropland, and land in forage. Agricultural land not classified as cropland, or as forage land, is assumed pasture. In 2002, Oklahoma and Cleveland Counties were nearly 92% and 97% pasture and forage, respectively. Based on this review, all agricultural land in the basin was classified as pasture in SWAT. Figure 2 presents the baseline landuse scenario for the watershed. Except where urban areas are concentrated, the distribution in the watershed is primarily agricultural (pasture) or vacant land with dispersed areas of medium density residential land use.

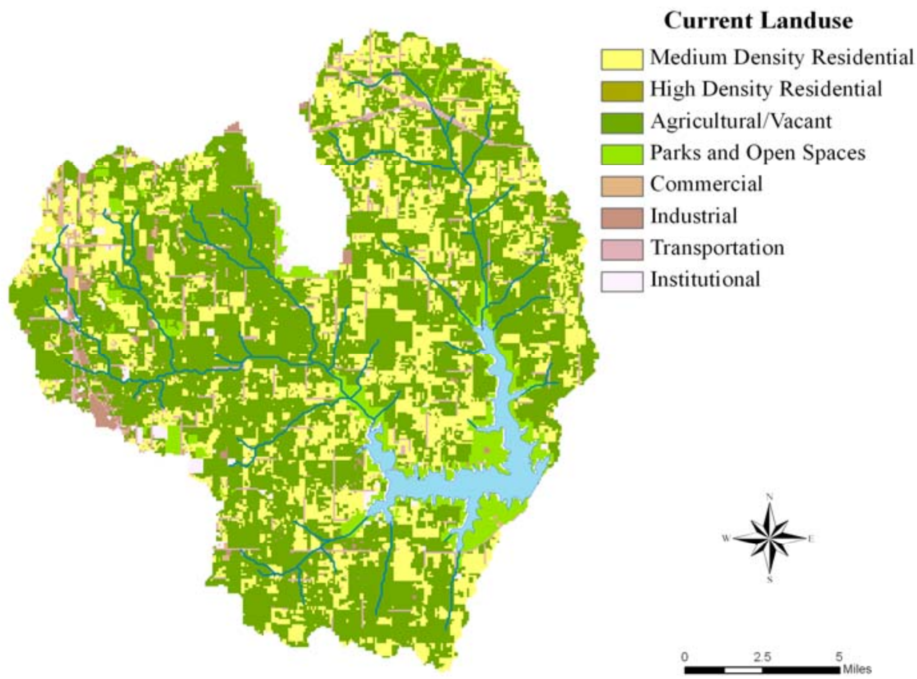


Figure 3 Landuse distribution for the baseline scenario

Through conversion, the build-out scenario essentially reduces the baseline agricultural/vacant activities by approximately 50% and introduces two additional levels of residential housing; agricultural residential (areas with 5-10 acres per dwelling unit) and suburban residential (areas with 1-4 acres per dwelling unit). Table 3 shows the change in landuse between the baseline and build-out landuse scenarios with the two new residential landuse classifications and reduction of agricultural land by nearly 50% due to conversion. Figure 4 presents the build-out landuse scenario for the watershed. In the build-out scenario, agricultural landuse is concentrated near the lake. Urban areas have replaced agriculture in most of Oklahoma City, and the western boundary of the watershed in Norman and Moore. Conversion takes place in the upper reaches of the watershed to the west and along the OKC-Moore-Norman urban corridor, and a large area of conversion east of Lake Stanly Draper in the Hog Creek Arm of the Lake.

Table 3 Comparison of baseline and build-out landuse scenarios

Baseline Landuse %	Build-out Landuse %	SWAT Landuse Categories
26.00	30.69	Residential Medium Density (URMD)
0.07	0.22	Residential High Density (URHD)
53.84	27.95	Agricultural – Pasture (PAST)
7.62	12.11	Agricultural-Generic (parks and open spaces) (AGRL)
0.00	13.02	Residential Med/Low Density (URML)
0.00	1.37	Residential-Low Density (URLD)
0.68	1.33	Commercial (UCOM)
1.39	2.35	Industrial (UIND)
4.18	4.36	Transportation (UTRN)
1.17	1.54	Institutional (UINS)
5.05	5.05	Open Water (WATR)

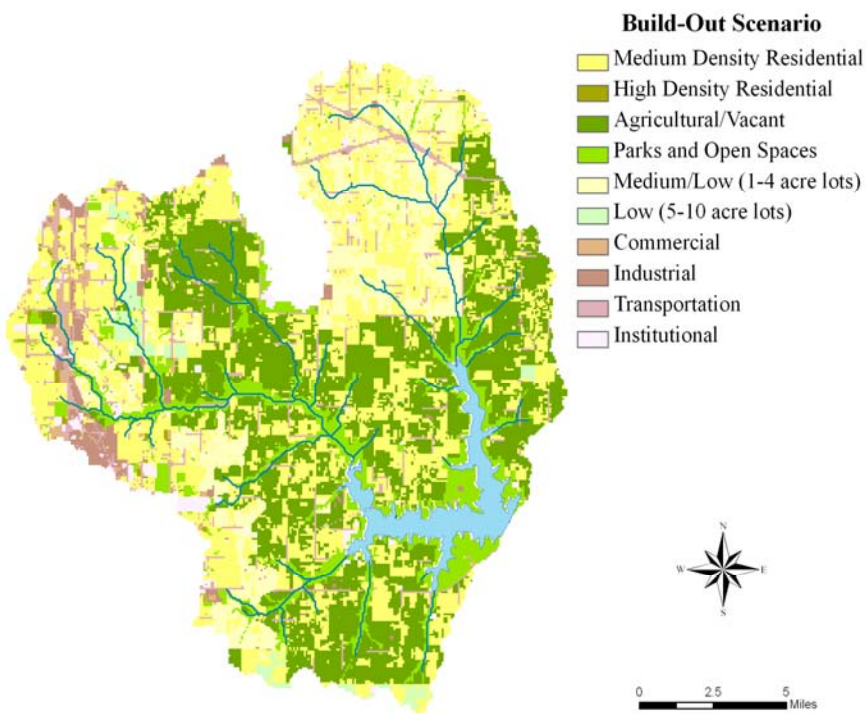


Figure 4 Landuse distribution in the build-out scenario

2.2 Other Pollutant Sources

Information on point discharge and bypass-discharge of untreated waste was obtained from Oklahoma Department of Environmental Quality (ODEQ) and COMCD for evaluation. The Lake Thunderbird watershed is designated as a Sensitive Water Supply in the Oklahoma Water Quality Standards [OAC 785:45, Appendix A, Table 5]. The SWS designation prohibits wastewater discharges under almost all circumstances [OAC 785:45-5-25(c)(4)]. (Oklahoma DEQ, October 2006). Hence, there are no permitted point-discharges within the Lake Thunderbird watershed.

Bypass-discharges that occur in the Lake Thunderbird watershed are reported to COMCD on a quarterly basis. Bypass-discharges from June 2004 through August 2006 were reviewed. The primary cause of by-pass discharges was from sewer main breaks. The City of Moore had 59,930 gallons in by-pass discharge to the Little River, including a 39,000 gallon discharge in August 2005 due to overflow at the POTW. The City of Norman discharged 44,483 gallons to the Little River over the same period, including as 12,049 gallon discharge from a broken main in Hall Park in July 2004.

In general, raw sewage contains approximately 4-15 mg/L water-soluble phosphorus (Chapra, 1997). When considering the sum of all discharges, this equates to 2-5 kilograms of phosphorus from by-pass discharges over the reviewed period of time. Annual phosphorus load to the lake from non-point sources is on the order of 20,000 kilograms of phosphorus. Non-point sources are four orders of magnitude larger than point sources.

Lake Stanley Draper is a municipal lake owned and operated by the City of Oklahoma City. Lake Stanley Draper is a municipal water supply lake for the City of Oklahoma City. The lake provides terminal storage for waters received via pipeline from Lake Atoka and the McGee Creek Reservoir in southeast Oklahoma. Lake Stanley Draper and associated watershed was excluded from Lake Thunderbird watershed analysis because discharges are not allowed over the spillway. In addition, the contributing drainage area to the Lake Stanley Draper is only 12 mi^2 and the lake has been characterized by the OWRB as oligotrophic (nutrient poor) (OWRB, 2005). The only water entering the Lake Thunderbird watershed from Lake Stanley Draper is by seepage under the dam (OWRB, 2007). Lake Stanley Draper is not considered a source of phosphorus load to Lake Thunderbird.

2.4 SWAT Model Setup

The SWAT model was developed by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas, and is in the public domain. Modeling of the baseline and buildout scenarios is accomplished with the SWAT 2005 model version with the ArcSWAT interface (Arnold *et al.*, 1998). ArcSWAT is an ArcGIS/ArcView extension and a graphical user input interface for the SWAT model for generating model parameters from geospatial information. SWAT is a river basin scale model developed to quantify the impact of land management practices in watersheds. SWAT incorporates weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth, groundwater flow, reach routing, and nutrient load.

A continuous simulation of the SWAT model using the baseline landuse scenario is performed for the period 1970-2004. The 20-year period from 1985 through 2004 was utilized for calibration. The basin was subdivided into 92 subbasins based on the geomorphology of the basin and a stream threshold of 400 100-meter cells (Figure 5). Hydrologic response units (HRUs) within the basin were established with a 5% threshold for soils and landuse (default threshold 20%). Precipitation from the Norman and Oklahoma City gauges was input for the entire model period (Figure 5). For periods where gauge data was missing, SWAT generated precipitation. By inputting the precipitation data, we are able to generate a consistent rainfall timeseries for all calibration runs. The SWAT database for the Oklahoma City weather station was used to generate maximum/minimum temperature, solar radiation, wind speed and relative humidity for the basin.

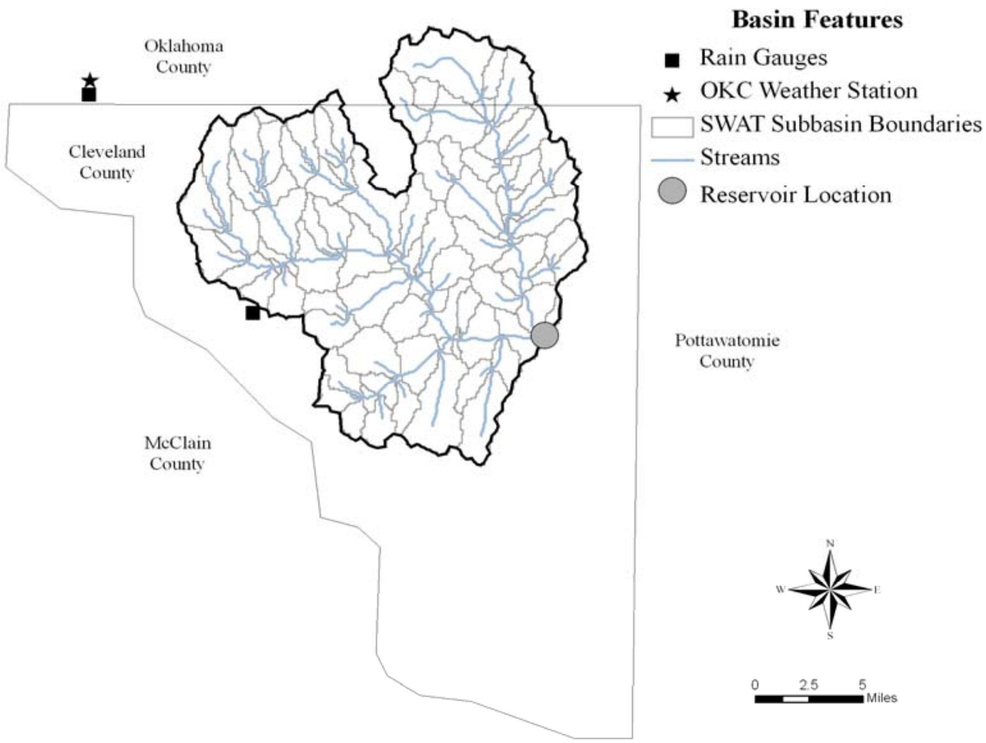


Figure 5 SWAT subbasins, weather station, and rain gauge locations

Lake Thunderbird was added to the outlet subbasin as a reservoir. SWAT parameters required for reservoirs include those listed in Table 4. To initialize the lake, phosphorus concentrations were obtained from OWRB BUMP data from 1999-2004.

Table 4 Lake Thunderbird reservoir initialization

SWAT field	Reservoir Value
Initial year reservoir was in operation	1965
Surface area of the lake at emergency spillway	2219 ha
Volume of lake at emergency spillway	24,200 x 10^4 m^3

SWAT field	Reservoir Value
Surface area of the lake at top of conservation pool	2219 ha
Volume of the lake at top of conservation pool	14,750 x 10^4 m^3
Initial volume of the lake	13,750 x 10^4 m^3 Jan 85
Sediment (TSS)	20.99 mg/L
Phosphorus setting rate	11.14 m/yr
Nitrogen settling rate	5.5 m/yr
Initial concentration of organic phosphorus in the lake	0.033 mg/L
Initial concentration of soluble phosphorus in the lake	0.025 mg/L

3.0 In-Lake Water Quality Modeling

In-lake water quality modeling is performed to identify the effects of nutrient load on the water quality of the lake on an average annual basis. This includes the development of a hydrologic water balance, use of a simple phosphorus mass balance model to predict in-lake total phosphorus concentration, identification of the sediment-to-water phosphorus interaction, and a chlorophyll-a-to-total phosphorus concentration model to quantify the impacts of various targeted management practices. A phosphorus-sediment resuspension model is used to evaluate the impact of the Little River branch on the water quality of the main body of the lake.

