A THREE-LAYER STEADY-STATE VERTICAL DISSOLVED OXYGEN MODEL IN GRAND LAKE

By

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A THREE-LAYER STEADY STATE VERTICAL DISSOLVED OXYGEN MODEL IN GRAND LAKE

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Abstract

Grand Lake O' The Cherokees provides recreational activities, water supply, hydroelectric power and flood control to the residents of Oklahoma and beyond. Grand Lake has experienced high eutrophication levels resulting in hypoxia during summer stratification. A three-layer steady state vertical dissolved oxygen model for summer-stratified conditions was developed to investigate oxygen profiles above and below the thermocline. The model was used to determine the relative effect of source and loss terms for oxygen and sediment oxygen demand (SOD) on bottom water hypoxia under summer-stratified conditions. The source terms investigated were atmospheric reaeration and phytoplankton production in the surface layer, while the loss terms were phytoplankton respiration, decomposition of organic matter, nitrification, and SOD. Observed water quality data, kinetic coefficients, and physical data obtained on Grand Lake were used in pre-processing calculations to derive estimates to the model inputs. Spatial gradients along the length of Grand Lake for riverine, transition, lacustrine zones and a site close to the dam were analyzed using data collected in 2013 and 2015 under stratified conditions when the hypolimnion was depleted of oxygen in June, July, and August. Predictions from the four stations provided reasonable agreement to the observed dissolved oxygen profiles. Phytoplankton production, high light limitation, and phosphorus were identified as the most critical factors controlling the source for oxygen production in the surface layer, while nitrification and organic carbon decomposition were the largest dominant loss terms controlling oxygen consumption over the entire water column. Sediment oxygen demand was identified as the least critical factor for oxygen demand in the water column.

Keywords: Vertical dissolved oxygen model, eutrophication, phytoplankton, growth, primary production, respiration, oxygen demand, steady state, hypoxia, stratified conditions, reservoir.

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CHAPTER I

INTRODUCTION

1.1 Nutrient Enrichment, Eutrophication and Hypoxia

While it is beneficial to maintain some level of nutrients and productivity in lakes, rivers, streams, and other water bodies that are exposed to high levels of nutrients experience eutrophication (Correll, 1999). Eutrophication is defined as the over enrichment of lakes and reservoirs with nutrients (mainly nitrogen and phosphorus) which can result in algal blooms and alterations to aquatic communities (Elser, 2000). Specific effects of eutrophication include: harmful algal blooms, increased bacterial production and resulting reductions in dissolved oxygen concentration, hypolimnetic anoxia and alteration in the natural ecology of the lakes through the loss of habitats (Smith, 2003; Dodds et al., 2008, Carter and Dzialowski, 2012). In the United States, approximately 60% of lakes, rivers, and reservoirs impairment are as a result of eutrophication (Smith, 2003). Freshwater bodies that are impaired due to eutrophication have been documented to greatly affect the economy of the country, state, or region that they are located in (Smith, 2003; Dodds et al., 2008). For example, eutrophic lakes and reservoirs that provide drinking water services and other recreational activities have high treatment costs of over 1 million United States (US) dollars per algal bloom event. Monitoring costs can also exceed $50 million US dollars annually (Smith, 2003).

Eutrophication control in lakes has historically focused on the reduction of external inputs of nutrient loads (Anderson, 2002). The major pathway through which nutrients enter water bodies is by watershed runoff during and after rainfall events. These events carry dissolved materials and sediments containing nutrients that stimulate algal production, settling and decomposition of organic matter, and depletion of dissolved oxygen within the bottom hypolimnion layer of the lake (Anderson, 2002). Nutrients also accumulate in the sediment bed and then are released back into the water column under different environmental conditions, further contributing to eutrophic conditions and hindering restoration efforts in lakes, streams, rivers, and other water bodies (Nurnberg, 2009).

Nutrient cycling between sediments and the water column is one of the primary sources of phosphorus in surface waters (Nurnberg, G.K. 2009). In summer, the weather patterns encourage convective mixing in lakes and reservoirs especially when the thermoclines rises resulting into cooling of the surface water (EPA, 2000). According to Nowlin (2005), a lake that is highly productive due to high nutrient loads after summer stratification will have biological activity that occurs in the sediment bed. This activity affects hypolimnetic dissolved oxygen concentration as the available oxygen is consumed by bacteria and other organisms present at the bottom of the lake.

Hypolimnetic anoxia is deep-water depletion of dissolved oxygen that normally occurs because of nutrient loading and stagnation of lake bottom waters during the summer (Nowlin, 2005). It is often found in deep productive water supply reservoirs and it causes phytoplankton blooms in lakes (Nowlin, 2005). Theses algal blooms die, biodegrade through the action of aerobic microorganisms, and sink into the hypolimnion

(Nowlin, 2005). Thermal stratification occurs in summer due to temperature increases in the atmosphere, which confines the hypolimnion from reaeration (Beutel, 2003).

Anoxia often occurs closer to lake bottoms and can alter many ecological processes that affect water quality in lakes (Beutel, 2003). The effect of summer stratification on dissolved oxygen is graphically illustrated in Figure 2 below.

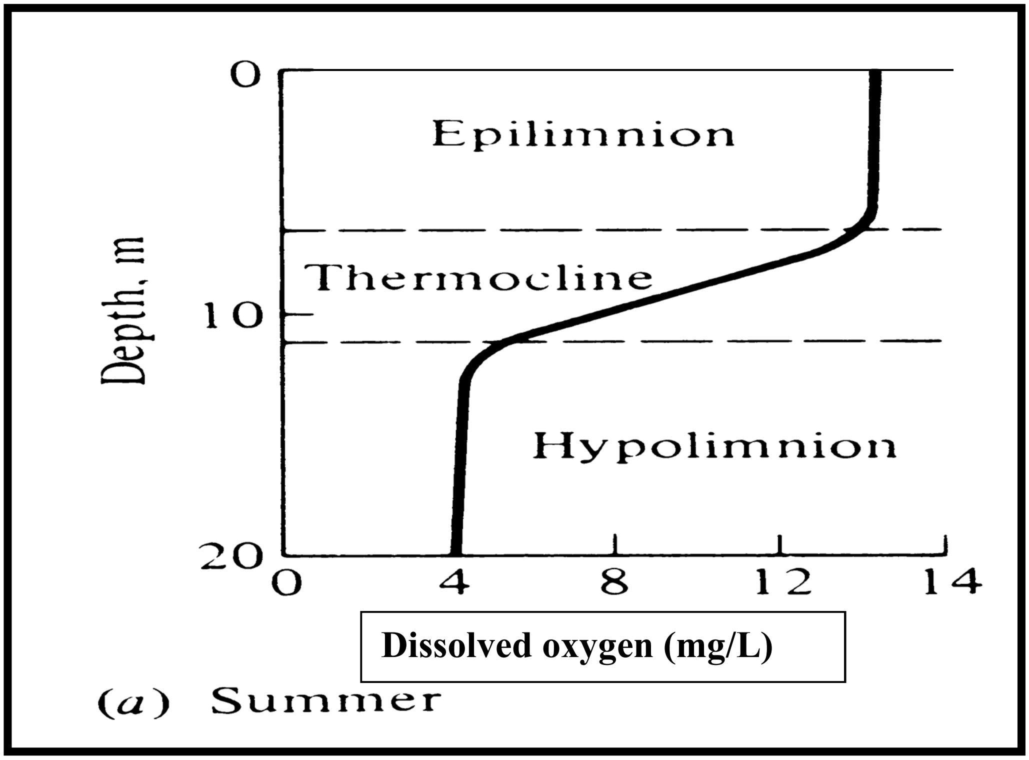

Figure 1: Graphical illustration of the effect of summer stratification on dissolved oxygen. (Retrieved from: http://www.zo.utexas.edu/courses/bio301/chapters/Chapters2-7/fig4.17.gif)

Sediment beds and sediment-water release of nitrogen and phosphorus are prominent internal sources of nutrients to freshwater ecosystems. Studies regarding the release of nutrients from sediment have been ongoing for decades. Literature reviews show that phosphorus released from sediments in lakes has more attention in terms of research than nitrogen and this is due in part to the complex behavior of nitrogen (Nowlin et al., 2005, Mortimer, 1941, 1942; Nurnberg, 1987; Andersen & Jensen, 1992; Gardner et al., 2001).

1.2 Characteristics of Reservoirs and Lakes

Three types of zones exist in reservoirs, which are located along the upstream gradient. The horizontal gradient helps to distinguish reservoirs from the natural lakes as shown in Figure2 (Green, et al., 2015).

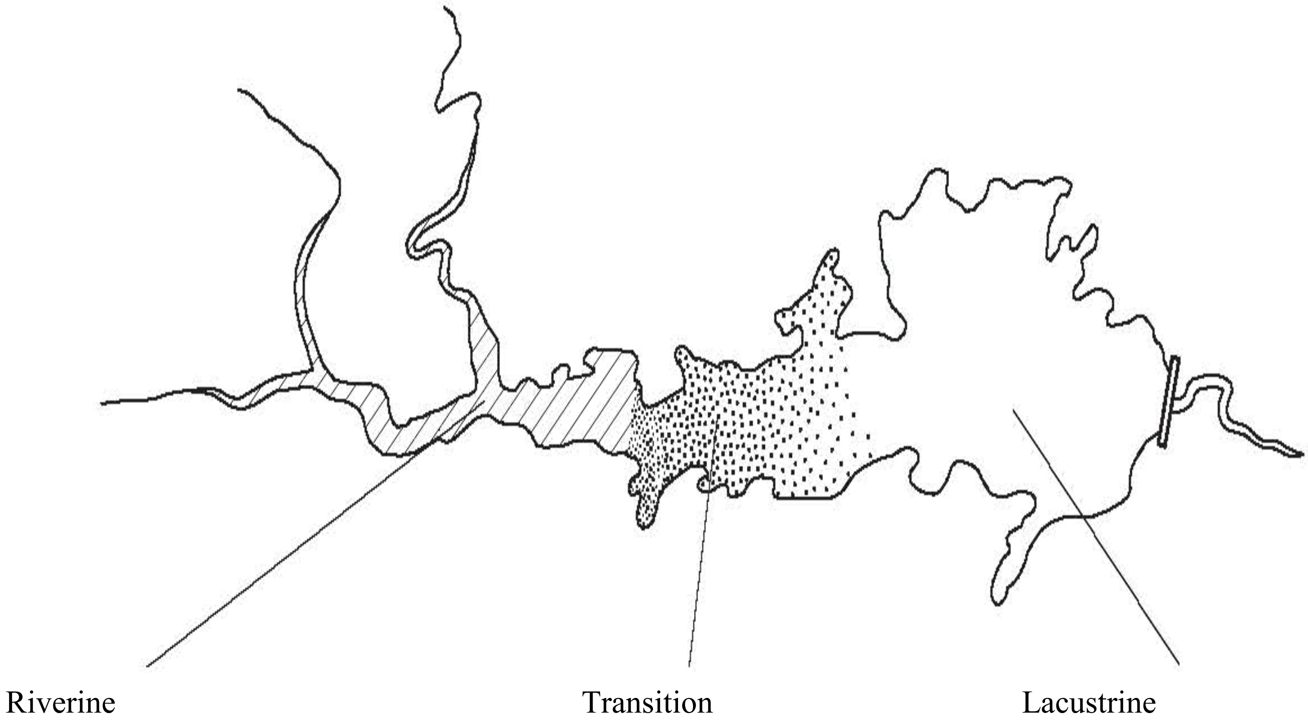

Figure 2: Schematic illustration of the three zones in reservoirs (Green, et al., 2015).

These zones include:

Riverine zone: is the upstream segment of a reservoir and is characterized by shorter residence time, higher flow velocity, high concentrations of bioavailable nutrients and suspended solids, and has less light limitation compared to the downstream sections of the reservoir (Green, et al., 2015).

Transition zone: is an intermediate zone that is important due to distinct biological processes that take place. The transition zone is characterized by lower flow velocity, increases in sedimentation rates of mostly fine silts and clay particles, lower turbidity, higher light penetration, and it has the most productivity and is the most fertile zone of reservoirs with high phytoplankton biomass (Green, et al., 2015).

Lacustrine zone: is an area close to the dam that is characterized by low nutrients and suspended sediment concentrations, low flow velocity, longer residence time, higher water clarity, and has a deeper photic zone than the transition zone (Green, et al., 2015).

1.3 Trophic classification in Reservoirs and Lakes

The trophic states of reservoirs and lakes are classified in various ways. One of the most widely used classification systems is the trophic state index (TSI). This index uses calculated values based on the surface-water concentrations of chlorophyll *a*, Secchi depth, and total phosphorus (Green, et al., 2015; Carlson, 1977). The equations developed by Carlson (1997) are used to place chlorophyll-*a* concentration (TSI_{Chl}), Secchi depth (TSI_{SD}), and phosphorus concentrations (TSI_{P}) on similar scales, which allows comparison of trophic state in different lakes or different zones of the same lake. The monthly averages of summer water quality data were used to compute the Trophic State Indexes for Grand Lake.

Table 1: Trophic State Index classification of different trophic state attributes based on computed concentration of chlorophyll, secchi depth, and total phosphorus (Green, et al., 2015).

TSI	Chl mg/L	SD (m)	TP mg/L	Trophic state attributes
<30	<0.95	>8	<6	Oligotrophic
30-40	0.95-2.6	8-4	6-12	Hypolimnion can become anoxic
40-50	2.6-7.3	4-2	12-24	Mesotrophic
50-60	7.3-20	2-1	24-48	Eutrophic
60-70	20-56	0.5-1	48-96	Blue –green algal dominate
70-80	56-155	0.25-0.5	96-192	Hypereutrophic
>80	>155	<0.25	192-384	Algal scums

1.4 Grand Lake Water Quality Problems

Grand Lake is eutrophic and has experienced severe anoxia and internal release of phosphorus from the sediments through the months of summer stratification (Nikolai and Dzialowski, 2014). Eutrophic lakes can experience harmful algal blooms, which lead to the production of toxins that pose threat to aquatic organisms, pests, livestock, and humans (Bricker *et al*., 2007). Over $2.2 billion is spent on freshwater bodies annually as treatment cost to treat eutrophic lakes in the United State (Dodds et al., 2009). Grand Lake was listed on the Oklahoma 303 (d) list as an impaired water body in 2010, 2012 and 2014 (Integrated Water Quality Assessment, 2015), the causes of impairment are listed as shown in Table 2, which indicates that dissolved oxygen (DO) was among the potential causes for the impairment in 2010, 2012, and 2014, and algal blooms is an important factor to DO depletion in lakes and reservoirs (Diaz and Rosenberg, 2008).

Grand Lake experienced a significant algal bloom on July 4, 2011 causing the Grand River Dam Authority (GRDA) to prohibit swimming in the lake. This type of occurrence might have resulted in significant economic losses to both the state of Oklahoma and GRDA.

While there are a number of potential sources and sinks for dissolved oxygen (DO) in the reservoir, there is limited information on the processes that affect anoxia. Specifically, it is not known how lake mixing, sediment oxygen demand (SOD), water column respiration, and algal production interact to affect the dissolved oxygen balance in Grand Lake.

1.5 Goals and research objectives

The goal of this study is to develop a three-layer steady-state vertical dissolved oxygen model in Grand Lake considering the following objectives:

1. Develop and test a three-layer steady-state vertical dissolved oxygen model using observed data from the Grand Lake.
2. Use physical and water quality data from Grand Lake with kinetic processes and coefficients to estimate model input rates for oxygen production and oxygen consumption.
3. Use model input rates and kinetic processes to determine the relative effect of oxygen source terms, and oxygen consumption terms including SOD on bottom water hypoxia under summer-stratified conditions in Grand Lake.

4. Compare secchi depth, total nitrogen (TN), total phosphorus (TP), and chlorophyll-*a* concentration observed in Grand Lake to observed water quality data reported by Jones and Knowlton (1993) for Midwest reservoirs.
5. Compare estimates of DO respiration for Grand Lake to the range of measured data reported in the literature for Midwest reservoirs by Jones and Knowlton (1993).
6. Conduct a sensitivity analysis of the DO model with SOD and vertical mixing rates using Grand Lake data.

Combined, these objectives allow for the development of a three-layer steady state vertical DO model as a simplified approach to provide insight into the key physical, chemical, and biological factors that influence the occurrence of anoxia and hypoxia during summer stratification below the thermocline.

CHAPTER II

METHODOLOGY

2.1 Study Area

Grand Lake O' The Cherokees is located in northeastern Oklahoma, which is contained in Ottawa, Delaware, and Mayes Counties. Grand Lake is a multi-use reservoir that provides flood control, hydroelectric power supply, drinking water, recreational activities, and fish and wildlife propagation for the state of Oklahoma. As such, it provides great economic values to the state as long as the ecological, environmental, and hydrologic health of the region is maintained (GRDA, 2008).

The Grand River Dam Authority is responsible for ecosystem management of the lake (GRDA, 2008). Grand Lake was formed through the construction of the Pensacola Dam on the Grand Neosho River in 1941 (Nikolai et al., 2012). Over the years, Grand Lake has been known to be Oklahoma's most popular tourist and recreation area in the state. The surface area of the reservoir is approximately 18,000 ha, with a mean depth of 11.06m and maximum depth of 41.54m close to the Pensacola Dam.

It holds 1.7million acre-feet of water with a total drainage area of 10,300 square miles (OWRB, 1995; Nikolai et al., 2012). Three major and important tributaries of Grand Lake are the Neosho River, Elk River, and Spring River as shown in Figure 3.

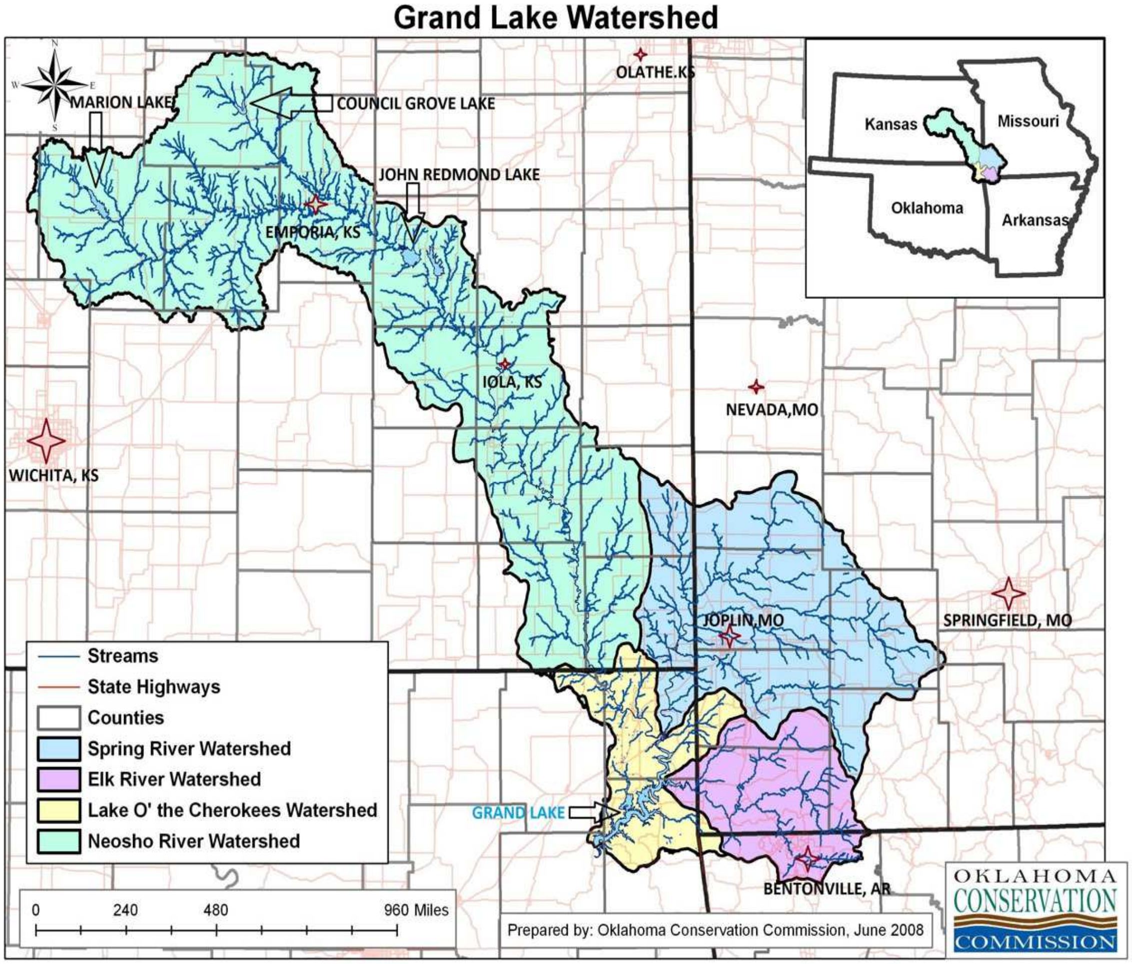

Figure 3: Location map showing the three major watersheds and tributaries of Grand Lake (GLWAF, 2008).

