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Simulations of Water Quality in Cisco Lakes in Minnesota

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Abstract

This report is the second in a series of three reports that describe model simulations of cisco (tullibee) lakes for the Minnesota Department of Natural Resources. This report describes the adaption, calibration and application of the year-round water quality model MINLAKE2010, used for the year-round simulation of daily water temperature and dissolved oxygen (DO) profiles in 28 lakes in Minnesota. The results of this report will be applied in the third report to make projections of potential (refuge) habitat for cisco, a cold-water fish, in Minnesota lakes under warmer future climate scenarios. Twenty-one cisco lakes and seven non-cisco habitat lakes were selected for the model simulations including adaptation, calibration and application of the model. Lake bathymetry data and measured water quality data (water temperature and dissolved oxygen profiles, Secchi depths, chlorophyll-*a* concentrations) were assembled and analyzed. Weather data were assembled for the periods 1961 to 2008 from six Class I weather stations, and 1991 to 2008 from three Class II weather stations. In order to more accurately project water quality conditions in cisco lakes, which are typically deep mesotrophic or oligotrophic lakes, modifications and refinements were made in the MINLAKE96 computer program, especially the simulation procedures and utility functions of the model. The model simulations of daily water temperature and DO profiles in the 28 lakes were calibrated using six calibration parameters. After calibration the average standard error of estimate (S.E.) against measured data for all 28 lakes is 1.47 ^{o}C for water temperature (range from 0.8 to 2.06 ^{o}C) and 1.50 mg/L for DO (range from 0.88 to 2.76 mg/L). The average regression coefficient (R^2) is 0.92 for water temperature (range from 0.84 to 0.97) and 0.75 for DO (range from 0.12 to 0.91). Simulation results are presented as profile plots and time-series plots. Individual model calibration parameters were analyzed, and regional values were proposed for cisco lakes without data. The model performance using proposed calibration parameter values was examined.

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Chapter 1 Introduction

Climate warming has the potential to reduce coldwater fish habitat in lakes by direct warming of the water and, in addition, increased hypolimnetic oxygen depletion during periods of stratification and thermocline deepening (Schindler et al. 1996; Stefan et al. 1996; Magnuson et al. 1997; Fang et al. 2004). Cisco is the most common coldwater stenothermal fish in Minnesota lakes. Minnesota Department of Natural Resources (MN DNR) netting assessments have sampled cisco from 648 lakes since 1946 (Minnesota DNR files). The lakes are scattered throughout much of the central and northern portions of the state and cross several ecoregions (boreal forest, hardwood forest, and prairie) and land uses (agricultural, urban, and forested). The wide distribution suggests that cisco are somewhat more eurythermal than other native, lentic coldwater stenotherms such as lake whitefish *Coregonus clupeaformis* (sampled in 155 lakes), lake trout *Salvelinus namaycush* (124 lakes) and burbot *Lota lota* (233 lakes). The combination of a wide distribution and a requirement for cold, oxygenated water, make cisco an excellent "canary in a mineshaft" species that is a sensitive indicator of climate change.

The objective of the study described in this report plus two others is to apply the University of Minnesota lake simulation and fish habitat model MINLAKE96 to better understand the potential effects of climate warming on cisco habitat in Minnesota lakes, and to determine the characteristics of potential refuge lakes for cisco if global warming projections materialize. Previous research (Stefan et al. 1995b; Stefan et al. 1996; Stefan et al. 2001; Fang et al. 2004) suggests that habitat for coldwater fish such as cisco will be greatly reduced as atmospheric CO_2 increases. Deep lakes with a large, oxygenated hypolimnion may offer refuge for coldwater stenotherms such as cisco, even if surface water temperatures in lakes rise, and periods of summer stratification lengthen. Projections of range reductions of cisco in Minnesota undergoing climate warming may be lessened by the identification of refuge lakes. Lake watershed protection efforts could be initiated and directed at refuge lakes to prevent any deterioration of water quality in these lakes by anthropogenic activities. This may include prevention of increased nutrient loading that would change the trophic state of refuge lakes and thereby threaten hypolimnetic oxygen levels (Hypolimnetic oxygen will be an increasingly important ecological resource in a warmer Minnesota).