There is a complex relationship between the various nutrients within the water column and the growth of aquatic plants. The nutrient that has the most control over the amount of plant biomass is the nutrient with the lowest concentration (Thomann and Mueller, 1987 p. 398). Looking at the amount of nutrients in the water body one can arrive at the N/p ratio. Evaluation of surface water samples from the lake indicates that the lake is phosphorus limited. Using the simple phosphorus model, the effects of the Little River Arm of Lake Thunderbird above Alameda on the main body of the lake could be evaluated, as well as, the effects of urban development on water quality in the lake.

A model of the total phosphorus concentration in the lake is obtained by a phosphorus mass balance. The phosphorus mass balance model is related to the regression relationship between chlorophyll-a and total phosphorus concentrations. The regression model is then used to identify the change in chlorophyll-a concentration for purposes of evaluating whether management practices will achieve water quality goals set for the lake. The water quality goal set for the lake at 20 µg/L of chlorophyll-a is used to measure the impacts of management practice on lake water quality under baseline and build-out scenarios.

The surface runoff model (SWAT) is then calibrated to the inflow to the lake. An improved estimate of the load to the lake is determined using the calibrated model. Inflow to the lake is estimated from the hydrologic water balance as described in the next section.

3.1 Hydrologic Water Balance

Because nutrient load to the lake depends on runoff, a water balance is needed to estimate this component. An annual hydrological water balance was developed for Lake Thunderbird based on historical climatological data, reservoir stage and discharge records. The runoff generated from precipitation is the driving source of runoff and nutrient load to the lake. Identification of the inflow to the lake is required to estimate the nutrient load. Since the surface inflow to the lake is a distributed process, a direct measurement of inflow is not possible. A schematic of the hydrologic water balance is shown in Figure 6.

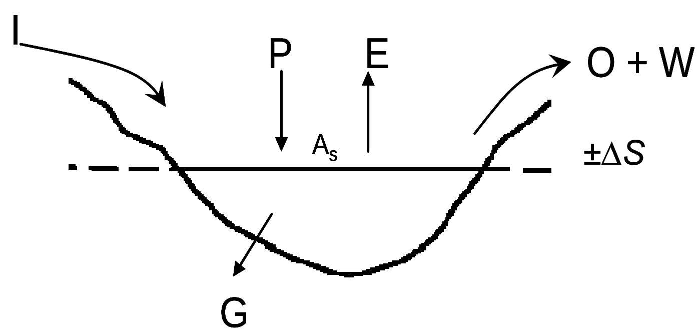


Figure 6 Lake Thunderbird hydrologic water balance

The hydrologic water balance (Eq. 1) is solved for inflow (I) to the lake (Eq. 2).

$$\Delta S = I + PA_s - O - W - EA_s - G \quad (1)$$

$$I = \Delta S + O + W - PA_s + EA_s + G \quad (2)$$

Availability of a large number of observed inputs and outputs to Lake Thunderbird provides a unique modeling situation. Measurement of the change in storage (±ΔS) is provided by USGS gauge 07229900 located in the lake. Measurement of outflow (O) is provided by USGS gauge 07230000 located below the Norman Dam (Figure 6). The OWRB provided current bathymetric data (OWRB, 2002).

3.1.1 Storage

Reservoir storage was obtained for the USGS gauge 07229900 for the period 1965 – 2004 (Figure 7). The Bureau of Reclamation provided end of month storage for this period. Storage within the lake is determined from the stage-storage, or capacity curve for the lake. The SWAT model was setup and simulated starting in 1970 when the lake reached the normal pool elevation of 1039 ft.

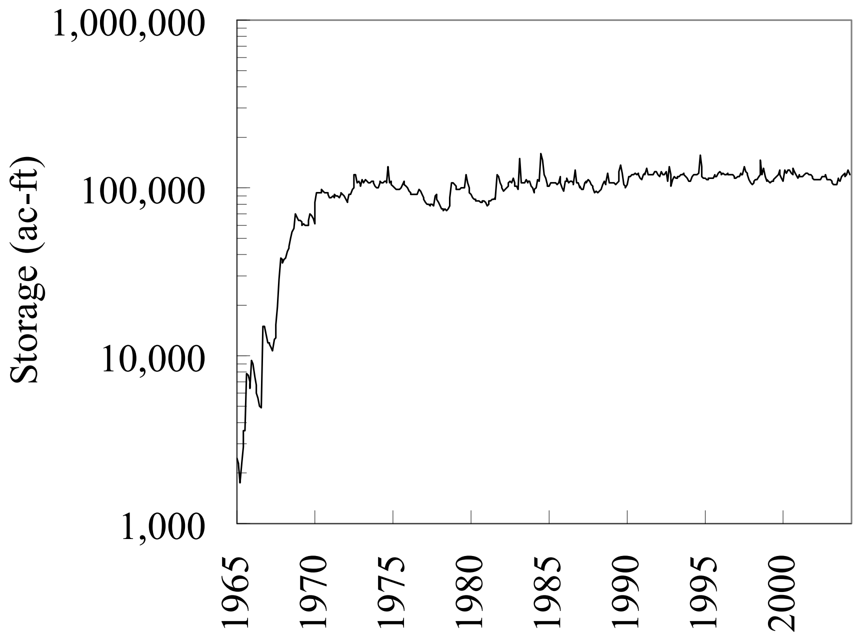


Figure 7 End of month storage for Lake Thunderbird 1965 - 2004

3.1.2 Outflow

Outflow from the basin is obtained from the USGS gauge 07230000. A plot of mean monthly discharge (Figure 8) downstream of the lake shows the reservoir stabilized around 1973. A prolonged reduction in outflow from the lake is seen between 2002 and 2004. The mean monthly discharge is 74.5 cfs from 1973 through 2001, excluding the periods of prolonged reduction in outflow.

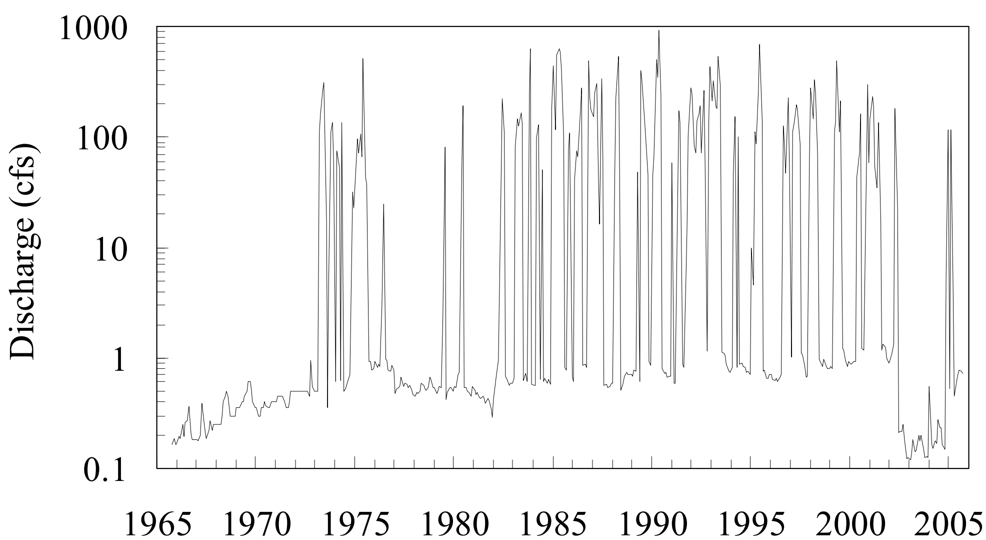


Figure 8 Mean monthly discharge from USGS gauge 07230000 downstream of Lake Thunderbird

3.1.3 Water Supply

Norman, Midwest City, and Del City rely on Lake Thunderbird for water supply. Water supply demand was obtained from COMCD for the period from 1978– 2004. The average annual water supply demand is 17,375 ac-ft (5,662 million gallons). Figure 9 shows that peak water supply demand occurs during July and August with the lowest demand during February. For the period of record, the highest monthly demand of 2,405 ac-ft (783 million gallons) occurred during August 2000.

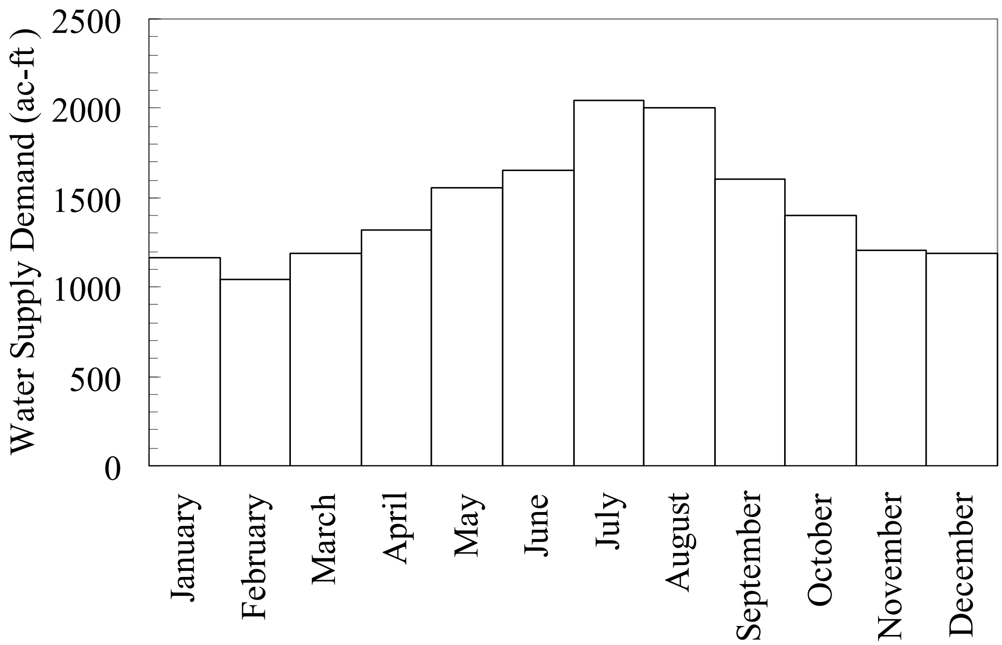


Figure 9 Mean Monthly Water Supply Demand

3.1.4 Precipitation

Precipitation directly over the lake was estimated from a rain gauge operated by COMCD. Rainfall is assumed to be spatially uniform over the lake. The mean annual rainfall recorded by the gauge is 41.28 inches for the 1985 – 2004 period of record.

3.1.5 Evaporation

Evaporation (E) is estimated using an evaporation pan at the lake along with a pan coefficient of 0.7 (Farnsworth, 1982). The maximum monthly evaporation of 9.58 inches occurred during July 2004. The average annual evaporation rate is 41.25 inches for the 1985 – 2004 period of record.

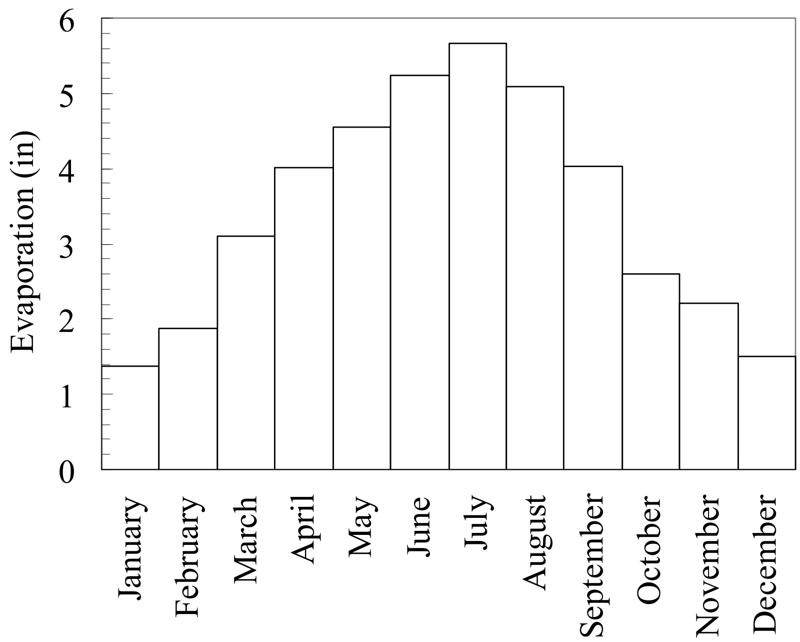


Figure 10 Climatological monthly lake evaporation

3.1.6 Groundwater Seepage

Inflow to the lake is composed of surface runoff from precipitation and subsurface discharge to perennial streams (Christenson, 1996). The distinction between surface runoff and subsurface discharge is important because the majority of phosphorus load to the lake is assumed to be in the surface runoff during storm events. Phosphorus load from groundwater is assumed negligible due to low concentrations generally found in groundwater.

An investigation of the groundwater seepage from the lake is investigated to identify reasons for the negative water balance in summer periods. By comparing the stage within the lake with the evaporation calculated on a daily basis, an estimate of the seepage is determined.

