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METALIMNETIC OXYGEN MINIMUM IN GREEN LAKE, WISCONSIN

By

Mahta Naziri Saeed

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

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This thesis has been approved in partial fulfillment of the requirements for the Degree of
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Abstract

Green Lake, located in Green Lake County, Wisconsin, has been experiencing summer Metalimnetic Oxygen Minima (MOM). The severity of the MOM has increased in recent years and the lake was listed as impaired in 2014. To investigate the MOM, the lake was monitored during 2017 and 2018 at two sites using moored temperature and oxygen sensors recording at 1-hour intervals. Using these data, a hydrodynamic model (Simstrat) was configured for the lake. A new model was then developed to simulate the oxygen changes in the lake. Productivity, respiration, sediment oxygen demand (SOD) and fluxes were included, and hydrodynamics were driven by Simstrat output (diffusivity). The model provided a good fit and predicted oxygen concentrations and MOM intensity well. However, the modeled MOM occurred at shallower depths than were observed, potentially due to underestimation of mixing within the metalimnion by Simstrat. The model suggests that productivity affects the oxygen production, and therefore, concentrations in the epilimnion, but does not significantly affect the intensity and location of MOM formation. However, respiration terms affect the overall model behavior, MOM location, and MOM intensity. The availability of oxidizable materials or biomass appears to be the most important factor in explaining the MOM in this lake. By reducing the initial concentration of biomass to 2/3 of the initial value, the MOM occurrence can be managed and the minimum concentration of oxygen in the metalimnion can be kept above the critical value of 5 mg/l.

1 Introduction

1.1 Dissolved Oxygen in Lakes

Fish, macroinvertebrates, and other aquatic organisms require oxygen to live. Therefore, it is important for aquatic bodies to contain sufficient concentrations of oxygen to allow respiration to occur without depleting the oxygen. Although water contains oxygen molecules (H_2O) these cannot be utilized by aquatic organisms. They rely on dissolved oxygen (DO) to survive. Different aquatic environments contain various levels of DO. Rivers and moving water tend to contain more DO compared to stagnant waterbodies. The saturation concentration of DO in an inland fresh waterbody, at 20°C and at sea level, is expected to be around 9 mg l⁻¹ (Kalff, 2001). However, a waterbody can become depleted in DO and the oxygen levels can drop below the saturation level. Excess of organic matters, especially in stagnant waterbodies, intensifies the bacterial activities and can cause oxygen depletion. When the DO level drops below 2-3 mg l⁻¹, It becomes hypoxic (Senn, et al., 2016). Ecosystem alteration caused by low DO concentration can affect the aquatic life. Many of the aquatic organisms cannot survive in hypoxic environments, and the surface layers are too warm for them to reside in. During warmer seasons, this problem becomes more serious and can cause summertime fish kills (Michaud, 1991).

1.1.1 DO Solubility

The solubility of a gas in a liquid is a function of the properties of the gas, air pressure, temperature, and water salinity. Solubility of gases in water can be described using Henry's Law. Henry's law states that at a given temperature, the amount of a gas absorbed by a given volume of a liquid, is proportional to the pressure that the gas exerts (Chapra, 1997; Cole, 1979).

$$He = \frac{p}{c} \quad 1-1$$

Where:

He = Henry's constant (atm m³ mole⁻¹)

p = Partial pressure exerted by the specific gas (atm)

c = Water concentration (mole m⁻³)

Henry's law states that a decrease in partial pressure causes a decrease in the solubility of the gas in equilibrium with the atmosphere. Therefore, an increase in altitude results in lower solubility of gases in water. (Cole, 1979).

Water temperature is the primary controller of DO solubility in fresh water (Kalff, 2001). Cold water can hold more gas. Therefore, at a constant partial pressure, an increase in temperature reduces the amount of the gas dissolved in water. The amount of DO that can be held by a water body in equilibrium to atmosphere, at a given temperature, pressure and salinity is known as the saturation concentration (Kalff, 2001). The DO concentration at saturation in pure water at various temperatures is given in Table 1.1 (Benson & Krause, 1980; Kalff, 2001), or different temperatures, at sea level (1 atm). This table shows that at 0°C, 14.62 mg l⁻¹ DO can be dissolved in water. This number decreases to 11.288 mg l⁻¹ at 10°C, 8.263 mg l⁻¹ at 25°C and 6.412 mg l⁻¹ at 40°C.

Table 1: Dissolved oxygen concentration in pure water in equilibrium with saturated air at 1 atm (Benson & Krause, 1980; Kalff, 2001)

T (°C)	DO (mg l ⁻¹)	T (°C)	DO (mg l ⁻¹)	T (°C)	DO (mg l ⁻¹)	T (°C)	DO (mg l ⁻¹)
0	14.621	11	11.027	22	8.7431	33	7.1831
1	14.216	12	10.7766	23	8.5776	34	7.0641
2	13.8293	13	10.5366	24	8.4176	35	6.9493
3	13.46	14	10.3057	25	8.2628	36	6.8368
4	13.1072	15	10.0837	26	8.113	37	6.7269
5	12.7699	16	9.8702	27	7.9679	38	6.6196
6	12.4473	17	9.6647	28	7.8272	39	6.5147
7	12.1385	18	9.4667	29	7.6908	40	6.4119
8	11.8427	19	9.2759	30	7.5584		
9	11.5593	20	9.092	31	7.4298		
10	11.2876	21	8.9145	32	7.3048		

Salinity is another important factor affecting a gas solubility in water, though typically of little influence in inland systems. Highly saline lakes or sea water with salinity of 35000 mg l⁻¹ hold 20% less oxygen compared to pure water at the same temperature (Kalff, 2001). The lower capacity of saline lakes to hold oxygen makes them more susceptible to hypoxia.

1.2 Sources and Sinks of Oxygen in a Lake

The oxygen concentration in the water column of a lake is controlled by the following equation:

$$\frac{dDO}{dt} = \text{Productivity} - \text{Respiration} \pm \text{Fluxes} - \text{SOD} \quad 1-2$$

Negative terms are sinks of oxygen whereas positive terms are sources of oxygen. Each term is defined and discussed below.

Fluxes: The addition of atmospheric oxygen into the lake or its loss from the lake across the air-water interface is defined by this term. In order for atmospheric oxygen to move into the water body, a negative partial pressure gradient is required. In other words, the water at the air-water interface should be undersaturated in order to absorb oxygen from the air (Cole, 1979). The oxygen transfer between air and water can be described by Whitman's two-film theory (Whitman, 1923). The bulks of liquid in the waterbody and gas in the air are turbulently mixed. These two turbulent bodies are assumed to be homogenous. At the air-water interface, liquid and gas are in equilibrium and Henry's law is valid. Oxygen transfer happens across a thin laminar film at the air-water boundary. The transfer happens via molecular diffusion and its rate is defined by pressure gradients between gas and liquid phases. Turbulent diffusion, on the other hand, is primarily what transfers the oxygen throughout the water column and into deeper layers via circular motions (eddies) (Cole, 1979). Wind events and waves form stronger eddies and result in greater mixing rates through a lake's water column. If the surface water is supersaturated, the direction of the fluxes will be out of the lake, and the *Fluxes* term in the equation would represent a sink of DO.

Productivity: This term shows the amount of oxygen introduced into a waterbody via photosynthesis during the photoperiod. In lakes, this process is carried out by submerged macrophytes, periphyton and free-floating microscopic organisms like phytoplankton, according to a simplified photosynthesis equation (Kalff, 2001):

However, photosynthesis only occurs when and where there is sufficient light. This happens during the photoperiod, which is the fraction of the day where incident solar

energy is sufficient for photosynthesis. The photic zone is the depth of a lake that can be penetrated by solar radiation and provide the energy for organisms to photosynthesize. Photic zone is defined as the depth of a lake where more than 1% of incident light is present. This depth is highly dependent on the lake's productivity and algal community and is a function of Secchi depth. By submerging a Secchi disk into a lake, the Secchi depth can be defined as the distance from the surface of the lake to the deepest point the Secchi disk is visible. The depth of the photic zone is typically twice of the Secchi depth. Productivity is a function of solar energy and temperature.

Respiration: Equation 1-3 is reversible and the progression of this process in the opposite direction implies oxygen consumption. Plant, animal, and microbial respiration act as a sink for oxygen (Kalff, 2001). Unlike productivity, respiration is present through the whole water column. A more nutrient-rich lake will be more productive, containing higher concentrations of algae and plants that can produce oxygen. However, when the organic matter produced decomposes, oxygen is consumed. Respiration consumes dissolved oxygen, lowering the oxygen concentration in a waterbody. For this reason, wider seasonal fluctuations in oxygen levels are more common in eutrophic and hypereutrophic lakes.

SOD: Sediment Oxygen Demand (or SOD) results from the oxidation of settled organic matter at the bottom of a lake. In most eutrophic lakes, the settled organic matter can accumulated at the bottom of the lake and drive SOD (Chapra, 1997). SOD, on a volumetric basis, is a function of both sediment contact area and temperature. Sediments are present at all depths of the waterbody. However, the ratio of the lake's volume at a given depth to the sediment contact area gets greater with depth. Therefore, the effect of SOD gets greater as this ratio grows with increase in depth, which can be computed from the lake's bathymetry.

1.3 Thermal Stratification

Seasonal patterns of thermal stratification occur in inland lakes – deep lakes in temperate climates in particular. Most lakes located in temperate regions are dimictic lakes. A dimictic lake is defined as a lake with temperature below 4°C in winter, large thermal gradients and two full primary mixing periods in spring and fall. An unstratified temperate lake becomes stratified when the wind energy is unable to transform the solar energy absorbed at the surface layer to the deeper layers via mixing. In other words, when the absorbed heat at the surface increases, the density differences between the top mixed layer and lower layers increase. At the point where wind induced currents are dominated by buoyant forces deep mixing stops, and the lake becomes stratified. This can be quantified by Richardson number (Chapra, 1997).

$$Ri = \frac{\text{Buoyancy}}{\text{Shear}} = \frac{\left(\frac{g}{\rho}\right)\left(\frac{\partial \rho}{\partial z}\right)}{\left(\frac{\partial u}{\partial z}\right)^2} \quad 1-4$$

Where:

z = depth, positive in the downward position (L)

g = Acceleration due to gravity ($L T^{-2}$)

ρ = Density of Water ($M L^{-3}$)

u = Horizontal velocity ($L T^{-1}$)

If the Richardson number is significantly greater than 0.25, the lake is most likely stratified as a result of higher buoyant forces relative to shear. A Richardson number significantly lower than 0.25 implies stronger shear forces and the lake should mix (Chapra, 1997).

1.4 Temperature and Oxygen Dynamics in Lakes

Thermal stratification divides a lake into three separate mixed layers. The top layer (epilimnion) is in direct contact with the atmosphere and absorbs the most solar radiation, and therefore has the highest temperatures. In this layer, productivity usually dominates respiration. The bottom layer (hypolimnion) has the lowest water temperature, is not in contact with the atmosphere and is dominated by respiratory processes. Metalimnion is the area between hypolimnion and epilimnion, where rapid change in temperature can be witnessed. In the hypolimnion (beneath the photic zone), respiration is the dominant mechanism and depletes the water column from oxygen via decomposition of settled organic matter from the epilimnion. The hypolimnion can become anoxic if the respiration rate of the settled organic matter exceeds the hypolimnetic DO accumulated in the layer during overturns. At the end of summer and beginning of fall, surface water of the lake starts cooling down and increases in density. This causes vertical mixing due to convection and results in fall overturn, as the overlying water is denser than the water in deeper layers (Chapra, 1997).

Oxygen's vertical profile is also highly dependent on thermal stratification (Figure 1.1). During stratification, when there is little mixing between the epilimnion and hypolimnion, Oxygen exchange between different layers of the water column is reduced. Therefore, the highest level of Oxygen can be found at the surface of the lake, where water is in contact with surface fluxes and solar radiation is present to drive photosynthesis. Below the photic zone, there will be limited oxygen production and it will primarily be consumed by respiration in the water column and sediments. Hence, the lowest levels of oxygen are usually observed at the bottom of a lake.