Before applying a simulation model to predict water temperature and dissolved oxygen (DO) conditions in cisco lakes, it is necessary to re-examine the assumptions made in previous regional lake studies of year-round water quality. The previously used regional DO model for the open water season (Stefan and Fang 1994) had been calibrated against data measured in seven eutrophic or mesotrophic lakes with Secchi depth ranging from 1.0 to 3.4 meters. The model was later calibrated for one oligotrophic lake – Thrush Lake with surface area of 0.07 km^2

and maximum depth of 14.6 m (Stefan et al. 1995a). An analysis of 620 cisco lakes in Minnesota described in the first report of this study (Fang et al. 2009) has shown that cisco lakes are deeper, more transparent and less trophic than average Minnesota lakes. They are preferentially located in north central and northeastern Minnesota. About 19 percent of the cisco lakes have a mean summer Secchi depth greater than 4.5 m, about 24 percent of the cisco lakes have a maximum depth greater than 24 m, and about 10 percent of the cisco lakes have a surface area greater than 10 km^2 (Fang et al. 2009). Therefore, it is necessary to adapt, refine and recalibrate the previously used regional year-round water quality model using a set of representative cisco lakes in Minnesota. In this report the modifications made to the water quality model MINLAKE96 and its calibration will be described. The resulting model will be called MINLAKE2010. The work described in this report is concerned solely with the simulation of daily water temperature and dissolved oxygen (DO) profiles when the lake bathymetry, the trophic status of the lake and the daily weather are known. Projections of fish habitat for cisco derived from this information will be described in the third and last report of the study.

Chapter 2 of this report will give an overview of the year-round water quality model MINLAKE96 that will be modified and recalibrated for the simulation in Minnesota cisco lakes. Chapter 3 will summarize information for the 28 individual Minnesota lakes that were selected for simulation in this study. Twenty-one (21) of these 28 lakes are known to provide habitat for cisco populations; in the other seven lakes no cisco have been caught. Data on lake bathymetry and measured water quality (water temperature and dissolved oxygen profiles, Secchi depths, chlorophyll-a concentrations) were assembled and analyzed. Weather data from nine weather stations were assembled for the model simulation study (Chapter 4). To more accurately predict water quality conditions in cisco lakes, which are often deep mesotrophic or oligotrophic lakes, modifications and refinements were made in the simulation program, particularly of the simulation procedures and utility functions. These changes will be described in Chapter 5. The model outputs for each of the 28 lakes were calibrated against field measurements using six model calibration parameters (Chapter 6). Quantitative measures of model performance (error parameters developed from simulated and measured data pairs) were developed. Simulation results were presented as profile plots and time-series plots. Model calibration parameters were further analyzed and regional calibration values were proposed for cisco lakes in Minnesota (Chapter 7). Chapter 8 will provide a summary of the lake water quality modeling study. Five appendices of this report, provide supporting results and information. Appendix A shows satellite images of the 28 study lakes and their surroundings, depth contour maps, and plots of bathymetric curves. Appendix B gives measured Secchi depths in 15 Minnesota lakes. Appendix C gives the information on input files and their formats required by the MINLAKE2010 model for the simulations in 28 Minnesota lakes. Appendix D provides plots of simulated and measured water temperature and dissolved oxygen profiles in 28 Minnesota lakes, and Appendix E has time-series plots of simulated and measured water temperature and dissolved oxygen in 15 Minnesota lakes.

Chapter 2 Model Overview

A deterministic year-round water quality simulation model, MINLAKE96 (Fang and Stefan 1996a), will be used with some modifications in this study to determine potential effects of climate change on water quality and cisco habitat in Minnesota lakes. The updated or modified model is called MINLAKE2010. MINLAKE96 was developed from MINLAKE95, an earlier one-dimensional, regional, year-round water temperature and dissolved oxygen (DO) model (Stefan et al. 1994b). In this study the MINLAKE96 model will be modified and customized in order to apply it to individual or virtual cisco-habitat lakes and to further quantify the impact of future climate conditions on the cisco fish habitat. A brief review of the year-round water temperature and dissolved oxygen model, MINLAKE96, is given below.

2.1 Year-round water temperature and ice-cover model

The numerical simulation model for water temperature profiles in lakes solves the one-dimensional, unsteady heat transfer equation

$$\frac{\partial T_w}{\partial t} = \frac{1}{A}\frac{\partial}{\partial z}\left[K_z A \frac{\partial T_w}{\partial z}\right] + \frac{H_w}{\rho c_p} \qquad (2.1)$$