For the period from 10/1/2005 to 03/18/2006, the loss to evaporation is 0.147 in/day, whereas the measured decrease in stage within the lake of 0.184 in/day (Figure 11). Therefore, assuming the unaccounted loss is due groundwater seepage (i.e., minimum withdrawals for water supply), the seepage loss rate is -0.037 in/day which is -1.12 in/month.

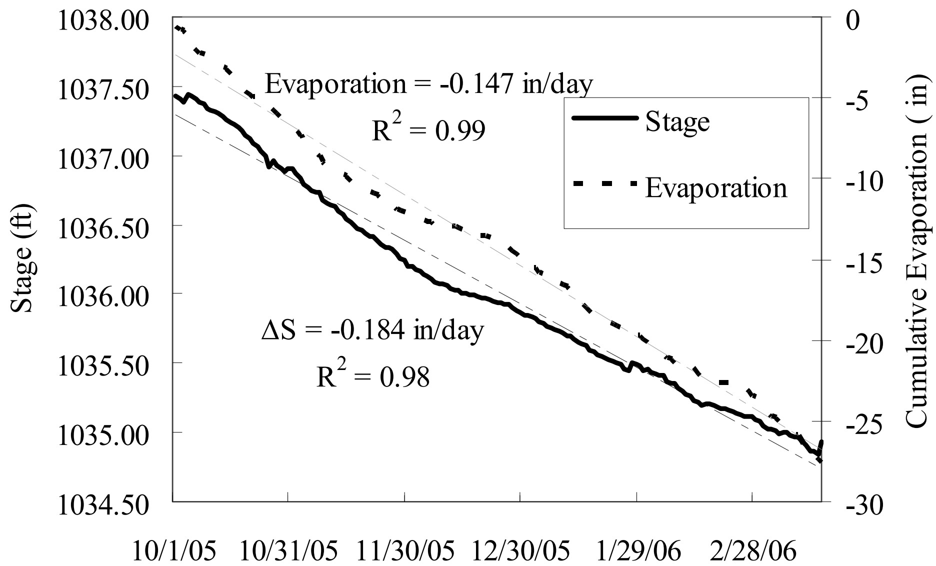


Figure 11 Groundwater seepage estimate fall 2005

For the period from 7/12/2006 to 10/14/2006 the loss to evaporation is 0.358 in/day, whereas the measured decrease in stage within the lake was 0.344 in/day (Figure 12). Therefore, the lake is gaining water during this period at a rate of +0.014 in/day (+0.426 in/month).

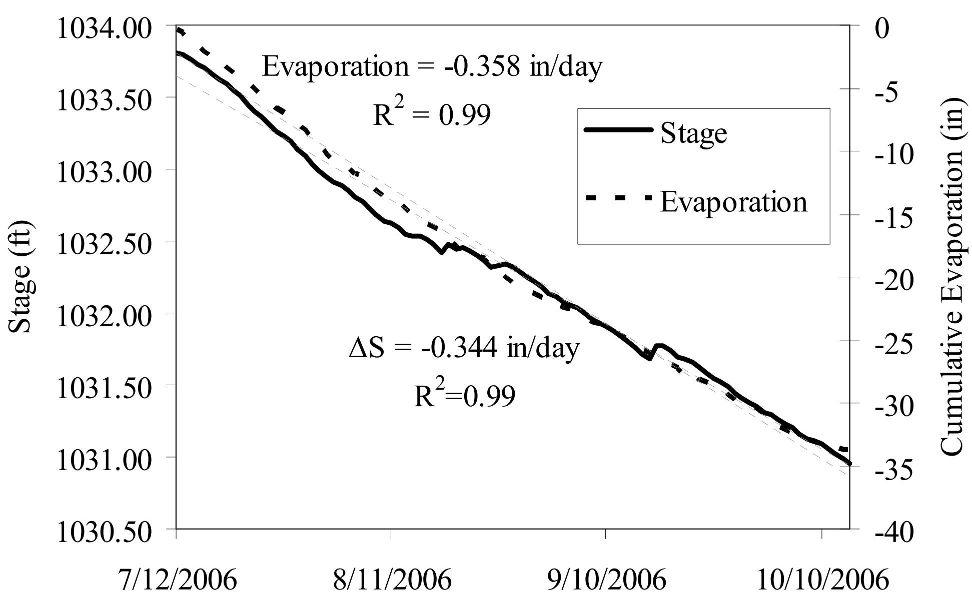
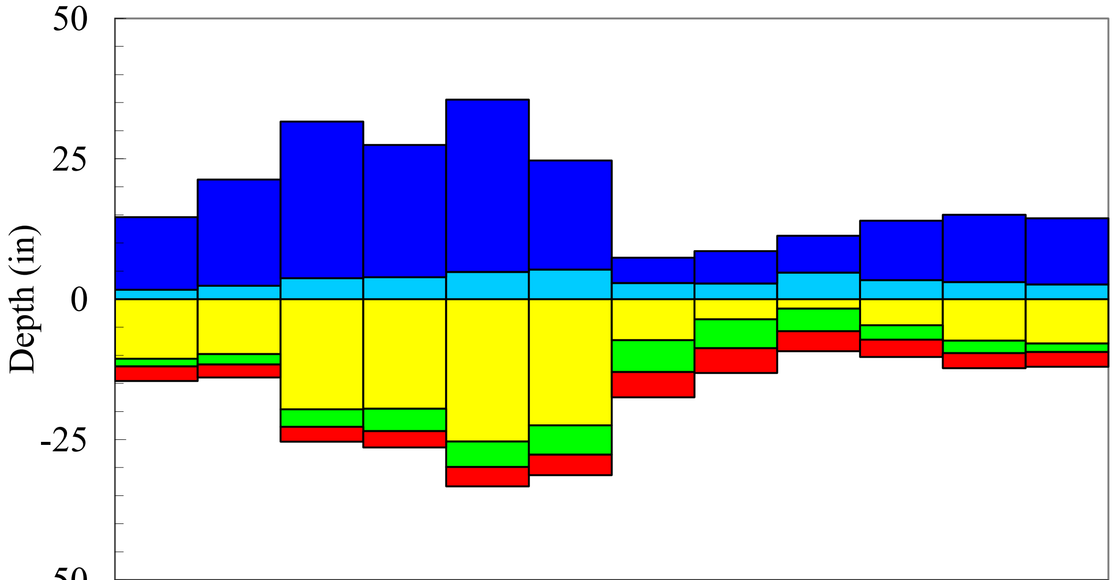


Figure 12 Groundwater seepage estimate for summer 2006

From these two periods, it is observed that depending on the period the lake may be gaining or losing flow to groundwater seepage. Depending on the period of observation, the lake is either gaining or losing volume, but at small rates. In any case, the seepage loss compared to the other components is small in magnitude and can be assumed negligible over the period of investigation. The hydrologic water balance is summarized in Figure 13 as average annual lake depth (inches). From the hydrologic water balance, the inflow to the lake reaches a maximum during the spring months (March – May). Peak water supply and evaporation occur during July when the inflow to the lake is at a minimum.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Inflow	13	19	28	24	31	19	5	6	7	11	12	12
Precipitation	2	2	4	4	5	5	3	3	5	3	3	3
Water Supply	-3	-2	-3	-3	-3	-4	-5	-4	-4	-3	-3	-3
Evaporation	-1	-2	-3	-4	-5	-5	-6	-5	-4	-3	-2	-2
Outflow	-11	-10	-20	-20	-25	-22	-7	-4	-2	-5	-7	-8

Figure 13 Monthly climatological water balance for Lake Thunderbird

Negative quantities indicate water removed from the lake, while positive values are those components that flow into the lake, i.e. inflow and precipitation. The change in storage is assumed to be on average zero, which indicates a conservation of mass.

3.2 Phosphorus Mass Budget Model

Development of a phosphorus mass budget model provides the relationship between the phosphorus load from watershed runoff to the lake with the concentration of phosphorus in the lake that is available for algae production.

The load rate to the lake from the entire watershed can be estimated from the event mean concentration based on landuse types within the watershed following the Eq (3) where V is volume of the lake (m^3); t is time (yr): W is the mass phosphorus load to the lake (mg/yr): Q is outflow rate for lake (m^3/yr); v is apparent settling velocity within lake (m/yr); A_s = bottom area over which settling occurs (m^2); and p is in-lake phosphorus concentration (mg/m^3). The phosphorus mass budget model assumes a well-mixed lake (i.e. no stratification) and phosphorus limited conditions.

$$V \frac{dp}{dt} = W - Qp - vA_s p \tag{3}$$

The mass load of total phosphorus from external sources could be from point or non-point sources. The mass load is the input of total phosphorus to the lake. The product of average annual outflow and total phosphorus is the mass of phosphorus leaving the lake as overflow over the spillway, capturing the flushing characteristics of the lake. The settling of particulate phosphorus out of the water column is the apparent settling velocity of phosphorus because the velocity is a net settling velocity that includes both resuspension and settling. If the velocity is positive, it means that there is more phosphorus settling than being resuspended. If the velocity is negative there is more phosphorus that is resuspended than is settling out. The applicability of this model is to long-term averages and does not account for seasonal or interannual variations.

3.3 Steady State Phosphorus Mass Balance

For steady state conditions when there is no mass accumulation of phosphorus within the lake, the phosphorus mass balance equation reduces to Eq. 4,

$$p = \frac{W}{Q + vA_s} \tag{4}$$

where p is the in-lake phosphorus concentration (mg m^{-3}); W is mass load to the lake (mg /yr); v is apparent settling velocity within lake (m/yr); and A_s is lake bottom area over which settling occurs (m^2). This equation shows the balance between the load applied to the lake (W) and with the assimilative capacity of the lake to remove phosphorus, which is Q + vA_s. The assimilative capacity of the lake is composed of lake flushing characteristics (Q) and settling characteristics of the lake (vA_s).

Therefore, for a high flushing lake (large overflow, Q) the phosphorus concentration in the lake is reduced by the flushing of the phosphorus downstream. Settling velocity represents the process where total phosphorus is removed from the water column by settling and sequestration of particulate phosphorus.

The critical unknown in the equation is the apparent settling velocity within the lake (v). In the well known Vollenweider's first analysis, a settling velocity for lakes of 10 m/yr was assumed (Vollenweider, 1976). This approximation is used as a starting point to estimate the settling velocity. The steady state model in Eq. 4 is used to determine the total phosphorus concentration in the lake, which can be re-arranged to estimate the settling velocity.

$$v = \frac{\frac{W}{p} - Q}{A_s} \tag{5}$$

An estimate of settling velocity can be obtained by assuming that the settling velocity is related to the hydraulic detention time (t_d) and hydraulic overflow rate of the lake (q_s).

$$v = q_s \cdot t_d^{0.5} \tag{6}$$

Where detention time of the lake is given by volume of the lake (V) divided by the overflow rate (Q).

$$\tau_w = \frac{V}{Q} \tag{7}$$

The hydraulic overflow rate (q_s) is the overflow rate (Q) divided by the surface area of the lake (A).

$$q_s = \frac{Q}{A} \tag{8}$$

Based on the lake's hydraulic parameters obtained from the bathymetric data provided by the OWRB (OWRB, 2002), the detention time of the lake is 1.79 years; the hydraulic overflow rate is 3.31 m/yr; and the settling velocity is 11.14 m/yr. This estimate for settling velocity is used in the analysis and calculation of the phosphorus concentration presented in the lake in Section 4.5.

3.4 Little River Arm Evaluation

To evaluate the effect of the Little River Arm on water quality of the main water body, several factors are taken into consideration, including the annual phosphorus loading rate, net settling rate and burial velocity of phosphorus, hydrological characteristics of the Little River Arm and resuspension of phosphorus in the Little River Arm. The long-term lake water quality impacts are evaluated with respect to the effects of turbulent resuspension of sediment and nutrients in the shallow area upstream of Alameda on the Little River arm of Lake Thunderbird (Figure 14). The OWRB provided nutrient data for the sample points in Lake Thunderbird from 1995-2004, which included on location within the Little River Arm upstream of Alameda Street.

The evaluation of the Little River Arm of Lake Thunderbird is conducted using a phosphorus-sediment resuspension model (Chapra, 1975). The purpose of this model is to determine the likely effects of resuspension of phosphorus from the sediment layer on the total phosphorus concentration within the main body of the lake. The phosphorus mass balance for the phosphorus in the water column subject to resuspension (V_L) is,

$$V_L \frac{dp}{dt} = W - Qp - v_s A_s p + v_r A_s p_b \tag{9}$$

where, W is mass phosphorus load to the lake (m/yr); v_s is settling velocity of particulate phosphorus (m/yr); v_r is resuspension velocity of particulate phosphorus (m/yr); A_s is the surface area of Little River Arm (m^3); Q is the average annual discharge from the Little River Arm (m^3/yr); p is total phosphorus concentration in water column (mg m^{-3}); and p_b is total phosphorus concentration in sediment (mg m^{-3}).