Grand Lake is a nutrient rich lake that is receiving an elevated and excessive amount of nutrients from Neosho River subwatershed, Spring River watershed, and Elk River (Grand Lake O' the Cherokees Watershed Alliance Foundation, Inc., 2008). The

Oklahoma Water Resource Board (OWRB) and the Beneficial Use Monitoring Program (BUMP) in collaboration with Grand River Dam Authority (GRDA) are the groups responsible in carrying out the monitoring activities in the lake. Grand Lake was listed on the Oklahoma 303 (d) list as an impaired water body in 2010, 2012 and 2014 (Integrated Water Quality Assessment, 2015); the causes of impairment are listed as shown in Table 2.

Table 2: Potential water impairment for Grand Lake in 2010, 2012, and 2014 (ODEQ, 2015).

Years	Causes of Imperilment	Reservoir section
2010	Lead, DO	Lower
	DO, Lead, and Turbidity	Middle
	Lead, Turbidity	Upper
2012	Lead, DO	Lower
	Lead, Turbidity	Middle
	Lead, Turbidity	Upper
2014	Lead, DO	Lower
	Lead	Middle
	Lead, Turbidity	Upper

The causes of impairment were similar in the lower, mid, and upper portion of the lake in 2010, 2012, and 2014. This indicates that not much change has occurred in the water quality of the lake over the past few years. Major water quality impairment in many reservoirs, including Grand Lake, is dissolved oxygen depletion (hypoxia and anoxia) in the hypolimnion during summer months when lakes are stratified. During summer-stratified conditions, the vertical gradient of oxygen is much larger than the horizontal gradients of oxygen (Grand Lake Management Plan, 2008)

The Grand Lake Watershed is dominated mostly by agricultural activities including crops and animal farming that are the contributors of nitrogen and phosphorus to the Neosho River, Spring River, and Elk Rivers (GLWAF, 2008). With regards to the land use practices; 36% of the watershed is used for planted pasture, 21% is grassland which can be grazed, 20% is cropland, 14% cover by forest, 6% is developed land space (residential area, parks, and golf courses) and 3% is in open water and wetlands (GLWAF, 2008). In terms of major agricultural land uses, the Northwest is covered by cropland and grassland and dominated by cattle production. The Southeast is dominated by poultry production. The land use practices shown in Figure 4 greatly influence the water quality in Grand Lake.

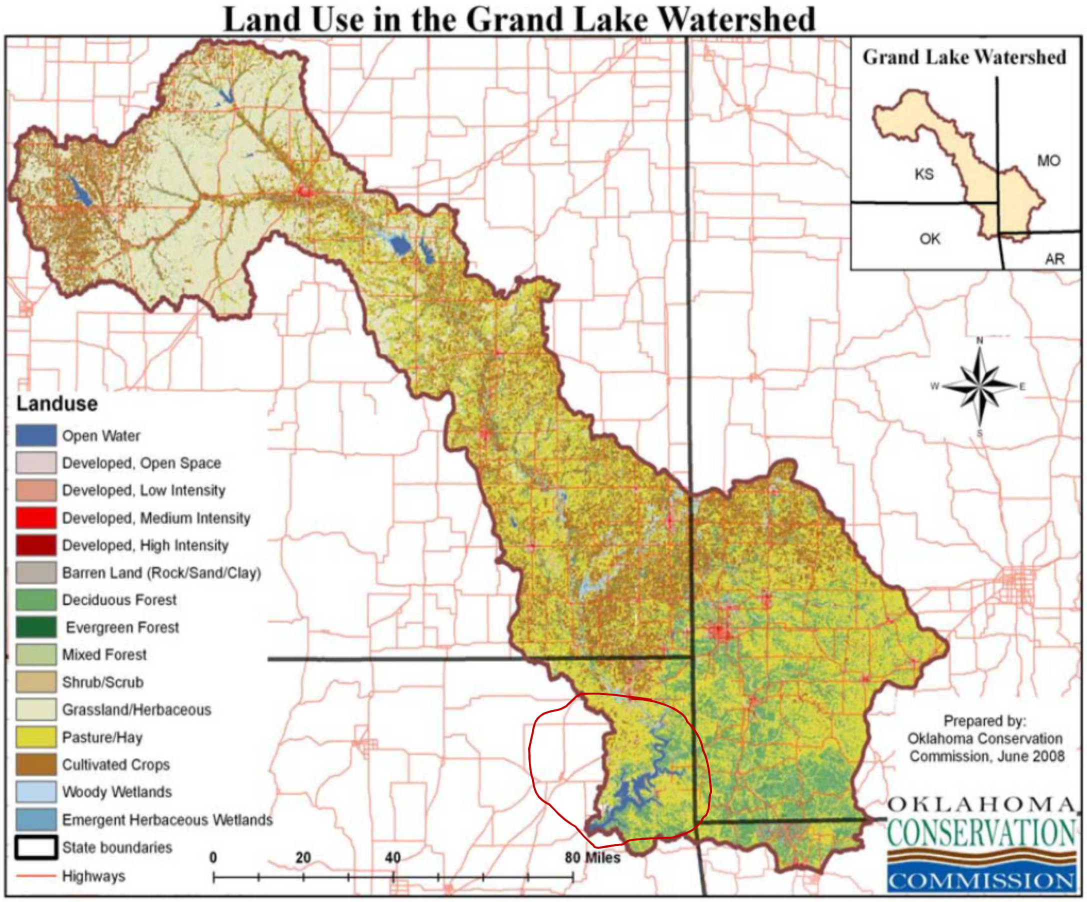
Land Use in the Grand Lake Watershed

Figure 4: Map showing land use patterns in the Grand Lake Watershed as demarcated in red (GLWAF, 2008).

2.2 Trophic State Calculations

Equations 1-3 were developed by Carlson (1997) to define trophic state in reservoirs and lakes. These are defined as: Oligotrophic (TSI values less than 40); Mesotrophic (TSI values between 40 – 50); Eutrophic (TSI values greater than 50); and Hypereutrophic (TSI values between 60 –70). The equations are shown below in Table 1 (Green, et al., 2015).

$$\mathbf{TSI_{C}} = 30.6 + 9.81\ [\ln \text{chlorophyll-a } (\mu g/L)] \ \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\mathbf{TSI_{P}} = 4.15 + 14.42\ [\ln \text{total phosphorus } (\mu g/L)] \ \ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$\mathbf{TSI_{SD}} = 60.0 - 14.41\ [\ln \text{secchi depth } (m)] \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

2.3 Model Development

Water quality is controlled by loading of pollutants, water body geometry, physical transport processes, and biological and chemical reactions. A water quality model provides a mathematical representation of the cause-effect relationships that link pollutant inputs to the water quality response in time and space. A water quality model is used to predict and interpret water quality responses using mathematical simulation techniques with a numerical formulation that represents the response of the water body to external inputs (Chapra, 1997). One of the major uses for a water quality model is the determination of the degree of environmental controls that must be instituted to achieve a specific water quality objective such as compliance with a water quality standard (Thomann and Mueller, 1987; Chapra, 1997).

Numerous water quality models are available to describe water quality in time (steady-state or time variable) and space (one, two, or three-dimensional) for multiple water quality constituents. Steady-state, one-dimensional water quality models include models such as QUAL2K. Time-variable, multi-dimensional water quality models include models like WASP7 (https://www.epa.gov/exposure-assessment-models/surface-water-models). For this research, a steady-state, one- dimensional analytical model (VERTDO3) was selected to describe the effect of stratification and biological-chemical processes on the vertical distribution of dissolved oxygen in lakes and reservoirs (HydroQual, 1986).

The model assumes steady-state conditions with negligible horizontal gradients of dissolved oxygen in the water body, while the dominant vertical gradient in the water column is represented with three-layers (epiliminion, metalimnnion, and hypolimnion). The model was designed by HydroQual (1986) as a simplified approach to provide insight into the key physical, chemical, and biological factors that influence the occurrence of anoxia and hypoxia below the thermocline. The underlying assumptions for the proposed three-layer steady-state vertical dissolved oxygen model are: (1) steady state and (2) horizontally well mixed.

Dr. Andrew Stoddard of Dynamic Solution, LLC, as part of a project performed for Oklahoma Department of Environmental Quality (ODEQ) (DSLLC, 2005), coded the equations of the three-layer dissolved oxygen model in FORTRAN. The model was made available to Oklahoma State University to support the research effort for this project.

Below is the general time and depth-dependent mass balance equation presented by HydroQual (1986) for a non-conservative substance:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(E\ \frac{\partial c}{\partial z}\right) - S(z,t) + S\ (z,t) \qquad \text{………… (Equation 4)}$$

Where,

c = Concentration of non-conservative substance (M/L^3)

E = Vertical dispersion coefficient (L^2/T)

S_O and S_1 = Sources or sinks of mass (M/L^3-T)

Z = vertical dimension (L)

t = time (T)

Taking into account the mass balance of dissolved oxygen, a source term includes atmospheric reaeration across the air-water interface and photosynthetic production of dissolved oxygen by algae. The sink terms include the water column respiration from algae, biochemical decomposition of organic matter, and nitrification and sediment oxygen demand on the lake bed. In such a scenario, the vertical mixing of the water body is completely dependent on wind forcing, water temperature profiles, and vertical density gradients within the water column (Thomann and Mueller, 1987; Chapra, 1997).

2.4 Steady-State Vertical Distribution of Dissolved Oxygen

The steady state assumed that ($\frac{\partial c}{\partial t} = 0$), and the equation given below is written for dissolved oxygen deficit (D) where the deficit is the difference (D = between the dissolved oxygen concentration (C) and the saturation concentration as:

(C_s): D = (Cs –C) ……………………………… … (Equation 5)

$0 = \frac{d}{dz}\left(E\ \frac{dD}{dz}\right) + R\ (z\ ) - P\ (z)$ ……….. (Equation 6)

The vertical structure of dissolved oxygen was analyzed using three-layers of water column DO data from Grand Lake. The three layers defined in the equation are: (1) surface euphotic zones layer; (2) thermocline layer across which vertical mixing is less due to stratification; and (3) hypolimnion layer in contact with the sediment bed (Thomann and Mueller, 1987; Chapra, 1997). Figure 5 shows a typical water temperature profile under stratified conditions with definition of the water column geometry terms used in development of the equations for the model.

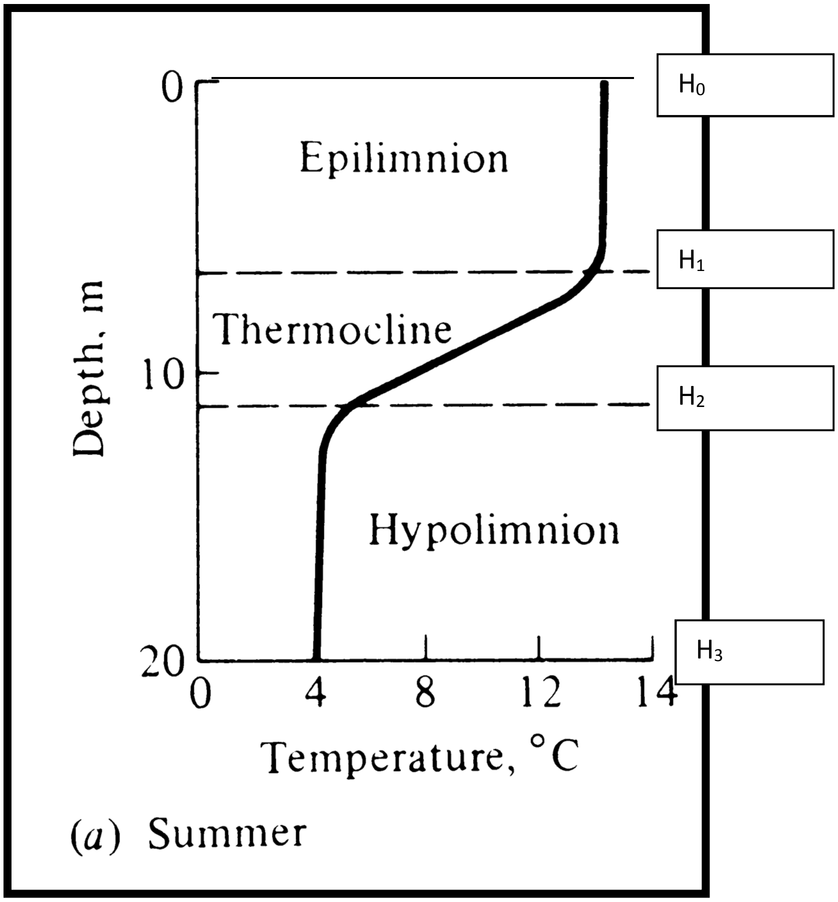

Figure 5: Typical vertical profile of water temperature in a stratified reservoir. (Retrieved from: http://www.zo.utexas.edu/courses/bio301/chapters/Chapters2-7/fig4.17.gif)

From water temperature and conductivity vertical profiles data, depth of the thermocline was estimated from the depth interval. This was defined by the large vertical gradient of density computed as a function of water temperature and conductivity. Because of wind mixing and due to the bottom friction in the lake, vertical mixing within the surface layer (E_1) and the hypolimnion (E_3) are much greater than the rate of vertical mixing within the middle, which is refer to as the thermocline layer (E_2) (Thomann and Mueller, 1987; Chapra, 1997).

The boundary conditions are across the air-water interface (Z =0) and the sediment-water interface (Z = H). The fluxes are specified by the transfer of oxygen from the air to the surface layer of the water column and the consumption of oxygen within the surficial sediment bed. In this case, the oxygen transfer coefficient [K_L (as L/T)], the saturation concentration of oxygen (C_S) and the surface layer concentration of oxygen (C_O) are the parameters used to specify the air- water flux of oxygen for the surface layer boundary condition (Z= 0). Sediment oxygen demand [S (as m/L^2-T)] is the parameter used to specify the sediment-water flux of oxygen for the bottom layer boundary condition (Z = H) (Thomann and Mueller, 1987; Chapra, 1997).

$$Z = 0 \quad E_z \frac{dD}{dz} = K_L D_O \qquad \text{………… (Equation 7)}$$

$$Z = H \quad E_z \frac{dD}{dz} = S \qquad \text{………… (Equation 8)}$$

Additional boundary conditions were specified at the layers interface and were defined by equalities in concentration of dissolved oxygen deficit. The mass flux from vertical mixing, where (n) and (n + 1) and were the layer numbers for the interface between the: (a) surface euphotic layer (n =1) to the thermocline layer (n = 2); and (b) the thermocline layer (n =2) to the hypolimnion layer (n=3).

The equation for the surface euphotic zone layer (n =1) is given by;

$$0 = \frac{d}{dz} \left(E_1 \frac{dD}{dz} \right) + R_1 - Pa \qquad \text{………………………… (Equation 9)}$$

In the equation for the surface layer, D is the oxygen deficit; E_1 is the rate of vertical mixing within the surface layer; and R_1 is water column consumption of oxygen from algal respiration, nitrification and decomposition of detrital organic carbon; whereas

Pa is the depth integrated algal photosynthetic production of oxygen within the euphotic zone (Thomann and Mueller, 1987; Chapra, 1997).

The equation for the thermocline layer (n = 2) and the hypolimnion layer (n =3) is depicted by;

$$0 = \frac{d}{dz}\left(E_n \frac{dD_n}{dZ}\right) + R_n \qquad \text{………… (Equation 10)}$$

The differential equations for each layer were integrated to give solutions for each of the layers (n = 1, n = 2, and n =3). The water column consumption computed for each layer starting from nitrification, algal biomass respiration and detrital organic carbon decomposition is depth- integrated over the entire water column to yield a depth-averaged rate of oxygen consumption applied as a constant (R) to each layer. The surface layer depth-averaged photosynthetic oxygen production rate (Pa) is computed from chlorophyll (algal biomass), carbon: chlorophyll and oxygen: carbon stoichiometric ratios for algae, and the algal growth rate computed as function of water clarity, light availability, ambient nutrient concentrations and water temperature (Thomann and Mueller, 1987; Chapra, 1997).