Figure 1.1. Temperature and dissolved Oxygen in Moose lake, 1986 and 1987, (Mitchell & Prepas, 1990)

Figure 1.2. Temperature and DO behavior in Big Green Lake

1.5 Metalimnetic Oxygen Minima

Oxygen depletion can also occur in the metalimnion of a stratified lake. In rare cases, there can be a drop in the oxygen level occurs through the metalimnion, with an higher concentrations in the lake's hypolimnion. This phenomenon is called a Metalimnetic Oxygen Minimum (MOM) (Figure 1.3). Although MOM is rare, it has been documented in different lakes around the world. In this section, some of these lakes and the proposed mechanisms driving the formation of Metalimnetic Oxygen Minima in them will be briefly summarized.

Figure 1.3. The MOM in Big Green lake (5/11/2017-9/11/2017)

Introduction of low-oxygen water into a waterbody via streams or oxygen depleted zones is one reason for MOMs. In Lake Ontario, horizontal transport of low-oxygen water from one region to another may be a factor in occurrence of MOM (Boyd, 1972). Introduction of reduced species from oxygen depleted zones and their advective transport throughout the DeGrey Reservoir is example of introduction of low-oxygen water into a waterbody and its effect on MOM (Nix, 1981)

The kinematic consequences of the temperature gradient in the metalimnion in combination with biological respiration processes can be another reason for the MOM. In

Lake Ontario, the kinematic consequences of temperature gradient include decreased velocity of settling seston as they enter the metalimnion from epilimnion. This phenomenon is caused by the higher density and viscosity of the metalimnetic water and results in the accumulation of seston in metalimnion as it is settling in more quickly than they are settling out. The elevated concentration of seston, in turn, increases oxygen demand in the region (Boyd, 1972). As the settling velocity of POC decreases when it enters the metalimnion, it either accumulates, or becomes a source of organic matter for bacteria and crustacean filter feeders. This is an indication of a productive layer which can result in Oxygen depletion (Schram & Marzolf, 1994). The high concentration of phytoplankton in metalimnion of Cannonsville Reservoir also seemed to be caused by their slow descendance (Effler, et al., 1998). Introduction of organic matter from upper layers into the metalimnion of DeGrey Reservoir is considered as one of the reasons of MOM in this reservoir (Nix, 1981). This phenomenon was also documented in Kentucky Lake.

In-situ activities have been discussed as one of the main causes of MOM in different lakes and reservoirs. It is suggested that an annual metalimnetic oxygen minimum in Lake Washington was caused by in situ respiration (Shapiro, 1960). It was concurrently observed that the number of copepods in the metalimnion was unusually high. Until mid-July, the maximum copepod population occurs above 10m and after that time, they migrate to deeper layers. In most cases, the correlation between the maximum number of copepods and minimum DO concentration was very good. Results suggested that a considerable amount of the oxygen lost in mid layer could be explained by copepod respiration (Shapiro, 1960). In Lake Ontario, the lowest metalimnetic oxygen minima has been observed in the area with the highest productivity. Therefore, phytoplankton and zooplankton respiration and bacterial decomposition can be considered as one of the causes of MOM in this lake (Boyd, 1972). In Kentucky Lake, in Kentucky, settled particulate organic carbon acts as a substrate for bacteria and a food source for zooplankton which results in Oxygen depletion in metalimnion (Schram & Marzolf, 1994). In Cannonsville Reservoir, in New York, the respiration of a high concentration of phytoplankton biomass in the metalimnion located below the compensation point appeared to be the reason for a MOM (Effler, et al., 1998).

Location of the compensation point is another factor potentially influencing MOM formation. The compensation point is the depth where respiration and productivity are equal. When the compensation point is located above the metalimnion, only respiration can happen in the metalimnion and the region becomes oxygen deficient. Lake Ontario has low transparency during its stratification period and therefore, it's very likely that its compensation point is located above the metalimnion (Boyd, 1972).

1.6 Metalimnetic Oxygen Minima in Green Lake

Many agricultural activities around Green Lake have introduced high loads of nutrients into this lake and resulted in degradation of its water quality over the years. Treated wastewater from the city of Ripon discharges into Silver Creek and large rain events also contribute to high nutrient loads in runoff entering this lake (Stauffer, 1985). This lake has been experiencing a MOM since at least the early 1900s, but the condition appears to be getting worse in recent decades based on data collected and assembled by the U.S. Geological Survey (Watras, et al., 2014). This lake was listed as “impaired” by Wisconsin Department of Natural Resources in 2014, due to the extent of its metalimnetic and hypolimnetic hypoxia (Watras, et al., 2014).

According to Stauffer (1985), the MOM in Green Lake can be explained by the settling of the oxidized seston and water column respiration. However, the phenomenon has not been thoroughly studied or modeled, and quantitative information about the MOM is required for effective management of the lake. A main goal of this study aims was to develop a 1-D oxygen model for Green Lake to better understand the drivers of the MOM.

2 Methods

2.1 Study Site

Green Lake is a drainage lake located in Green Lake County, Wisconsin, USA. It is the deepest natural lake in Wisconsin with a mean and maximum depth of 31 m and 72 m, respectively. The surface area of the lake is 29.7km^2 (Stauffer, 1985).

Figure 2.1. Hydrographic map of Green Lake, Wisconsin (University of Wisconsin-Madison)

The main tributary to the lake is Silver Creek. This tributary carries wastewater from the city of Ripon and enters on the eastern corner of the lake. Other tributaries are White Creek, Dakin Creek, Hill Creek, HWY K tributary, and the lake's outflow is via the Puchyan River. The hydraulic residence time is estimated to be about 18 years (Panuska, 1999); however, recent calculations shows the residence time is much lower than the value calculated by Panuska, and is estimated to be 13-15 years (D. Robertson, U.S. Geological Survey, personal communication). The thermocline in the lake usually forms around 8-10 m in midsummer and deepens to about 12m by mid-September.

2.2 Monitoring

Continuous in-situ monitoring was carried out during the years of 2017 and 2018. In 2017, two sites were selected for monitoring, one located in the east and the other on the west side of the lake (Figure 2.2). Moorings were deployed supporting an array of oxygen and temperature sensors mounted on a cable and attached to a buoy. These sensors were deployed on May 10th and retrieved on September 11th of 2017. Oxygen sensors collected data from 6 different depths (1m, 5m, 9m, 13m, 17m and 21m) on an hourly basis over the monitoring period (Figure 2.3, left). These depths were selected to measure the oxygen near the surface, mid-epilimnion, upper metalimnion, thermocline, lower metalimnion, and hypolimnion. Temperature sensors were placed at depths of 1m-17m (every m depths), 19m, 22m, 23m and 25m and programmed to record temperature on an hourly basis over the monitoring period. In 2018, the main focus was to obtain a set of data with higher resolution to study the behavior of the lake's metalimnetic region in more detail. Monitoring was performed at only the west site using a concentrated number of sensors. The sensors were deployed from June 12th to October 8th of 2018. Oxygen sensors were placed at three depths in the epilimnion (1m, 3m, 5m), throughout the whole assumed metalimnion (each meter between 8m-14m) and at two depths in the hypolimnion (17m and 21m) and programmed to record data on an hourly basis over the sampling period (Figure 2.3, right). Temperature sensors were placed at every meter down to 25m, sampling hourly over the deployment period.

Figure 2.2. Green Lake sampling site locations

Figure 2.3. Mooring design and the number of DO sensors on 2017 (left) and 2018 (right). DO was measured in depths of 1m, 5m, 9m, 13m, 17m and 21m from May 10th to September 11th on 2017 and in depths of 1m, 3m, 5m, 8m-14m, 17m and 21m from June 12th to October 8th on 2018. Temperature was measured at every meter from 1m-25m

Sensors and Calibration: Temperature was measured using the HOB0 Water Temp Pro v2 (U22-001) data logger. This sensor/recorder can be used to measure temperature in saltwater and freshwater and can operate in depths up to 120 m. It has the memory to record 42000 12-bit temperature measurements and doesn't require any calibration prior to launching. Oxygen was measured using HOB0 Dissolved Oxygen Logger (U26-001). This sensor/recorder measures temperature as well as DO. It employs an optical sensor that can measure DO with a 0.2 mg/L accuracy. These sensors were calibrated prior to deployment using HoboWare software (Onset, Inc.). Prior to calibration, new sensor caps were installed and initialized (caps expire after 6 months of use). A two-step calibration process was then applied where the DO sensor was placed in 100% and 0% saturation

conditions. The 0% saturation step is especially important if the sensor will be deployed in an environment with DO levels of 4mg/L or less. The 100% saturation calibration was performed by placing a water-saturated sponge into the logger's calibration boot. In order to calibrate the U26-001 to 0% saturation, the sensor end of the logger was submerged into sodium sulfite 5% w/v for approximately 15 minutes. After calibration, this logger was set for a delayed start to collect data on the launching day.

Green Lake has a maximum depth of 72m, but practical limitations prevented placing the moorings at such great depths. In 2017, the U.S. Geological Survey (USGS) also measured full sonde profiles from 1m-67m on June 7th, July 11th and 27th, August 8th and 25th, and September 13th. The purpose of this study is to model the oxygen behavior of the whole lake and at every depth. Therefore, the DO and temperature data from the moorings were augmented with linearly interpolated sonde profiles to reconstruct measurements for depths from 26m to 67m (Figure 2.4).

Figure 2.4. Temperature profiles from USGS sonde measurements (deep hole) compared with sensor measurements (interpolated from 26-67m). Both the sonde profile and the sensor measurements were taken from the East site.

2.3 Lake Analyzer

Analyzing a lake's physical aspects is the first step to fully understand the physical behaviors of the lake such as its stratification patterns, mixing events and location of any of the mixed layers (epilimnion, metalimnion and hypolimnion). Therefore, defining indices to quantify and monitor the stability of a lake and its extent of mixing is important in water quality management (Robertson, et al., 1990). These indices were calculated using the Lake Analyzer R package (Read et al., 2011). This package was used to calculate the top and bottom depths of the metalimnion, thermocline depth, Schmidt Stability, Wedderburn Number, and Lake Number.

Schmidt Stability: Schmidt Stability (S_t) is a number that represents the stability of a lake based on the amount of work required to mix the whole lake to a uniform density, without adding or subtracting heat. Lower S_t values show less resistance to mixing. Schmidt Stability can be calculated using the following equation (Robertson, et al., 1990).

$$S_t = \int_0^{Z_m} (z - Z_g) \times A_z \times \rho_z \times dz \quad (2-1)$$

Where:

- z = Depth above the bottom
- Z_m = Maximum depth of the lake
- Z_g = Center of volume of the lake
- A_z = Area of the lake at depth z
- ρ_z = Density of water at depth z

Lake Analyzer calculates Schmidt Stability using the lake's bathymetry and temperature time-series as inputs (Read, et al., 2011). However, the extent of mixing in a lake cannot be determined based solely on the Schmidt Stability. A lake can have a small S_t , but if it experiences very weak wind events, very little mixing might happen. Therefore, it can be said that S_t displays the potential of mixing in a lake, not the amount of mixing that actually occurs.

Lake Number: Lake number (L_N) is a dimensionless number that can represent the extent of mixing and lake stability. This number is defined as a ratio of stabilizing force of gravity due to stratification to the destabilizing forces due to the wind, inflow, outflow and destabilizing devices. By assuming that the effects of other destabilizing factors of inflow and outflow are negligible, wind becomes the most dominant force for mixing, and L_N can be calculated using the following equation (Robertson, et al., 1990).

$$L_N = \frac{g S_t (1 - \frac{Z_t}{Z_m})}{\rho_0 (u^*)^2 A_0^{3/2} (1 - \frac{Z_g}{Z_m})} \quad (2-2)$$

Where:

g = Acceleration of gravity (m/s^2)

S_t = Schmidt Stability (J/m^2)

Z_t = Thermocline height from the bottom (m)

Z_m = Maximum depth of the waterbody (m)

ρ_0 = Water density at the surface (kg/m^3)

u^* = Water friction velocity due to wind stress (m/s)

A_0 = Surface area (m^2)

Z_g = Height to the center of volume of the waterbody from the bottom (m)

And u^* can be calculated as:

$$u^* = (1.612e - 6 \times U_w^2)^{1/2} \quad (2-3)$$

Where U_w is the wind velocity at 10m above the water surface (m/s).