Eq. 10 is a separate phosphorus mass balance for the phosphorus in the sediment where v_b is burial velocity of particulate phosphorus (m/yr). The relationship between resuspended phosphorus from the bottom sediment ($v_rA_sp_b$), the amount settling from the water column (v_sA_sp), and removal from the system due to burial ($v_bA_bp_b$) settling is illustrated in Figure 14.

$$V_s \frac{dp_b}{dt} = v_s A_s p - v_r A_s p_b - v_b A_s p_b \tag{10}$$

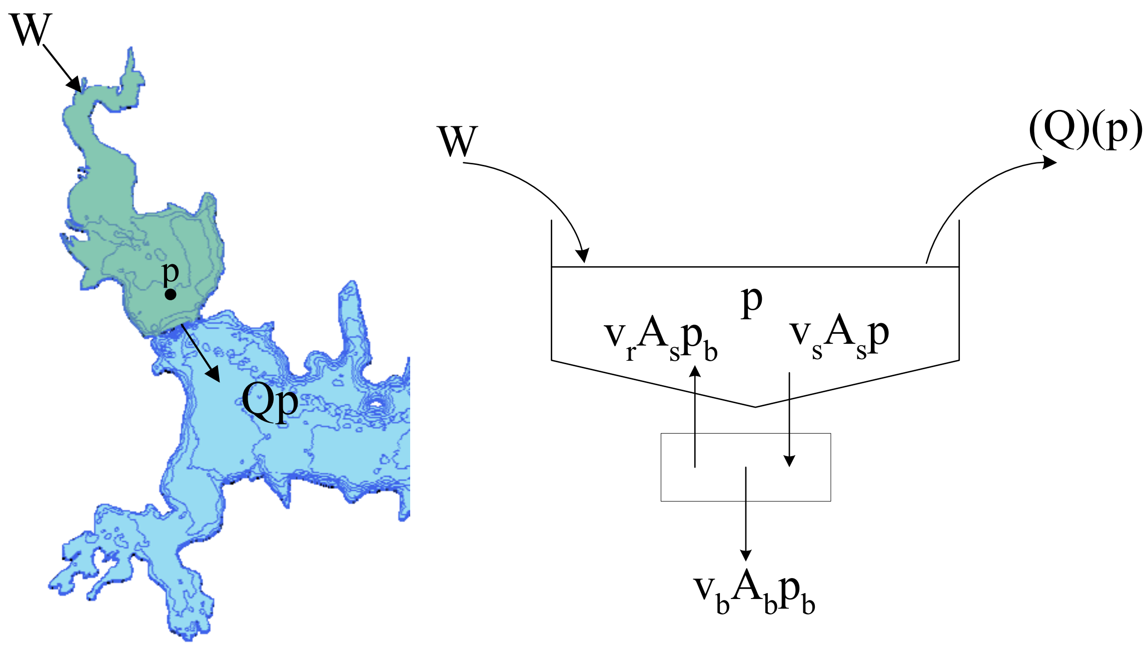


Figure 14 Sediment resuspension model

Solving Eqs. 9 and 10 at steady state, reduces the mass balance for the water to Eq. 11 and the mass balance for the sediment to Eq. 12.

$$0 = W - Qp_L - v_sA_sp_L + v_rA_sp_s \tag{11}$$

$$0 = v_s A_s p_L - v_r A_s p_s - v_b A_s p_s \tag{12}$$

3.4.1 Phosphorus Inputs

The inputs to this portion of the lake are the load from the watershed (W) and the resuspended phosphorus from the bottom sediment ($v_rA_sp_b$). The watershed load (W) is determined from the SWAT model for the Little River Arm of the lake.

3.4.2 Phosphorus Outputs

The outputs from this portion of the lake are the mass flowing out of the Little River Arm into the main body of the lake (Qp), the amount settling from the water column (v_sA_sp), and removal from the system due to burial ($v_b A_b p_b$). An estimate of the phosphorus concentration within the water column (p) for this portion of the lake is obtained from OWRB sampling data (Figure 14).

The concentration of phosphorus within the sediments (p_b) is estimated from the following equation, where ϕ is the total porosity and ρ is the density of "suspended solids".

$$p_b = (1-\phi)\rho \tag{13}$$

The actual phosphorus concentration within the bottom sediment is given by:

$$p_b = \frac{M_p}{V_T} \tag{14}$$

Sediment cores from the lake bottom would provide an improved estimate of the phosphorus sediment concentration.

3.4.3 Resuspension Factor

Solving the mass balance equations for steady state conditions and substituting the concentration of phosphorus within the sediments results in the phosphorus concentration within the lake (p) and the resuspension factor (F_r).

$$p = \frac{W}{Q + v_s A_s (1 - F_r)} \tag{15}$$

$$F_r = \frac{v_r}{v_r + v_b} \tag{16}$$

If the resuspension factor (F_r) is close to 0 then the model reduces to a well mixed lake. However if the resuspension factor (F_r) is closer to 1, the inflow concentration is equal to the incoming load (e.g. continual resuspension).

The unknowns in the calculation of the resuspension factor are the settling (v_s), resuspension (v_r), and the burial (v_b) velocities. Adding Eqs. 9 and 10 and solving for the burial velocity (v_b) results in,

$$v_b = \frac{W - Qp}{A_s (1-\phi)\rho} \tag{17}$$

Using the steady state version of Eq. 10 and solving for the resuspension velocity,

$$v_r = v_s \frac{p}{(1-\phi)\rho} - v_b \tag{18}$$

An estimate of the settling velocity can be obtained through the use of Stokes' law,

$$v_s = \alpha \frac{g}{18}\left(\frac{\rho_s - \rho_h}{\mu}\right) d^2 \qquad (19)$$

Assuming a dynamic viscosity of 0.014 g cm^{-3}, and acceleration of gravity of 981 cm s^{-2} the settling velocity may be expressed Eq. 20 where v_s is settling velocity (m/yr); ρ_s is particle density (g cm^{-3}); ρ_w is density of water (g cm^{-3}); α is form factor for particle shape; and d is effective particle diameter (μm);

$$v_s = 365(0.033634\alpha)(\rho_s - \rho_h)d^2 \qquad (21)$$

A first estimate of the settling velocity assuming a spherical shape (α=1), a particle diameter (10 μm), and a particle density for phytoplankton (ρ_s = 1.027 g cm^{-3}) yields a settling velocity of 33.1 m/yr.

A sensitivity analysis is used to assess the impact of various settling velocities on the resuspension factor. By analyzed settling velocities from 33 - 64 m/yr the resuspension factor ranges from 0 – 0.4 (Figure 15) indicating a well-mixed lake.

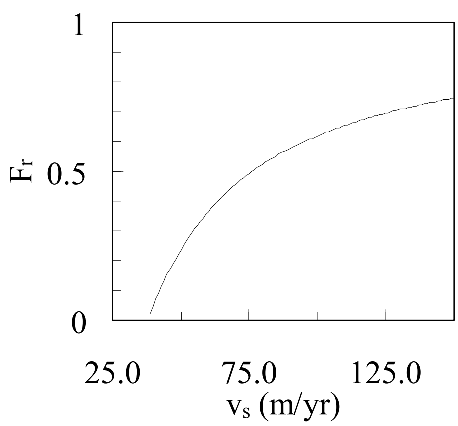


Figure 15 Sensitivity of resuspension factor to settling velocity

Based on the sensitivity analysis, the assumption of a well-mixed lake provides an adequate model of the in-lake process.

3.4.4 Influence of Little River Arm on Phosphorus Removal

To determine the effectiveness of phosphorus reduction by the Little River Arm, the phosphorus concentration to the lake without the Little River Tributary was calculated and compared to the load after it passes through the Little River Arm. Using Eq. 4, the phosphorus concentration in the main body of the lake was calculated with and without the Little River Arm.

The phosphorus concentration in the lake without the Little River Arm would be 0.066 mg/L, while the phosphorus concentration with the Little River Arm is 0.049 mg/L. The Little River Arm has the effect of reducing the phosphorus load to the main body of Lake Thunderbird by 36%. For comparison, the OWRB BUMP data was summarized without phosphorus concentrations in the Little River Arm. The average in-lake total phosphorus concentration without the Little River Arm would be 0.049 mg/L. The influence of this area serves to reduce total phosphorus arriving in the main body of the lake and is therefore beneficial.

4.0 Results

This section presents results from watershed and in-lake modeling for nutrients and sediment to the lake. The total phosphorus concentration in the lake is calculated from the total phosphorus load for the baseline and build-out scenarios. The chlorophyll-a concentration for the baseline and build-out scenarios is evaluated based on a relationship developed for the lake by the OWRB between total phosphorus concentration and chlorophyll-a.

4.1 Calibration of Baseline Landuse Scenario

The model is first calibrated against the water-balance for the lake. The hydrologic water balance is used to determine the inflow to the lake. Inflow to the lake is then used to calibrate the SWAT model based on a continuous simulation of annual inflow. The initial cumulative average annual in flow for the uncalibrated model is much higher than the cumulative inflow observed from the water balance. Recommendations from SWAT documentation for calibration of flow were reviewed and applied to the model in a systematic manner. The following summary describes the model parameters that are adjusted to produce simulated volume in agreement with observed.

- Soil Evaporation Compensation Factor (ESCO) is 0.100.
- Curve Number (CN) was tested before and after adjusting ESCO. The model showed little response to changes in runoff curve number. CN was set to the default, which averaged 83.
- Urban Curve Numbers were replaced for each landuse type (USDA, 1986) (Table 5).

Table 5 Urban landuse curve numbers

Urban Landuse Type	Urban Curve Numbers
Residential-High Density	77
Residential-Medium Density	57
Residential-Med/Low Density	54
Residential-Low Density	51
Commercial	89
Industrial	81
Transportation	81
Institutional	81

- Precipitation derived from Oklahoma City and Norman National Weather Service rain gauges.
- Fraction Connected Impervious (FCIMP) was set to 60% of the default values.
- Threshold Depth of Water in the Shallow Aquifer (GWQMIN) was set to the default of 0.
- The Base Flow Recession Constant (Alpha Bf) was adjusted to 0.05.
- The method of calculating potential evapotranspiration was set to Penman-Montieth method.
- Crack-Flow was enabled allowing bypass flow through the soils.

Application of the calibrated model achieved agreement of the cumulative average annual inflow to Lake Thunderbird to within 8% of the observed average annual inflow to the lake. Figure 16 shows a plot of observed cumulative flow over time compared to the uncalibrated and calibrated model for the baseline condition. The simulated cumulative volume agrees much more closely after calibration.

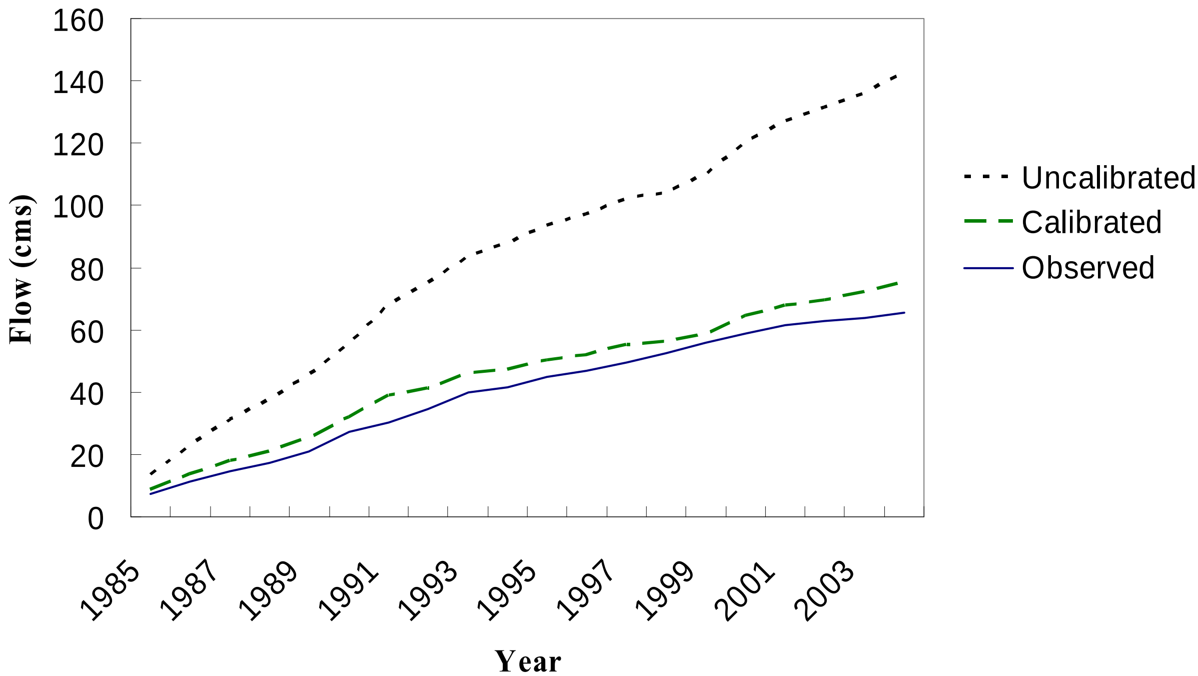


Figure 16 Cumulative volume from the uncalibrated, calibrated and observed time series.

With the model calibrated for average annual flow, a SWAT model was created to represent the build-out landuse scenario, where only landuse was changed and other factors remained constant. The build-out model is simulated with the same weather, precipitation, and calibration factors as the calibrated baseline model. The methodology for estimating phosphorus load based on landuse is presented in the following sections.