At the air-water boundary of the surface layer (n =1) the dissolved oxygen deficit is computed from:

$$D_o = \frac{S}{K_L} + \frac{RH}{K_L} + \frac{P_{aH_1}}{K_L} \qquad \text{………… (Equation 11)}$$

Where,

D_O = is the oxygen deficit (mg/L)

S= is sediment oxygen demand (g O_2 $m^{-2}day^{-1}$)

R= is depth averaged water column oxygen consumption (g O_2 /m^3 –day)

Pa= is euphotic zone algal oxygen production (g O_2 /m^3 –day)

H= is the water column depth at the sediment bed-water interface (m)

H_1= is the depth at the bottom of the surface euphotic layer (m)

Systematic representation of oxygen deficit in the surface layer (n =1) was computed from:

D_1 (z) = { $\frac{S}{K_L}$ (1 + $\frac{K_L z}{E_1}$) + $\frac{RH}{K_L}$ [1 + $\frac{K_{LZ}}{E_1}$ (1 - $\frac{Z}{2H}$)]} – {$\frac{P_{aH_1}}{K_L}$ [1 + $\frac{K_{LZ}}{E_1}$ (1- $\frac{Z}{2H_1}$) (Equation 12)

Definition of terms and units for surface layer (n =1) solutions are:

$D_{1(Z)}$ = dissolved oxygen deficit at depth, z with the layer (mg/L)

Z = depth in layer (Z =0 is air-water interface) (m)

S = sediment oxygen demand (g O_2 /m^2-day)

R = depth averaged water column oxygen consumption (g O_2 /m^3 –day)

$P_{a=}$ euphotic zone algal oxygen production (g O_2 /m^3 –day)

H= depth at sediment bed-water interface (m)

H_1= depth of the surface layer (n = 1) at interface with thermocline layer (n =2) (m)

K_L= air-water transfer coefficient for oxygen (m/day)

E_1 = vertical mixing rate for surface layer (n =1) (m^2/ day)

For the oxygen deficit for the sub-surface layers (n = 2 and n = 3) is computed from:

$$D_n(z) = \frac{S}{K_L} [1 + \frac{K_{LZ}}{E_n} + \sum_{i=2}^{n} \frac{K_{LH_{i-1}}}{E_1} (1 - \frac{H_{i-1}}{2H}) (\frac{E_1}{E_{i-1}} - 1)]$$

$$+\frac{RH}{K_L}\left[1+\frac{K_{LZ}}{E_n}\left(1-\frac{Z}{2H}\right)+\sum_{i=2}^{n}\frac{K_{LH_{i-1}}}{E_1}\left(1-\frac{H_{i-1}}{2H}\right)\left(\frac{E_i}{E_{i-1}}-1\right)\right]-\frac{P_aH_1}{K_L}\left[1+\frac{K_{LH_1}}{2E_1}\right]\ldots$$

(Equation...13)

Where,

D_n (z) = Oxygen deficit at depth, z within layer n=2 and n=3 (mg/L)

Z= depth in layer n=2 and n=3 (Z=0 is air-water interface; z=H is bottom depth (m)

$H_{1=}$ depth of upper layer (n=1) at interface with the thermocline layers (n=2) (m)

H_2 = depth of thermocline layer (n=2) at interface with hypolimnion layer (n=3) (m)

H_3 = depth of hypolimnion layer (n=3) at interface with sediment bed (n=3) (m)

H = depth at sediment bed-water interface (i.e., bottom depth) (m)

E_2 = vertical mixing rate for thermocline layer (n=2) (m^2/day)

E_3 = vertical mixing rate for hypolimnion layer (n=3) (m^2/day)

After computation of the oxygen deficit, the concentration of dissolved oxygen, C (Z), is compute as a function of depth (z) for each of the three layers as:

$$C(z) = C_S - D_n(z) \qquad \text{... (Equation 14)}$$

The oxygen deficit, D_n (z), is also computed using sub-surface equations within each of the layer ‘’n’’ at 1m intervals. The lake saturation concentration of dissolved oxygen (C_s) was computed as a function of the lake level elevation, and water temperature and conductivity at the surface (Z ~ 0) (Chapra, 1997). Conductivity was assumed zero for calculating saturation concentration of dissolved oxygen.

2.5 Model Input Parameters

A summary of input data for the three-layer vertical dissolved oxygen model includes the following parameters:

Water column geometry (meters)

- H_0, depth at surface ($H_0=0$)
- H_1, depth at top of thermocline
- H_2, depth at bottom of thermocline
- H_3,depth at bottom of hypolimnion
- H, total water column depth from surface to bottom ($H=H_3$)

Vertical mixing (m^2/day)

- E_1, vertical mixing coefficient within Layer 1 (surface layer above thermocline)
- E_2, vertical mixing coefficient within Layer 2 (thermocline layer)
- E_3, vertical mixing coefficient within Layer 3 (hypolimnion layer to bottom)

Air-water and sediment-water interfaces

- Cs, saturation concentration of dissolved oxygen at surface
- K_L, air-water transfer coefficient for atmospheric reaeration of oxygen
- SOD, sediment oxygen demand rate

Euphotic layer oxygen production (mg/L-day)

- Pa, Layer 1, photosynthetic oxygen production from $z=0$ to $z=H_1$

Water column oxygen consumption (mg/L-day)

- R_1, Layer 1 oxygen consumption from $z=0$ to $z=H_1$
- R_2, Layer 2 oxygen consumption from $z=H_1$ to $z=H_2$

- R_3, Layer 3 oxygen consumption from $z=H_2$ to $z=H$
- R, Total water column oxygen consumption, depth integrated from $z=0$ to $z=H$

2.6 Pre-Processing and Derivation of Model Coefficients

The layer-dependent rates for oxygen production and oxygen consumption were based on water temperature, kinetic rate reactions and the concentrations of organic carbon, ammonia-N and chlorophyll-*a*.

Oxygen Consumption

The general temperature dependent equation used to estimate oxygen consumptions in the layers was computed from:

$$R\ (k) = [WQ\ (k)]\ K\ (20)\ Ø^{(T-20)} \left(\frac{Oxygen}{WQ}\right) \qquad \text{… (Equation 15)}$$

Where:

R (k) = oxygen respiration rate for layer ‘k’ with units of mg DO/L-day

WQ (k) = ambient water quality concentration for layer ‘k’ (WQ=Org Carbon, NH4-N, Chlorophyll)

K (20) = kinetic reaction rate referenced to 20ºC with units of per day

Ø= temperature dependence coefficient for kinetic rate reaction,

Oxygen: WQ = stoichiometric conversion from ambient WQ units to oxygen (oxygen: carbon; oxygen: nitrogen)

R (k), this relationship was used to calculate respiration rate in each layer (k=1, 2, 3) and was derived as a sum of the layer-dependent oxygen consumption terms for Organic Carbon, NH4-N and phytoplankton chlorophyll-a, which was computed from;

$$R\ (k) = R_{OrgC}\ (k) + R_{NH4\ (k)} + R_{Chl}\ (k) \quad \ldots\ldots\ldots\ldots \quad \text{(Equation 16)}$$

The depth-integrated respiration rates (R) in mg DO/L-day were computed from:

$$R = \frac{[R1(\Delta H1) + R2\ (\Delta H2) + R3\ (\Delta H3)]}{H} \quad \ldots \text{(Equation 17)}$$

$\Delta H1 = (H1 - H0)$ =Layer1 Thickness

$\Delta H2 = (H2 - H1)$ = Layer2 Thickness

$\Delta H3 = (H2 - H3)$ =Layer3 Thickness

$H = (H3 - H0)$ = TotalWaterColumnDepth

Thomann and Mueller (1987) and Chapra (1997) present the equations used to compute respiration for organic carbon, phytoplankton biomass and nitrification.

Labile Organic Carbon

Organic matter is comprised of a mix of materials that decay either slowly or rapidly. The refractory fraction of organic carbon is characterized by a slow decay rate. The refractory component of organic matter is ignored in the oxygen consumption analysis because it does not contribute much of an effect to water column oxygen respiration. The labile fraction is characterized by a much faster reaction rate for decomposition and must be considered to develop estimates of water column oxygen consumption. The oxygen consumption in each layer of the water column is related to the labile component of total organic carbon. The labile component of organic matter is what is measured in the Biological Oxygen Demand (BOD) test. The labile component of organic matter is needed as input to the vertical DO model (Thomann and Mueller, 1987; Chapra, 1997).

The equation used to estimate labile total organic carbon (LTOC) is given as:

$$\text{Labile\_TOC} = \text{TOC} * \text{Labile fraction} - Chl\frac{C}{Chl} \qquad \text{… (Equation 18)}$$

Where,

TOC = Total organic carbon (mgC/L)

Labile fraction = fraction

Chl = Chlorophyll μg Chl/L

C/Chl= Carbon: Chlorophyll ratio as μg C/μg Chl

The equation used to derive oxygen consumption rate for labile total organic carbon as mg/L-day is computed from:

$$R\,(\text{Labile TOC}) = [\text{Labile\_TOC}] * K_d\,(20)\,Ø^{(T-20)} * \frac{Oxygen}{Carbon} \quad \text{… (Equation 19)}$$

Where,

K_d (20) = is the reaction rate of labile organic carbon at 20ºC with units of day^{-1}

Ø = is the temperature dependence coefficient for decomposition

T = is the water temperature ºC

Phytoplankton Respiration

The oxygen consumption rate for phytoplankton respiration computed for input to the model as mg/L-day is:

R (phytoplankton) = [Chl] K_r (20) $Ø^{(T-20)} (\frac{Carbon}{Chl} \frac{Oxygen}{Carbon})$ … (Equation 20)

Where,

Chl = Chlorophyll/algal biomass as µg/L

Kr (20) = Phytoplankton respiration rate Kr (20◦C) 1/day

Ø = is the temperature dependence coefficient for phytoplankton respiration

C/Chl= Carbon: Chlorophyll ratio as µg C/µg Chl

Oxygen: Carbon = Oxygen: Carbon ratio as mg O2/mg C

Nitrification

The oxygen consumption rate for nitrification of ammonia as mg/L-day is computed for input to the model from:

R (NH_4) = [NH_4] K_n (20) $Ø^{(T-20)} (\frac{Oxygen}{Nitrogen}$ … (Equation 21)

Where,

NH4 = Ammonia-N concentration as mg-N/LK_n (20) = is the rate reaction for nitrification at 20ºC with units of day^{-1}

Ø = is the temperature- dependence coefficient for nitrification of ammonia-N

T = Water temperature in at the layer ºC

Oxygen: Nitrogen ratio is the oxygen derived from nitrification as mg O2/mg N.

Oxygen Production

Thomann and Mueller (1987) and Chapra (1997) present the equations used to compute phytoplankton growth and oxygen production. The equation presented below is the general equation used for temperature, light and nutrient-dependent algae growth to estimate oxygen production in the euphotic zone (layer 1);

$$Pa = Chl\ [Kg\,(T, N, P, I)]\,\frac{Carbon}{Chl}\,\frac{Oxygen}{Carbon}\,\frac{1mgC}{1000\mu gC} \qquad \text{... (Equation 22)}$$

Water Temperature Dependence

The dependence of phytoplankton growth on temperature is computed from:

$$K_g\,(20) = K_g\,(20)\ Ø_g{}^{(T-20)} \qquad \text{… (Equation 23)}$$

Where;

K_g (20) = maximum growth rate of phytoplankton at 20ºC (day^{-1})

$Ø_g$ = Temperature coefficient 1.06 for phytoplankton growth

T = Water temperature ºC

Nutrient Limitation Dependence

The dependence of phytoplankton growth on nitrogen and phosphorus are calculated from the half-saturation equations below:

$$f(N) = \frac{N}{Kn+N} \qquad \text{……….. (24)}$$

$$f(P) = \frac{P}{Kp+P} \qquad \text{……….. (25)}$$

Where:

f (Limiting Nutrient) = Min [f (N), f(P)] ………... (26)

Where,

N = is the dissolved inorganic nitrogen concentration (NH4-N +NO2-N +NO3-N) (µg N/L)

P = is the dissolved inorganic ortho-phosphate (OPO4-P) concentration (µg P/L)

K_n and K_p= are the nutrient limitation half saturation constants (as µg/L) for nitrogen and phosphorus

Light Dependence

The equation used to estimate the daily average light was computed from:

$$I_a = \left(\frac{ITOT}{f}\right) \text{fPAR} \qquad \text{… (Equation 27)}$$

Where,

I_a = Daily average light received as langleys/day

f = Photoperiod as fraction of 24 hr day

ITOT = Total daily solar radiation as langleys/day

fPAR=fraction of measured light that is photosynthetically available radiation

$$f(Light) = \frac{2.718f}{k_e \Delta H}[\exp(-\alpha_1) - \exp(-\alpha_0)] \text{ ………………………………….. (Equation 28)}$$

The terms for α_0 and α_1 are given by the following:

$$\alpha_0 = \frac{I_a}{I_s}\exp(-k_e H_0) \text{ ……………………………………… (Equation 29)}$$

$$\alpha_1 = \frac{I_a}{I_s}\exp(-k_e H_1) \text{ ……………………………… (Equation 30)}$$

The daily average primary production in units of C m^2 –day^{-1} is estimated as:

$$Pr = Chl\ [K_g\ (T, \text{Nutrients}, I)\ (\Delta H) \frac{Carbon}{Chl}\frac{1}{1000\mu gC}\frac{1000L}{1m3} \text{ ……….. (Equation 31)}$$

Final estimated production rate of DO inputted to the vertical oxygen model as mg/L-day is:

$$Pa = \frac{Pr}{\Delta H}\frac{m3}{1000L}\frac{Oxygen}{Carbon} \text{ ……….. (Equation 32)}$$

Where,

Pr = Carbon fixation rate (g C m^2 –$day^{-1)}$

ΔH= Thickness of the euphotic layer (meters)

Pa= Oxygen production (mg/L-day)

Kinetic coefficients and parameters used to perform the pre-processing calculations are listed in Table 3.

Table 3: Model Parameters and Kinetic coefficients needed for pre-processing calculation of the vertical DO model.

	KINETIC COEFFICIENT	**UNITS**
1	Max phytoplankton growth rate, Gmax	1/day
2	Temperature dependence, Gmax	Theta
3	Nitrogen Half-Saturation constant, Kn	ugN/L
4	Phosphorus Half-Saturation constant, Kp	ugP/L
5	Light saturation for Phytoplankton, Isat	Ly/day
6	Carbon: Chlorophyll, CCHL	ug C/ug Chl
7	Total sunlight for sample day, ITOT	Ly/day
8	PAR fraction of Total Light (ITOT), Fpar	fraction
9	Photoperiod for sample day, F	fraction 24 hr
10	Phytoplankton respiration rate, Kr (20C)	1/day
11	Temperature dependence, Kr	Theta
12	Oygen:Carbon ratio, 02:C	mgO_2/mgC
13	Clear Extinction coeff, Keo	1/meter
14	Oxygen: Nitrogen ratio, 02:N	mgO_2/mgN
15	Air-water oxygen transfer, KL (20C)	m/day
16	Decomposition rate, OrgC, Kd (20C)	1/day
17	Temperature dependence, Kd	Theta
18	Nitrification rate, Kn(20C)	1/day
19	Temperature dependence, Kn	Theta
20	Coeff=Ke × Sd = Ke × Secchi Depth	Coefficient
21	Labile fraction of total organic carbon	fraction
22	Dissolved fraction of total organic carbon	fraction
23	Redfield ratio C:N	g C/g N
24	Redfield ratio N:P	g N/g P
25	Wind speed	m/sec
26	Lake elevation	feet, above mean sea level

2.7 Data Sources for Grand Lake

Monitoring on Grand Lake (Hydrologic Unit Code (HUC_8) 11070206) has been conducted since June of 1986. However, the number of sampling points and sample sites has varied over the years. Currently, 13 different sampling points are being monitored.

The water quality parameters that are monitored include surface grab samples at 1-meter depth of dissolved oxygen (DO), water temperature, pH, total nitrogen (TN), total phosphorus (TP), chlorophyll a, nitrate (NO_3^-), Secchi depth, turbidity (NTU), and conductivity. Subsurface water chemistry samples were also collected within the hypolimnion layer and near the bottom.

In this study, the lake was divided into three zones (Riverine, Transition, and Lacustrine), as shown in Figure 3. The lake layers were determined based on temperature variation at different depths (epiliminion, thermocline, and hypolimnion). The epiliminion and hypolimnion were defined by the change in water temperature as it reaches $\leq 1^{\circ}C\ m^{-1}$ (Nikolai, 2012) and the thermocline was defined by the rate of maximum changes within the metalimnnion. The strongest stratification in Grand Lake is observed in June and July, which causes the water column to become anoxic especially in the deeper part of the lake close to the dam. Calibration of the model was performed using observed water column data collected by GRDA in 2013 and 2015.

2.8 Model Coefficients

In a three-layer steady state vertical dissolved oxygen model, observed water quality data collected on Grand Lake in 2013 and 2015 from four different stations were analyzed to derive estimates of oxygen production in the surface layer and oxygen consumption rates within each layer of the lake (epiliminion, thermocline, and hypolimnion). The monthly vertical profile data for the various survey dates in the summer months for 2013 and 2015 were used to analyze water temperature and dissolved oxygen profiles to determine the depth or thickness of each layer. The average of each water quality (WQ) input parameters estimated were based on the thickness or depths of the layers. The calculated values were input variables for pre-processing of the model input parameters for the vertical DO model. The 2013 and 2015 data were used to analyze the temporal and spatial patterns of temperature and DO in Grand Lake.

Data used in the pre-processing calculations gives estimates of oxygen production and consumption rates that were obtained from measured data for water temperature, secchi depth, Ammonia-N, Nitrate-N, Ortho-phosphate, Total phosphorus, and chlorophyll-*a* for the four selected stations within the reservoir. Observed water quality data were used with stoichiometric C: N: P Redfield ratios to derive estimates of Total Organic Carbon (TOC) and Total Nitrogen (TN).

Grand Lake was divided into lacustrine, transition, riverine, and dam zones with a site selected within each zone as shown in Figure 6.

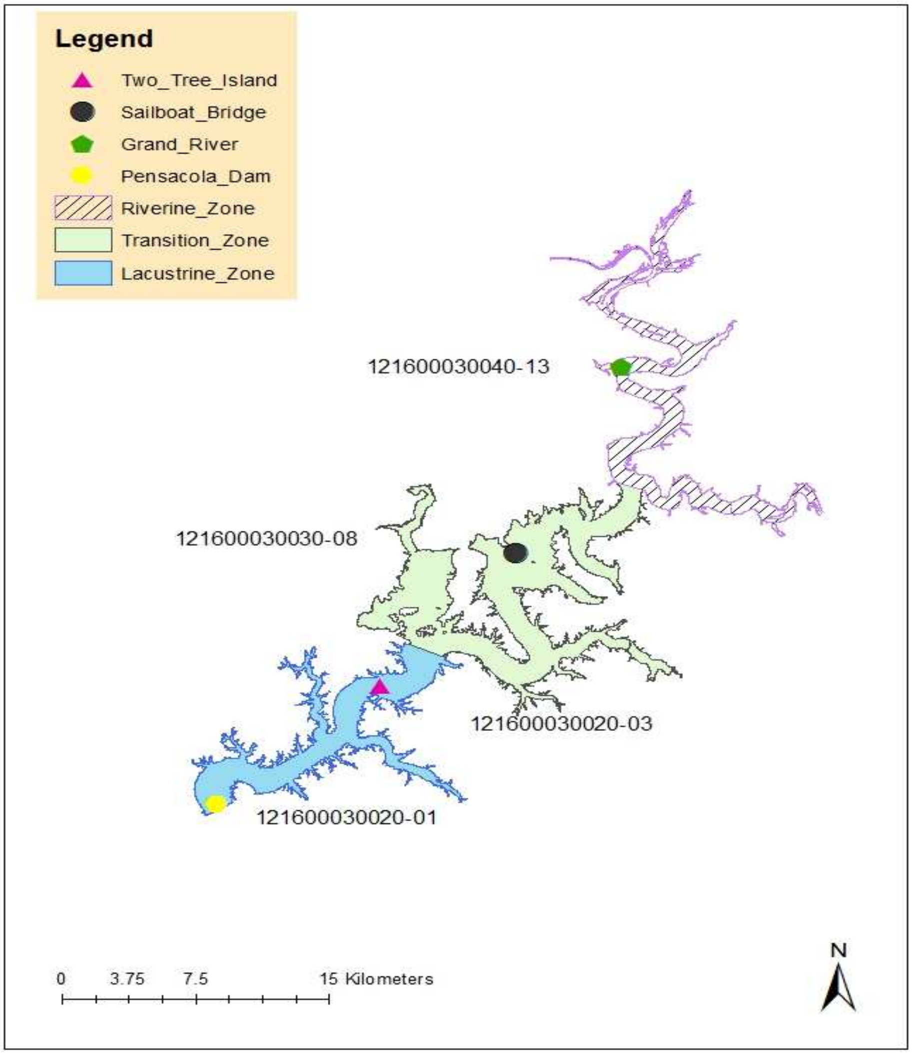

Figure 6: Map of Grand Lake showing transition, lacustrine, and riverine zones with the four sampling sites.