If $L_N > 1$, the stratification is strong and stabilizing forces are more dominant compared to wind events. In this case, stratification is expected to be horizontal with little turbulent mixing in the metalimnion and hypolimnion. When $L_N < 1$, the destabilizing forces are dominant, thermocline is unstable and more turbulent mixing is expected to reach the bottom of the lake. Lake number is an indicator of water column mixing from top to bottom of the lake. This number, therefore, is mostly used to identify the periods of complete mixing when the lake is not stratified. During stratification, when total mixing of the lake is not taking place, this number cannot be a good indicator of mixing. Mixing during stratification is limited to separate mixed layers rather than the whole lake.

Wedderburn Number: The Wedderburn Number (W), another index of stability, is a function of Richardson Number. W is based on a similar concept as L_N as is defined as a ratio of the depth-based buoyancy to the length-based wind mixing. It is calculated using the following equation:

$$W = Ri \frac{H}{L} = \frac{g' H^2}{\mu_*^2 L} \quad (2-4)$$

Where:

Ri = The bulk Richardson Number

H = The thickness of the mixed layer (m)
 g' = Reduced gravitational acceleration (m/s^2)
L = Length of the lake at thermocline (m)
 μ_*^2 = Shear friction velocity, which is calculated as:

$$\mu_*^2 = \left(\frac{\rho_a}{\rho_0} \right) C_D U_w^2 \quad (2-5)$$

$$\frac{\rho_a}{\rho_0} = 1.23 \times 10^{-3}$$

$C_D = 1.3 \times 10^{-3}$ and 10^{-3} for large and small lakes, respectively

U_w = Wind velocity at 10m above the water surface (m/s).

Lake Analyzer calculates W using the lake's bathymetry data, water temperature time series, and wind speed as inputs (Read & Muraoka, 2011).

2.4 Simstrat

The goal of this study is to understand the spatial and temporal patterns of DO in Green Lake. In order to model the production and consumption of DO, understanding the affects of physical transport throughout the water column is crucial (Goudsmit, et al., 2002). As the vertical transport of materials in a stratified lake is $10^3 - 10^5$ times slower than the horizontal one (Goudsmit, et al., 2002) vertical one-dimensional models are appropriate for describing this phenomenon, especially in a stratified system. The hydrodynamical one-dimensional models used to determine the extent of vertical transport of components in a waterbody usually fall into one of these categories:

- *Advective-diffusive models* are usually easier to develop, with simple parameterization schemes or given vertical transport rates, and require less input data. However, these models can be case-specific and empirical (Goudsmit, et al., 2002)
- *Models based on turbulence closure schemes* in which vertical transport rates are not directly parameterized but are determined by external forces related to turbulent kinetic energy (k- ϵ models). They are more difficult to develop but are more precise in simulating vertical transport processes (Gloor, et al., 2000; Goudsmit, et al., 2002). Most of these models can successfully predict the depth of a mixed layer, but for deeper layers of a stratified water column, the values predicted for turbulent kinetic energy are typically presumed as negligible, resulting in molecular scale predicted diffusivity. Experiments have shown that

many deep lakes experience high diffusivity at lower depths due to remineralization and failing to determine the correct values of diffusivity coefficient results in underestimating the transport of water components. It is observed that the actual rates of these components' transport, such as oxygen, are 10^5 to 10^6 times higher than the molecular scale transport rate (Goudsmit, 2002).

Simstrat is a numerical model that predicts density stratification in lakes and reservoirs. It is not only a buoyancy-extended k- ϵ model but also includes an additional seiche excitation and damping model to determine the turbulent diffusivity of a lake below the surface mixed layer (Goudsmit, 2002). Before studying the structure of this model in more detail, it's important to understand the effect of a seiche on physical and biological processes in a lake. This is especially important as Green Lake experiences significant seiche events.

Seiches or long internal waves in lakes usually take the form of standing waves (Lemmin, et al., 2005). These wind-induced waves have been recognized since 1950 and usually occur in large or intermediate lakes (Pannard, et al., 2011). A seiche following wind set up (or tilting of the thermocline) continues to oscillate with decreasing amplitude after the wind ceases and its period can vary from hours to even days. This large displacement of water layers can transfer kinetic energy over large distances and drive mixing (Ostrovsky, et al., 1996). Lake's stability and the indices that were discussed in the previous section, play an important role in determining a seiche's mode. A seiche's frequency and structure are determined by the basin's shape and water column stability (Lemmin, et al., 2005).

2.4.1 Model Structure

Simstrat assumes there is no river intrusion into the lake and therefore, there is no vertical advection term in the governing equations. The main equations used in this model are the heat transfer equation (equation 2-4), mean horizontal velocity equations with respect to x (equation 2-5) and with respect to y (equation 2-6), the turbulent kinetic energy equation (TKE) (equation 2-7) and TKE dissipation rate equation (equation 2-8):

$$\frac{\partial T}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left(A(v'_t + v') \frac{\partial T}{\partial z} \right) + \frac{1}{\rho_0 C_p} \frac{\partial H_{sol}}{\partial z} + \frac{dA}{dz} \frac{H_{geo}}{A \rho_0 C_p} \quad (2-6)$$

$$\frac{\partial u}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left(A(v_t + v) \frac{\partial u}{\partial z} \right) + fv \quad (2-7)$$

$$\frac{\partial v}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left(A(v_t + v) \frac{\partial v}{\partial z} \right) - fu \quad (2-8)$$

$$\frac{\partial k}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left(A v_k \frac{\partial k}{\partial z} \right) + P + P_{Seiche} + B - \epsilon \quad (2-9)$$

$$\frac{\partial \epsilon}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left(A v_\epsilon \frac{\partial \epsilon}{\partial z} \right) + \frac{\epsilon}{k} (c_{\epsilon 1} (P + P_{Seiche}) + c_{\epsilon 2} B - c_{\epsilon 3} \epsilon) \quad (2-10)$$

Where:

- T = Temperature (°C)
- u = Horizontal velocity component with respect to x (m/s)
- v = Horizontal velocity component with respect to y (m/s)
- k = TKE per unit mass (J/kg)
- ε = TKE dissipation rate (W/kg)
- ρ₀ = Lake water density (kg/m³)
- c_p = Specific heat of lake water (J/kg/K)
- A = Surface area of the lake at depth z (m²)
- H_{sol} = Shortwave solar radiation penetrating the lake water (W/m²)
- H_{geo} = Geothermal heat flux (W/m²)
- f = Coriolis parameter (s⁻¹)
- ν = Turbulent viscosity (kg.m/s)
- ν_t = Molecular viscosity or momentum (kg.m/s)
- ν' = Turbulent diffusivity of temperature (m²/s)
- ν'_t = Molecular diffusivity of temperature (m²/s)
- ν_ε = Turbulent diffusivity of TKE dissipation (m²/s)
- ν_k = Turbulent diffusivity of TKE (m²/s)
- P = Shear stress production (W/kg)
- B = Buoyancy production (W/kg)
- P_{Seiche} = Production of TKE due to seiche (W/kg)
- c_{ε1}, c_{ε2}, c_{ε3} = Model constants

Table 2: Simstrat model constants (Goudsmit, 2002)

Model Constant	Value
$c_{\epsilon 1}$	1.44
$c_{\epsilon 2}$	1.92
$c_{\epsilon 3} (B < 0)$	-0.4
$c_{\epsilon 3} (B > 0)$	1

During stratification, the amount of TKE directly produced by wind stress is small but internal seiches can form below the epilimnion due to wind forcing. The energy loss caused by damping of these internal waves is assumed to be the main source of TKE below the mixed layer (Goudsmit, et al., 2002).

A simple equation to describe seiche behavior is (Gloor, et al., 2000; Goudsmit, 2002):

$$\frac{dE_{seiche}}{dt} = PW - LS \quad (2-11)$$

Where:

- E_{Seiche} = Total energy of the seiche motion (J)
- PW = Production of seiche energy due to wind forcing (W)
- LS = Loss of seiche energy due to friction (W)

Because the seiche is excited by the wind forcing, the production of seiche energy is assumed to be proportional to the amount of wind energy introduced at the surface (Goudsmit, 2002).

$$PW = \alpha A_0 \rho_{air} c_{10} (u_{10}^2 + v_{10}^2)^{3/2} \quad (2-12)$$

Where:

- A_0 = Surface area of the lake (m^2)
- ρ_{air} = Density of air (kg/m^3)

u_{10} = East component of the wind speed measured at 10m above the water surface (m/s)

v_{10} = North component of the wind speed measured at 10m above the water surface (m/s)

c_{10} = The drag coefficient

α = Constant of proportionality, is a model parameter showing the amount of energy transferred to the seiche motion and is subject to model calibration.

Loss of seiche energy occurs due to friction within the waterbody and at the boundaries. This value is especially high after a strong excitation. Studies have shown that in the deep water, the dissipation rate is two orders of magnitude higher at the bottom boundaries compared to the open water (Goudsmit, et al., 2002). It can be calculated using the following equation:

$$LS = -\gamma E_{seiche}^{3/2} \quad (2-13)$$

Where:

γ = Constant of proportionality which depends on the bottom friction and the basin's geometry and is estimated to be approximately $2 \times 10^{-10} \text{ m}^{-1} \text{ kg}^{-1/2}$ for lake Alpnach (Goudsmit, et al., 2002)

The equation used to calculate γ is:

$$\gamma = A_0 V_0^{-3/2} \rho_0^{-1/2} C_{Def} \quad (2-14)$$

Where:

V_0 = Volume of the lake (m^3)

C_{Def} = The effective bottom friction coefficient assumed to be independent of depth

In calculation of γ for Alpnach lake, C_{Def} is assumed to be 0.002. In the current model, C_{Def} is estimated during model calibration.

2.4.2 Model Setup

Simstrat is run via an executable file and is governed with a parameter file in JSON format (Bärenbold, 2018; Gaudard, et al., 2015). The parameter file shows the location of the input and output files, model configuration, simulation timesteps and model parameters. The parameter file is described in detail in Appendix A.

Input files: The depths over which the model operates must fall within the limits set in the lake's morphology file, and the time series must fall in the frame defined in the parameter file (Bärenbold, 2018; Gaudard, et al., 2015). *Morphology* specifies the shape of a basin. Areas should be given for the entire depth range of the lake from the surface to the bottom in order for the model to predict accurate results. The input file for morphology consists of two rows, one for the depth values (m) and the other for their related areas (m²). Depth values are defined as zero at the surface and the axis is negative downward (Bärenbold, 2018; Gaudard, et al., 2015). The lake's volume is plotted in Figure 2.5 in 0.25-m intervals:

Figure 2.5: Green Lake Bathymetry

Initial conditions is a text file that shows the condition of the lake at the beginning of the simulation at known depths. The depths should not exceed the range given in the morphology file. It requires the horizontal velocity terms (u and v) (m/s), temperature (°C), Salinity (‰), TKE (J/kg) and its dissipation rate ϵ (W/kg) at corresponding depths (Bärenbold, 2018; Gaudard, et al., 2015).

Forcing is a file that contains time series of atmospheric conditions applied to the surface of the lake. These data should be defined based on one of the five forcing modes given in the parameter file and data availability. These modes are defined in Appendix A (Bärenbold, 2018; Gaudard, et al., 2015). The forcing data used as initial conditions of this model for 2017 is obtained from a weather station located at Green Lake, by UW-Madison. The obtained data consists of wind speed (m/s), air temperature (°C), solar radiation (watt/m²) and vapor pressure (mbar).

It's important to note that even though the time data should be on daily basis, the input files do not accept time as date format, and they should be converted to numbers. The forcing mode chosen for this simulation is the second mode. The absence of precipitation data shouldn't significantly affect the model performance.