4.2 Phosphorus

Given the calibrated lake inflow, the phosphorous load to the lake can be computed. The average annual phosphorus load was calculated from percent imperviousness of each landuse type for the baseline landuse scenario. Average annual phosphorus load was compared to average annual discharge. The average annual phosphorus load calculated based on percent impervious area of 17,510 kg/yr of phosphorus delivered to the lake or 0.265 kg/yr·ha. The total average annual phosphorus load from the calibrated SWAT model yielded 16,004 kg/yr or 0.241 kg/yr·ha.

However, review of the SWAT results revealed that phosphorus load from urban areas was underestimated when evaluated against NSQD (Pitt, et. al., 2005), and the reported values for Rock Creek in COMCD (2006). Evaluation of SWAT theory documentation revealed that

SWAT uses different methods for estimating load from urban versus agricultural areas. For urban areas, SWAT uses the USGS regression equation developed by Driver and Tasker (USGS, 1990) which is valid for very small drainage areas. The drainage area, percent impervious, and total phosphorus concentrations was calculated with the Driver and Tasker equation and compared to the concentrations of samples collected for the COMCD study (2006). The equation works very well for one site which had a drainage area of 0.02 square miles, but did not hold up in for drainage areas over 1 square mile, i.e. severely underestimated.

Subsequently, a methodology was developed using percent impervious for each landuse from SWAT and calculating the phosphorus load for urban areas using Eq. 22, which was developed for the Rock Creek Watershed (located within the Lake Thunderbird basin) (COMCD, 2006),

$$L = 1.6 \cdot (1 - e^{(0.1 - IMP \cdot 20}) \tag{22}$$

where L is the annual load rate, and IMP is the percent impervious area.

To obtain more realistic results specific to urban areas within the watershed, the loading from SWAT is re-computed based on the Rock Creek study (COMCD, 2006). Table 6 presents the landuse types in the basin along with the impervious area of each landuse obtained from SWAT input tables. The impervious area for each landuse type in the Lake Thunderbird watershed is used in Eq. 22 to calculate the total phosphorus load in mass/area/year. The total phosphorus load is then applied to the area of each landuse within the subbasin to calculate the total annual load for the urban areas. The urban phosphorus load was combined with the agricultural load by subbasin to arrive at the total load by subbasin.

Table 6 Percent impervious area and calculated load per acre by urban landuse type

Landuse	Impervious	Total P (lbs/ac/yr)	Total P (kg/ha/yr)
Residential-High Density (URHD)	0.6	1.60	1.79
Residential-Medium Density (URMD)	0.38	1.59	1.79
Residential-Med/Low Density (URML)	0.2	1.38	1.55
Residential-Low Density (URLD)	0.12	0.53	0.59
Commercial (UCOM)	0.67	1.60	1.79
Industrial (UIDU)	0.84	1.60	1.79
Transportation (UTRN)	0.98	1.60	1.79
Institutional (UINS)	0.51	1.60	1.79

By adjusting the phosphorus load from urbanized areas the Total P load to the basin is increased by a factor of 2. The aggregated total phosphorus load for each subbasin was multiplied by a calibration factor of 0.5 to bring the calculated load into agreement with the calibrated SWAT model output. This reduction is justified by dilution from runoff in areas not fertilized within the watershed.

Under the baseline scenario, the phosphorus load ranges from 0.0-0.63 kg/ha in the model subbasins discharging to the main channels in the watershed. The areas contributing the highest load per unit area are urbanized areas, notably in Moore, and Oklahoma City. Figure 17 shows the average annual total phosphorous load by subbasin under the baseline landuse scenario. Under the build-out scenario, the phosphorus load to the main channels ranges from 0.0-0.90 kg/ha. Figure 18 shows the average annual total phosphorus load under the build-out landuse scenario. Increased load is associated with the urbanization of the basin, especially as evidenced by landuse conversion of agricultural land in Norman, and Oklahoma City.

The range in total phosphorus load for the baseline scenario is 0-0.63 kg/ha, which increases to 0.06-0.90kg/ha under the build-out scenario. On average, total phosphorus load by subbasin more than doubled from 0.25 to 0.54 kg/ha due to urban development in the watershed.

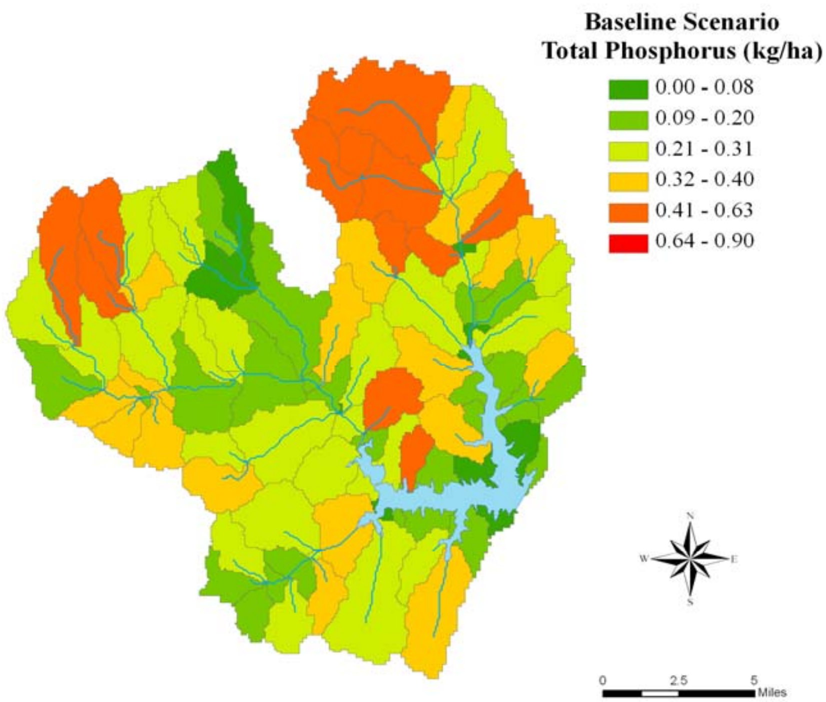


Figure 17 Baseline average annual total phosphorus load by subbasin

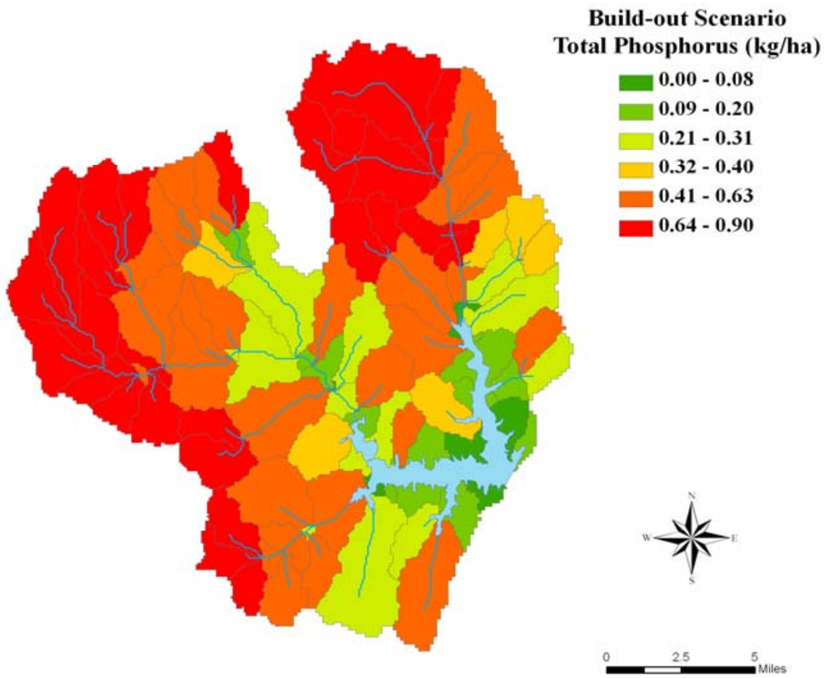


Figure 18 Build-out average annual total phosphorus load by subbasin

Using the landuse categories and percent impervious area, we can identify the change in the imperviousness as a guide for targeting areas with increased runoff and nutrient load (Figure 19). This helps identify areas within the drainage basin that will impact the water quality as the basin is developed, and used to further identify locations for management practices to reduce the impact of further urbanization. Parks were assigned zero percent impervious area because many floodplain areas are classified as parks in the landuse map. Imperviousness is a key factor affecting loading rates in the watershed.

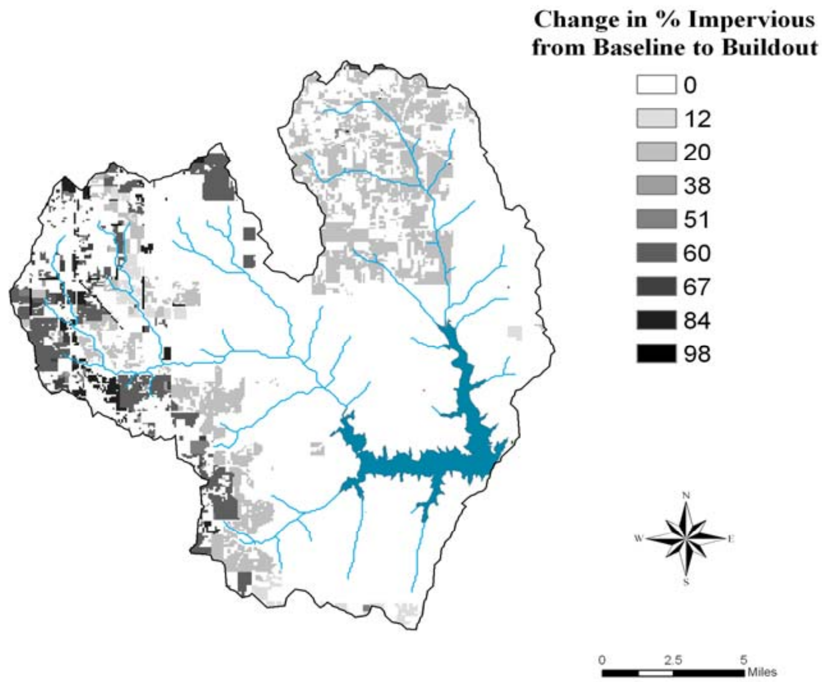


Figure 19 Percent change in percent impervious area from baseline to build-out

To further assist in the evaluation of the impact of the urbanization and to verify output results, the phosphorus load by subbasin was overlain with percent imperviousness for the baseline and build-out scenarios in Figure 20 and Figure 21, respectively. In these figures, urbanized land is shaded grey, regardless of the degree of imperviousness. From these illustrations, the association between urbanization and increased phosphorus load to the main channel is evident. As the basin is built-out, the phosphorus load to the lake increases dramatically.

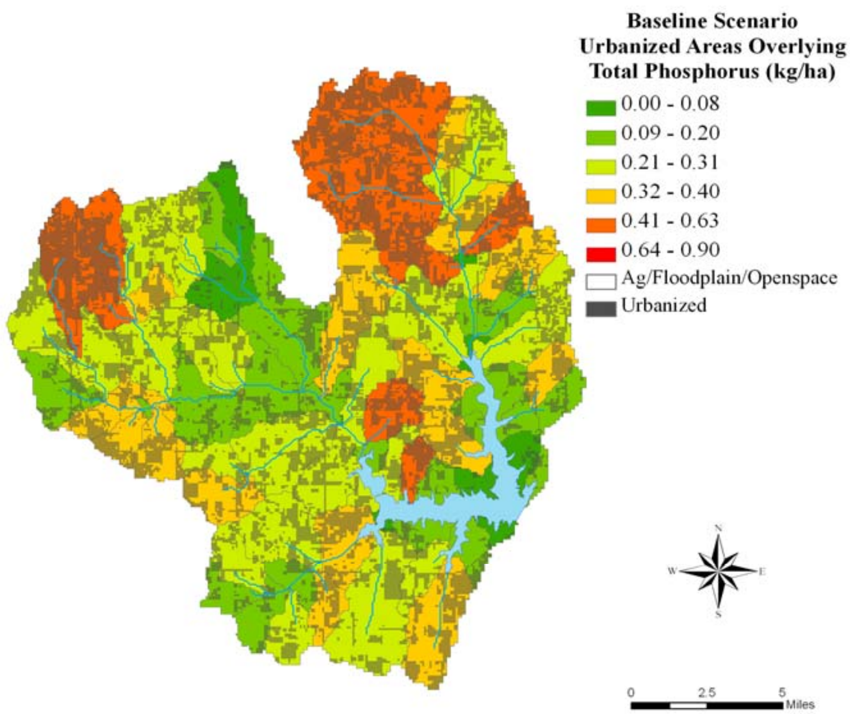


Figure 20 Baseline urban areas overlying total phosphorus load from each subbasin.