Table 4 presents a list of input observed water quality parameters used in the pre-processing calculations to develop the three-layer steady-state vertical dissolved oxygen model for Grand Lake with data collected in 2013 and 2015, respectively. Compiled values of each of the observed water quality parameters listed in Table 4 for all selected stations in 2013 and 2015 are available in Table A-1, Appendix A.

Table 4: Input observed water quality parameters for the vertical dissolved oxygen model use for Grand Lake.

INPUT OBSERVED WATER QUALITY	UNITS
Water Temperature	◦C
Dissolved Oxygen	mg/L
Specific Conductance	micro-mhos/cm
Secchi Depth	meters
Ammonia-N	mg N/L
Nitrate-N	mg N/L
Ortho-Phosphate	mg P/L
Total- Phosphorus	mg P/L
Phytoplankton biomass	µg Chl/L
Total Organic Carbon	mgC/L

2.9 Observed Surface Layer Water Chemistry Data

Observed water chemistry data for 2013 and 2015 surface layer 0-1m depths along the riverine, transition, lacustrine, and dam zone were compiled and used as inputs to the pre-processing calculations to derive estimates to the vertical DO model as shown in Table 5 and 6, respectively. The right side of Table 5 and 6 shows observed water chemistry data for total phosphorus (TP), Ortho-Phosphate (PO_{4}), Nitrate – N (NO_3), and ammonia-N (NH_{4}), while the left side of Tables 5 and 6 shows derived water chemistry data for surface layer 0-1m depth samples. The derived water chemistry data were water chemistry data that were not available for Grand Lake and are needed for the pre-processing calculation. Thomann and Mueller, 1987; Chapra, 1997 presented the equations below used to derive total nitrogen (TN), total organic nitrogen (TON), total organic carbon (TOC), and labile organic carbons (LTOC).

Total nitrogen = Total phosphorus * Nitrogen: Phosphorus ………………. (Equation 29)

Organic Nitrogen = Total nitrogen – (Ammonia-N)-(Nitrate-N) ………… (Equation 30)

Total organic carbon = Organic Nitrogen *Carbon: Nitrogen ratio ………. (Equation 31)

Labile Organic Carbon = Total organic carbon * Labile fraction TOC… (Equation 32)

The compiled water chemistry data are presented in Table 5 and 6, respectively.

Table 5: Summarized water chemistry data for observed surface layer sample and derived values along the riverine, transition, lacustrine, and dam for Grand Lake in 2013.

Observed water quality data at 0-1m depth samples						Derived water quality data at 0-1m Depth sample			
Zones	Survey dates	TP (mgP/L)	PO_4 (mgP/L)	NO_3 (mgN/L)	NH_4 (mg/L)	TN (mgN/L)	TON (mgN/L)	TOC (mgC/L)	LTOC (mgC/L)
Riverine	July 17, 2013	0.16	0.03	0.31	0.02	1.15	0.82	4..33	4.08
Transition	✓	0.08	0.01	0.27	0.02	0.58	0.28	1.54	1.38
Lacustrine	✓	0.08	0.01	0.22	0.03	0.58	0.32	1.75	1.58
Dam	✓	0.08	0.01	0.27	0.01	0.58	0.29	1.62	1.46

The Table 5 shows a summary of the observed water chemistry data obtained at 0-1m depth samples used in the pre-processing calculations to derive inputs to the model. Table 5 only presents surface data. The subsurface data for the middle and bottom layers are presented in Table A-1, Appendix A. Spatial assessment of the observed water chemistry data and the derived data presented in Table 5 and 6 along the riverine, transition, lacustrine, and dam zones are summarized below.

As shown in Table 5, the total phosphorus concentrations was high in the riverine zone with 0.16 mgP/L and subsequently lower in the transition, lacustrine, and the dam zones with a value of 0.08 mgP/L. Ortho-phosphate concentration was high in the riverine zone with 0.03mgP/L and lower in the transition, lacustrine, and the dam zone with a value of 0.01mgP/L. Similar patterns were observed for nitrite, and ammonia concentrations in all the zones except ammonia concentration was a bit higher in lacustrine zone with 0.03 mg/L and lower in riverine, transition, and dam zone as shown in Table 5. The right side of Table 5 showed derived values for TN, TON, TOC, and LTOC for the surface layer 0-1m depth in Grand Lake on July 17, 2013. The derived values were high for TN, TON, TOC, and LTOC for the surface layer 0-1m in the riverine zone, and comparatively lower in the transition, lacustrine, and the dam zone (Table 5).

Table 6: Summarized water chemistry data for observed surface layer sample and derived values along the riverine, transition, lacustrine, and dam for Grand Lake in 2015.

Observed water quality data at 0-1m depth samples						Derived water quality data at 0-1m depth samples			
Zones	Survey dates	TP (mgP/L)	PO_4 (mgP/L)	NO_3 (mgN/L)	NH_4 (mg/L)	TN (mgN/L)	TON (mgN/L)	TOC (mgC/L)	LTOC (mgC/L)
Riverine	8/11/ 2015	0.16	0.1	0.22	0.26	1.13	0.65	3.62	3.25
Transition	6/ 16/ 2015	0.17	0.06	0.37	0.0169	1.25	0.86	4.76	4.28
Lacustrine	7/ 29/2015	0.04	0.01	0.0008	-0.0021	0.28	0.28	1.57	1.41
Dam	7/29/2015	0.03	0.01	0.038	-0.0019	0.19	0.16	0.89	0.80

Table 6 summarizes observed water quality data as well as derived water chemistry data obtained for riverine, transition, lacustrine, and dam zone for 2015 for each survey date in Grand Lake. Both the observed and the derived water chemistry data varied completely alongside the survey dates. The ammonia concentrations showed negative on July 29, 2015 in the lacustrine zone with a value of -0.0021 mg/L, and dam zone with -0.0019 mg/L. In the pre-processing calculation, ammonia for the surface layer was set to zero in the spreadsheet to derive estimates for nitrification in lacustrine and dam zones. Total nitrogen was higher in the riverine with 1.13 mgN/L and transition zones with a value of 1.25 mgN/L and lower in the lacustrine with 0.28 mgN/L and dam zone 0.19 mgN/L as shown in Table 6. Total organic carbon and labile organic carbon were higher in the transition zone and lower in the dam zone (Table 6).

2.10 Sensitivity Analysis

Model sensitivity analysis is recognized as a key component in modeling, as it characterizes the effect of changes in model inputs on the output results. Sensitivity analyses help to predict the potential outcome of model results if input parameters or coefficients are changed. The results of a sensitivity analysis are compared to a baseline set of model results to evaluate any differences from the major baseline predictions (Tang et al., 2006). The results of a sensitivity analysis can be used to develop estimates of confidence limits for a model.

Sensitivity analysis was performed on the Grand Lake data set collected at Tree Station (lacustrine zone) on July 17, 2013. The sediment oxygen demand (SOD) and vertical mixing coefficient (E_2) were the two variables that sensitivity analyses were performed on. Varied values for both terms were tested with a low and high range for SOD and the vertical mixing term. The purpose of the sensitivity analysis is to observe possible effects that changes in the parameter values for SOD and the vertical mixing coefficient may have on the oxygen profile within the epiliminion, thermocline, and hypolimnion layers.

CHAPTER III

RESULTS AND DISCUSSION

3.1 Trophic State Index for Grand Lake

The TSI for Grand Lake was hypereutrophic on July 17, 2013 based on chlorophyll-*a*, total phosphorus, and secchi depths (Table 7). The transition, lacustrine, and dam zones were all classified as eutrophic. Similar TSI were determined based on 2015 data for riverine (hypereutrophic), transition (hypereutrophic), lacustrine (eutrophic), and dam (eutrophic) zones (Table 8).

Table 7: Means and ranges of Trophic State Index (TSI) for chlorophyll-*a*, secchi depth, and total phosphorus (0-1m depth samples) for 2013 Grand Lake data set.

Zones	Mean	Range	Survey dates	TSI for Grand Lake	Chl (μg/L)	SD (meters)	TP ((μg/L)
Riverine	65	57-77	7/17/2013	Hypereutrophic	15.0	0.88	0.16
Transition	58	51-67	7/17/2013	Eutrophic	8.80	1.21	0.08
Lacustrine	57	51-67	7/17/2013	Eutrophic	8.08	1.40	0.08
Dam	58	50-67	7/17/2013	Eutrophic	7.82	1.18	0.08

Table 8: Means and ranges of Trophic State Index (TSI) for chlorophyll-*a*, secchi depth, and total phosphorus (0-1m depth samples) for 2015Grand Lake data set.

Zones	Mean	Range	Survey dates	TSI for Grand Lake	Chl (μg/L)	SD (meters)	TP ((μg/L)
Riverine	67	61-77	8/11/2011	Hypereutrophic	22.6	0.75	0.15
Transition	67	57-78	6/16/2015	Hypereutrophic	14.8	0.57	0.17
Lacustrine	57	54-62	7/29/2015	Eutrophic	24.5	1.42	0.03
Dam	55	51-60	7/29/2015	Eutrophic	16.3	1.28	0.12

Grand Lake observed water chemistry data for 2013 and 2015 for chlorophyll-*a*, secchi depth, TN, TP, and DO respiration (0-1m sample) estimated from the pre-processing calculations are presented in Table 9. The minimum and maximum values for each parameter measured in Grand Lake were compared to data reported for Midwest reservoirs in the same ecoregion (Ozark Highlands) presented in Jones and Knowlton (1993) in Table 9. Interestingly, the Grand Lake data were similar with the data reported in Jones and Knowlton (1993), especially for DO respiration rates that we estimated for Grand Lake. This similar DO respiration rates suggests that the model estimated values from the pre-processing calculation are accurate and reliable.

Table 9: Comparison of observed water chemistry data and estimated results from Grand Lake with data reported in Jones and Knowlton (1993) for Midwest reservoirs.

QW parameters	Unites	Grand Lake		Ozark Highlands (25 reservoirs)	
		Min	Max	Min	Max
Chlorophyll	µg/L	7.8	24	1	23
Total Nitrogen	mg N/L	0.19	1.25	0.1	0.59
Total phosphorus	µg/L	1	80	6	38
Secchi depth	Meters	0.57	1.42	0.6	3.7
DO respiration	mg/L-day	0.08	0.6	<0.1	0.96

The riverine and transition zone water chemistry data needed for the pre-processing calculation to derive inputs to the vertical DO model for 2013 and 2015 was only available for the surface layers and no data was available for the subsurface middle and bottom layers. The vertical profile for water temperature data represents good stratification conditions in each of those locations, but due to the lack of the subsurface water chemistry data, riverine and transition zones were not modeled.

3.2 Pre-Processing and Estimation of Model Input Parameters: 2013

The pre-processing calculations give estimates for oxygen production terms using the general equation for oxygen production terms (equation 22), as well as oxygen respiration/consumption terms using the general equation for oxygen consumption terms (equation 15) within each layers of the water column. Results obtained from the pre-processing are summarized in Table B-1, Appendix B for 2013 and Table C-1, Appendix C for 2015. The results presented are discussed in comparison of the four zones (riverine, transition, lacustrine, and dam) and layers (1, 2, and 3).

Daily Primary Production Rates for Oxygen ($gO_2/m^2/day$)

The daily primary production rates for oxygen were computed for July 17, 2013 along the riverine, transition, lacustrine, and dam zone for Grand Lake. The results presented in Table B-1, Appendix B only report surface 0-1m depth for riverine and transition zone. The results reported for lacustrine and dam zone shows for surface, middle, and bottom layer. For the riverine and transition zones, water chemistry data for subsurface samples were not available.

Daily primary production rates for oxygen are highest in the dam zone with 12.468 gO_2/m^2/day and riverine zone with 7.294 gO_2/m^2/day, while lower values were obtained for both the transition with 5.462 gO_2/m^2/day and lacustrine zone with 5.642 gO_2/m^2/day. The daily primary production in the lacustrine and dam zone significantly reduces at the middle and bottom layer as shown in Table B-1, Appendix B. The reduction in primary production rates at the subsurface layer was due to decrease in light limitation at the subsurface (Table B-1, Appendix B).

Daily Primary Production Rate for Carbon ($gC/m^2/day$)

Daily primary production rates for carbon in Grand Lake on July 17, was highest in the dam zone at surface 0-1m depth with a value of 4.66 g C/m^2/day. The result indicates low levels in the riverine, transition and lacustrine zones with similar patterns of 2.73 g C/m^2/day in the riverine zone, 2.04 g C/m^2/day in the transition 2.11gC/m^2/day and lacustrine zones. Production rates decreased significantly in the middle and bottom layers for the lacustrine and dam zones. This was due to the low light limitation in the middle and bottom layer (Table B-1, Appendix B).

Phytoplankton Production (mgO$_2$/L-day)

Phytoplankton production calculated for Grand Lake on samples collected on July 17, 2013 along the riverine, transition, lacustrine, and the dam zones indicate the highest amount of phytoplankton production was observed in the riverine zone of 0-1m depth with a value of 3.647 mgO$_2$/L-day. The transition, lacustrine, and dam zone have similar values for phytoplankton production with 1.820 mgO$_2$/L-day in the transition, 1.128 mgO$_2$/L-day, and 1.558 mgO$_2$/L-day in the dam zone. The results show a decrease in the phytoplankton production from the surface to the bottom layer**.**

Organic Carbon Respiration (mgO$_2$/L-day)

Organic carbon respiration computed along the riverine, transition, lacustrine, and dam zone for July 17, 2013 survey date in Grand Lake results indicate high levels at the 0-1m surface sample in the dam zone with value of 0.053 mgO$_2$/L-day and the riverine zone with a value of 0.043 mgO$_2$/L-day. The transition and lacustrine zones shows varying values at the surface, middle and bottom layers as shown in Table B-1, Appendix B.

Ammonia Nitrification (mgO$_2$/L-day)

On the July 17, 2013 survey date, the ammonia nitrification rates calculated for Grand Lake along the riverine, transition, lacustrine, and dam zones shows similar patterns for rates obtained at the surface layers with values of 0.018 mgO_2/L-day in the riverine, 0.0151mgO_2/L-day in the transition, 0.021mgO_2/L-day in the lacustrine, and a low level of 0.004mgO_2/L-day in the dam zone. The oxygen demand from nitrification increases in the middle and bottom layers of the lacustrine and dam zones as shown in Table B-1, Appendix B.

Phytoplankton Respiration (mgO_2/L/day)

Phytoplankton respiration in the surface layer of the riverine zone is high with a value of 0.260 mgO_2/L/day and low levels in the dam zone with a value 0.067 mgO_2/L/day. The transition and lacustrine zones shows similar patterns of phytoplankton respiration rates obtained with 0.147 mgO_2/L/day in the transition and 0.134 mgO_2/L/day in the lacustrine zone. The oxygen demand from phytoplankton respiration decreases in the middle and bottom layers.

Phytoplankton Growth (1/day)

The phytoplankton growth was highest at the surface layer of the riverine zone with a value of 1.829 1/day and lowest in the lacustrine zone with value of 1.0461/day**.** Similar patterns of phytoplankton growth rates were observed in the transition and dam zones**.** These values were reduced at the middle and bottom layers in the lacustrine and dam zones as shown in Table B-1, Appendix B. The riverine, transition zones maximum phytoplankton growth rate used were (3.01/day), while the lacustrine and dam zone maximum phytoplankton used varied. The lacustrine maximum growth rate was set at 3.5 1/day and 6.0 1/day for the dam zones. A summary of the various kinetic coefficients, which were adjusted in some cases to get a good match with the observed dissolved oxygen are shown in Table D-1, Appendix D

Nitrogen Limitation (fraction 0-1)

The nitrogen limitation was computed on parameter values of dissolved inorganic nitrogen and nitrogen half saturation constant. Results obtained in the riverine, transition, lacustrine, and dam zones shows a normal trend of little or no variation at all, indicating that nitrogen limitation is almost the same at the surface, middle, and bottom layer of the lake as shown in Table B-1, Appendix B.

Phosphorus Limitation (fraction 0-1)

Phosphorus limitation was calculated from ortho-phosphate and phosphorus half saturation constant. Results indicate that phosphorus limitation occurs at about the same rates in surface, middle, and bottom layer. There was not much of a difference was observed in the riverine, transition, lacustrine, and dam zone. The estimated parameters compiled in Table B-1, Appendix B shows that phosphorus was the limiting factors for primary productivity in most cases.

Light Limitation f (I)

Light limitation was observed to be high in the surface layer of the riverine and transition zones with values of 0.363 (I) in the riverine and 0.33 (I) in the transition zone. The lacustrine and dam zones results show a little lower value as compare to the riverine and transition zones (Table B-1, Appendix B). In the middle and bottom layers of the lacustrine and dam zones, light limitation values reduce significantly, which resulted in a reduction in primary productivity.

Layer Respiration (mgO_2/L-/day)

The layer respiration rates were obtained from the sum of the phytoplankton respiration, organic carbon decomposition rates, and ammonification contributing to oxygen consumption at each layer. The riverine zone indicates high levels in layer respiration rates, with a value of 0.32 mgO_2/L-/day at the surface 0-1m depth, while the transition, lacustrine, and dam zones have similar respiration rates ranges from 0.12 to 0.16 mgO_2/L-/day (Table B-1, Appendix B).

Water Column Respiration (mgO_2/L-/day)

Depth-integrated water column respiration was obtained from the sum of layer respiration rates from layer 1, 2, and 3 at each layers divided by the total water column depth at the station. Each estimated value was used as input to the model. The lacustrine and dam zones indicate similar water column respiration rates (Table B-1, Appendix B).

3.3 Pre-Processing and Estimation of Model Input Parameters: 2015

Daily Primary Production Rates for Oxygen (gO_2/m^2/day)

The daily primary production rates for oxygen (Table C-1, Appendix C) shows highest in the surface layer of the riverine and dam zone with a value of 11.220 gO_2/m^2/day in the riverine and 11.190 gO_2/m^2/day in the dam zone. The transition and lacustrine zones show low levels in the surface layer with values of 3.1814 gO_2/m^2/day in the transition zone and 8.792 gO_2/m^2/day in the lacustrine zone (Table C-1, Appendix C). The daily primary productivity rates for oxygen were recorded in the transition zone with a value of 3.1814 gO_2/m^2/day. The results indicate a decrease in the rates of production at both the middle and bottom layer of the lacustrine and dame zones. Compared to the daily primary production rates for oxygen indicate lower value for the riverine and higher value in the dame zone as shown in Table B-1, Appendix B. The transition and lacustrine zone have significant differences in values at the surface layers.

Daily Primary Production Rate for Carbon (gC/m^2/day)

Daily primary productivity rates for carbon in 2015 indicate high levels in the riverine and dam zones at the surface layer with values of 4.202 g C/m^2/day in the riverine and 4.191 g C/m^2/day in the dam zone. The lowest value was recorded in the transition zone with value of 1.428 g C/m^2/day. The lacustrine and dam zone middle and bottom layers decreased significantly as compared to the results in 2013. The results obtained for productivity rates in the dam zone indicate similar patterns in both years with values of 4.669 g C/m^2/day in 2013 and 4.191 g C/m^2/day in 2015 (Table C-1, Appendix C.