where T_W (^oC) is the water temperature, t (day) is the time, A (m^2) is the horizontal area of a lake as a function of depth z (m), K_Z (m^2 day^{-1}) is the vertical turbulent heat diffusion coefficient, ρc_p (J m^{-3} $^oC^{-1}$) represents heat capacity per unit volume and is equal to the density of water (ρ) times heat capacity of water (c_p), and H_w (J m^{-3} day^{-1}) is the heat source or sink strength per unit volume. Solar radiation absorption in the water column contributes to the heat source term. Heat exchange between the atmosphere and the water during the open water season (Figure 2.1) is treated as a source/sink term for the topmost water layer in a lake. For the open water season the computational scheme and the determination of source and sink terms have been discussed e.g. by Edinger et al. (1968), Ford and Stefan (1980), Harleman (1982), Hondzo and Stefan (1992; 1993b), among others. Equation (2.1) is solved numerically using an implicit finite difference scheme and a Gaussian elimination method, e.g., for time steps of one day and water layer thicknesses of one meter. The model uses a stacked layer system to represent a lake and its environment in the open-water and winter ice-cover periods. Besides the water layers, the lake sediments, the ice cover and the snow cover are included in the model by separate sub-models (Fig. 2.1). Weather parameters: daily average air temperature, dew point temperature, wind speed, sunshine percentage, total daily solar radiation and precipitation (rainfall and snowfall), are used as model input parameters to calculate heat fluxes across the water surface or ice and snow cover in winter. The dew point temperature can be calculated from air temperature and relative humidity. Sunshine percentage can be estimated from daily solar radiation when it is not available. Climate conditions and variations over seasons are driving forces of seasonal variations of water temperature in a lake.

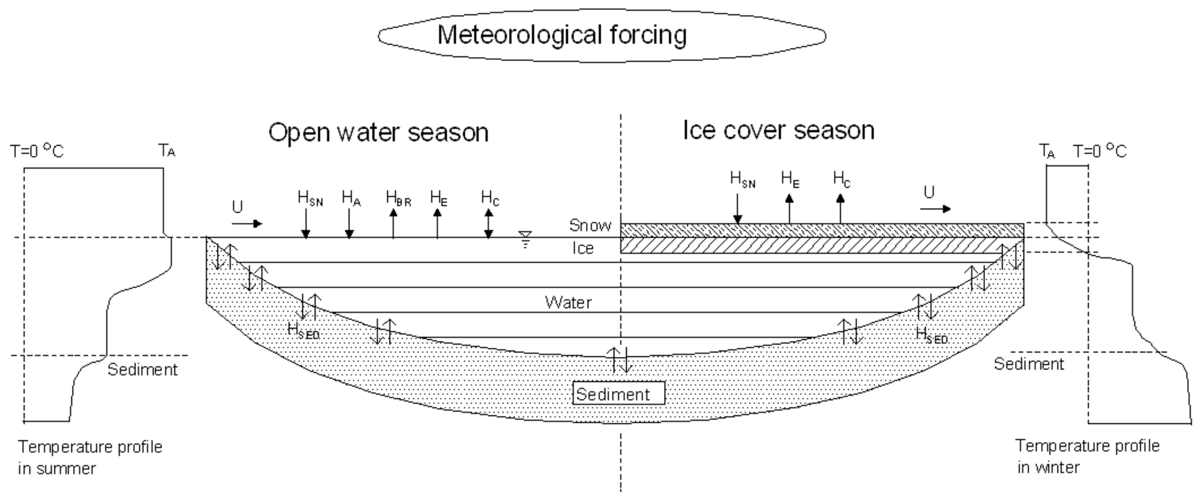

Figure 2.1 Schematic of a stratified lake with a 10 m sediment layer showing heat transfer components and water/sediment temperature profiles in the open water season and in the ice cover period.

Compared to the regional water temperature model for the open water season (Hondzo and Stefan 1992), the year round water temperature simulation model has been expanded significantly by simulating ice and snow covers above the water and including the heat exchange between each water layer and its adjoining sediments. The sediment-water heat flux is treated as a contribution to the source/sink term for each water layer from the water surface to the lake bottom (Fang and Stefan 1994). The direction of the heat flux between the sediment and the water reverses frequently on shorter, e.g., daily timescales (Fang and Stefan 1996b). Heat can transfer into or out of the lake sediment during both the open water season and the winter ice cover period. The lake sediments not only provide seasonal heat storage, but also add significant thermal inertia to the water column. Sediment heat fluxes are most important in shallow lakes and during winter ice-cover period.

The snow and ice thickness sub-models developed by Gu and Stefan (1990) have been used with some modification for the simulations. The complete set of equations used for ice and snow cover simulation has been summarized by Fang and Stefan (1994). During the ice cover period, the model simulates ice thickness and sediment temperature profiles (heat conduction equation) first, then determines the heat source/sink term H_W in equation (2.1), and finally solves the heat transfer equation (2.1) to obtain water temperature profiles below the ice. At the air/snow interface (or air-ice interface if snow is absent), the net heat flux from the atmosphere into or out of the snow/ice cover is calculated. Contributions of heat flux are made by solar radiation (H_{SN}), evaporation (H_E), and convection (H_C). Snow thickness is determined from snow accumulation (precipitation), followed by compaction and snow melting. The model simulates melting of snow by surface heat input (convection, rainfall, solar radiation), melting within the snow layer due to internal absorption of short wave radiation, and transformation of wetted snow to ice when cracks in the ice cover allows the water to migrate on the ice surface (Fang and Stefan 1996a). In the model ice growth occurs at the ice/water interface and from the ice surface (Fang and Stefan 1996a), also ice decays at the snow/ice interface, ice/water interface, and within the ice layer.