Absorption specifies light attenuation coefficients as a function of time and depth. The number and the depths in which the light attenuation factors are defined should be specified. This input file requires time (d), number of depths and their corresponding values (m) and light attenuation coefficients for each time and depth (m⁻¹). In the following table, the first row is the header. The number on the second row specifies the number of depths in which light attenuation coefficient is known. The first number in the third row is a dummy value, and the second one indicates the depth where light attenuation factor is specified. The third to n+1 columns are for specifying the light attenuation factor in other depths (Bärenbold, 2018; Gaudard, et al., 2015).

Because of the Green Lake's long residence time, the effect of inflow and outflow in its simulation has been neglected and accordingly input files were not developed for tributaries.

2.4.3 Optimization Methods:

Simstrat was parameterized by matching output temperature profiles with the data gathered from the loggers. The cost function (optimization function) defined for temperature model calibration is a simple equation and the goal is to minimize the differences between the modeled temperature profile and the actual temperature profile gathered by the data loggers. Thermocline depth is also incorporated into the cost function to emphasize fit in the region of most interest. The cost function is defined as:

$$C(D, T) = RMSE\left(\frac{D_{sim} - D_{true}}{D_{sim}}\right) + RMSE\left(\frac{T_{sim} - T_{true}}{T_{sim}}\right) \quad (2-15)$$

Where:

$C(D, T)$ = The cost function

D_{sim} = Simulated thermocline depth of the lake (m)

D_{true} = Actual thermocline depth of the lake (m)

T_{sim} = Simulated temperature of the lake (°C)

T_{true} = Actual temperature of the lake (°C)

The parameters that were optimized using this cost function are (Bärenbold, 2018; Gaudard, et al., 2015):

Table 3: Parameters that were determined by model calibration

Calibrated Parameters	Description
a_seiche	Fraction of wind energy which goes into seiche energy
q_nn	Fit parameter for distribution of seiche energy
f_wind	Ratio of forcing wind to wind speed at 10 m above lake level
c10	Wind drag coefficient
cd	Bottom drag coefficient
hgeo	Geothermal heat flux [W/m ²]
k_min	Minimum value for TKE [J/kg]
p_sw	Fit parameter for absorption of short-wave radiation from sky
p_lw	Fit parameter for absorption of IR radiation from sky
p_windf	Fit parameter for convective and latent heat fluxes
beta_sol	Fraction of short-wave radiation directly absorbed as heat by water
wat_albedo	Water albedo

Simulated Annealing was found to most efficiently optimize the system. This method is especially useful when there are many inter-related parameters that require changing to optimize the cost function. When the number of parameters increases, the chance of falling into local minimum increases as well. Unlike methods that only accept parameter values that lower the cost function and only compare the cost function value with its adjacent points, the Simulated Annealing algorithm is defined in a way to avoid falling into local minimums by making a series of random moves (Carr, 2020). At each iteration, a point is randomly generated and is automatically accepted if it lowers the cost function. However, values that increase the cost function are also accepted with a certain probability. This lowers the chance of the algorithm getting trapped into a local minimum and increases the probability of identifying a global minimum.

2.5 Seiche and Data Smoothing Processes

Although the data obtained from both East and West site show good agreement in determining the overall behavior of the lake, they fail to report identical profiles at specified times. The plotted DO profiles for depths of 9m and 21m are presented in Figure 2.6. These plots clearly show the effect of the seiche in shallow waters as well as deeper layers. The effect of the seiche is depicted in these figures as a delay in water movement from one site to another. When the seiche is in its excitation mode, stratification is deepened on one side of the lake (downwind) and is shallower on the other side of the lake (upwind). When the wind velocity decreases, the water begins to return to its stable horizontal condition, but overshoots the stable condition, and thus begins a rocking motion. This up and down movement of the water column is depicted in Figure 2.6, as if the behavior of the water column is mirrored between these two sites.

Figure 2.6: Comparison of East and West oxygen profiles in the lake at 9m (top) and 21m (bottom) , (5/10/2017-9/11/2017).

In order to obtain the best results and avoid errors in modeling when using a 1 dimensional model, the effect of the seiche needed to be eliminated; therefore, lakewide profiles of oxygen and temperature for the whole lake were computed. The method used for smoothing both temperature and oxygen data was the LOWESS (Locally Weighted Scatterplot Smoothing) method (Glen, 2013). This is a nonparametric regression method. This means that no prior distribution or equation is forced to the data to determine the curve's fit (Glen, 2013). It's called a locally weighted smoothing method because the fitting at each point is weighted towards the points close to it. The distance of each point from neighboring points is incorporated into the smoothing process as α and performed in R using(Statsdirect, 2020). The weight of the neighboring points on the fit is measured by "span". "Span" can have a value between 0 and 1. The greater the span, the smoother the fit (Prabhakaran, 2016). Through trial and error, span was set to 0.5. The smoothed oxygen time series at 9m and 21m are shown in Figure 2.7.

Figure 2.7: Comparison of East and West smooth oxygen profiles of the lake at 9m (top) and 21m (bottom), (5/10/2017-9/11/2017).

2.6 Oxygen Model

The oxygen model developed in this study is a 1-D vertical box-model (Figure 2.8), based on two equations that are solved simultaneously:

$$\frac{dDO}{dt} = P(T, I) - R(T, DO, Biomass) - SOD(T, DO) \pm Fluxes \quad (2-16)$$

$$\frac{Biomass}{dt} = P(T, I) - R(T, DO, Biomass) \pm Fluxes \quad (2-17)$$

Where:

P = Productivity (gDO m^{-3}), as a function of temperature (T °C), light intensity (I watt m^{-2}) and biomass (gDO m^{-3}),

R = Respiration (gDO m^{-3}), as a function of temperature (T °C), dissolved oxygen concentration of the layer (gDO m^{-3}), and biomass (gDO m^{-3}),

SOD = Sediment Oxygen Demand (gDO m^{-3}), as a function of temperature (T °C), and dissolved oxygen concentration of the layer (gDO m^{-3}),

$Fluxes$ = A term including water column fluxes and air/water fluxes ($\text{g m}^{-3} \text{h}^{-1}$)

$Biomass$ = The oxidizable contents at each layer of the water column, in units of oxygen (gDO m^{-3}).

In this model, the lake is divided into 67 boxes and the transfer is assumed to be only vertical direction and governed by the diffusivity coefficients. Each of these boxes are assumed to be well mixed and diffusion is assumed to be occurring uniformly across the layer boundaries. The diffusivity coefficients were obtained from the output of the optimized Simstrat model. DO is assumed to follow water movement and therefore the extent of mixing between each layer can be used to calculate the amount of oxygen transferred between the layers.

Figure 2.8 A schematic of the 1-D boxed oxygen model

Equation 1.3 takes productivity, water column respiration, fluxes and sediments oxygen demand into account. To better describe the model, each of these terms will be studied separately.

2.6.1 Fluxes

The oxygen model is developed step by step. The first parameters incorporated into the equation are the fluxes. Fluxes term consists of the water column fluxes and air-water fluxes. The air-water transfer mechanism was described in the introduction part. As it was mentioned, this transfer follows the Henry's law and the two-film theory. The behavior of surface water in contact with air can be described in the following equation (Chapra, 1997):

$$\frac{dO}{dt} = k_{gas}(O_s - O) \quad (2-18)$$

Where:

k_{gas} = air-water transfer coefficient (h^{-1})

O_s = oxygen saturation concentration (g m^{-3})

O = oxygen concentration at the surface of the lake (g m^{-3})

k_{gas} is calculated using the Lake Metabolizer package in R. This package offers many ways to calculate the air-water transfer coefficient (Winslow, et al., 2016). The method used in this study is based on Cole and Caraco model. This model is developed based on a relationship between k_{600} and the wind speed (Cole & Caraco, 1998). k_{600} is a gas exchange coefficient normalized to the Schmidt of 600. k_{600} can be calculated as (Winslow, et al., 2016):

$$k_{600} = 2.07 + (0.215 \times U_{10}^{1.7}) \quad (2-19)$$

Where:

U_{10} = wind speed at height of 10m above the water surface (m/h)

U_{10} can be calculated using the following equation (Winslow, et al., 2016):

$$U_{10} = \text{wind} \times \left(\frac{10}{H_{\text{wind}}} \right)^{\frac{1}{7}} \quad (2-20)$$

Where:

wind = observed wind speed at the surface (m h^{-1})

H_{wind} = height of the wind observation (m)

k_{600} then needs to be converted into gas transfer coefficient based on the temperature of the water and the type of gas. This value was converted to gas transfer coefficient for oxygen and at the lake's surface temperature using the *k600.2.kGAS* function in lake metabolizer package (Winslow, et al., 2016).

O_s can be calculated based on the dependence of oxygen saturation on oxygen, using the following equation (Chapra, 1997):

$$\begin{aligned} \ln O_s = & -139.34411 + \frac{1.575701 \times 10^5}{T_a} - \frac{6.642308 \times 10^7}{T_a^2} \\ & + \frac{1.243800 \times 10^{10}}{T_a^3} - \frac{8.621949 \times 10^{11}}{T_a^4} \end{aligned} \quad (2-21)$$

Where T_a is the absolute temperature (K).

The water column diffusion can be calculated using the following equation:

$$J = -k_d \frac{AdO}{Vdz} \quad (2-22)$$

Where:

A = Surface area of the lake (m^2)

V = Volume of the lake (m^3)

k_d = Diffusion Coefficient ($\text{m}^2 \text{h}^{-1}$)

J = Mass flux between the volumes ($\text{g m}^2 \text{h}^{-1}$)

Z = Depth (m)

The following equation can be solved numerically for each cell (excluding the top and bottom cell):

$$\frac{O_i^{n+1} - O_i^n}{dt} = k_{d_i}^n \frac{A_i(O_{i+1}^n - O_i^n)}{V_i l} - k_{d_{i+1}}^n \frac{A_{i+1}(O_{i+1}^n - O_{i+2}^n)}{V_{i+1} l} \quad (2-23)$$

Where l is the depth of each layer in meters and i and n indicate the number of depths and timesteps respectively. This equation is then solved numerically over the whole grid to calculate the diffusivity coefficients in and out of each layer.

2.6.2 Sediment Oxygen Demand (SOD)

SOD occurs due to the oxidation of organic matter in the sediments of a waterbody. SOD is dependent on the water temperature, the oxygen level of the overlying water and nutrient availability. An overall equation for SOD can be written as:

$$k_{SOD}(T, O, N) = k_{SOD,T} \phi O \phi N \quad (2-24)$$

Where:

$k_{SOD,T}$ = Maximum growth rate at a particular temperature

ϕO = Attenuation factor for oxygen limitation

ϕN = Attenuation factor for nutrient limitation

Michaelis-Menten equation is used to determine oxygen limitation:

$$\phi O = \frac{O}{k_{s,O} + O} \quad (2-25)$$

Where:

O = Oxygen concentration (g m^{-3})

$k_{s,O}$ = Half saturation value for the dependence (g m^{-3})

$k_{s,O}$ is assumed to be equal to 1 g m^{-3} in this model, however, many other values can be found in the literature (varying from 0.7 to 1.4 g m^{-3}) (Chapra, 1997).

Although ϕN is defined as attenuation factor for nutrient limitation (SOD is dependent on accumulated organic matters at the bottom of the lake. Part of these organic matters are originated from photosynthetically produced plant matter, and the concentration of

these settled materials is dependent on the level of nutrients in the lake and the lake's productivity.), in this study this term defines the effect of oxidizable content on SOD. The effect of carbon content of the water column and change in sediments properties on the SOD rate is incorporated into the model by defining an exponential depth-dependent equation as:

$$\phi_N = k_{s,20}d^b \quad (2-26)$$

Where:

d = location of each layer, with downward positive axis (m)

$k_{s,20}$ = areal SOD rate at 20°C ($\text{g m}^{-2} \text{h}^{-1}$) calculated by model calibration

b = depth dependency parameter calculated by model calibration

SOD can be calculated as a function of temperature, using the following equation (Chapra, 1997):

$$k_{SOD,T} = k_{s,20}\theta_{SOD}^{T-20} \quad (2-27)$$

Where:

θ_{SOD} = SOD temperature dependency

θ_{SOD} has a reported range of 1.04 to 1.13 (Chapra, 1997) and in this model is determined via model calibration.