Phytoplankton Production (mgO_2/L-day)

The lowest phytoplankton production rates were recorded in the transition zone in 2015 with a value of 0.635 mgO_2/L-day. The riverine, transition and dam zones had similar values with 2.805 mgO_2/L-day in the riverine, 2.198 mgO_2/L-day in the lacustrine and 2.797 mgO_2/L-day in the dam zone. The production rates also decreased in the middle and bottom layers of the lacustrine and dam zone. Compared to the values reported in 2013, the highest value of phytoplankton production rates were recorded in the riverine zone of the surface layer with value of 3.647 mgO_2/L-day, whereas the lowest value of production was recorded in the transition for 2015 with value of 0.635 mgO_2/L-day (Table C-1, Appendix C.

Organic Carbon Respiration (mgO_2/L-day)

Organic carbon respiration results were high in the transition zone with a value of 0.0417 mgO_2/L-day. The values in the riverine, lacustrine, and dam zone were 0.0049 mgO_2/L-day in the riverine, 0.00163 mgO_2/L-day in the lacustrine, and 0.01 mgO_2/L-day in the dam zone. The middle and bottom layer results indicated higher values as compared to the values reported at the surface layer (Table C-1, Appendix C). Compared to the results of 2013, similar observations were made with little differences in values (Table B-1, Appendix B and Table C-1, Appendix C).

Ammonia Nitrification (mgO_2/L-day)

The nitrification result for this zone was available for surface layer in the riverine with a value of 0.199 mgO_2/L-day and transition zone with a value of 0.009mgO_2/L-day. No results were obtained for the surface layer in lacustrine and dam zones. Results were available for the middle in the lacustrine zone with 0.102 mgO_2/L-day, 0.122 mgO_2/L-day for the bottom layer and in the dam zone with 0.098 mgO_2/L-day for the middle layer, 0.106 for the bottom layers as shown in Table C-1, Appendix C. This was due to the fact that in those zones ammonia concentration was negative and so in the pre-processing calculation to estimate nitrification, ammonia at the surface layer was set to zero.

Phytoplankton Respiration Rate (mgO_2/L/day)

Phytoplankton respiration rates indicate high levels in the surface layer of the riverine zone with a value of 0.406 mgO_2/L/day and significantly lower in the dam zone as compared to the transition and lacustrine with values of 0.202 mgO_2/L/day in the transition zone and 0.179 $mgO_2/L/day$ in the lacustrine zone. As compared to results in 2013, the lowest phytoplankton respiration rates were recorded in the dam zone and highest in the riverine zone, which indicate similar patterns of phytoplankton respiration rates in both years (Table B-1, Appendix B, and Table C-1, Appendix C).

Phytoplankton Growth (1/day)

In 2015, the results obtained for phytoplankton growth show the highest values in the dam zone at the surface layer with value of 1.971 1/day and lower in the transition zone with value of 0.320 1/day. The middle and bottom layer results indicate a decrease in the lacustrine with 0.025 1/day in the middle, 2.70×10^{-7} 1/day in the bottom layer and dam zones with 0.015 1/day in the middle, 4.87×10^{-7} 1/day for the bottom layer. Compared to 2013, there were similar patterns in phytoplankton growths in all the four zones as shown in Table B-1, Appendix B.

Nitrogen Limitation (fraction 0-1)

In 2015, the results indicate low levels for nitrogen limitation in the surface layer of the lacustrine zone with a value of 0.388 and highest values in riverine, transition, and dam zones with similar patterns showing small differences in both the surface and bottom layers (Table C-1, Appendix C). Compared to results obtained in 2013, similar values were also obtained for nitrogen limitation, indicating great similarity as shown in Table B-1, Appendix B and Table C-1, Appendix C.

Phosphorus Limitation (fraction 0-1)

Phosphorus limitation obtained for the riverine, transition, lacustrine, and dam zones indicate similar pattern of values for 2015. The results showed no significant differences in all the four zones as shown in Table C-1, Appendix C. In comparison to the results obtained in 2013, the date in 2015 followed similar patterns.

Light Limitation f (I)

In 2015, the light limitation was highest in lacustrine zone with value of 0.305 (I) and lowest in the transition zone with value of 0.0758 (I). The light limitation decreases in both the middle and bottom layer of the lacustrine and dam zones. Compared to the 2013 results, the light limitation was lowest in the dam zone and highest in the riverine, which indicates no similarity or patterns in results.

Layer Respiration (mgO$_2$/L-/day)

The layer respiration rates obtained from the phytoplankton respiration, organic carbon decomposition rates, and ammonification contributing to oxygen consumption at each layer was observed to be higher in the riverine and transition zones. The lacustrine and dam zone results indicated low levels in layer respiration rate as shown in Table C-1, Appendix C.

Water Column Respiration (mgO$_2$/L-/day)

The depth-integrated water column respiration results obtained from the sum of layer respiration divided by the total depth were similar for both the lacustrine and dam zones as presented in Table C-1, Appendix C. These values were used as inputs to the vertical DO model.

3.4 Summary of Oxygen Production and Oxygen Consumption Rates

Algal respiration rates and phytoplankton production rates estimated by the model pre-processing calculations were used to calculate the net primary production rate at each zone. It was found that the lacustrine zone on July 17, 2013 had a net production rate of 1.0 mgO_2/L-day and a gross primary production of 2.0 mgO_2/L-day on July 29, 2015. The Dam zone gross primary production on July 17, 2013 was 1.5 mgO_2/L-day, while Dam zone on July 29, 2015 gross primary production was 2.8 mgO_2/L-day. In comparison of the gross primary production for 2013 and 2015, it was observed that the sum of net production rates for 2015 stations were highest with value of 4.8 mgO_2/L-day, while 2013 stations recorded the lowest with 2.5 mgO_2/L.

The total depth-integrated water column respiration was compared for 2013 and 2015. Results indicate that the sum of water column respiration in 2015 was highest with a value of 0.85 mgO_2/L-day as compared to 2013 with 0.54 mgO_2/L-day. Also, the individual respiration terms for 2013 and 2015 were compared and it was found that organic carbon respiration for 2015 was the highest with 0.27 mgO_2/L-day compared to 0.15 mgO_2/L-day in 2013, nitrification was 0.22 mgO_2/L-day in 2015 compared to 0.16 mgO_2/L-day in 2013, phytoplankton respiration was the highest with 0.27 mgO_2/L-day in 2015 as compared to 0.15 mgO_2/L-day in 2013 and SOD computed as a volumetric rates computed over the total depth of the water column was observed to be highest in 2013 with 0.09 mgO_2/L-day (1.00 g O_2/m^2-day) compared to 0.08 mgO_2/L-day (1.90 g O_2/m^2-day) in 2015.

The differences observed in the source terms were consistently higher in 2015 and lower in 2013. A similar scenario was also observed for the sink terms for oxygen in 2013 and 2015. The exception was that SOD was higher in 2013 and lower in 2015. The oxygen demand from organic carbon decomposition rates for both 2013 and 2015 were similar to the oxygen demand from phytoplankton respiration rates in 2013 and 2015. In addition to the comparison made for combined respiration terms for 2013 and 2015, individual respiration values were used to compute the percentage contributions from each term of oxygen consumption (SOD, algal respiration, nitrification, organic carbon decomposition) to the total oxygen demand in the water column.

For the lacustrine zone on July 17, 2013, the contribution of nitrification to oxygen demand was 33 percent while phytoplankton respiration accounted for 27 percent, organic decomposition accounted for 23 percent and SOD accounted for 16.2 percent. For the lacustrine zone on July 17, 2015 nitrification accounted for 44 percent of the oxygen demand while phytoplankton respiration accounted for 26.6 percent, organic matter decomposition accounted for 15.1 percent, and SOD accounted for 13.4 percent. Similar computations were analyzed for the Dam zone for the 2013 and 2015 sets of data. The results indicate that in the Dam zone on July 29, 2013, nitrification contribution to oxygen consumption in the entire water column was 25 percent while phytoplankton respiration accounted for 28.4 percent, organic matter decomposition accounted for 29.3 percent, and SOD accounted for 16.5 percent.

For the Dam zone on July 29, 2015, nitrification term contribution to oxygen consumption was 17.6 percent while phytoplankton respiration accounted for 34.1 percent, organic matter decomposition accounted for 40.9 percent and SOD accounted for 7.4 percent.

3.5 Model Simulation results

Estimates from the pre-processing calculations for the oxygen production terms and oxygen consumptions terms together with the physical parameters for each layer were used to provide inputs to the vertical DO model to produce the observed DO profile for each selected station in the various zones, the parameters used in some cases were adjusted according to ranges reported in Bowie et al., (1985) and Glaser et al., (2009). A summary of model coefficients and parameters used for each case is given in Table D-1, Appendix D. The water temperature profiles and simulation results of the model in comparison with the observed dissolved oxygen profiles for the varied survey dates are presented below.

3.6 Vertical Oxygen Profiles: Comparison of Model Results and Observed Data for Lacustrine Zone (TREE): July 17, 2013.

The plot shown in Figure 7 illustrates a typical water temperature profile for Grand Lake Tree Station on July 17, 2013 sampling date. For a simplified water quality model like the three-layer steady-state vertical dissolved oxygen model, water temperature and conductivity helps to define the boundary of the epiliminion, thermocline, and hypolimnion as shown in Figure 7 for water temperature. Based on the various break points in the water temperature, the input parameters for grab sample dissolved oxygen, and chlorophyll-a concentration were used in the pre-processing calculations to derive inputs to the DO model for layer 1, 2 and 3.

For Tree Station on July 17, 2013, the water temperature for the surface layer was 28.27ºC, layer 2 was 27.27 ºC, and layer 3 was 18.63 ºC. The vertical water temperature and assigned water temperature based on averaging are presented in Table A-1, Appendix A.

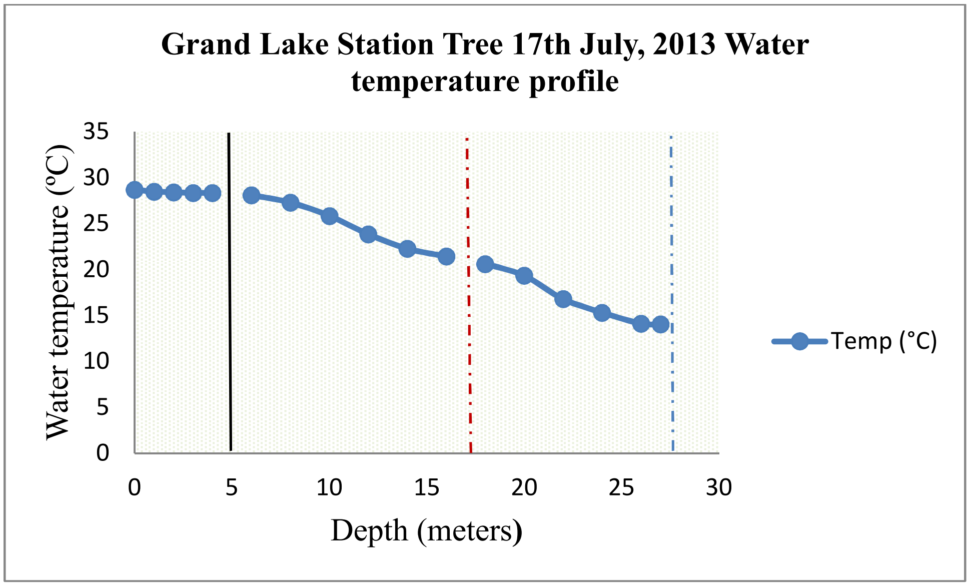

Figure 7: Plot of observed water temperature profile for Grand Lake Tree Station on 17 July 2013 in Grand Lake.

The simulation results of the model in comparison with the observed dissolved oxygen profile for Tree Station on the July 17, 2013 survey date are presented in Figure 8.

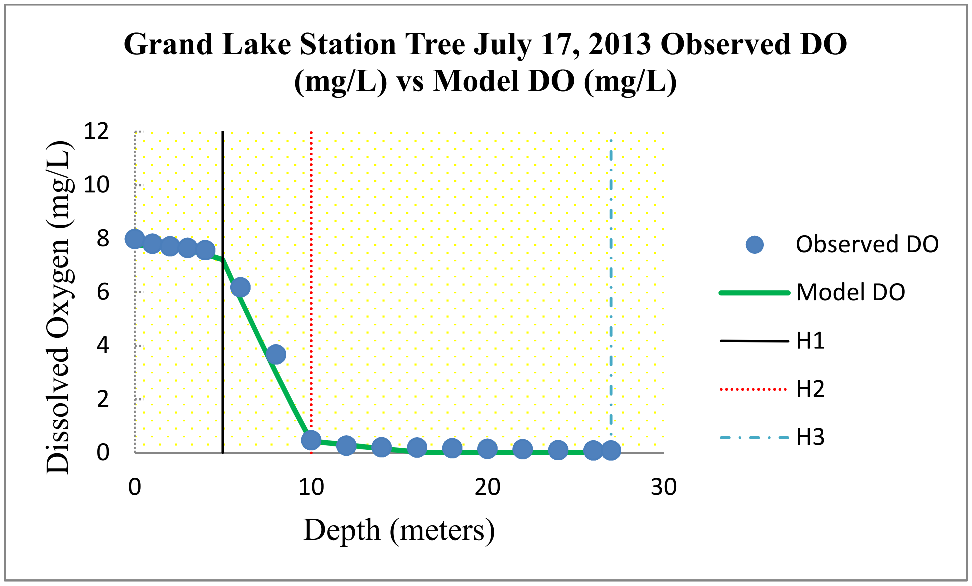

Figure 8: Grand Lake Tree Station July 17, 2013 observed and model predicted dissolved oxygen.

The ticked green line indicates result of the predicted model dissolved oxygen profile and the circular tick blue marks indicate observed dissolved oxygen.

In Figure 8, the application of the simplified model of the vertical distribution of dissolved oxygen to Tree Station on July 17, 2013 provides excellent agreement with the observed profile data for dissolved oxygen. Looking at the observed dissolved oxygen data in Table 13a- 1, the surface z=4m depth ranges from 7.75 to 8.0 mg/L with slight saturation of 103% at (z=0-4m). As seen in Table A-1, Appendix A, the depth at the thermocline decreased in dissolved oxygen from 8.0mg/L to 3.44mg/L.

The vertical mixing rate initially assigned at each layer (epiliminion, thermocline, and hypolimnion) was obtained from HydroQual (1986) were E_1= 3.0 cm^2/sec for the epiliminion layer, E_2 = 0.75 cm^2/sec for the thermocline layer, and E_3 = 6.9 cm^2/sec for the hypolimnion layer. For the model to achieve a reasonable or excellent match, E_1 and

E_3 remained the same, whereas E_2 was adjusted from $E_2 = 0.75$ cm^2/sec to value of 0.45 cm^2/sec.

3.7 Vertical Oxygen Profiles: Comparison of Model Results and Observed Data for Lacustrine Zone (Tree Station): July 29, 2015

Figure 9 is a plot of the water temperature profile for Tree Station on July 29, 2015 in Grand Lake. The temperature profile gives a clear picture of summer-stratified conditions in temperate lakes such as Grand Lake. The broken lines indicate the break points at each layer from the top to the bottom of the lake. Water temperatures used as inputs to the pre-processing calculations were averages of station vertical profile data. The vertical water temperature profiles data were used as inputs to the model and averaged water temperature data used in the pre-processing calculations are presented in Table A-1, Appendix A.

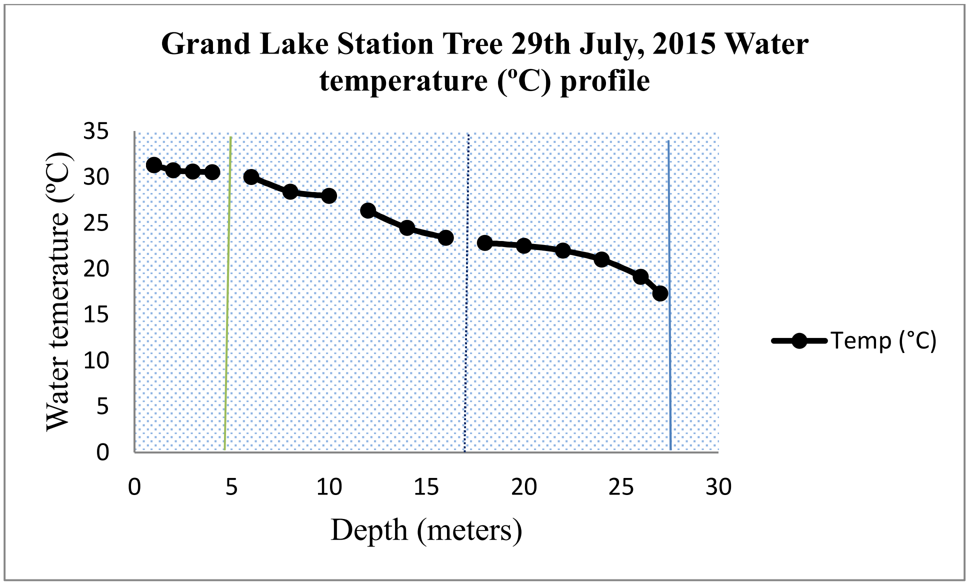

Figure 9: Observed water temperature profile for Tree Station on 29 July, 2015 in Grand Lake.

The simulation result of the model in comparison with the observed water quality dissolved oxygen for Tree Station on July 29, 2015 survey date is presented in Figure 10.

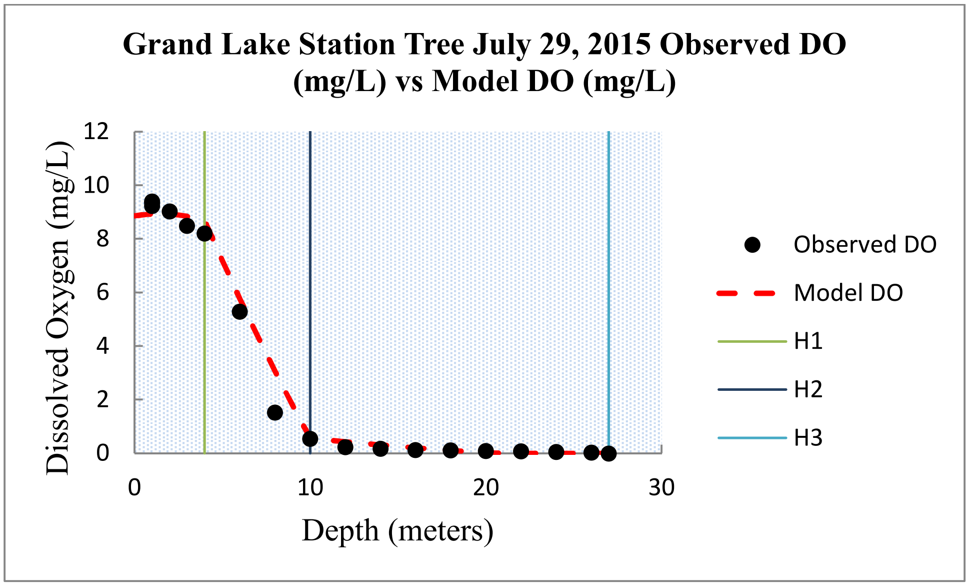

Figure 10: Grand Lake Tree Station July 29, 2015 observed and model predicted dissolved oxygen.

The red dotted lines indicate the model prediction for dissolved oxygen profile and the black circular marks indicates the observed dissolved oxygen profile, while the three vertical lines on the graph indicates the different depths that were used as an input to the model (H_1 =4m, H_2 =10m, and H_3 = 27m). The application of the simplified vertical distribution of dissolved oxygen model to the Tree Station data set collected on July 29, 2015, gives a reasonable agreement with the observed profile of dissolved oxygen as shown in Figure 10.