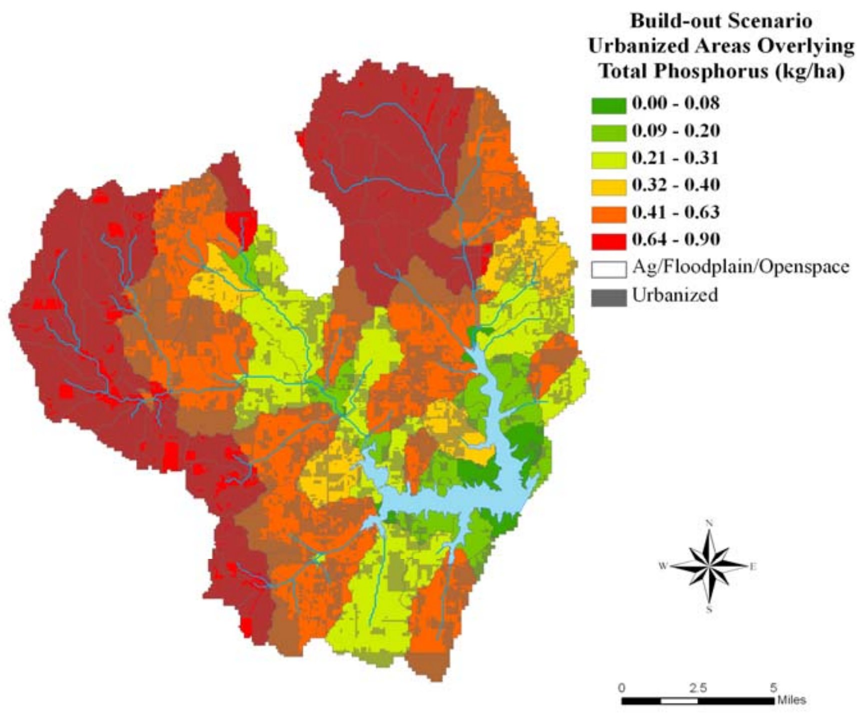


Figure 21 Build-out urban areas overlying total phosphorus load from each subbasin.

4.3 Nitrogen

The analysis of nitrogen loading is implemented using the same methodology developed for phosphorus. A specific difficulty with nitrogen is that SWAT output for the HRUs provided nitrogen in surface runoff as nitrate (NO_3) only. The COMCD equations tracked nitrate plus nitrite. The equation is applied without modification, with the understanding that results may be underestimated, because SWAT does not track NO_2.

Using Eq. 23 (COMCD, 2006), the nitrogen load for urban areas was calculated using the percent impervious from SWAT for urban landuses (Table 7). Nitrogen load (NO_3) from the SWAT HRU file was used for the agricultural areas. The agricultural and urban loads for each HRU were added together for each subbasin.

$$L = 1.8 \cdot (1 - e^{(0.1 - IMP \cdot 20}) \tag{23}$$

Where, the term (L) is the annual load rate and IMP is the percent impervious area.

Table 7 Calculated urban load rates for nitrate plus nitrite

Landuse	Impervious	NO2+NO3 (lbs/ac/yr)	NO2+NO3 (kg/ha/yr)
Residential-High Density (URHD)	0.6	1.80	2.02
Residential-Medium Density (URMD)	0.38	1.79	2.01
Residential-Med/Low Density (URML)	0.2	1.56	1.74
Residential-Low Density (URLD	0.12	0.59	0.67
Commercial (UCOM)	0.67	1.80	2.02
Industrial (UIDU)	0.84	1.80	2.02
Transportation (UTRN)	0.98	1.80	2.02
Institutional (UINS)	0.51	1.80	2.02

Because the transport of nitrogen is similar to that of phosphorus and is directly related to runoff, the same calibration factor (0.5) was applied to nitrogen as phosphorus. Differences in calibration of the nitrogen load as compared to phosphorus are not investigated.

The nitrogen load by subbasin for the baseline and build-out scenarios is presented in Figure 22 and Figure 23, respectively. The nitrogen load for the baseline scenario varies from 0-0.75 kg/ha and ranges from 0.07-1.01 kg/ha for the build-out scenario. The average load by subbasin increased from 0.34 to 0.56 kg/ha due to urban development in the watershed.

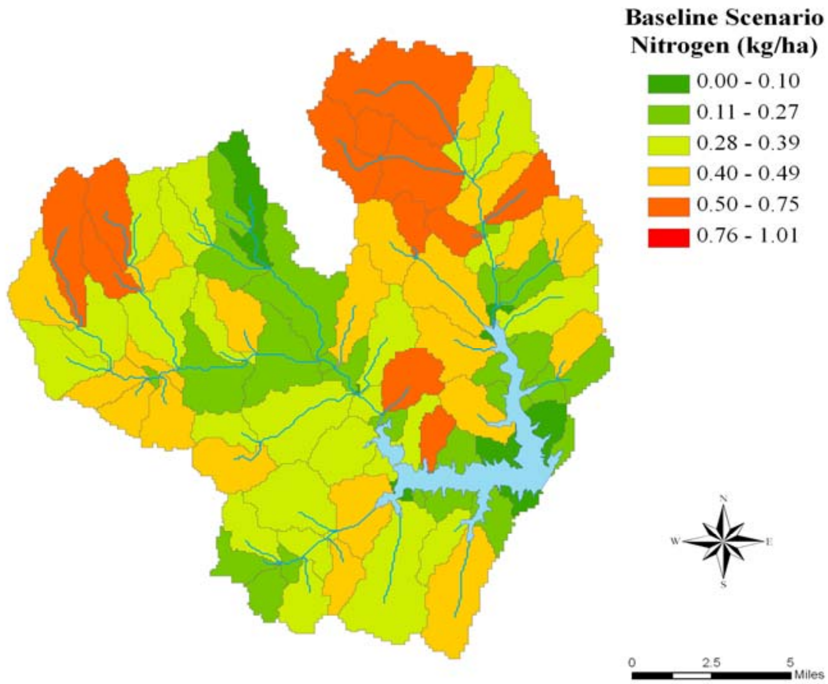


Figure 22 Baseline average annual nitrogen load by subbasin

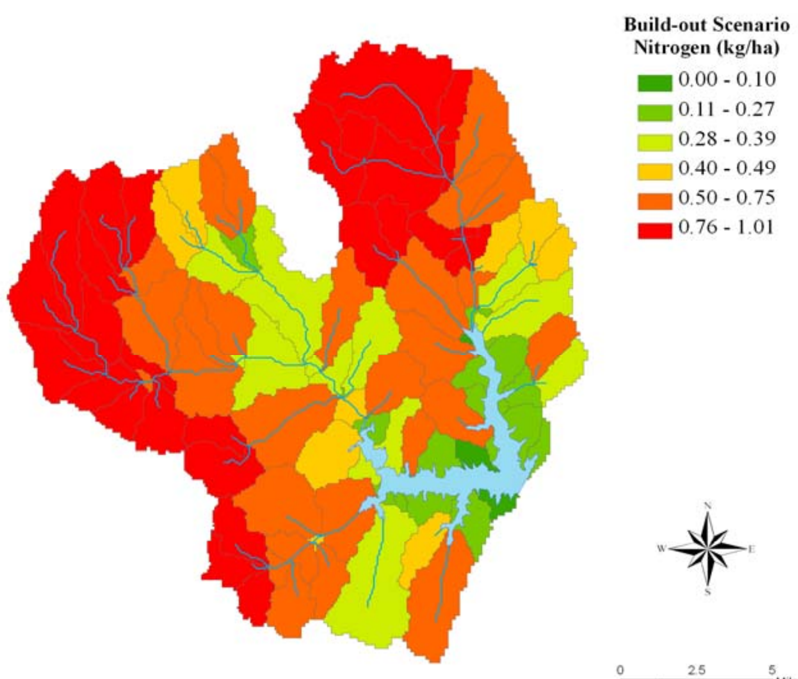


Figure 23 Build-out average annual nitrogen load by subbasin

4.4 Sediment

The sediment yield analysis also implemented the same methodology developed for phosphorus. Sediment yield from the SWAT HRU file was used for the agricultural areas. The agricultural and urban loads for each HRU were added together for each subbasin. Because the transport of sediment is directly related to runoff and is similar to that of phosphorus, the same calibration factor was applied to sediment yield as was to phosphorus and the total load by subbasin was adjusted by a factor of 0.5. Using Eq 24 (COMCD, 2006), the sediment yield for urban areas was calculated using the percent impervious from SWAT for urban landuses (Table 8).

$$L = 350\cdot\ (1 - e^{(0.1 - IMP\cdot\ 8})\tag{24}$$

where, L is the annual loading rate; and IMP is the percent impervious area.

Table 8 Calculated urban load rates for sediment yield

Landuse	Impervious	TSS (lbs/ac/yr)	TSS (kg/ha/yr)
Residential-High Density (URHD)	0.6	343.59	385.11
Residential-Medium Density (URMD)	0.38	312.74	350.53
Residential-Med/Low Density (URML)	0.2	192.73	216.02
Residential-Low Density (URLD)	0.12	51.75	58.00
Commercial (UCOM)	0.67	346.34	388.19
Industrial (UIDU)	0.84	349.06	391.24
Transportation (UTRN)	0.98	349.69	391.95
Institutional (UINS)	0.51	336.83	377.53

The sediment yield by subbasin for the baseline and build-out scenarios is presented in Figure 22 and Figure 23, respectively. The sediment yield for the baseline scenario varies from 0-163 kg/ha and ranges from 0.65-187 kg/ha for the build-out scenario. The average load by subbasin increased from 78 to 87 kg/ha due to urban development.

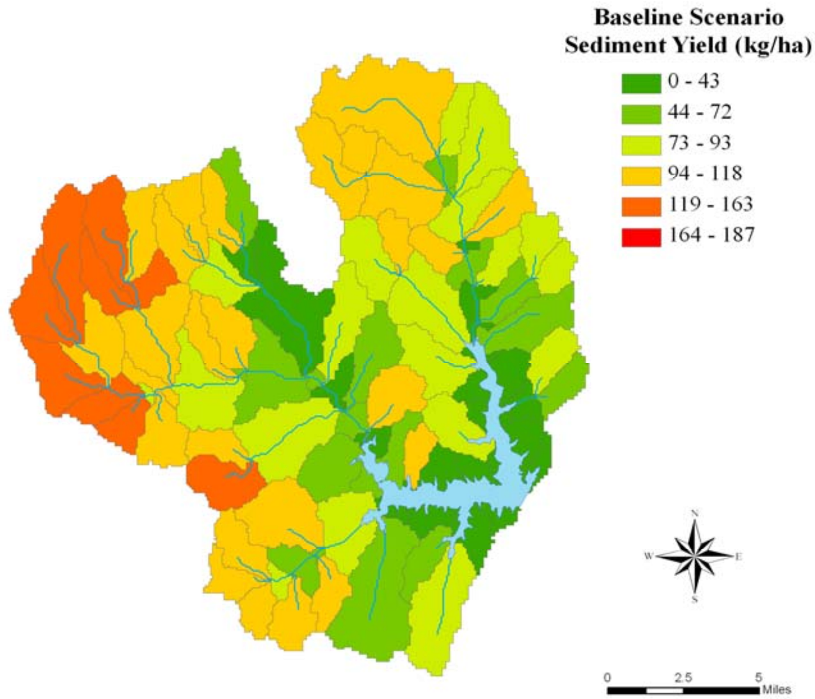


Figure 24 Average annual sediment yield by subbasin under baseline scenario

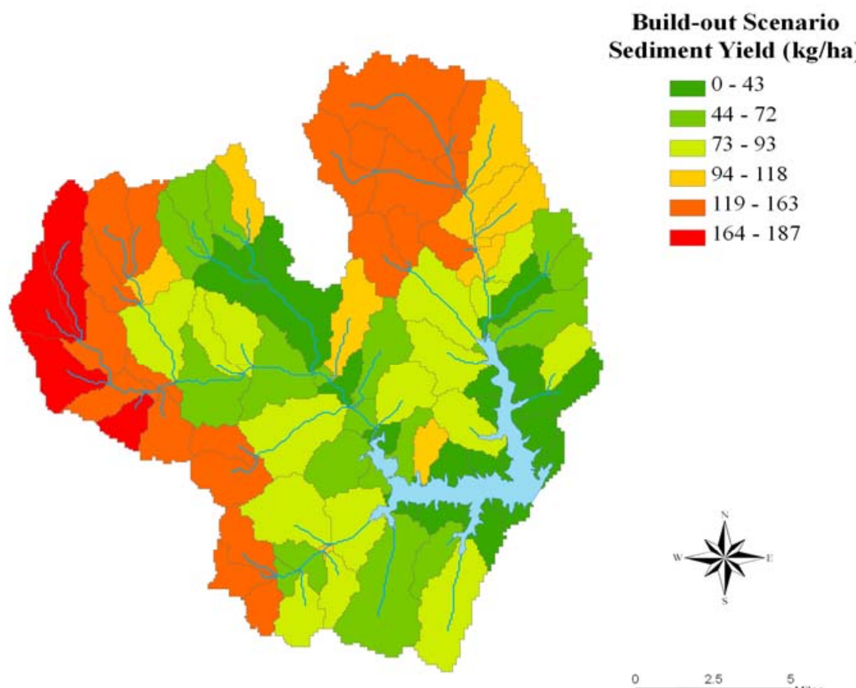


Figure 25 Average annual sediment yield by subbasin under build-out scenario

4.5 Phosphorus and chlorophyll-a Relationship with Build-out

SWAT generates the phosphorus load delivered to the lake as organic and mineral phosphorus. From these values we can calculate the average annual phosphorus concentration in the lake using the steady state model.