The effect of the carbon content on SOD is more pronounced at deeper layers (with higher d values) as the accumulation of oxidizable contents are higher at the bottom layers of the lake. By substituting $k_{SOD,T}$, ΦO and ΦN in equation 2-21, the final equation for SOD can be written as:

$$k_{SOD}(T, O, N) = k_{s,20}d^b \times \frac{O}{k_{s,o} + O} \times \theta_{SOD}^{T-20} \times \frac{A_s}{V} \quad (2-28)$$

2.6.3 Water Column Respiration

The process of aerobic respiration utilizing oxygen and releasing carbon dioxide also occurs throughout the water column. Water column respiration is also a function of temperature, oxygen and biomass (B). The following equation can be written for water column respiration:

$$k_r(T, B, O) = k_{r,20} \theta_R^{T-20} \frac{O}{k_{s,o} + O} \times B \quad (2-29)$$

Where:

θ_R = respiration temperature dependency

$k_{r,20}$ = water column respiration rate at 20°C (h⁻¹)

B = oxidizable contents of each layer in oxygen units (g DO m⁻³)

A value of 1.08 is assumed for θ_R in the literature, however, in this model θ_R is calculated by model calibration. Values of $k_{r,20}$ ranges from 0.01 d⁻¹ to 0.5 d⁻¹. This term is what controls the level of biomass. The production of biomass is dependent on the level of nutrients and initial spring bloom in the lake. The biomass budget of the lake is highly dependent on the level of spring bloom. Respiration is responsible for limiting the level of biomass in the lake.

2.6.4 Productivity

The productivity term accounts for algal photosynthesis and the resulting oxygen production. The algal growth rate depends on temperature, light and nutrients. An overall equation for algal growth can be written as (Chapra, 1997):

$$k_g(T, N, I) = k_{g,T} \phi N \phi I \quad (2-30)$$

However, in this model the limiting effect of nutrients is not included. This doesn't mean that the nutrient's effect is neglected, but it is assumed to be the same throughout the monitoring period. As the limiting effect of nutrients is not a variable through this study, productivity is only a function of light and temperature:

$$k_g(T, I) = k_{g,T} \phi I \quad (2-31)$$

The term for productivity temperature dependency is similar to SOD and water column respiration and can be written as:

$$k_{g,T} = k_{g,20} \theta_g^{T-20} \quad (2-32)$$

The value suggested for theta in the literature is 1.066 (Chapra, 1997), however, in his model theta is calculated by model calibration.

The relation between light and phytoplankton growth is more complicated and is dependent on the depth of the photic zone. As light penetrates a waterbody, its behavior

is not linear and it decays exponentially. The distance between the water surface and the deepest point of a waterbody where light can penetrate is considered the photic zone. Secchi depth is a good indication of the photic zone. USGS has provided data for the Secchi depth on June 7th, July 11th and 27th, August 8th and 25th, and September 13th. By interpolating between those data, Secchi depth for the whole period was calculated. The light extinction coefficient was then calculated using the Secchi depth with the following equation:

$$k = \frac{1.7}{\text{secchi depth}} \quad (2-33)$$

Where k = light extinction coefficient (m^{-1})

Given a time-dependent light extinction coefficient, the light intensity at each depth and on each day can be calculated using the Beer's law:

$$\frac{I_z}{I_0} = e^{-kz} \quad (2-34)$$

Where:

I_z = solar radiation intensity at depth z (watt m^{-2})

I_0 = net solar radiation penetrating the surface (watt m^{-2})

z = depth of the water layer in which light intensity is calculated (m)

By obtaining the whole profile of the light intensity at each time and depth, the relationship between light and phytoplankton growth can be calculated using the Steele equation (Chapra, 1997):

$$\phi I = \frac{I_z}{I_s} e^{-\frac{I_z}{I_s} + 1} \quad (2-35)$$

Where I_s is the optimal light level and is calculated by model calibration.

The dependency of oxygen budget of the lake on biomass is studied by assuming it has a similar behavior to BOD. An equation for the biomass budget can be written as:

$$B = k_g(T, I) - k_{r,20} \theta_g^{T-20} \frac{DO}{k_{so} + DO} \times B \pm \text{Fluxes} \quad (2-36)$$

This equation should be solved iteratively. An initial value for B is chosen, and the final value of B can be calculated by model calibration. This equation should be solved along

with the developed equation for oxygen to incorporate the effect of water column oxidizable contents into the model.

The final oxygen equation can be written as:

$$\begin{aligned}
 dO(g/m^3)/dt(h) &= (k_{g,20}(g/m^3 h^{-1})\theta_g^{T(^{\circ}C)-20} \times \frac{I(watt/m^2)}{I_s(watt/m^2)} e^{\frac{I}{I_s}} \\
 &+ Fluxes(\frac{g}{m^3 h}) \\
 &- B(g/m^3) \times \frac{O(g/m^3)}{k_s(g/m^3) + O} \\
 &\times k_{r,20}(h^{-1})\theta_R^{T(^{\circ}C)-20} \\
 &- k_{s,20}(\frac{g}{m^2 h})\theta_{SOD}^{T(^{\circ}C)-20} \times d^b \times \frac{O(g/m^3)}{k_s(g/m^3) + O} \\
 &\times \frac{A_s(m^2)}{V(m^3)})
 \end{aligned} \tag{2-37}$$

The model was calibrated using smoothed 2017 oxygen data from the West site. The cost function used for model calibration is written as:

$$C(O) = RMSE(O_{sim} - O_{true}) \tag{2-38}$$

Where:

$C(O)$ = The cost function

O_{sim} = Simulated dissolved oxygen concentration of the lake ($g m^{-3} h^{-1}$)

O_{true} = Smooth oxtgen data collected from West site in 2017 ($g m^{-3} h^{-1}$)

A list of calibrated parameters and their final values are listed in table 4.

Table 4: parameters used in DO model development and their calibrated values

Parameter Description	Parameter Value
B (oxidizable content of the water column, $\text{g m}^{-3} \text{ h}^{-1}$)	15.328732
k_g (algal oxygen production rate, h^{-1})	0.145398
θ_g (temperature coefficient for productivity)	1.171717
I_s (optimal light level, watt m^{-2})	200
k_r (respiration rate, h^{-1})	0.004633
θ_r (temperature coefficient for respiration)	1.219751
k_{SOD} (SOD rate, $\text{g m}^{-2} \text{ h}^{-1}$)	0.508886
θ_{SOD} (temperature coefficient for SOD)	0.041206
b (SOD depth dependency)	1.024031

3 Results and Discussion

3.1 Temperature and Oxygen

The temperature and oxygen profiles of the lake as measured in-situ in 2017 for west and east sites are shown in Figures 3.1-3.4. The time is shown as Julian days. Data were interpolated between the depths of the temperature loggers (1m-17m, 19m, 22m, 23m and 25m), and extrapolated to greater depths (26m-67m) using USGS 2017 sonde profiles collected on June 7th, July 11th and 27th, August 8th and 25th, and September 13th. The temperature plots (Figures 3.1 and 3.2) show the lake is completely mixed at the beginning of the monitoring period. Around day 150, the lake starts to stratify, and the thermocline starts to form. The average location of the thermocline is around 13m. Similar to temperature figures, plots of oxygen (Figures 3.3 and 3.4) show the uniform profiles of oxygen until day 150 when the lake is completely mixed. After beginning of stratification, the behavior of oxygen profiles changes and metalimnetic oxygen minimum forms at around 13m. this corresponds with the location of thermocline.

Figure 3.1: Temperature (°C) for the West (left) and the East (right) sites for the first 25 meters (5/10/2017-9/11/2017).

Figure 3.2: Temperature ($^{\circ}\text{C}$) for the West (left) and the East (right) sites for all the depths of the lake (5/10/2017-9/11/2017).

Figure 3.3: Dissolved oxygen (g/m^3) for the West (left) and the East (right) sites for the first 25 meters (5/10/2017-9/11/2017).

Figure 3.4: Dissolved oxygen (g/m^3) for the West (left) and the East (right) sites for all the depths of the lake (5/10/2017-9/11/2017).

The thermocline depth, top layer of the metalimnion (meta T) and the bottom layer of the metalimnion (meta b) are shown in Figure 3.12. When the lake is well mixed and prior to the onset of stratification (before mid-June), these layers overlap and become one. After the stratification begins in the middle of June, the metalimnion begins to form and the top and bottom boundaries of the metalimnion becomes distinct.

Figure 3.5: Depths of the top and bottom layers of metalimnion and location of the thermocline for the East site (5/10/2017-9/11/2017).

Loggers were retrieved to download data on July 11, 2017 and immediately redeployed. Due to the steep slope at the western site, the loggers on the West site were inadvertently redeployed at a shallower depth than the first period. This can be seen in Figures 3.3 and 3.4 as a discontinuity at day 191. For this reason, modeling was based primarily on the data obtained from the East site in 2017. However, the lake's stratification period and depth of the thermocline generally agreed well between the sites.

Figures 3.5 and 3.6 present the temperature and oxygen profiles of Green Lake during 2018. The data obtained by the loggers for the first 25 meters were interpolated and extrapolated for greater depths (25m-67m) using USGS sonde profiles collected on June 12th, July 10th, August 2nd, August 23rd and September 11th. Monitoring of Green Lake started at June 12th on 2018, and therefore, the lake was stratified at the beginning of the monitoring period. The location of the MOM during 2018 also corresponds with the thermocline depth and happens at around 8-11 meters.

Figure 3.6: Temperature (°C) and dissolved oxygen (g/m³) in the lake for the first 25 meters (West site 2018).

Figure 3.7: Temperature (°C) and dissolved oxygen (g/m³) in the lake for all the depths of the lake (West site 2018).

Figure 3.8: Temperature profiles from USGS sonde measurements (deep hole) compared with sensor measurements (interpolated from 26-67m) on 7/10/2018.

Figure 3.8 shows plots of sonde measurements taken by USGS on July 10th 2018 and its comparison with data gathered by data loggers. They show a pretty good agreement. However, as the West site has a very steep slope, there is a 2 meters difference between these two measurements due to possible loggers slipping. More plots of the sonde and loggers comparisons on other dates are presented in Appendix B.

3.1.1 Secchi Depth and Light Attenuation Coefficients

The Secchi depths for 2017 and 2018, collected by USGS, are shown in Figure 3.9. The light attenuation coefficient is calculated based on these values. The average Secchi depth for 2017 is 3.5 m and for 2018 is 5.15 m. These data indicate that the lake is more transparent during 2018 sampling and light, therefore, penetrated more deeply into the lake.

Figure 3.9: Secchi depth plots for 2017 and 2018

The calculated depth of the photic zone ($2.7 \times$ Secchi depth) for 2017 and 2018 is shown in Figure 3.10. It can be seen from these figures that $>1\%$ light is present occasionally below 16 meters during the 2018 study period, and photosynthesis is therefore theoretically still occurring at these depths.

Figure 3.10: Photic depth (photic zone) plots for 2017 and 2018

Compensation Depth: Shapiro (Shapiro, 1960) and Boyd (Boyd, 1972) listed the location of compensation depth as one of the reasons for MOM formation. Their theory proposes that MOM occurs when the compensation point is located above the metalimnion. However, this theory for MOM formation in Green Lake is not valid. By studying the temperature colormaps of year 2017 (Figure 3.1 and Figure 3.2), the thermocline is forming at approximately 13m. Plotting the photic zone depths for year 2017 (Figure 3.8) shows the photic zone to be as deep as 16m. The same phenomenon is present during 2018 monitoring period. The thermocline is forming at around 8-11m (Figures 3.5 and 3.6), and the photic zone is as deep as 18m. As the photic zone is located below the thermocline and with MOM still present in the lake despite that, location of the compensation depth cannot be a reason for MOM formation in Green Lake.

3.2 Water column stability

Schmidt Stability (Figure 3.11) shows the lake's resistance to mixing. When S_t is low, deep mixing can occur with relatively low wind velocities. The figure below shows the lake could mix with relatively light winds at the beginning of the sampling period, when the water temperature throughout the water column is relatively uniform. As the stratification strengthens, the lake's ability to mix declines. At the peak of stratification in mid-summer, the S_t is the highest and mixing is at a minimum.