The surface dissolved oxygen ranges from 8.95 to 9.0 mg/L with high supersaturation of 126.7% at the surface layer (z = 4m) depth. Dissolved oxygen reduced significantly from 8.95 to 2.45 mg/L a little below the thermocline layer, while the hypolimnion became an anoxic with dissolved oxygen of 0.1mg/L. In achieving a reasonable agreement between the model prediction results and the observed dissolved oxygen data, the SOD and vertical mixing coefficients for the middle layer were adjusted.

The vertical mixing rates assigned to layer 1, 2, and 3 presented in the HydroQual 1986 report was: (E_1= 3.0 cm^2/sec, E_2 = 0.75 cm^2/sec, and E_3 = 6.9 cm^2/sec) whereas, the good match with the model was achieved by adjusting the vertical mixing at the middle layer from E_2 = 0.75 cm^2/sec to E_2 = 0.40 cm^2/sec. In addition, sediment oxygen demand was adjusted at 1.0 g O_2 /m^2-day as presented in Table D-1, Appendix D.

3.8 Vertical Oxygen Profiles: Comparison of Model Results and Observed Data for Lacustrine Zone near Dam (P-DAM): July 17, 2013.

Figure 11 shows a plot of observed vertical water temperature against water column depths on data collected for P-Dam on 17 July 2013 in Grand Lake. The water temperature recorded indicates stratification conditions in a temperate lake during summer months. The average water temperature used in the pre-processing calculations and the profile data for water temperatures provides inputs to the model as shown Table A-1, Appendix A. Each vertical line on the graph indicates the boundary assigned between the layers based on the change in temperature with depths.

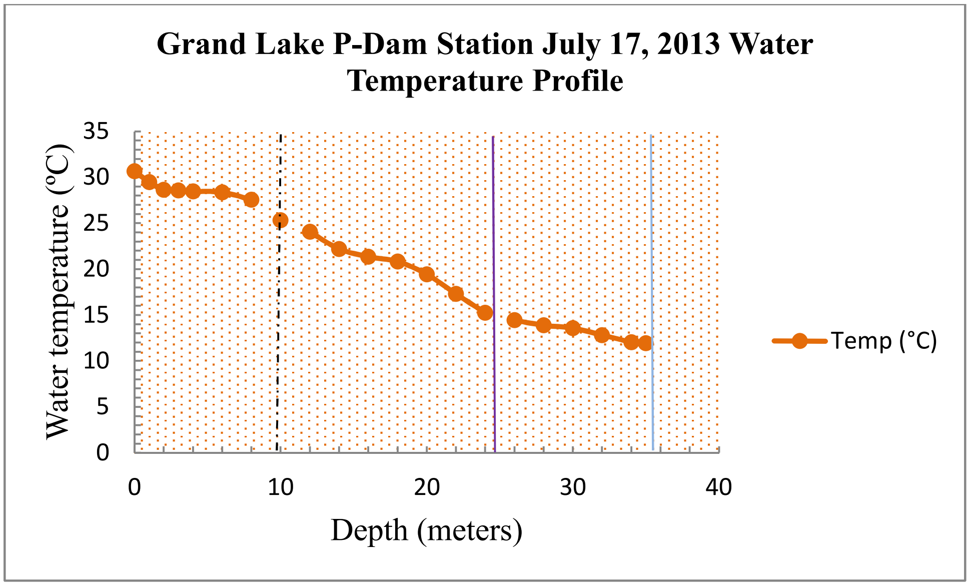

Figure 11: Observed water temperature profile for P-Dam Station on 17 July 2013 in Grand Lake.

The simulation result of the model in comparison with the observed water quality dissolved oxygen for P-Dam Station on July 17, 2013 survey date is presented in Figure 12.

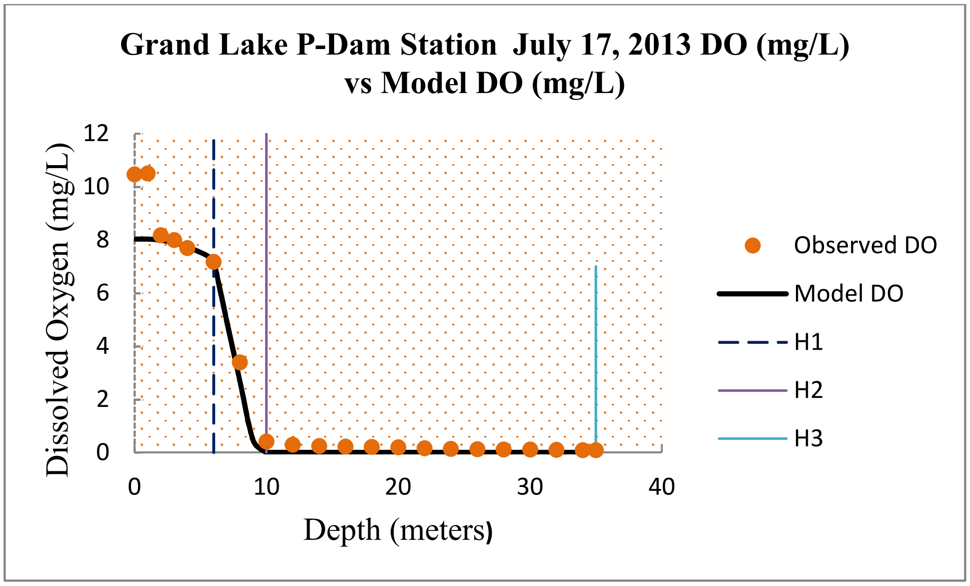

Figure 12: Grand Lake Station P-Dam July 29, 2013 observed and model predicted dissolved oxygen.

Figure 12 presents the result of the observed and model predicted dissolved oxygen for Grand Lake P-Dam Station on 17 July 2013. The black line indicates the model predicted dissolved oxygen and the tick circular orange marks indicates the observed dissolved oxygen. The three vertical lines show the various depths, which clearly defined the surface, middle, and the bottom layers (H_1 = 8m, H_2= 10m, and H_3 = 35m), respectively. Water column depths and assigned water temperature data obtained from averaging used as inputs to the model are presented in Table A-1, Appendix A. Comparison of the vertical distribution of dissolved oxygen model to data obtained from P-dam Station on July 17, 2013 provides a reasonable agreement at the hypolimnion layer, as well the thermocline layer. However, it did not give a good match at the surface layer (Figure 12). The disagreement in model result at the surface was due to several reasons:

1. Higher light availability at the photic zone and very high dissolved oxygen was observed at the surface on that survey date.
2. Supersaturated conditions of 140 percent at the surface of the water column on that survey date as a result of high phytoplankton biomass and productivity in the upper depths of the surface layer.

In order to achieve a reasonable agreement for the middle and bottom layers as shown in Figure 12, the SOD and vertical mixing coefficient were adjusted from the model 1.0 g O_2 /m^2-day to an adjusted value of 1.9 g O_2 /m^2-day and vertical mixing coefficient of (E_2 = 0.36 cm^2/sec) was adjusted from the calibrated value of (E_2 = 0.45 cm^2/sec).

3.9 Vertical Oxygen Profiles: Comparison of Model Results and Observed Data for Lacustrine Zone near Dam (P-DAM): July 29, 2015.

Figure 11 is a plot of the observed water temperature profile for Dam Station on July 29, 2015 in Grand Lake. Good vertical water temperature data were obtained on that survey date and the average of each break point based on depths were used as input in the pre-processing calculations to derive estimates to the vertical DO model (Table A-1, Appendix A).

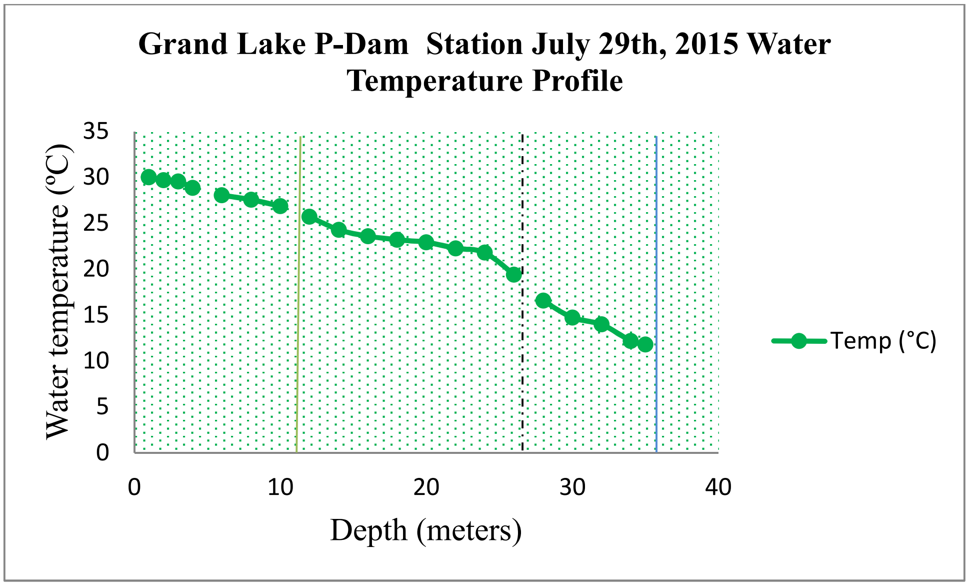

Figure 13: Observed water temperature profile for P-Dam Station on July 29, 2015 in Grand Lake.

The simulation result of the model in comparison with the observed water quality dissolved oxygen for P-Dam Station on July 29, 2015 survey date is presented in Figure 14.

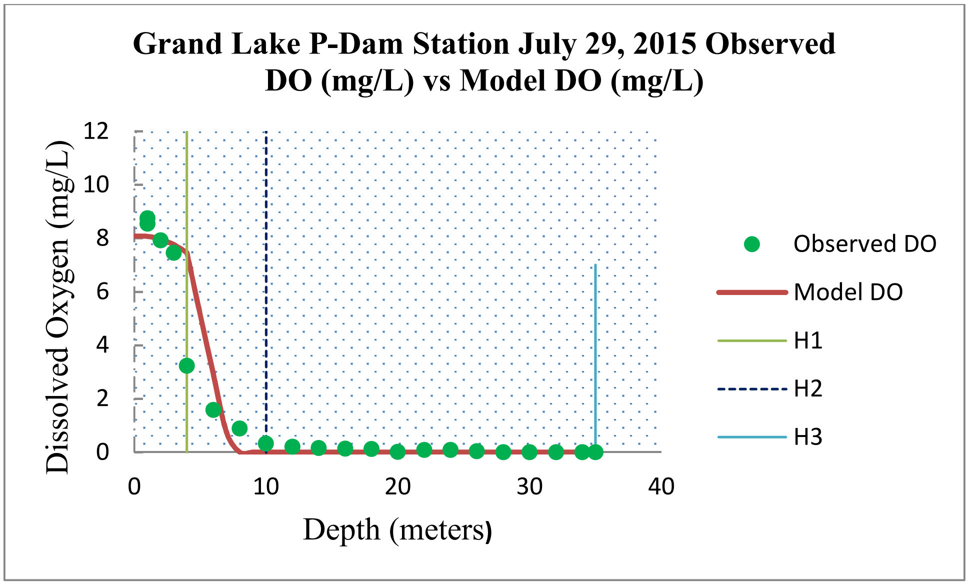

Figure 14: Grand Lake P-Dam Station July 29, 2015 observed and model predicted dissolved oxygen.

Figure 14 presents simulation results of the simplified model of the vertical distribution of dissolved oxygen to P-Dam Station on July 29, 2015 set of data in Grand Lake. The green circular marks indicate the observed dissolved oxygen and the red line indicates the simulated dissolved oxygen results. The three vertical lines indicate the various depths used as inputs to the model.

Applying the simplified model to the data set obtained on July 29, 2015 for P-Dam Station gives a reasonable agreement with the observed profile of dissolved oxygen as shown in Figure 14. For this station, the surface layer dissolved oxygen ranges from 7.17 to 8.0 mg/L with slight supersaturation of 95.8% at the surface (z = 4m) depth. At the depth of the thermocline layer, dissolved oxygen greatly decreased from 7.17 to 0.93 mg/L. In achieving this agreement between the simulated dissolved oxygen with the observed dissolved oxygen profile, the adjusted parameters were E_2 = 0.45 cm^2/sec and SOD=1.50 g O_2 /m^2-day.

3.10 Sensitivity Analysis of Vertical Oxygen Model

Model sensitivity analysis is recognized as a key component in modeling, as it characterizes the effect of model inputs on the output results and it helps to predict the outcome of result if different from the major prediction (Tang et al., 2006). Sensitivity analysis was performed on Grand Lake data set collected at Tree Station on July 17, 2013.

The sediment oxygen demand and vertical mixing coefficient (E_2) were the two variables that sensitivity analysis was performed on. The results are presented in Figure 15 and 16, respectively. The purpose of the sensitivity analysis is to observe possible effects that SOD and the vertical mixing coefficient had on the oxygen profile within the epiliminion, thermocline, and hypolimnion layers.

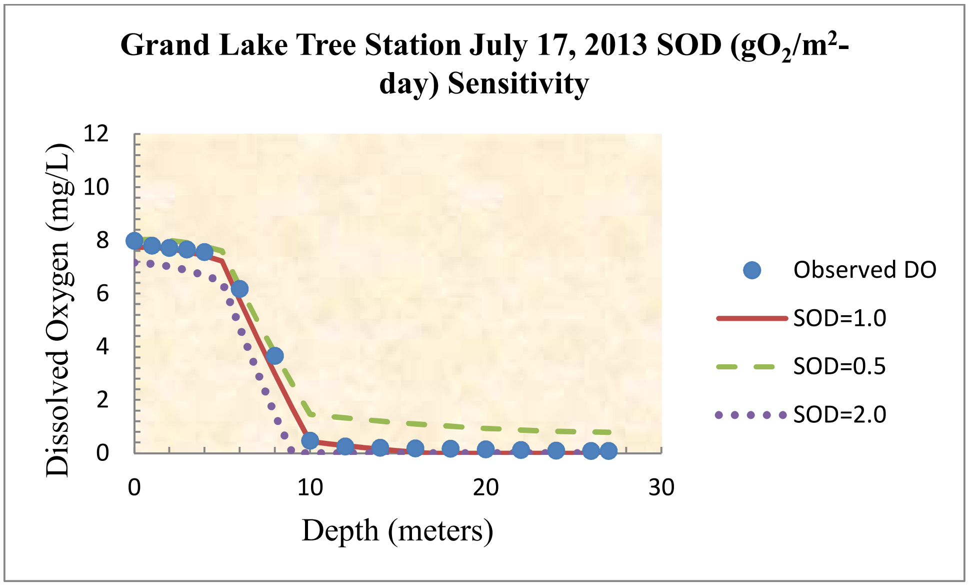

Figure 15: Grand Lake Tree Station July 17, 2013 sediment oxygen demand sensitivity results.

Figure 15 illustrates the result of the sediment oxygen demand sensitivity analysis on Grand Lake Tree Station July 17, 2013. The circular blue marks are the observed dissolved oxygen, the red line is the base value of SOD = 1.0gO$_2$/m^2-day, the green line is the tested SOD with value of 0.5 g O$_2$ /m^2-day, and the purple line is another tested result for the SOD=2.0 g O$_2$ /m^2-day. From the graph, the SOD of 1.0 g O$_2$ /m^2-day had good agreement with the observed DO at the epiliminion, thermocline, and epiliminion layers. In addition to SOD=1.0 g, O$_2$ /m^2-day, 0.5 g O$_2$ /m^2-day, and a higher value of 2.0 g O$_2$ /m^2-day were also tested and the results obtained could not achieve any agreement with the observed DO.

As shown in Figure 15, SOD has an effect on the water column oxygen profile in all layers within the epiliminion, thermocline, and hypolimnion.

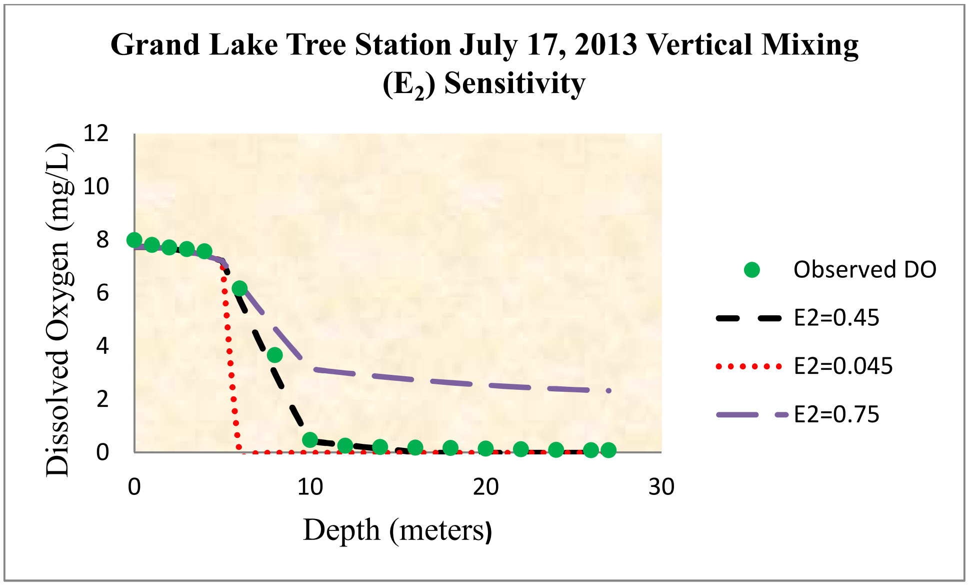

Figure 16: Shows Grand Lake Tree Station July 17, 2013 vertical mixing coefficient (E_2) sensitivity results.

In addition to the sensitivity analysis runs with varied SOD presented in Figure 15, the vertical mixing coefficient assigned to the thermocline layer was adjustable for the application of the vertical oxygen model. Figure 16 presents the results of the sensitivity analysis for Tree Station on July17, 2013 in Grand Lake, where the parameter value of the vertical mixing used in the vertical oxygen model calculations were $E_2 = 0.045$ cm^2/sec, $E_2 = 0.45$ cm^2/sec, and $E = 0.75$ cm^2/sec, respectively.

The green circular marks are the observed dissolved oxygen, the red dotted line indicates result of the sensitivity runs of $E_2 = 0.045$ cm^2/sec, which deviated from the base value of $E_2 = 0.45$ cm^2/sec. The simulation result has no agreement with observed DO especially at the thermocline layer. The purple line is the result of runs $E = 0.75$ cm^2/sec, which also could not achieve an agreement with the observed DO at the thermocline and hypolimnion layers. The black dashed lines are the base or calibrated vertical mixing coefficient and it is in good agreement with observed DO. Increases and decreases in the vertical mixing coefficient are observed to have a greater effect on the oxygen profile in the thermocline and hypolimnion layers than the effect seen with changes to SOD.

CHAPTER IV

4.0 Summary, Conclusions and Recommendations

A three-layer steady-state model of the vertical structure of dissolved oxygen in a stratified lake has been successfully developed based on observed water chemistry data, physical data such as water column depth and water temperature, and kinetic coefficients to derive input data to the vertical dissolved oxygen model. The model was applied to water quality data collected during the summer months of in 2013 and 2015 for the different zones in Grand Lake. Application of the model to a set of water quality data obtained for 2013 and 2015 gives an understanding of eutrophication processes and how physical, chemical and biological processes are connected to oxygen production and consumption in the epiliminion, thermocline, and hypolimnion layers of the lake.