The average annual phosphorus loads to the lake from SWAT for baseline and build-out conditions are used as input to Eq. 4 to arrive at the total phosphorus concentration in the lake based on the average annual load delivered to the lake under the baseline and build-out scenarios. Parameters for Eq. 4 are summarized in Table 9.

Table 9 Lake Thunderbird parameters for phosphorus concentration calculation

Parameter	Value	Description
Q	72,841,495 m^3/yr	Average annual Discharge from USGS records 1982-2005
v_s	11.14 m/yr	Calculated based on hydraulic residence time (Eq 6)
As	22,006,825 m^2	From the 2001 Lake Thunderbird Hydrographic Survey, surface area at normal pool elevation:
$W_{baseline}$	18,241,040 g/yr	Baseline Scenario average annual total phosphorus load into the lake from SWAT reservoir output file
$W_{build\text{-}out}$	24,906,520 g/yr	Build-out Scenario average annual total phosphorus load into the lake from SWAT reservoir output file

A relationship was developed by the OWRB using 2001-2003 BUMP data for surface waters in Lake Thunderbird (0.1 meters below lake surface). This relationship between chlorophyll-a (ug/L) and total phosphorus (mg/L) is:

$$\text{Chl-a} = -5.49 + 632 \cdot \text{Total P} \qquad (25)$$

From this relationship, we can estimate the chlorophyll-a concentration in the lake for the baseline and build-out scenarios.

Baseline Total Phosphorus Concentration = 0.057 mg/L
Baseline chlorophyll-a Concentration = 30.8 µg/L (3.08 mg/L)
Percent over water quality goal = 54%

Build-out Total Phosphorus Concentration = 0.078 mg/L
Build-out chlorophyll-a = 44.0 µg/L (4.40 mg/L)
Percent over water quality goal = 120%

The calculated chlorophyll-a concentration for the baseline condition is within the range of values used to develop the relationship. The maximum chlorophyll-a concentration from 2001-2003 BUMP data was 38.4 mg/L. Using the above relationship; the chlorophyll-a concentration in the lake increases from 30.8 µg/L to 44 µg/L, an increase of 43%, due to the effects of urbanization. Of immediate concern are the values for baseline conditions, which already exceed the established chlorophyll-a water quality goal for the lake of 20µg/L with concentration in the lake of 30.8ug/L, which is 54% higher than the water quality goal. chlorophyll-a concentrations in excess of 20 μg/L result in hypereutrophic water conditions with excessive algae growth.

5.0 Targeted Management Practices

Management practices for the basin are evaluated for implementation in the Lake Thunderbird watershed on a targeted basis. Specific recommendations for control of non-point source and stormwater discharge from urbanized areas were identified and compiled from sources that include the Virginia Storm Water Management Manual (Virginia, 1999) and the Handbook for Developing Watershed Plans to Restore and Protect our Waters (USEPA, 2005). A table of prospective management practices for urban areas is contained in Appendix A and includes the phosphorus removal efficiency, maintenance requirements, other benefits, associated problems with the management practice, and applicable landuse conditions.

5.2 Management Practices Recommendations

After SWAT was calibrated to the hydrologic water budget and known nutrient levels in the lake, build-out conditions were evaluated to identify areas for making recommendations for targeted management practices, which were appropriate to the local landuse based on imperviousness. Review of the applicability of management practices resulted in the consolidation and removal of several management practices based largely on the functional lifespan of the management practice ability to maintain the management practice. Management practices in Table 10 are considered for the Lake Thunderbird watershed. Additional information for each of these management practices is contained in Appendix A, including maintenance requirements, additional benefits, and problems that may be associated with the management practice.

Table 10 Applicable management practices for urbanized areas

Best Management Practice	Phosphorus Removal Efficiency	Applicable Landuse Conditions
Sediment Forbay	Required for performance of structural management practices	Required to improve efficiency and life span of most other management practices. Also facilitates maintenance of other management practices.
Grassed Swale	15%	Residential 16-21% impervious cover. If water quality swales are incorporated, will work with higher density development up to 37% impervious area.
Voluntary Urban Nutrient Management	10%	Residential 16-21% impervious cover.
Statutory Urban Nutrient Management	22%	Residential 16-21% impervious cover.
Constructed Wetlands	30%	Percent impervious cover 22-37%. Basin requires minimum drainage of 10 acres and may not be located near (within 100 feet) of septic systems. Permeable soils are not suited for constructed wetlands. May not be suited for highly visible sites or adjacent to highly manicured sites.

Best Management Practice	Phosphorus Removal Efficiency	Applicable Landuse Conditions
Extended Detention-Enhanced	50%	Percent impervious cover 38-66%. See Extended Detention Basin
Retention Basin II (4xWQ Vol)	50%	Percent impervious cover 22-37%. Basin requires minimum drainage of 10 acres and not located near (within 100 feet) of septic systems. Permeable soils are not suited for retention basins.
Retention Basin III (4xWQ Vol with aquatic bench)	65%	Percent impervious cover 22-37%. Basin requires minimum drainage of 10 acres and not located near (within 100 feet) of septic systems. Permeable soils are not suited for retention basins.
Bioretention filter	50%	Percent impervious cover 38-66%.

Using the phosphorus removal efficiencies for each management practice, effectiveness is estimated for each management practice by subbasin. To facilitate the process, all structural management practices are grouped into one category called structural controls. These management practices include detention basins, retention basins, and bioretention filters. Structural management practices will only meet their optimal phosphorus reduction capacity with the installation and proper maintenance of sediment forebays. Appendix B contains the reduction in Total P for the baseline and build-out scenario for each landuse within a subbasin.

Applicability of management practice(s) is based mainly on the percent impervious for the landuse and activities associated with the landuse. Parks, floodplains and pastures within the basin are assumed to not be fertilized. An exception may be golf courses, which would need to be evaluated separately outside of this study. Management practices are applied to landuse types from the SWAT output using the aggregated Total P estimates. Table 11 summarizes the effect of management practices evaluated in Appendix B under the baseline scenario. The locations of areas where these management practices are applicable are illustrated in Figure 26. All management practices are applicable to residential areas evaluated.

Table 11 Baseline scenario management practice application summary

Baseline Scenario	Phosphorus removal efficiency	Applied to % Impervious Areas	Applicable SWAT LU Classifications	Net Total P Load Reduction for Practices Applied To:	
				Entire Basin	Norman Only
Voluntary Fertilizer Reduction	10%	12-38%	URMD	7%	3%
Statutory Fertilizer Reduction	22%	12-38%	URMD	16%	8%
Wetlands	30%	20-38%	URMD	21%	10%
Structural Practices	50%	20-67%	URMD, UCOM, UINS	37%	18%

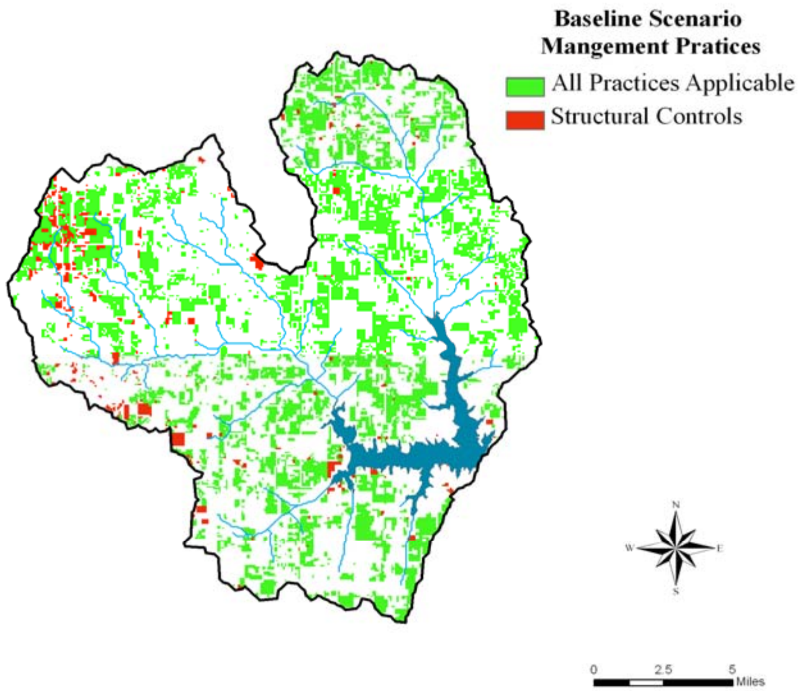


Figure 26 Baseline Scenario Management Practice Applicability

Table 12 summarizes the effect of management practices evaluated in Appendix B under the build-out scenario. The locations of areas where these management practices are applicable are illustrated in Figure 27. Management practices are applicable based percent impervious area. All management practices are applicable to residential areas evaluated. Structural control are the most effective means of reducing phosphorus in highly impervious areas such as commercial, and institutional landuse areas.

Table 12 Build-out scenario management practice application summary

Build-out Scenario	Phosphorus removal efficiency	Applicability Impervious (%)	Applicable SWAT LU Classifications	Net Total P Load Reduction for Practices Applied To:	
				Entire Basin	Norman Only
Voluntary Fertilizer Reduction	10%	12-38%	URLD,URML, URMD	8%	4%
Statutory Fertilizer Reduction	22%	12-38%	URLD,URML, URMD	18%	8%
Wetlands	30%	20-38%	URLD,URML, URMD	24%	10%
Structural controls	50%	20-67%	URML,URMD, UCOM, UINS	42%	18%

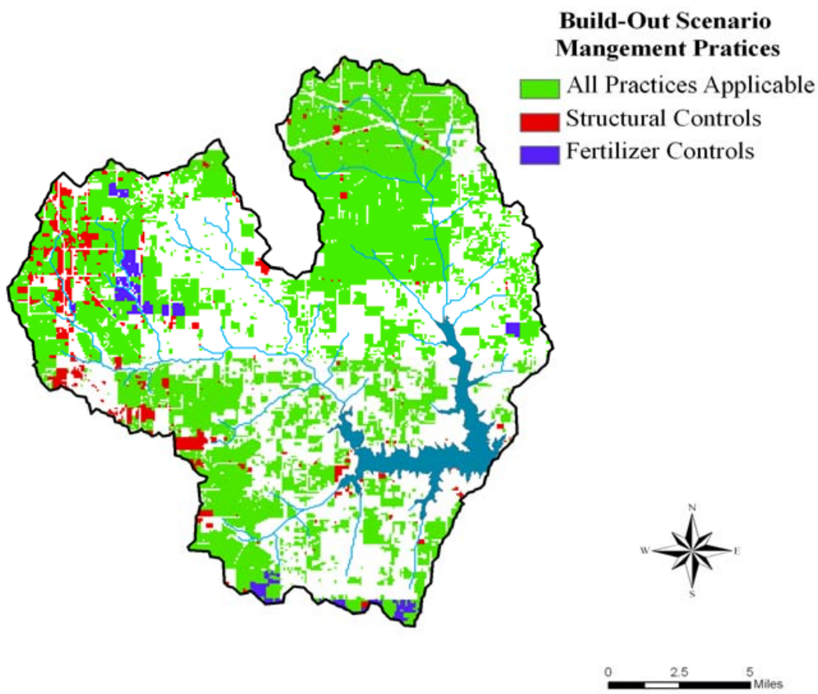


Figure 27 Build-out Scenario Management Practice Applicability

By combining the effects of management practices for maximum Total P reduction, i.e., statutory fertilizer reduction, wetlands, and structural controls to the entire basin, the net Total P load can be reduced 74% for the baseline scenario and 84% for the build-out scenario. Where the initial Total P load is adjusted for urban areas and calibrated for the basin as described in Section 4.2. This difference is attributed to the greater agricultural (pasture) area in the basin for the baseline scenario. There is a greater reduction in the build-out scenario because more of the pastureland has been converted to urban residential landuse to which the management practices are applied.

Application of the aggregated management practices to the entire basin shows significant reduction in chlorophyll-a concentrations in the lake, well below the water quality goal for the lake of 20µg/L. Under the baseline scenario the water quality goal could be met by application of *voluntary* fertilizer reduction and structural controls throughout the entire basin, including areas that are already developed (Table 13). Under the build-out scenario, the water quality goals can be attained by *statutory* fertilizer reduction and structural controls throughout the entire basin (Table 14). In order to achieve these goals, the management practices must be properly designed, and strictly enforced with implementation and maintenance in all applicable areas in the basin. The aggregated management practice indicated in Tables 13 and 14 by the superscript [1] is the practice that most closely achieves the water quality goal of 20µg/L Chl-a.