Figure 3.11: Schmidt Stability for the East site (5/10/2017-9/11/2017)

Lake Number is another indicator of lake's resistance to deep mixing as described in section 2.2. When this number is greater than one, the lake loses its ability to mix completely given the ambient wind speeds. Schmidt stability shows the lake's resistance to mixing and is an indicator of the lake's "stability". It shows if the lake is stable or not and does not indicate the extent of mixing or if and when the lake gets mixed. Lake number provides a criterion to understand the lake's mixing given the ambient winds and when it has the ability to be mixed to the bottom. Wedderburn number, however, is the number which indicates the state of the lake and amount of mixing even after the lake stratifies. The numbers this index provides, can be used to study the extent of the lake's mixing at any point. A plot of the Wedderburn number is provided in Figure 3.12. The wind speed used in calculating the lake number and Wedderburn number is obtained from a weather station at Green Lake by UW-Madison. The data is measured every 15 minutes; however, the wind speed data is averaged to obtain hourly data which is used to calculate lake number. The hourly wind speed data is used throughout the lake's hydrodynamic modeling as well.

Figure 3.12: Wedderburn Number for the East site (5/10/2017-9/11/2017)

3.3 Simstrat

The model setup and required files are described in detail in section 2.3. The input files are given in Appendix A. In the first step, Simstrat was run using the default parameter values (Bärenbold, 2018) for 2017 forcing data. The parameters and their initial values are also given in Appendix A. Then, the model was calibrated using the 2017 East site temperature data by optimizing 12 introduced parameters in Table 3.

The uncalibrated results from the Simstrat model for East site in 2017 (prior to parameter optimization) are shown in Figure 3.13. Although the simulated model predicts the lake's stratification period correctly, it overestimates the intensity of stratification and locates the thermocline at a shallower depth. The epilimnetic temperature is also overestimated possibly due to overestimation of mixing in the epilimnion and higher light absorption rate. The maximum temperature at the surface is simulated to be around 40°C when the model is run with uncalibrated parameters while the actual maximum measured temperature in upper layers of epilimnion is 27 °C.

Figure 3.13: Raw output of Simstrat simulation for Green Lake (right) VS actual temperature data (East site, left) (5/10/2017-9/11/2017).

The results from the Simstrat simulation for the East site in 2017 following parameter optimization are presented in Figure 3.14 and Figure 3.15. The optimized parameters are presented in Appendix A. After optimization, the simulated model presents a very good fit. The location of the thermocline, extent of mixing and temperature of the epilimnion are correctly simulated. The maximum temperature simulated at the surface agrees well with actual measured data at the East site.

Figure 3.14: Optimized output of Simstrat simulation for Green Lake (right) vs. monitored temperature data (East site, left) plotted for the first 25 meters of the lake (5/10/2017-9/11/2017).

Figure 3.15: Optimized output of Simstrat simulation for East site temperature data (right) VS actual temperature data (left) plotted for all layers of the lake (5/10/2017-9/11/2017).

3.3.1 Hydrodynamic model validation

Simstrat was also run using the optimized parameters based on 2017 data to simulate the lake's physical behavior for 2018. The simulation shows good agreement with actual 2018 data and predicts the thermocline at a correct depth (Figures 3.16 and 3.17).

Figure 3.16: Output of Simstrat simulation for 2018 temperature data using 2017 calibrated parameters (right) VS actual 2018 temperature data (left) plotted for the upper 25 m of the lake (6/12/2018- 10/8/2018).

Figure 3.17: Output of Simstrat simulation for 2018 temperature data using 2017 calibrated parameters (right) VS actual 2018 temperature data (left) plotted for all layers of the lake (6/12/2018- 10/8/2018).

3.3.2 Diffusivity Coefficients

The diffusivity coefficients between layers were obtained as output from Simstrat (Figure 3.18). These coefficients are used to describe the vertical movement of water, and therefore, required for the estimation for the transfer of dissolved oxygen between the layers. The diffusivity coefficients for both years within 0-0.5 m²/h are plotted below. These figures show high turbulence at the surface of the lake due to wind events and at the bottom of the lake due to the lake's bottom friction. More turbulence and therefore more mixing is observed during 2017 as compared with 2018. The wind data has been obtained from two different sites during these two study periods. During 2017, the data has been obtained from University of Wisconsin-Madison and during 2018, the data has been obtained from Fond du Lac County Airport. The differences in diffusivity coefficients might have been caused by this reason.

Figure 3.18: Diffusivity coefficients modeled for 2017 (left) and 2018 (right)

3.4 Oxygen Model

The development of the oxygen model is presented here step by step, to illustrate the effects of each term on the overall oxygen behavior. Model output considering only water column fluxes and the air/water exchange is shown in Figure 3.19. There is no biological oxygen production or consumption occurring during this step. The only flux of oxygen into or out of the system at this step occurs at the surface layer of the lake via air-water exchange. The oxygen introduced into the waterbody then gets transferred into deeper layers via diffusion. Before stratification, the oxygen distribution throughout the waterbody is uniform as the lake is well mixed and oxygen gets transferred throughout the lake. After stratification, the minimum concentration of oxygen is witnessed in the epilimnion and corresponds to the saturation level of oxygen at the lake's surface temperature and is in equilibrium with the air. The temperature is lower in the metalimnion, and therefore it contains more oxygen compared to the epilimnion. However, metalimnetic water gets over-saturated as there is no sink of oxygen present there and there is no mixing present after stratification.

Figure 3.19: Water column fluxes and air/water exchange plot

The most dominant effect on oxygen concentrations at the bottom of the lake is oxygen consumption by SOD (section 2.5.2). Although SOD is present throughout the lake, its effect strengthens exponentially as the lake gets deeper and has relatively more sediments and organic matter present at deeper layers due to focusing. The output of the model incorporating the effect of SOD is shown in Figure 3.20. In this step, there is still no internal production of oxygen. Oxygen is exchanged at the air/water boundary and gets consumed at the sediment-water interface via SOD. As it is presented in Figure 3.20, there is no change in the oxygen budget of the surface layers compared to Figure 3.19 as there is no new source or sink of the oxygen added to those layers. The ratio of the sediment surface area to the volume gets greater with depth due to the lake's bathymetry and therefore, the effect of SOD is more pronounced at the deeper layers. This term is responsible for the oxygen consumption at the bottom of the hypolimnion and its effect is visible in Figure 3.20.

Figure 3.20: Model of Fluxes + SOD

Next oxygen production via photosynthesis, which occurs within the photic zone, was added. During 2017, the photic zone was approximately the upper 11 meters of the lake and photosynthesis happens in that region. In Figure 3.21, the effect of oxygen production due to algal photosynthesis is visible in the photic zone. There is still no internal sink of oxygen in the epilimnion and the only transfer happens via air/water exchange at the surface.

Figure 3.21: Model of Fluxes + SOD + productivity

The final step in developing the lake's oxygen model is the introduction of water column respiration as additional sink of oxygen. Water column respiration is present through the whole lake and corresponds with the community respiration in the layers. In the developed model, the respiration rate is a function of oxygen concentration of the overlying layer, temperature of the layer and biomass concentration of the layer. The level of biomass present in the lake is dependent on the level of spring bloom which is settled through the lake and is available for oxidation. The final model output is presented and compared with data in Figure 3.22. This model predicts the magnitude of oxygen throughout the lake accurately and it predicts the MOM. However, the model predicts the MOM at a shallower depth. The collected data shows formation of MOM at around 13 meters, but the predicted MOM is forming at around 10 meters. The overall model shows high oxygen concentration in epilimnion that fails to mix with deeper layers. This low estimated mixing rate due to possible underestimation of diffusivity coefficients can be the reason behind formation of MOM at shallower depths. As the effect of nutrients is neglected in the oxygen model, the extent of spring bloom and water column biomass concentration might not be exactly calculated. The lower level of oxidizable content in the layers, underestimation of diffusivity coefficients and absence of settling term are the possible reasons of MOM prediction at shallower depths compared to actual measured data.

Figure 3.22: Plots of actual smooth oxygen data (left) and modeled oxygen (right) for 2017 data.

There is a relationship between the biomass or available oxidizable content of the lake and respiration rates (equations 2-34, 2-35). Biomass gets depleted at the same region in which the MOM occurs. This may be an indicator of high in-situ respiratory activities. The behavior of modeled biomass in the lake is plotted in Figure 3.23:

Figure 3.23: behavior of biomass in the lake

3.5.1 Oxygen model validation

The developed model's performance was tested by forcing the calibrated version using 2018 hydrodynamic output and clarity data. The results are presented in Figure 3.24. The depth of the MOM is predicted accurately, but the rate of oxygen consumption is more intense in the 2018 model compared to the actual data. This may be caused by overestimation of the respiration rate by the calibrated oxygen model. This high respiration rate is visible throughout the whole lake as the overall oxygen concentration of the lake in 2018 model is lower compared to the actual 2018 data. Lower calculated values for the diffusivity coefficient by Simstrat and lower water column mixing rates may be another reason behind the higher intensity of MOM in 2018. It appears the highly oxygenated epilimnetic water fails to get mixed into deeper layers. Therefore, the oxygen concentration is overestimated in the epilimnion and underestimated in the metalimnion.

Figure 3.24: Comparison of the modeled oxygen for 2018 data (right) and the actual 2018 data.

3.5 Sensitivity Analysis

Understanding the model components and their effect on the overall behavior of oxygen in this lake is of utmost importance, especially when translating model results to management actions. Although all the parameters were adjusted during model calibration, the same approach might not be necessary in the future works as some of these parameters might not be very sensitive to change. A sensitivity analysis can be helpful for this purpose. Below, the behavior of the model is presented after increasing and reducing each parameter. All the parameters (with the exception of theta values) are multiplied and divided by 2 and their effect on the model is studied. Theta values affect the model exponentially and the reported values falls within the range of 1-1.1. However, a range of 1-1.5 was set for thetas during the model optimization process. Therefore, this range is assumed to be the set criteria and the theta values are assumed not to exceed the range of 1-1.5.

Figure 3.25: Effect of change in initial B (biomass) on the model output. The model initial B is obtained by model calibration.

Figure 3.26: Effect of change in k_g (algal oxygen production rate) on the model output. The model k_g is obtained by model calibration.

Figure 3.27: Effect of change in θ_g (Temperature coefficient for productivity What is this?) on the model output. The model θ_g is obtained by model calibration.

Figure 3.28: Effect of change in I_s (optimal light level) on the model output. The model I_s is obtained by model calibration.

Figure 3.29: Effect of change in k_r (respiration rate) on the model output. The model k_r is obtained by model calibration.

Figure 3.30: Effect of change in θ_r (temperature coefficient for respiration) on the model output. The model θ_r is obtained by model calibration.

Figure 3.31: Effect of change in k_{SOD} (sediment oxygen consumption rate) on the model output. The model k_{SOD} is obtained by model calibration.

Figure 3.32: Effect of change in b (SOD depth dependency) on the model output. The model b is obtained by model calibration.

Figure 3.33 Effect of change in θ_{SOD} (what is this) on the model output. The model θ_{SOD} is obtained by model calibration.

Sensitivity analysis points out that all the growth parameters k_g (oxygen production rate) and θ_g (productivity temperature dependency) affect the epilimnetic DO concentrations, however, they don't seem to have a significant effect on the MOM. The location of MOM and its intensity stays the same after increasing and reducing the mentioned values. The term I_s (optimum light level) doesn't seem to have any significant effect on the overall model when it's doubled or decreased in half. Greater changes in this value might be required for its effect to be seen in the model. A set value of 200 (watt/m^2) can be defined for this term for future works.

Changes in the SOD terms (k_{SOD} , b and θ_{SOD}) highly affects the overall behavior of the model. Change in k_{SOD} (rate of oxygen consumption by sediments) results in an overall change in the oxygen budget of the whole lake whereas changes in b (SOD depth dependency) and θ_{SOD} (SOD temperature dependency) have a great impact on the oxygen budget at the bottom of the lake. k_{SOD} affects the location of the MOM and its value should be considered and studied in any future model development.