Results obtained from the model simulations in each of the zones gives reasonable agreement between the predicted versus observed dissolved oxygen profiles at the lacustrine zone (Station Tree) and dam zone (Station P-dam). Observed data collected on July 17, 2013 and July 29, 2015were used to develop the model for these stations. For the set of data collected on July 17, 2013 at Station P-dam in the dam zone, the model results could not match the supersaturated levels of dissolved oxygen in the thin layer (0-2 m) upper part of the surface layer.

Reasons for the inability of the model to reproduce the observed high dissolved oxygen levels include high light limitation at the surface, supersaturation of oxygen (140%) and depth-averaging of light limitation and phytoplankton oxygen production terms in the model over the entire thickness of the surface layer.

From the pre-processing to model estimates, the vertical DO model successfully accounted for both the oxygen production terms and oxygen consumption terms. Based on the percentage analysis for each term, the pre-processing data clearly identified the importance of each component term for oxygen production and oxygen consumption. In summary, the relative effects on oxygen production in the photic zone were based on phytoplankton biomass, high light limitation, and nutrient limitation. The relative effects on oxygen consumption were based on the phytoplankton biomass and the levels of organic matter and ammonia level in the water column. In a study of Lake Erie, Clevinger (2013) found that SOD contributed 19.2 percent to the total oxygen demand in the hypolimnion, while nitrification accounted for 32.6 percent in the hypolimnion and 28 percent in the epiliminion layer. In contrast to the studies reported by Pace et al (2005) where sediment oxygen demand accounted for a large component of hypolimnetic oxygen demand, Clevinger's results are more consistent with the results derived from this analysis of the contributions of nitrification and sediment oxygen demand to water column oxygen consumption in Grand Lake.

From data derived used in pre-processing calculation to model analysis, key findings from the study are that high light limitation at the surface layer, phytoplankton growth rate, and phosphorus were the most critical factors for oxygen production within the epiliminion layer and the least critical factor was nitrogen. Based on all the calculations, phosphorus was the limiting factor to phytoplankton production in most cases, except for dam zone on July 17, 2013 where it was found that nitrogen was the limiting factor for phytoplankton production due to supersaturation of 140 percent at the 0-2m depth and high light limitation observed at the surface.

For the sink terms for oxygen (phytoplankton respiration, nitrification, organic carbon decomposition, and sediment oxygen demand), the most critical factor for oxygen consumption within the entire water column was nitrification and the least critical factor was sediment oxygen demand.

The effect of stratification on the oxygen profile was demonstrated with the model in the sensitivity analyses simulation results. The analysis clearly showed that a smaller mixing coefficient will result in stronger stratification, while a larger mixing coefficient will result in weaker stratification. The model is very useful to provide insight into the relative contributions of the different physical and kinetic processes for development of the oxygen profile in a stratified lake including the relative importance of the different terms in the model on the occurrence of hypoxia and anoxia in the hypolimnion.

The equations of the three-layer vertical DO model are developed by depth integration of the model parameters over the thickness of each layer. The model results are computed at 1 meter intervals within each layer, but the equations are based on depth integration of terms for each layer. The 1m resolution of the model results shows how the patterns of the oxygen profile looks like from the epiliminion layer to the hypolimnion.

Recommendations drawn from the study are:

The initial scope of this project was to develop a vertical DO model using data collected in 2013 and 2015 on four zones including lacustrine, dam; transition, and riverine zones. In the process of data compilation for observed water chemistry data, it was realized that water chemistry data was not available for the subsurface layers for the riverine and transition zones in 2013 and 2015.

Based on the findings of this study, it is recommended that GRDA should start collecting water chemistry data in each layer of the lake from surface to bottom at all the 13 stations in Grand Lake. It is recommended that the GRDA monitoring team should expand monitoring efforts to collect (1) sediment bed solids, carbon, nitrogen and phosphorus data and (2) benthic flux data for ammonia-N, phosphate-P, and sediment oxygen demand at key sites in each zone of the reservoir during the summer stratification period (starting June to late September). Benthic flux data can provide a key component for effective lake water quality management because it helps to tell the story of how much nutrient loading comes from the external watershed and point sources and how much nutrient loading is contributed by internal loading from decomposition processes in the sediment bed.

Finally, collecting water chemistry data throughout the water column at all stations and benthic flux data for nutrients and SOD would help to support future analyses such as a characterization of the effect of benthic flux of nitrogen and phosphorus and SOD on dissolved oxygen and nutrients in the hypolimnion layer. Collecting water chemistry over the entire water column in each characteristic layer and benthic flux data would also support future water quality analyses in Grand Lake including development of water quality models of the reservoir.

For water quality management in Grand Lake, the benthic flux data can help GRDA evaluate the relative magnitude of nutrient loads from the watershed and internal nutrient loads from sediment bed processes. Without measured benthic flux data it is difficult to develop a complete assessment of the role of external watershed loading of nutrients in eutrophication processes in Grand Lake since the nutrient loading contributed by internal sediment flux into the lake will be unknown.

Severe oxygen depletion in the hypolimnion of the lake occurs every summer. In several reservoirs, mechanical methods are used to improve oxygen levels in the hypolimnion. One approach is to increase mixing in the epiliminion to increase vertical transport of oxygen into the hypolimnion to increase oxygen levels. A second approach is to inject oxygen into the bottom waters of the hypolimnion to increase the oxygen content of the hypolimnion.

The three-layer steady state vertical DO model can be used to evaluate the effectiveness of alternative mechanical methods to improve the oxygen content of the hypolimnion in Grand Lake. As demonstrated with the sensitivity analysis of vertical mixing, changes in vertical mixing within the thermocline layer have a significant impact on the oxygen profile in the middle and lower layers of the water column. The model could also be used to test mechanical methods based on bottom water injection of oxygen. The model can provide water quality managers with a useful screening tool to help develop preliminary designs for either vertical mixing in the thermocline layer or bottom water oxygen injection. The input of oxygen from mechanical injection would be represented as a new source term of oxygen in the lower layer.

REFERENCES

Anderson, D. M., Glibert, P. M., & Burkholder, J. M. (2002). Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries*, *25*(4), 704-726.

Andersen F.O. & Jensen H.S. (1992) Regeneration of inorganic phosphorus and nitrogen from decomposition of seston in freshwater sediment. Hydrobiologia, 228, 71–81.

Bostro¨ M, B., J. M. Anderson, S. Fleischer, and M. Jansson. 1988. Exchange of phosphorus across the sediment water interface. Hydrobiology 170:229–244.

Bowie, G. L., Mills, W. B., Porcella, D. B., Campbell, C. L., Pagenkopf, J. R., Rupp, G. L., & Barnell, T. O. (1985). Rates, constants, and kinetics formulations in surface water quality modeling. *EPA*, *600*, 3-85.

Beutel, M. W. (2003). Hypolimnetic anoxia and sediment oxygen demand in California drinking water reservoirs. *Lake and Reservoir Management*, *19*(3), 208-221.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD.

Cornett, R. J. and Rigler, F. H. 1987. Decomposition of seston in the hypolimnion. Can. J. Fish. Aquat. Sci., 44: 146–151.

Clevinger, C. C. (2013). *Nitrifiers and their contribution to oxygen consumption in Lake Erie* (Doctoral dissertation, Kent State University)

Carter, L. D., & Dzialowski, A. R. (2012). Predicting sediment phosphorus release rates using landuse and water-quality data. *Freshwater Science*, *31*(4), 1214-1222

Carlson, R. E. (1977). A trophic state index for lakes. *Limnology and oceanography*, *22*(2), 361-3.

Chapra, S.C. (1997) *Surface Water Quality Modeling*. New York: McGraw Hill Publishing, 844 pp.

Correll, D. L. (1998). The role of phosphorus in the eutrophication of receiving waters: A review. *Journal of Environmental Quality*, *27*(2), 261-266

Correll, D. L. (1999). Phosphorus: a rate limiting nutrient in surface waters. *Poultry Science*, *78*(5), 674-682.

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., ... & Thornbrugh, D. J. (2008). Eutrophication of US freshwaters: analysis of potential economic damages. *Environmental Science & Technology*, *43*(1), 12-19.

DSLLC. (2005). EFDC Support Services to Oklahoma DEQ to Support Development of Total maximum Daily Load (TMDL) for Tenkiller Ferry Lake, Task 4B Technical Memorandum An Analysis of the Vertical Structure of Dissolved Oxygen in a Stratified Lake. Technical memorandum prepared by Dynamic Solutions, LLC, Knoxville, TN for Oklahoma DEQ, Oklahoma City, OK.

Diaz, R. J., R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. Science. Vol. 321, pp. 926-929.

Elser, J. J., Sterner, R. W., Galford, A. E., Chrzanowski, T. H., Findlay, D. L., Mills, K. H., & Schindler, D. W. (2000). Pelagic C: N: P stoichiometry in a eutrophied lake: responses to a whole-lake food-web manipulation.*Ecosystems*, *3*(3), 293-307.

EPA (2000) Final Report: Natural Convection in Stratified Lakes and Reservoirs—Impacts on Pollutant Transport, Oxygen Budget, and Nutrient Dynamics. EPA Grant Number: R825428, Final Report.

Gardner W.S., Yang L., Cotner J.B., Johengen T.H. & Laventyev P.J. 2001. Nitrogen dynamics in sandy freshwater sediments (Saginaw Bay, Lake Huron). Journal of Great Lakes Research, 27, 84–97.

Grand Lake O' the Cherokees Watershed Alliance Foundation, Inc. 2008. Grand Lake Watershed Plan for Improving Water Quality throughout the Grand Lake.

W. R., Robertson, D. M., & Wilde, F. D. (2015). *Chapter A10. Lakes and reservoirs: Guidelines for study design and sampling* (No. 9-A10). US Geological Survey.

Gardner W.S., Yang L., Cotner J.B., Johengen T.H. & Laventyev P.J. 2001. Nitrogen dynamics in sandy freshwater sediments (Saginaw Bay, Lake Huron). Journal of Great Lakes Research, 27, 84–97.

Glaser, D., Rhea, J. R., Opdyke, D. R., Russell, K. T., Ziegler, C. K., Ku, W., & Mastriano, J. (2009). Model of zebra mussel growth and water quality impacts in the Seneca River, New York. *Lake and Reservoir Management*, *25*(1), 49-72.

Hydro Qual, Inc. (1986) Development of a hydrodynamic and water quality model of Chesapeake Bay. Prepared by Hydro Qual, Inc. for Battelle Columbus Laboratories and U.S. Environmental Protection Agency, Chesapeake Bay Program, Annapolis, MD

Hudnell HK [Ed] (2008) Cyanobacterial Harmful Algal Blooms (ISOC-HAB): State-of the-Science and Research Needs. New York, Springer Press: Advances in Experimental Medicine and Biology, 619:1-949.

Hutchinson, G. E. 1957. Treatise of Limnology. Vol I: Geography, Physics and Chemistry. John Wiley and Sons, New York.

Hudnell HK (2013) An Alternative Approach to Regaining Designated Uses of Clean Water Act Section 303(d) Impaired Waters. Florida Water Resources Journal, 65:20-26.

Hecky, R. E., and P. Kilham. 1988. Nutrient limitation of phytoplankton in freshwater and marine environments: Are view of recent evidence on the effects of enrichment.Limnol. Oceanogr. 33: 796–822.

Integrated water quality assessment (2015), Oklahoma Department of Water Quality, Retrieved from: http://www.deq.state.ok.us/WQDNew/305b_303d/index.html.

Jones, B. (2011). Oxygen—The most important water quality parameter. *Water Column*, *23*(1), 1-4.

Kromkamp JC and Walsby AE (1989) A computer model of buoyancy and vertical migration in cyanobacteria. J Plankton Res, 12/1, 161-183.

Mortimer C. (1941) The exchange of dissolved substances between mud and water in lakes, 1–2. Journal of Ecology, 29, 280–329.

Mastriano, J. (2009). Model of zebra mussel growth and water quality impacts in the Seneca River, New York. *Lake and Reservoir Management*, *25*(1), 49-72.

Nikolai, S. J. (2012). *Eutrophication in Grand Lake, Oklahoma: Nutrient limitation and the effect of internal phosphorus loading*. Oklahoma State University.

Nikolai, S. J., & Dzialowski, A. R. (2014). Effects of internal phosphorus loading on nutrient limitation in a eutrophic reservoir. *Limnologica-Ecology and Management of Inland Waters*, *49*, 33-41.

Nurnberg, G.K. 2009. Assessing internal phosphorus Load-Problems to be solved. Lake and Reservoir Management 25, 419-432.

Nowlin, W. H., Evarts, J. L., & Vanni, M. J. (2005). Release rates and potential fates of nitrogen and phosphorus from sediments in a eutrophic reservoir. *Freshwater Biology*, *50*(2), 301-322.

Nu¨rnberg G.K. (1987) A comparison of internal phosphorus loads in lakes with anoxic hypolimnia: laboratory incubation versus in situ hypolimnetic phosphorus accumulation. Limnology and Oceanography, 32, 1160–1164.

Paerl, H. W. (1988). Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnology and Oceanography*, *33*(4part2), 823-843.

Pace, M. L., & Prairie, Y. T. (2005). Respiration in lakes. *Respiration in aquatic ecosystems*, 103. 121

Paerl, H. W. (1982). Factors limiting productivity of freshwater ecosystems. In *Advances in microbial ecology* (pp. 75-110). Springer US.

Rhee, G., & Gotham, I. J. (1981). The effect of environmental factors on phytoplankton growth: temperature and the interactions of temperature with nutrient limitation. *Limnology and Oceanography*, *26*(4), 635-648.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*(2), 126-139.

Thomann, R. V., & Mueller, J. A. (1987). *Principles of surface water quality modeling and control*. Harper & Row, Publishers.

Tang, T., Reed, P., Wagener, T., & Van Werkhoven, K. (2006). Comparing sensitivity analysis methods to advance lumped watershed model identification and evaluation. *Hydrology and Earth System Sciences Discussions*, *3*(6), 3333-3395.

APPENDIX

Appendix A- Water Chemistry Data for 2013 and 2015

Table A-1: Water chemistry data for Tree-station 2013.

	Smoothed Depth (m)	Temp (°C)	DO (mg/L)	Cond (mS/cm)	Chl(Ug/L)	NH4	NO3	PO4	TP
Layer 1	0	28.68	7.99	0.219	6.8	0.0329	0.228	0.01	0.08
	1	28.48	7.81	0.22	11				
	2	28.4	7.72	0.22	8.2				
	3	28.35	7.66	0.221	7.1				
	4	28.33	7.57	0.221	7.3				
	5								
Layer 2	6	28.1	6.18	0.224	5.2				
	8	27.28	3.67	0.228	4.2				
	10	25.84	0.47	0.227	4.3				
Layer 3	12	23.83	0.26	0.222	5				
	14	22.26	0.21	0.219	5.2				
	16	21.44	0.19	0.218	4.5				
	17					0.142	0.503	0.162	0.24
	18	20.6	0.17	0.22	5.4				
	20	19.33	0.15	0.228	5.3				
	22	16.78	0.13	0.252	5.1	0.319	0.395	0.209	0.33
	24	15.3	0.1	0.267	4.4				
	26	14.1	0.09	0.278	4.5				
	27	14.04	0.09	0.279	9.3	0.393	0.743	0.129	0.22

Table A-2: Water chemistry data used for Tree-station 2013 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Water tempt	DO	Cond	Chl	**NH4**	**NO3**	**PO4**	**TP**
0-5 m	28.448	7.75	0.2202	8.08	0.0329	0.228	0.01	0.08
5-10 m	27.073333	3.44	0.226333	4.566667	0.158783	0.3875	0.088333	0.171667
10-27 m	18.631111	0.154444	0.242556	4.925	0.284667	0.547	0.166667	0.263333

Table A-3: Water chemistry data for Tree-station 2015.

	Smoothed Depth (m)	**Temp (°C)**	**DO (mg/L)**	**SpCond (mS/cm)**	**CHL(Ug/L)**	**NH4**	**NO3**	**PO4**	**TP**
Layer 1	1	31.35	9.35	265	22	-0.00213	0.000825	0.0118	0.0391
	1	31.33	9.4	264	20.7				
	1	31.31	9.24	265	25				
	2	30.76	9.03	263	26.4				
	3	30.62	8.5	264	27.6				
	4	30.56	8.21	264	25.8				
	5								
Layer 2	6	30.04	5.29	268	16.7				
	8	28.43	1.53	311	10.2				
	10	27.95	0.54	306	7.8				
	11								
Layer 3	12	26.35	0.23	260	9.8				
	14	24.47	0.17	235	10.1				
	16	23.4	0.13	224	10.1				
	17					0.09	0.622	0.195	0.245
	18	22.83	0.11	226	10.1				
	20	22.54	0.09	227	11				
	22	22	0.08	227	9.6	0.267	0.494	0.226	0.311
	24	21.02	0.06	236	9.6				
	26	19.13	0.03	269	8.3				
	27	17.34	0	301	9.3	0.623	0.0596	0.274	0.34

Table A-4: Water chemistry data used for Tree-station 2015 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Wtemp	DO	SpCond	Chl	**NH4**	**NO3**	**PO4**	**TP**
0-4m	30.98833	8.955	264.1667	24.58333	-0.00213	0.000825	0.0118	0.0391
4-10m	28.80667	2.453333	295	11.56667	0.162268	0.196346	0.121733	0.1688833
10-27m	22.12	0.1	245	9.766667	0.326667	0.391867	0.231667	0.2986667

Table A-5: Water chemistry data for P-Dam-station 2013.

	Smoothed Depth (m)	**Temp (°C)**	**DO (mg/L)**	**SpCond (mS/cm)**	**CHL(Ug/L)**	**NH4**	**NO3**	**PO4**	**TP**
Layer 1	0	30.66	10.46	0.212	7.3				
	1	29.49	10.5	0.211	14	0.01	0.275	0.01	0.08
	2	28.63	8.18	0.213	9				
	3	28.56	7.99	0.213	6.9				
	4	28.45	7.69	0.214	6.4				
	6	28.36	7.17	0.214	5.8				
	8	27.55	3.39	0.218	5.4				
	9								
Layer 2	10	25.31	0.42	0.217	4.6				
	11								
Layer 3	12	24.06	0.3	0.216	4.7				
	14	22.2	0.25	0.208	5.1				
	16	21.35	0.22	0.209	4.8				
	18	20.82	0.21	0.21	4.9				
	20	19.44	0.2	0.221	5.3				
	22	17.29	0.16	0.249	4.4				
	24	15.25	0.14	0.266	4.2				
	25					0.0694	1.3	0.0895	0.2
	26	14.43	0.13	0.272	3.6				
	28	13.88	0.11	0.276	3.9				
	30	13.56	0.11	0.277	3.9	0.205	1.15	0.13	0.23
	32	12.82	0.1	0.285	3.7				
	34	12.05	0.09	0.303	3.3				
	35	11.93	0.09	0.305	3.9	0.637	0.58	0.173	0.29
	36	11.92	0.08	0.306	4				

Table A-6: Water chemistry data used for P. Dam-station 2013 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Wtemp	DO	SpCond	Chl	**NH4**	**NO3**	**PO4**	**TP**
0-8m	28.81429	7.9114286	0.213571	7.828571	0.01	0.275	0.01	0.08
8-10m	25.31	0.42	0.217	4.6	0.1569	0.6425	0.070417	0.16
10-36m	16.5	0.1564286	0.257357	4.264286	0.3038	1.01	0.130833	0.24

Table A-7: Water chemistry data for P-Dam-station 2015.