Table 13 Effect of aggregated management practices applied to the entire basin: baseline scenario

Scenario	Application of Aggregated Management Practices	Effective Phosphorus Reduction	Total P load (kg/yr)	Phosphorus Concentration (mg/L)	chlorophyll-a Concentration (ug/L)
Baseline	None	0%	22854	0.07	40
Baseline	Voluntary Fertilizer Reduction and Wetlands	28%	16455	0.05	27
Baseline	Statutory Fertilizer Reduction and Wetlands	37%	14398	0.05	23
Baseline[1]	Voluntary Fertilizer Reduction and Structural Controls	44%	12798	0.04	20
Baseline	Statutory Fertilizer Reduction and Structural Controls	53%	10742	0.03	16
Baseline	Wetlands and Structural Controls	58%	9599	0.03	14
Baseline	Voluntary Fertilizer Reduction, Wetlands, and Structural Controls	65%	7999	0.03	10
Baseline	Statutory Fertilizer Reduction, Wetlands, and Structural Controls	74%	5942	0.02	6

Table 14 Effect of aggregated management practices applied to the entire basin: build-out scenario

Scenario	Application of Aggregated Management Practices	Effective Phosphorus Reduction	Total P load (kg/yr)	Phosphorus Concentration (mg/L)	chlorophyll-a Concentration (ug/L)
Build-Out	None	0%	32641	0.10	59
Build-Out	Voluntary Fertilizer Reduction and Wetlands	32%	22196	0.07	39
Build-Out	Statutory Fertilizer Reduction and Wetlands	42%	18932	0.06	32
Build-Out	Voluntary Fertilizer Reduction and Structural Controls	50%	16321	0.05	27
Build-Out[1]	Statutory Fertilizer Reduction and Structural Controls	60%	13057	0.04	20
Build-Out	Wetlands and Structural Controls	66%	11098	0.03	17
Build-Out	Voluntary Fertilizer Reduction, Wetlands, and Structural Controls	74%	8487	0.03	11
Build-Out	Statutory Fertilizer Reduction, Wetlands, and Structural Controls	84%	5223	0.02	5

Analysis is performed to identify whether management practices applied only to the subbasins within the City of Norman can achieve water quality goal for chlorophyll-a. This evaluation included subbasins with 50% or greater of their area within the Norman corporate limits as indicated in Figure 28.

Figure 28 Subbasins with 50% or greater area within the City of Norman

Under the baseline scenario, the minimum achievable chlorophyll-a concentration in the lake is 24µg/L with statutory fertilizer reduction, wetlands, and structural controls (Table 15). With the same management practices applied under the build-out scenario, the chlorophyll-a concentration in the lake increases to 36µg/L indicative of hyper-eutrophic water quality conditions (Table 16). Under the baseline and build-out scenarios, if application is only to basins within the City of Norman, the aggregated management practices that achieves the in-lake water quality goal most closely is indicated by the superscript [2] in Tables 15 and 16.

Table 15 Effect of aggregated management practices applied only in Norman: baseline scenario

Scenario	Application of Aggregated Management Practices	Effective Phosphorus Reduction	Total P load (kg/yr)	Phosphorus Concentration (mg/L)	chlorophyll-a Concentration (µg/L)
Baseline	None	0%	22854	0.07	40
Baseline	Voluntary Fertilizer Reduction and Wetlands	13%	19883	0.06	34
Baseline	Statutory Fertilizer Reduction and Wetlands	18%	18741	0.06	32
Baseline	Voluntary Fertilizer Reduction and Structural Controls	21%	18055	0.06	30

Scenario	Application of Aggregated Management Practices	Effective Phosphorus Reduction	Total P load (kg/yr)	Phosphorus Concentration (mg/L)	chlorophyll-a Concentration (µg/L)
Baseline	Statutory Fertilizer Reduction and Structural Controls	26%	16912	0.05	28
Baseline	Wetlands and Structural Controls	28%	16455	0.05	27
Baseline	Voluntary Fertilizer Reduction, Wetlands, and Structural Controls	31%	15769	0.05	26
Baseline[2]	Statutory Fertilizer Reduction, Wetlands, and Structural Controls	36%	14627	0.05	24

Table 16 Effect of aggregated management practices applied only in Norman: build-out scenario

Scenario	Application of Aggregated Management Practices	Effective Phosphorus Reduction	Total P load (kg/yr)	Phosphorus Concentration (mg/L)	chlorophyll-a Concentration (µg/L)
Build-Out	None	0%	32641	0.10	59
Build-Out	Voluntary Fertilizer Reduction and Wetlands	14%	28072	0.09	50
Build-Out	Statutory Fertilizer Reduction and Wetlands	18%	26766	0.08	48
Build-Out	Voluntary Fertilizer Reduction and Structural Controls	22%	25460	0.08	45
Build-Out	Statutory Fertilizer Reduction and Structural Controls	26%	24155	0.08	43
Build-Out	Wetlands and Structural Controls	28%	23502	0.07	41
Build-Out	Voluntary Fertilizer Reduction, Wetlands, and Structural Controls	32%	22196	0.07	39
Build-Out[2]	Statutory Fertilizer Reduction, Wetlands, and Structural Controls	36%	20891	0.07	36

Application of management practices in the City of Norman alone is not sufficient to meet the water quality goals set for the lake. Further study is needed to evaluate if enhanced wetlands at the Little River Branch above Alameda and at the upper reaches of the Hog Creek Arm of Lake Thunderbird could alleviate the impact of urbanization Oklahoma City and Moore.

6.0 Summary and Conclusions

The watershed tributary to Lake Thunderbird is evaluated in terms of the in-lake water quality for two landuse scenarios, baseline and build-out. Eutrophication under the build-out scenario is projected to increase due to impervious area and runoff, resulting from urban development within the watershed. As runoff increases the nutrient load, particularly phosphorus, to the lake increases that results in accelerated algal growth and production of chlorophyll-a. Effects of management practices in the watershed are evaluated in terms of the in-lake concentration of chlorophyll-a, which is a primary indicator of excessive algal growth. Practices that will reduce chlorophyll-a concentrations are targeted in watershed areas that produce the greatest nutrient loading to the lake. Using a simple in-lake model for phosphorus, the phosphorus/chlorophyll-a relationship is developed and used to evaluate the chlorophyll-a concentration in the lake under baseline and build-out conditions. chlorophyll-a concentrations currently exceed the existing water quality goal for the lake, averaging 30.8 µg/L under the baseline scenario. While under the build-out scenario, the chlorophyll-a concentration is projected to increase to 44 µg/L, which is well above the water quality goal set for this sensitive water supply lake.

Management practices that can reduce the phosphorus load to the lake are evaluated for the baseline and build-out scenarios. Application of multiple practices in both existing and build-out scenarios can result in significant reduction of phosphorus loading and Chorophyll-a levels within the lake. Combinations of several management practices could reduce the total phosphorus load to the lake to a level where the chlorophyll-a concentrations in the lake would remain below water quality goals. Application of management practices in the City of Norman alone is not sufficient to meet the water quality goals set for the lake. Applications of management practices to the City of Norman alone, however, will not achieve water quality goals set for Lake Thunderbird. Further study is needed to evaluate if enhanced wetlands at the Little River Branch above Alameda and at the upper reaches of the Hog Creek Arm of Lake Thunderbird could alleviate the impact of urbanization Oklahoma City and Moore. Specific conclusions may be summarized as follows:

1. The lake already exceeds the established chlorophyll-a water quality goal set for the lake. In-lake concentration of Chorophyll-a averages 30.8ug/L, which is 54% greater than the water quality goal of 20µg/L.
2. On average, total phosphorus load by subbasin more than doubled from 0.25 to 0.54 kg/ha due to urban development in the watershed under the build-out scenario.
3. chlorophyll-a concentration in the lake increases from 30.8 µg/L under baseline conditions to 44 µg/L due to the effect of urbanization, an increase of 43%.
4. By combining the effects of management practices for maximum reduction of Total P, i.e., statutory fertilizer reduction, wetlands, and structural controls to the entire basin, Total P load can be reduced 74% for the baseline, and by 84% for the build-out scenarios.
5. If statutory fertilizer reduction, wetlands, and structural controls are applied only to the subbasins within the City of Norman under the baseline scenario, the minimum achievable chlorophyll-a concentration in the lake is 24µg/L, still above the goal. While under the build-out scenario, the chlorophyll-a concentration in the lake is only 36µg/L indicative of hyper-eutrophic water quality conditions, and still above the water quality goal of 20 µg/L if management practices are applied only to subbasins within Norman.

7.0 References

Arnold, J.G., R. Srinivasan, R.S. Muttiah and J.R. Williams. 1998. Large Area Hydrologic Modeling and Assessment Part 1: Model Development. Journal of American Water Resources Association. 34 (1): 73-89.

Burns, R.T. and F. Rosa, 1980. In Situ Measurement of the Settling Velocity of Organic Carbon Particles and 10 Species of Phytoplankton. Limnology and Oceanography. 25:855-864.

Carlson, R.E. 1977. A trophic state index for lakes. Limnology and Oceanography. 22:361-369.

Carlson, R.E. and J. Simpson. 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society. http://dipin.kent.edu/tsi.htm Last accessed, 2/22/2007

Chapra, S.C., 1975. "Comment on 'An Empirical Method of Estimating the Retention of Phosphorus in Lakes,' by W.B. Kirchner and P.J. Dillon." Water Resources Research. 11: 1033-1034.

Chapra, S.C., and S. J. Tarapchack, 1976. A chlorophyll-a Model and Its Relationship to Phosphorus Load Plots for Lakes, Water Resources Research, 12(6):1260-1264.

Christenson, S and David Parkhurst, 1996. Ground-Water-Quality Assessment of the Central Oklahoma Aquifer, Oklahoma-Geochemical and Geohydrologic Investigations: U.S. Geological Survey Water Supply Paper 2357-C. p. c65.

COMCD, 2006. Rock Creek Watershed Analysis and Water Quality Evaluation. Prepared for the Central Oklahoma Master Conservancy District. August 2006.

Diluzio, M., Arnold, J.G., 2004. Formulation of a hybrid calibration approach for a physically based distributed model with nexrad data input. Journal of Hydrology. 298(1-4):136-154.

Farnsworth, R.K., and E.S. Thompson (1982) "Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States," NOAA Technical Report NWS 34, Washington, D.C., 82 p.

Neitsch, S.L., et al. 2005a. Soil and Water Assessment Tool Theoretical Documentation. Published by the Agricultural Research Service and Texas Agricultural Experiment Station, Temple, Temple Texas.

Neitsch, S.L., et al. 2005b. Soil and Water Assessment Tool User's Manual, Version 2005. Published by the Agricultural Research Service and Texas Agricultural Experiment Station, Temple, Temple Texas.

ODEQ, 2002. Water Quality Assessment Integrated Report. Prepared pursuant to Section 303(d) and 305(b) of the Clean Water Act.

OWRB, 2001. Evaluation of Lake Thunderbird Water Quality Management Practices for the Central Oklahoma Master Conservancy District.

OWRB, 2002. Lake Thunderbird Capacity and Water Quality for the Central Oklahoma Master Conservancy District. Final Report. June 2002.

OWRB, 2004a. Lake Thunderbird Water Quality 2003 for the Central Oklahoma Master Conservancy District. Final Report. May 2004.

OWRB, 2004b. Lake Thunderbird Algae 2003 for the Central Oklahoma Master Conservancy District. Final Report. May 2004.

OWRB, 2005. Report of the Oklahoma Beneficial Use Monitoring Program Lakes Report. Lakes Sampling 2004-2005. Published by the OWRB. http://www.owrb.state.ok.us/quality/monitoring/bump/2004-05-pdfs/BUMP-Lakes-Report.pdf Last accessed, 2/27/2007.

OWRB, 2006. Agency Rule Report, Amendments to Title 785. Oklahoma Water Resource Board Chapter 45. Oklahoma Water Quality Standards. February 14, 2006. http://www.owrb.state.ok.us/util/rules/pdf_rul/arreportchap45.pdf Last accessed, 2/22/2007.

OWRB, 2007. Central Planning Region, Regional Description. https://www.owrb.state.ok.us/supply/ocwp/pdf_ocwp/6acentral.pdf Last accessed, 2/22/2007.

Pitt, R., Maestre, A., and Morquecho, R., 2004. The National Stormwater Quality Database (NSQD, version 1.1). Department of Civil and Environmental Engineering, University of Alabama, Tuscaloosa, Alabama. Available on the internet at: http://rpitt.eng.ua.edu/Research/ms4/Paper/Mainms4paper.html last accessed 4/10/2007.

Schueler, T., 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Metropolitan Washington Council of Governments, Washington, DC.

Srinath, E.G., et.al., 1959. Rapid removal of phosphorus from sewage by activated sludge. Cellular and Molecular Life Sciences. ISN 1420-682X (print) 1420-9071 (online). Volume 15, Number 9, September 1959. http://www.springerlink.com/content/r7152306825vl631 Last accessed, 3/16/2007.

Srinivasan, R. and J.G. Arnold. 1994. Integration of a basin-scale water quality model with GIS. *Water Resources Bulletin* (30)3:453-462.

Thomann, R.V., and Mueller, J. A., 1987. Principles of Surface Water Quality Modeling and Control. Harper-Collins Publishers, Inc., ISBN 0-06-3507-5.

USDA, 1986. Urban Hydrology for Small Watersheds (TR-55). United States Department of Agriculture, Soil Conservation Service, Engineering Division. Technical Release 55. June 1986.

USDA, 2002. Agricultural Census from the National Agricultural Statistics Service. http://www.nass.usda.gov Last accessed, 3/16/2007.

USEPA, 2001. Better Assessment Science Integrating Point and Non-point Sources 3.0 (BASINS) User Manual. EPA-823B01001.

USEPA, 2005. Handbook for Developing Watershed Plans to Restore and Protect Our Waters. EP 841-B-05-005. October 2005.

Vollenweider, R.A., 1976. Advances in Defining Critical Load Levels for Phosphorus Load Concept in Limnology, Schweiz. Z. Hydrology. 37:53-83.

Appendices

Appendix A – Management Practices

Appendix B – Basin Specific Management Practices