Changes in the respiration parameters (B , θ_r and k_r) have great impact on overall model behavior, MOM intensity and MOM location. An increase in biomass value highly reduces the level of oxygen and causes an intense depletion in oxygen level, both in the metalimnion and the hypolimnion. Increasing biomass makes MOM form earlier and spread to deeper layers (up to 20m). It's possibly the most important factor in managing MOM in Green Lake. k_r (water column respiration rate) primarily affects the oxygen consumption of the water column. However, it also affects the depth of MOM formation

and its location. An increase in k_r results in a faster oxygen depletion in the water column and makes the MOM spread into deeper layers. A decrease in k_r value increases the oxygen throughout the lake, however it cannot stop MOM although it restricts it to a specific region. θ_r (respiration temperature dependency) also affects the oxygen of the whole lake. A decrease in its value results in the lake highly depleted of oxygen. However, increasing its value doesn't make the MOM to go away, but increases the oxygen budget of the hypolimnion.

Initial Oxygen Profile on the First Day: This possibility should always be considered that the model's results are determined by initial conditions. To explore the sensitivity of the model to initial conditions, a uniform profile of oxygen with 13 g/m^3 DO concentration is assumed and the model result is studied. The result shows an MOM still forms regardless of the initial profile of oxygen.

Figure 3.34: modeled oxygen for 2017 with uniform initial oxygen profile

Initial Biomass Profile on the First Day: As the importance of biomass content of the lake on MOM is evident, it's important to study its initial profile and its potential effects on MOM formation. The hypothesis that the initial biomass profile is causing the MOM can be evaluated by setting a uniform initial biomass profile and run the model. The set value for the profile is set to its optimized value of 15.3. The results are presented in Figure 3.34. The results show MOM still forms at the same spot it was initially modeled, and with greater intensity.

Figure 3.35: Modeled oxygen for 2017 with uniform initial biomass profile

Biomass management for MOM control: As it can be inferred from sensitivity analysis on biomass, this term has the most impact on MOM and is the most important factor in eliminating or reducing MOM. The sensitivity analysis shows that when the initial biomass concentration is reduced to half of its initial value from 15.3 to 7.65, the MOM intensity vastly decreases (Figure 3.25). When the model is run with 1/3 of the initial biomass value (reducing it from 15.3 to 5.3) MOM appears to almost disappear. The results are presented in Figure 3.36. However, as the oxygen concentration of 5 mg/l is reported as the critical value, it's important to understand the required level of biomass reduction to meet that criteria. It is shown in Figure 3.37 that reducing the biomass concentration to 2/3 of its initial value (from 15.3 to 10.3) brings the oxygen level above 5 mg/l. The level of initial biomass is related to the nutrients loading into the lake. Nutrients affect the level of productivity at the surface of the lake and spring bloom. The initial biomass is incorporating the effect of the spring bloom into the model. To study the effect of the biomass term on the overall oxygen budget of the lake, the relation between the level of the lake's nutrients and the intensity of this bloom should be studied in future works.

Figure 3.36: The effect of reducing biomass concentration to 1/3 of its initial value on MOM (right) and its comparison with the developed oxygen model for 2017.

Figure 3.37: The effect of reducing biomass concentration to 2/3 of its initial value on MOM (right) and its comparison with the developed oxygen model for 2017.

4 Conclusions

Green Lake, Wisconsin, was monitored using in-situ sensor arrays during the 2017 and 2018 growing seasons. Data from both years confirm the presence of a MOM. During 2017, MOM occurs at around 13 m and during 2018; it forms in a shallower depth and at approximately 8-11m. Despite this shallow occurrence of MOM, the magnitude of oxygen minima and the least observed values on both years is the same and they are close to zero. In general, there is good agreement between the east and west basins of the lake in terms of lake stratification, MOM depth, and MOM intensity. However, the presence of a strong seiche was revealed by comparing temperature and oxygen profiles from these two sites. Simstrat, a k-epsilon model used to incorporate the effect of seiche into modeling the hydrodynamics of the lake, was able to successfully predict the intensity and timing of stratification accurately.

An oxygen model, incorporating only terms for productivity, water column respiration, SOD and fluxes (vertical and air-water), predicts the formation of MOM in Green Lake successfully. The developed model also takes the effect of respiration of oxidizable materials or biomass into account, presented in oxygen units. Settling is not incorporated into the model, suggesting that its effect on overall oxygen behavior of the lake and MOM formation may be negligible, however, it might be the reason behind MOM formation at shallower depths.

A sensitivity analysis on production terms, water column respiration terms and SOD terms revealed the importance of respiration in controlling the MOM compared to other factors. The production terms affect oxygen production in the upper epilimnion, but fail to have any significant effects on the timing and location MOM formation or its intensity. SOD terms mostly affect the oxygen consumption at the bottom of the lake and its effects on MOM formation is also negligible. Respiration terms, and more specifically, the initial concentration of oxidizable materials (a proxy for the intensity of spring productivity) seem to be the most important factors in controlling the formation and intensity of MOM.

By reducing initial biomass to 1/3 of its default (calibrated) value, the MOM almost completely disappears. By reducing the initial biomass concentration to 2/3 of its initial value (from 15.3 to 10.3), the oxygen concentration in the metalimnion can be maintained above the critical value of 5 mg/l.

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A Simstrat Setup and Input Files

Table 5: Simstrat parameter file (Bärenbold, 2018; Gaudard, et al., 2015)

JSON key	Description
Input	
Initial conditions	Path to initial conditions file
Grid	Path to grid file / vector of grid / grid resolution
Morphology	Path to morphology file
Forcing	Path to forcing file
Absorption	Path to light attenuation file
Inflow	Path to inflow file
Outflow	Path to outflow file
Inflow temperature	Path to temperature inflow file
inflow Salinity	Path to salinity inflow file
Output	
Path	Path result folder (is created if non-existent)
OutputDepthReference	1: Lake bottom, 2: Lake water table
Depths	Path to file / vector of depths / output depth resolution
Times	Path to file / vector of times / output time resolution
ModelConfig	
MaxLengthInputData	Maximum size of initial input data (initial conditions, morphology, grid...)
CoupleAED2	Biogeochemistry model (0:off, 1:on)
TurbulenceModel	Turbulence model (1:k-ε, 2:M-Y)
StabilityFunction	Stability function (1:constant, 2:quasi-equilibrium)
FluxCondition	Flux condition (0:Dirichlet condition, 1:no-flux)
Forcing	Forcing (1:Wind+Temp+SolRad, 2:Wind+Temp+SolRad+VapP, 3:Wind+Temp+SolRad+VapP+Cloud, 4:Wind+HeatFlux+SolRad) 5:Wind+Temp+SolRad+VapP+Incoming_long_wave
UseFilteredWind	Use filtered wind to compute seiche energy (if "true", one more column is needed in forcing file)
SeicheNormalization	Seiche normalization (1:max N ² , 2:integral)
WindDragModel	Wind drag model (1:lazy (constant), 2:ocean (increasing), 3:lake (Wüest and Lorke 2003))
InflowPlacement	Inflow placement (0/default:manual, 1:density-driven)
PressureGradients	Pressure gradients (0/default:off, 1: Svensson 1978, 2:?)
IceModel	0: off, 1: on
SnowModel	0: off, 1: on (needs an additional column in the forcing file: precipitation)

Simulation	
Timestep s	Simulation timestep in seconds
Start d	Start time in days
End d	End time in days
DisplaySimulation	Display in terminal (0: off, 1: when data is saved, 2: at every iteration)
ModelParameters	
lat	Latitude for Coriolis parameter [°]
p_air	Air pressure [mbar]
a_seiche	Fraction of wind energy to seiche energy [-]
q_nn	Fit parameter for distribution of seiche energy [-]
f_wind	Fraction of forcing wind to wind at 10m [-]
c10	Wind drag coefficient (a physical constant around 0.001 if wind drag model is 1; a calibration parameter around 1 if wind drag model is 2 or 3) [-]
cd	Bottom drag coefficient [-]
hgeo	Geothermal heat flux [W/m2]
k_min	Minimal value for TKE [J/kg]
p_radin	Fit parameter for absorption of IR radiation from sky [-]
p_windf	Fit parameter for convective and latent heat fluxes [-]
beta_sol	Fraction of short-wave radiation directly absorbed as heat by water [-]
beta_snowice	Fraction of short-wave radiation directly absorbed as heat by snow and ice [-]
albsw	Albedo for reflection of short-wave radiation on water [-]
ice_albedo	Albedo for reflection of short-wave radiation on ice [-]
snow_albedo	Albedo for reflection of short-wave radiation on snow [-]
freez_temp	Freezing temperature of water [°C]

Table 6: Morphology input file. This file should be in DAT format and in two columns of depth (m) and area (m²). The data is put in different columns for presentation purposes.

depth [m]	area [m2]	depth [m]	area [m2]	depth [m]	area [m2]	depth [m]	area [m2]
0	26542600	-21.5	15485900	-42.5	11015800	-63.5	4343500
-1.5	24344700	-22.5	15300700	-43.5	10789200	-64.5	4026200
-2.5	23079800	-23.5	15113300	-44.5	10526200	-65.5	3799800
-3.5	21511200	-24.5	14918300	-45.5	10270100	-66.5	3620100
-4.5	20264700	-25.5	14721800	-46.5	9944600	-67.5	3165100
-5.5	19500100	-26.5	14514100	-47.5	9610300	-68.5	1195500
-6.5	19021000	-27.5	14286700	-48.5	9259600	-69.5	608400
-7.5	18660700	-28.5	14054800	-49.5	8910400	-70.5	251600
-8.5	18218400	-29.5	13818200	-50.5	8562600	-71.5	58000
-9.5	17963300	-30.5	13592400	-51.5	8288900	-72.5	9000
-10.5	17754900	-31.5	13369100	-52.5	8006500	-73.5	700
-11.5	17564400	-32.5	13153000	-53.5	7727100	-74.5	100
-12.5	17382000	-33.5	12945500	-54.5	7479800	-75.5	0
-13.5	17196000	-34.5	12765900	-55.5	7235900		
-14.5	17003200	-35.5	12587700	-56.5	6985700		
-15.5	16785600	-36.5	12404400	-57.5	6744900		
-16.5	16556200	-37.5	12204700	-58.5	6491000		
-17.5	16304900	-38.5	11999300	-59.5	6197400		
-18.5	16066700	-39.5	11770400	-60.5	5648400		
-19.5	15858300	-40.5	11497400	-61.5	5053100		
-20.5	15673700	-41.5	11253200	-62.5	4676100		

Table 7: Initial conditions input file for the first 10 meters of the lake. This file should be in DAT format.

depth (m)	u (m/s)	v (m/s)	T (°C)	S	k	eps
0	0	0	8.636921	0.2	3.00E-06	5.00E-10
-1	0	0	8.377625	0.2	3.00E-06	5.00E-10
-2	0	0	8.133999	0.2	3.00E-06	5.00E-10
-3	0	0	8.060717	0.2	3.00E-06	5.00E-10
-4	0	0	8.024102	0.2	3.00E-06	5.00E-10
-5	0	0	7.888632	0.2	3.00E-06	5.00E-10
-6	0	0	7.838915	0.2	3.00E-06	5.00E-10
-7	0	0	7.757678	0.2	3.00E-06	5.00E-10
-8	0	0	7.602409	0.2	3.00E-06	5.00E-10
-9	0	0	7.509313	0.2	3.00E-06	5.00E-10
-10	0	0	7.390034	0.2	3.00E-06	5.00E-10

Table 8: Forcing modes and their input requirements (Bärenbold, 2018; Gaudard, et al., 2015)