	Smoothed Depth (m)	**Temp (°C)**	**DO (mg/L)**	**SpCond (mS/cm)**	**CHL(Ug/L)**	**NH4**	**NO3**	**PO4**	**TP**
Layer 1	1	30.04	8.75	263	25	-0.00198	0.0388	0.0155	0.0274
	1	29.98	8.54	263	25.4				
	2	29.67	7.92	264	22				
	3	29.55	7.45	265	20.5				
	4	28.83	3.23	272	13.4				
	5								
Layer 2	6	28.05	1.58	269	10.5				
	8	27.55	0.89	266	7.5				
	10	26.86	0.32	260	7.9				
	6								
Layer 3	12	25.71	0.21	250	9.1				
	14	24.29	0.16	240	10.6				
	16	23.58	0.13	236	9.6				
	18	23.2	0.12	225	10.2				
	20	22.91	0.1	217	10.1				
	22	22.27	0.09	218	10.6				
	24	21.79	0.08	229	9.7				
	26	19.39	0.04	262	10.5				
	25					0.148	0.439	0.199	0.256
	28	16.58	0	297	7.1				
	30	14.71	-0.04	324	6.5	0.386	0.198	0.202	0.27
	32	13.98	-0.05	330	4.6				
	34	12.18	-0.09	340	4.2				
	35	11.79	-0.1	346	3.6	0.279	0.43	0.122	0.171

Table A-8: Water chemistry data used for P-Dam-station 2015 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Wtemp	DO	SpCond	CHl	**NH4**	**NO3**	**PO4**	**TP**
0-4m	29.614	7.178	265.4	21.26	-0.00198	0.0388	0.0155	0.0274
4-10m	27.48667	0.93	265	8.633333	0.13451	0.197233	0.094917	0.129867
10-35m	19.41385	0.05	270.3077	8.184615	0.271	0.355667	0.174333	0.232333

Table A-9: Water chemistry data for Grand-station 2013.

	Smoothed Depth (m)	**Temp (°C)**	**DO (mg/L)**	**SpCond (mS/cm)**	**CHL(Ug/L)**	**NH4**	**NO3**	**PO4**	**TP**
Layer 1	0	29.44	11.13	0.264	16.5	0.0261	0.31	0.0306	0.16
	1	29.15	10.47	0.264	18.2				
	2	28.69	8.63	0.267	10.1				
Layer 2	3	28.56	7.93	0.269	7				
	4	28.5	6.96	0.272	6.1				
Layer 3	5	28.28	3.32	0.285	5.8				
	6	28.05	1.36	0.293	4.5				
	7	27.02	0.44	0.31	5.8				

Table A-10: Water chemistry data used for Grand-station 2013 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Wtemp	DO	SpCond	Chl	**NH4**	**NO3**	**PO4**	**TP**
0-2m	29.09333	10.076667	0.265	14.93333	0.0261	0.31	0.0306	0.16
2-4m	28.53	7.445	0.2705	6.55				
4-7m	27.78333	1.7066667	0.296	5.366667				

Table A-11: Water chemistry data for Sail-station 2013.

	Smoothed Depth (m)	Temp (°C)	DO (mg/L)	SpCond (mS/cm)	CHL(Ug/L)	NH4	NO3	PO4	TP
Layer 1	0	28.96	9.6	0.247	7.6	0.0228	0.276	0.0147	0.08
	1	28.72	9.8	0.246	11.6				
	2	28.35	8.58	0.247	8.5				
	3	28.28	8.19	0.247	7.5				
	5								
Layer 2	4	28.21	7.64	0.248	6.4				
	6	27.82	3.64	0.255	4.7				
	7								
Layer 3	8	26.55	0.38	0.262	4.5				
	10	25.33	0.27	0.261	5.2				
	12	24.74	0.25	0.259	4.5				
	14	24.28	0.23	0.262	4.8				

Table A-12: Water chemistry data used for Sail-station 2013 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Wtemp	DO	SpCond	Chl	NH4	NO3	PO4	TP
0-3m	28.5775	9.0425	0.24675	8.8	0.0228	0.276	0.0147	0.08
3-7m	28.015	5.64	0.2515	5.55				
7-14m	25.225	0.2825	0.261	4.75				

Table A-13: Water chemistry data for Sail-station 2015.

	Smoothed Depth (m)	Temp (°C)	DO (mg/L)	SpCond (mS/cm)	CHL(Ug/L)	NH4	NO3	PO4	TP
Layer 1	0	26.18	0	292	15				
	1	26.17	5.96	292	15.2	0.0169	0.379	0.0617	0.174
	1	26.15	5.9	292	15.3				
	2	26.13	5.83	292	15.4				
	3	25.8	5.26	288	14.6				
	4	25.52	4.87	282	14				
	6	25.04	4.13	276	14.6				

Layer 2	8	24.67	3.77	266	13.4				
	9								
	10								
Layer 3	11	24.49	3.44	279	11.7				
	12	24.25	3.06	276	11.7				
	13	20.48	0.8	280	5.6				

Table A-14: Water chemistry data used for Sail-station 2015 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Wtemp	DO	SpCond	Chl	**NH4**	**NO3**	**PO4**	**TP**
0-6m	25.85571	4.564286	287.7143	14.87143	0.0169	0.379	0.0617	0.174
6-10m	24.67	3.77	266	13.4				
10-13m	23.07333	2.433333	278.3333	9.666667				

Table A-15: Water chemistry data for Grand-station 2015

	Smoothed Depth (m)	**Temp (°C)**	**DO (mg/L)**	**SpCond (mS/cm)**	**CHL(Ug/L)**	**NH4**	**NO3**	**PO4**	**TP**
Layer 1	1	30.82	8.82	359	26.2	0.26	0.22	0.1	0.157
	1	30.76	8.58	360	27.1				
	2	30.42	7.27	363	23.2				
	3	30.27	6.43	364	19.9				
	4	30.2	5.87	362	16.7				
Layer 2	6	29.43	1.94	366	12.4				
Layer 3	8	28.79	0.34	338	12.7				
	9	28.56	0.21	329	15.5				

Table A-16: Water chemistry data used for Sail-station 2015 in the pre-processing calculation for the DO model developed for Grand Lake.

Depth	Wtemp	DO	SpCond	Chl	**NH4**	**NO3**	**PO4**	**TP**
0-4m	30.494	7.394	361.6	22.62	0.26	0.22	0.1	0.157
4-6m	29.43	1.94	366	12.4				
6-9m	28.675	0.275	333.5	12.7				

Appendix B- Oxygen Production and Respiration Rates for 2013

Table B-1: Primary production and respirations rates in Grand Lake along the riverine (GRAND), transition (SAIL), lacustrine (TREE), and dam (P-DAM) zone for July 17, 2013.

Primary production/respiration	**Layer 1**	**Layer 2**	**Layer 3**
Daily primary production rate, Per oxygen ($gO_2/m^2/day$)	**($gO_2/m^2/day$)**	**($gO_2/m^2/day$)**	**($gO_2/m^2/day$)**
Riverine zone	7.294	—	—
Transition zone	5.462	—	—
Lacustrine zone	5.642	0.019	2.01×10^{-5}
Dam zone	12.468	0.001	3.01×10^{-6}
Daily primary production rate, per Carbon ($gC/m^2/day$)	**Layer 1 ($gC/m^2/day$)**	**Layer 2 ($gC/m^2/day$)**	**Layer 3 ($gC/m^2/day$)**
Riverine zone	2.732	—	—
Transition zone	2.045	—	—
Lacustrine zone	2.113	0.007	7.53×10^{-6}
Dam zone	4.669	4.34×10^{-5}	1.12×10^{-6}
Phytoplankton production (pa) (mgO_2/L-day)	**Layer 1 (mgO_2/L-day)**	**Layer 2 (mgO_2/L-day)**	**Layer 3 (mgO_2/L-day)**
Riverine zone	3.647	—	—
Transition zone	1.820	—	—
Lacustrine zone	1.128	0.003	1.18×10^{-6}
Dam zone	1.558	5.79×10^{-5}	1.20×10^{-7}
Phytoplankton respiration coefficient, Kr(T) (1/day)	**Layer 1 (1/day)**	**Layer 2 (1/day)**	**Layer 3 (1/day)**
Riverine zone	0.100	—	—
Transition zone	0.096	—	—
Lacustrine zone	0.095	0.086	0.045
Dam zone	0.049	0.037	0.019
Organic Carbon respiration (mgO_2/L-day)	**Layer 1 (mgO_2/L-day)**	**Layer 2 (mgO_2/L-day)**	**Layer 3 (mgO_2/L-day)**

Riverine zone	0.043	—	—
Transition zone	0.002	—	—
Lacustrine zone	0.008	0.058	0.063
Dam zone	0.053	0.138	0.092
Ammonia Nitrification, R (Ammonia) (mgO_2/L-day)	**Layer 1 (mgO_2/L-day)**	**Layer 2 (mgO_2/L-day)**	**Layer 3 (mgO_2/L-day)**
Riverine zone	0.018	—	—
Transition zone	0.015	—	—
Lacustrine zone	0.021	0.093	0.087
Dam zone	0.004	0.095	0.095
Phytoplankton respiration, R(Phyt) (mgO_2/L/day)	**Layer 1 (mgO_2/L/day)**	**Layer 2 (mgO_2/L/day)**	**Layer 3 (mgO_2/L/day)**
Riverine zone	0.260	—	—
Transition zone	0.147	—	—
Lacustrine zone	0.134	0.068	0.038
Dam zone	0.067	0.030	0.013
Phytoplankton Growth (N,P,I,T) (1/day)	**Layer 1 (1/day)**	**Layer 2 (1/day)**	**Layer 3 (1/day)**
Riverine zone	1.829	—	—
Transition zone	1.549	—	—
Lacustrine zone	1.046	0.006	1.79×10^{-6}
Dam zone	1.135	7.26×10^{-5}	1.65×10^{-7}
Phytoplankton Growth as a function of water temperature(1/day)	**Layer 1 (1/day)**	**Layer 2 (1/day)**	**Layer 3 (1/day)**
Riverine zone	5.364	—	—
Transition zone	5.190	—	—
Lacustrine zone	5.147	4.714	2.748
Dam zone	10.53	8.424	4.797
Nitrogen Limitation (fraction 0-1)	**Layer 1 (fraction 0-1)**	**Layer 2 (fraction 0-1)**	**Layer 3 (fraction 0-1)**
Riverine zone	0.971	—	—
Transition zone	0.967	—	—
Lacustrine zone	0.963	0.982	0.988

Dam zone	0.996	0.998	0.999
Phosphorus Limitation (fraction 0-1)	**Layer 1 (fraction 0-1)**	**Layer 2 (fraction 0-1)**	**Layer 3 (fraction 0-1)**
Riverine zone	0.938	—	—
Transition zone	0.880	—	—
Lacustrine zone	0.833	0.977	0.988
Dam zone	0.833	0.985	0.992
Light Limitation f (I)	**Layer 1 f (I)**	**Layer 2 f (I)**	**Layer 3 f (I)**
Riverine zone	0.363	—	—
Transition zone	0.339	—	—
Lacustrine	0.243	0.001	6.62×10^{-7}
Dam zone	0.129	8.74×10^{-6}	3.47×10^{-8}
Layer Respiration, R=Phyt + OrgC+NH4	**Layer 1 mgO_2/L-day**	**Layer 2 mgO_2/L-day**	**Layer 3 mgO_2/L-day**
Riverine zone	0.322		
Transition zone	0.165		
Lacustrine zone	0.164	0.220	0.190
Dam zone	0.124	0.260	0.201
Water Col Respiration, R=Phyt + OrgC+NH4			**Layer 3 mgO_2/L-day**
Riverine zone	—	—	
Transition zone	—	—	
Lacustrine zone	—	—	0.191
Dam zone	—	—	0.180

Appendix C- Oxygen Production and Oxygen Respiration Rates for 2015

Table C-1: Primary production and Respiration for Grand Lake along the riverine (GRAND), transition (SAIL), lacustrine (TREE), and dam (P-DAM) zones in 2015.

Primary production/Respiration	**Layer 1**	**Layer 2**	**Layer 3**
Daily primary production rate, Per oxygen (gO$_2$/m^2/day)	**(gO$_2$/m^2/day)**	**(gO$_2$/m^2/day)**	**(gO$_2$/m^2/day)**
Riverine zone	11.220	—	—
Transition zone	3.814	—	—
Lacustrine zone	8.792	0.225	5.63×10^{-5}
Dam zone	11.190	0.053	6.58×10^{-6}
Daily primary production rate, per Carbon (gC/m^2/day)	**Layer 1 (gC/m^2/day)**	**Layer 2 (gC/m^2/day)**	**Layer 3 (gC/m^2/day)**
Riverine zone	4.202	—	—
Transition zone	1.428	—	—
Lacustrine zone	3.293	0.084	2.10×10^{-5}
Dam zone	4.191	0.020	2.46×10^{-6}
Phytoplankton production (pa) (mgO$_2$/L-day)	**Layer 1 (mgO$_2$/L-day)**	**Layer 2 (mgO$_2$/L-day)**	**Layer 3 (mgO$_2$/L-day)**
Riverine zone	2.805	—	—
Transition zone	0.635	—	—
Lacustrine zone	2.198	0.037	3.31×10^{-6}
Dam zone	2.797	0.008	2.63×10^{-6}
Phytoplankton respiration coefficient, Kr(T) (1/day)	**Layer 1 (1/day)**	**Layer 2 (1/day)**	**Layer 3 (1/day)**
Riverine zone	0.112	—	—
Transition zone	0.078	—	—
Lacustrine zone	0.058	0.049	0.029
Dam zone	0.052	0.044	0.023
Organic Carbon respiration (mgO$_2$/L-day)	**Layer 1 (mgO$_2$/L-day)**	**Layer 2 (mgO$_2$/L-day)**	**Layer 3 (mgO$_2$/L-day)**

Riverine zone	0.004	—	—
Transition zone	0.041	—	—
Lacustrine zone	0.001	0.046	0.012
Dam zone	0.011	0.300	0.246
Ammonia Nitrification, R (Ammonia) (mgO_2/L-day)	**Layer 1 (mgO_2/L-day)**	**Layer 2 (mgO_2/L-day)**	**Layer 3 (mgO_2/L-day)**
Riverine zone	0.199	—	—
Transition zone	0.009	—	—
Lacustrine zone	—	0.102	0.122
Dam zone	—	0.098	0.106
Phytoplankton respiration, R(Phyt) (mgO_2/L/day)	**Layer 1 (mgO_2/L/day)**	**Layer 2 (mgO_2/L/day)**	**Layer 3(mgO_2/L/day)**
Riverine zone	0.406	—	—
Transition zone	0.202	—	—
Lacustrine zone	0.179	0.071	0.036
Dam zone	0.074	0.025	0.012
Phytoplankton Growth (N,P,I,T) (1/day)	**Layer 1 (1/day)**	**Layer 2 (1/day)**	**Layer 3 (1/day)**
Riverine zone	0.928	—	—
Transition zone	0.320	—	—
Lacustrine zone	0.712	0.025	2.70×10^{-7}
Dam zone	1.971	0.015	4.87×10^{-7}
Phytoplankton Growth as a function of water temperature (1/day)	**Layer 1 (1/day)**	**Layer 2 (1/day)**	**Layer 3 (1/day)**
Riverine zone	5.866	—	—
Transition zone	4.361	—	—
Lacustrine zone	6.005	5.500	3.206
Dam zone	7.577	6.613	3.948
Nitrogen Limitation (fraction 0-1)	**Layer 1 (fraction 0-1)**	**Layer 2 (fraction 0-1)**	**Layer 3 (fraction 0-1)**
Riverine zone	0.979	—	—
Transition zone	0.975	—	—
Lacustrine zone	0.388	0.997	0.998
Dam zone	0.974	0.995	0.998

Phosphorus Limitation (fraction 0-1)	**Layer 1 (fraction 0-1)**	**Layer 2 (fraction 0-1)**	**Layer 3 (fraction 0-1)**
Riverine zone	0.980	—	—
Transition zone	0.968	—	—
Lacustrine zone	0.855	0.983	0.991
Dam zone	0.939	0.989	0.994
Light Limitation f (I)	**Layer 1 f (I)**	**Layer 2 f (I)**	**Layer 3 f (I)**
Riverine zone	0.161	—	—
Transition zone	0.075	—	—
Lacustrine zone	0.305	0.004	8.50×10^{-7}
Dam zone	0.276	0.002	1.24×10^{-7}
Layer Respiration, R=Phyt + OrgC+NH4	**Layer 1 mgO_2/L-day**	**Layer 2 mgO_2/L-day**	**Layer 3 mgO_2/L-day**
Riverine zone	0.611		
Transition zone	0.253		
Lacustrine zone	0.181	0.219	0.171
Dam zone	0.086	0.424	0.366
Water Col Respiration, R=Phyt + OrgC+NH4			**Layer 3 mgO_2/L-day**
Riverine zone	—	—	
Transition zone	—	—	
Lacustrine zone	—	—	0.183
Dam zone	—	—	0.165

Appendix D- Kinetic Coefficients and Model Parameters

Table D-1: Summary of Kinetic Coefficients and Model parameters used in the development of the vertical DO model for Grand Lake at the four different stations.

		Two-Tree Island		Pensacola Dam		Grand River		Sail Bridge	
Kinetic Coefficient	Units	2013	2015	2013	2015	2013	2015	2013	2015
Max Phytoplankton growth rate	1/day	3	3.5	6	4.1	3	3	3	3
Nitrogen half saturation constant, Kn	µg N/L	10	1.3	1	1	10	10	10	10
Phosphorus half saturation constant	µg P/L	2	2	1	1	2	2	2	2
Light saturation for phytoplankton	Ly/day	150	140	147	147	150	150	150	150
Carbon: Chlorophyll	µg C/µg Chl	65	47	47	25	60	60	60	60
Photoperiod for sample day	Fraction 24hr	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Phytoplankton respiration rate Kr (20ºC)	1/day	0.05	0.025	0.025	0.025	0.05	0.05	0.05	0.05
Decomposition OrgC respiration rate Kd (20ºC)	1/day	0.0125	0.025	0.025	0.025	0.0125	0.0125	0.0125	0.0125
Nitrification rate Kn(20ºC)	1/day	0.075	0.07	0.07	0.09	0.075	0.075	0.075	0.075
Labile fraction TOC	fraction	0.4	0.4	0.4	0.7	0.4	0.4	0.4	0.4
Labile fraction of DOC	fraction	O.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Carbon: Nitrogen ratio	gC/gN	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56
Nitrogen: Phosphorus ratio	g N/gP	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Sediment Oxygen Demand	gO2/m^2-day	1.00	1.00	1.90	1.50	—	—	—	
Vertical mixing E_1	Cm^2/sec	3.00	3.00	3.00	3.00				
Vertical mixing E_2	Cm^2/sec	0.45	0.40	0.36	0.45	—	—	—	
Vertical mixing E_3	Cm^2/sec	6.900	6.90	6.90	6.90				
Air-water oxygen transfer, KL	m/day	1.75	1.75	1.75	1.75				

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