Forcing Mode	t	u	v	T	Sol	Vap	Cloud	Precipitation
1	Time [d]	Wind speed East [m/s]	Wind speed North [m/s]	Water surface temperature [°C]	Solar radiation [W/m2]			
2	Time [d]	Wind speed East [m/s]	Wind speed North [m/s]	Air temperature [°C]	Solar radiation [W/m2]	Vapor pressure [mbar]		(Precipitation [m/h])
3	Time [d]	Wind speed East [m/s]	Wind speed North [m/s]	Air temperature [°C]	Solar radiation [W/m2]	Vapor pressure [mbar]	Cloud cover [-]	(Precipitation [m/h])
4	Time [d]	Wind speed East [m/s]	Wind speed North [m/s]	Air temperature [°C]	Solar radiation [W/m2]			
5	Time [d]	Wind speed East [m/s]	Wind speed North [m/s]	Air temperature [°C]	Solar radiation [W/m2]	Vapor pressure [mbar]	Incoming long wave rad [W/m2]	

Table 9: Forcing input file for the first 10 days. This file should be in DAT format.

t	u (m/s)	v (m/s)	Tair (°C)	Fsol (W/m2)	vap (mbar)
42865.75	-0.06778	1.031108	14.25685	22.51667	13.83724
42865.79	0.924283	-0.46204	13.23704	5	12.42422
42865.83	-0.0596	-0.07183	12.60574	0.6	12.43192
42865.88	0	0	12.06583	0.6	12.60238
42865.92	0	0	11.85593	0.6	12.64922
42865.96	0	0	11.66185	0.6	12.68053
42866	-0.09017	-0.02409	11.69824	0.6	12.78277
42866.04	0	0	11.90824	0.6	12.87779
42866.08	-0.66831	1.450069	11.96898	0.6	13.04556
42866.13	0.321506	-2.04151	11.8113	0.6	12.99743

Table 10: Light absorption input for the first 10 days. This file should be in DAT format.

t	z_ga (1.row)	ga1 (rest)
1		
-1	1	
0	0.772532189	
42865.75	0.772532189	
42865.79	0.772091407	
42865.83	0.771651127	
42865.88	0.77121135	
42865.92	0.770772073	
42865.96	0.770333297	
42866	0.76989502	
42866.04	0.769457241	
42866.08	0.76901996	
42866.13	0.768583175	

Table 11: Initial values of simstrat parameters (Bärenbold, 2018)

Parameters	Description	Parameter Values
lat	Latitude for Coriolis parameter [°]	43.8441
p_air	Air pressure [mbar]	985
a_seiche	Fraction of wind energy to seiche energy [-]	0.01
q_nn	Fit parameter for distribution of seiche energy [-]	1
f_wind	Fraction of forcing wind to wind at 10m [-]	1
c10	Wind drag coefficient (a physical constant around 0.001 if wind drag model is 1; a calibration parameter around 1 if wind drag model is 2 or 3) [-]	1
cd	Bottom drag coefficient [-]	0.002
hgeo	Geothermal heat flux [W/m2]	0.1
k_min	Minimal value for TKE [J/kg]	1.00E-15
p_sw	Fit parameter for absorption of short-wave radiation from sky [-]	1
p_lw	Fit parameter for absorption of IR radiation from sky [-]	1
p_windf	Fit parameter for convective and latent heat fluxes [-]	1
beta_sol	Fraction of short-wave radiation directly absorbed as heat by water [-]	0.3
beta_snowice	Fraction of short-wave radiation directly absorbed as heat by snow and ice [-]	0.4
wat_albedo	Albedo for reflection of short-wave radiation on water [-]	0.08

Table 12: Simstrat parameters after model calibration

Parameters	Description	Parameter Values
lat	Latitude for Coriolis parameter [°]	43.8441
p_air	Air pressure [mbar]	985
a_seiche	Fraction of wind energy to seiche energy [-]	0.012263
q_nn	Fit parameter for distribution of seiche energy [-]	0.946940
f_wind	Fraction of forcing wind to wind at 10m [-]	1.190313
c10	Wind drag coefficient (a physical constant around 0.001 if wind drag model is 1; a calibration parameter around 1 if wind drag model is 2 or 3) [-]	1.596900
cd	Bottom drag coefficient [-]	0.000032
hgeo	Geothermal heat flux [W/m ²]	0.196185
k_min	Minimal value for TKE [J/kg]	2.653242E-16
p_sw	Fit parameter for absorption of short-wave radiation from sky [-]	1.215399
p_lw	Fit parameter for absorption of IR radiation from sky [-]	1.392101
p_windf	Fit parameter for convective and latent heat fluxes [-]	3.854007
beta_sol	Fraction of short-wave radiation directly absorbed as heat by water [-]	0.568910
wat_albedo	Albedo for reflection of short-wave radiation on water [-]	0.172939

B USGS Sonde Data and Data Loggers Comparison

Figure 5.1: Temperature profiles from USGS sonde measurements (deep hole) compared with sensor measurements (interpolated from 26-67m) on 6/12/2018.

Figure 5.2: Temperature profiles from USGS sonde measurements (deep hole) compared with sensor measurements (interpolated from 26-67m) on 7/24/2018.

Figure 5.3: Temperature profiles from USGS sonde measurements (deep hole) compared with sensor measurements (interpolated from 26-67m) on 8/2/2018

Simstrat Function:

79

```

"double", "double", "double", "double", "double", "double", "double",
"double", "double", "double", "double", "double", "double", "double",
"double", "double", "double", "double", "double", "double", "double",
"double", "double", "double", "double", "double", "double", "double",
"double", "double", "double"];
opts.ExtraColumnsRule = "ignore";
opts.EmptyLineRule = "read";

% Import the data
metal=T_True';
dTdx=abs(metal(:,2:end)-metal(:,1:end-1));
[T_Truemax,D1]=max(dTdx);

%
Tout = readtable("TestCases_Results_2017\T_out.dat", opts);
TTout=(Tout{2:end,10:end-1});
meta2=TTout';
dTdx2=abs(meta2(:,2:end)- meta2(:,1:end-1));
[TToutmax,D2]= max(dTdx2);

%

err = sqrt(mean(mean((D2-D1)./D2).^2))+sqrt(mean(mean(((TTout-
T_True))./TTout).^2)));

updatereport(par(1),par(2),par(3),par(4),par(5),par(6),par(7),par(8),pa
r(9),par(10),par(11),par(12),err)
end

```

Simstrat Inputs:

```

clear all
clc
fclose('all')

global T_True
T = readtable('Temp_East.csv');
TT=T{2:end,2:end};
T_True=flip(TT,2);

%
updatepar(a_seiche,q_nn,f_wind,c10,cd,hgeo,k_min,p_sw,p_lw,p_windf,beta
_sol,wat_albedo)

global variable_handle
global par0

```

```

%
updatepar(a_seiche,q_nn,f_wind,c10,cd,hgeo,k_min,p_sw,p_lw,p_windf,beta
_sol,wat_albedo)
variable_handle = [1,1,1,1,0,1,0,1,1,1,1,1];

par0=[0.044424,1,1.413078,1,0.002,0.1,2.653242e-
16,1.182900,1,2.247673,0.3,0.08];
par_start = par0(variable_handle == 1);

```

Simstrat Parameters Update:

```

function
updatepar(a_seiche,q_nn,f_wind,c10,cd,hgeo,k_min,p_sw,p_lw,p_windf,beta
_sol,wat_albedo)
    fid = fopen('TestCase_GreenLake_2017.par','r');
    i = 1;
    tline = fgetl(fid);
    A{i} = tline;
    while ischar(tline)
        i = i+1;
        tline = fgetl(fid);
        A{i} = tline;
    end
    fclose(fid);
    % Change cell A
    A{46} = sprintf('    "a_seiche"        : %f, ',a_seiche);
    A{49} = sprintf('    "q_nn"            : %f, ',q_nn);
    A{50} = sprintf('    "f_wind"         : %f, ',f_wind);
    A{51} = sprintf('    "c10"           : %f, ',c10);
    A{52} = sprintf('    "cd"            : %f, ',cd);
    A{53} = sprintf('    "hgeo"          : %f, ',hgeo);
    A{54} = sprintf('    "k_min"         : %e, ',k_min);
    A{55} = sprintf('    "p_sw"          : %f, ',p_sw);
    A{56} = sprintf('    "p_lw"          : %f, ',p_lw);
    A{57} = sprintf('    "p_windf"       : %f, ',p_windf);
    A{58} = sprintf('    "beta_sol"      : %f, ',beta_sol);
    A{59} = sprintf('    "wat_albedo"    : %f, ',wat_albedo);

    % Write cell A into txt
    fid = fopen('TestCase_GreenLake_2017.par', 'w');
    for i = 1:numel(A)
        if A{i+1} == -1
            fprintf(fid,'%s', A{i});
            break
        else
            fprintf(fid,'%s\n', A{i});
        end
    end
end
end

```

D DO Model Codes

DO Model Function:

```
function err = Eval1_phi3(par)

    global DO_1
    global T_True
    global variable_handle
    global par0
    global DOE
    global kgas
    global Cs
    global V1
    global light
    global x
    global t
    global Diff
    global A1
    global d

    par_f = par0;
    par_f (variable_handle==1) = par;
    par = par_f;

    %
    %
    %load BOD
    L=zeros(length(x)+1, length(t));

    L(1,1)=par(1);

    for i=2:length(x)

        L(i,1)=(1-0.011545).*L(i-1,1);

    End

    %load DO
    phi3=zeros(length(x)+1, length(t));
    phi3(1,1)=DOE(1,1);

    for i=2:length(x)
        phi3(i,1)=DOE(i,1);
        % SOD(i,1)=DOE(i,1);
    end
```

```

end

%      SOD=zeros(length(x)+1,length(t));

for k=1:70

    for i=2:length(x)
        for n=2:length(t)
            K00 = A1(i-1).*Diff(i-1,n)./V1(i);
            K11 = A1(i).*Diff(i,n)./V1(i);
            if i==length(x) K11=0; end

phi3(1,n)=(phi3(2,n).*(1+K00))+(kgas(1,n).*Cs(1,n))./(1+K00+kgas(1,n)
);

phi3(i,n)=par(2).*par(3)^(T_True(i,n)-20).*((light(i,n)/par(4)).*exp((-
light(i,n)/par(4))+1))-par(5).*L(i,n).*(phi3(i-1,n)/(phi3(i-
1,n)+1)).*(par(6)).^(T_True(i,n)-20)+(phi3(i,n-
1)./(1+K00+K11))+(K00/(1+K00+K11)).*phi3(i-
1,n)+(K11/(1+K00+K11)).*phi3(i+1,n)-
(par(7).*exp(par(8).*d(i,1))).*(phi3(i-1,n)/(phi3(i-
1,n)+1)).*(par(9)).^(T_True(i,n)-20).*((abs(A1(i)-A1(i-1)))/V1(i));
%
        if phi3(i,n)<0
            phi3(i,n) =par(2).*par(3)^(T_True(i,n)-
20).*((light(i,n)/par(4)).*exp((-
light(i,n)/par(4))+1))+(phi3(i,n-
1)./(1+K00+K11))+(K00/(1+K00+K11)).*phi3(i-
1,n)+(K11/(1+K00+K11)).*phi3(i+1,n);
        end
%
L(1,n)= par(2).*par(3)^(T_True(1,n)-20).*((light(1,n)/par(4)).*exp((-
light(1,n)/par(4))+1))+(L(1,n-
1)./(1+K00+K11))+(K00/(1+K00+K11)).*0+(K11/(1+K00+K11)).*L(2,n);

L(i,n)= par(2).*par(3)^(T_True(i,n)-20).*((light(i,n)/par(4)).*exp((-
light(i,n)/par(4))+1))-par(5).*L(i,n-1).*(par(6)).^(T_True(i,n)-
20).*(phi3(i-1,n)/(phi3(i-1,n)+1))+(L(i,n-
1)./(1+K00+K11))+(K00/(1+K00+K11)).*L(i-
1,n)+(K11/(1+K00+K11)).*L(i+1,n);

        end
    end

    phi3(:,end) = phi3(:,end-1);
    L(:,end) = L(:,end-1);

```

```

end

phi=phi3;
err = sqrt(mean(mean(phi(1:30,:)-DO_1(1:30,1:end-1)).^2));

updatereportphi3(par(1),par(2),par(3),par(4),par(5),par(6),par(7),par(8),par(9),err)
end

```