A process-descriptive algorithm which replaced previous empirical and lake size dependent criteria to predict the date of ice formation is incorporated in the model (Fang et al. 1996). Ice formation on small freshwater lakes generally occurs on a calm, cold night. Rising winds and daytime heating may subsequently break up this cover until calm and cold conditions occur again and the ice cover forms a second time (Ashton 1986). The ice-formation algorithm uses a full heat budget equation to estimate surface cooling, quantifies the effect of forced connective (wind) mixing and includes the latent heat removed by ice formation. The algorithm has a fine spatial resolution near the water surface where temperature gradients before freeze-over are the greatest. Detailed field measurements of water temperatures and local weather data leading to freeze-over of Ryan Lake, Minnesota, were used to verify the algorithm development. Inverse temperature stratification occurs in the near-surface water several hours before ice formation. The ice-formation algorithm is combined with the year-round temperature model and was tested previously against observations in Ryan Lake and eight other Minnesota lakes for multiple (9 to 36) years. The difference between the simulated and observed (permanent) ice formation dates was less than 6 days for all lakes studied.

2.2. Year-round dissolved oxygen model

The one-dimensional, deterministic, unsteady year-round dissolved oxygen transport equation, which is the basis of the DO model, is given as (Stefan and Fang 1994)

$$\frac{\partial C}{\partial t}=\frac{1}{A}\frac{\partial}{\partial z}\left(AK_Z\frac{\partial C}{\partial z}\right)-\frac{S_b}{A}\frac{\partial A}{\partial z}+P_{MAX}\,Min[L]Chla$$
$$-\frac{1}{YCHO2}k_r\theta_r^{\,T-20}Chla-k_b\theta_b^{\,T-20}BOD \qquad (2.2)$$

where C(z, t) is the dissolved oxygen concentration in mg l^{-1} as a function of depth (z) and time (t), A(z) is the horizontal area at different depths in m^2, K_z is the turbulent diffusion coefficient of DO in m^2 day^{-1}, S_b is the sedimentary oxygen demand coefficient in mg O_2 (m^{-2} day^{-1}), P_{max} is the maximum specific oxygen production rate by photosynthesis at saturating light conditions in [mg O_2 (mg Chla)$^{-1}$ hr^{-1}], Min[L] is the light limitation determined by the Haldane equation, Chla is the chlorophyll-a concentration in mg l^{-1}, YCHO2 is the yield coefficient which is the ratio of mg chlorophyll-a to mg oxygen, k_r and k_b are the first order decay for biochemical oxygen demand (BOD) and respiration rate coefficient (day^{-1}), respectively, θ_r and θ_b are the temperature adjustment coefficient for plant respiration and BOD, BOD is the biochemical oxygen demand concentration in mg l^{-1}, and T(z, t) is the water temperatures in ^oC. In the model, the oxygen transfer through the water surface (reaeration) is expressed as

$$k_e(C_s-C)/\Delta z_s \qquad (2.3)$$

It is used as an oxygen source or sink term in the topmost water (surface) layer. Diffusive oxygen flux at the lake bottom is set equal to zero as a boundary condition (sedimentary oxygen demand is treated as a source/sink term.)

For the dissolved oxygen simulations in a lake over the winter season (Figure 2.2), modifications had to be made in equation (2.2) to account for the presence of an ice cover and low temperatures. These modifications (Fang and Stefan 1994) include: (a) reaeration is zero (k_e is set equal to zero); (b) respiration rate coefficient k_r is zero, (c) water column oxygen demand, WOD, by detrital and other organic matter, is set constant (0.010 g O_2 m^{-3} day^{-1}) and independent of trophic status of a lake (Mathias and Barica 1980), and (d) sedimentary oxygen demand (S_b) is made dependent on trophic state and set equal to 0.226, 0.152, and 0.075 (g O_2 m^{-2} day^{-1}) for eutrophic, mesotrophic, and oligotrophic lakes, respectively.

It can be noted that water column oxygen demand in winter WOD is constant and very low, whereas the biochemical oxygen demand (BOD) in summer varies as a function of trophic status in the later description of the model (e.g. pages 22 and 55). Both WOD and BOD describe the same processes, i.e. microbial and chemical decomposition of detrital or non-living organic material, and can therefore be expected to depend on trophic state. However, the very limited database for WOD and its small value did not justify or require an adjustment of WOD for trophic state.

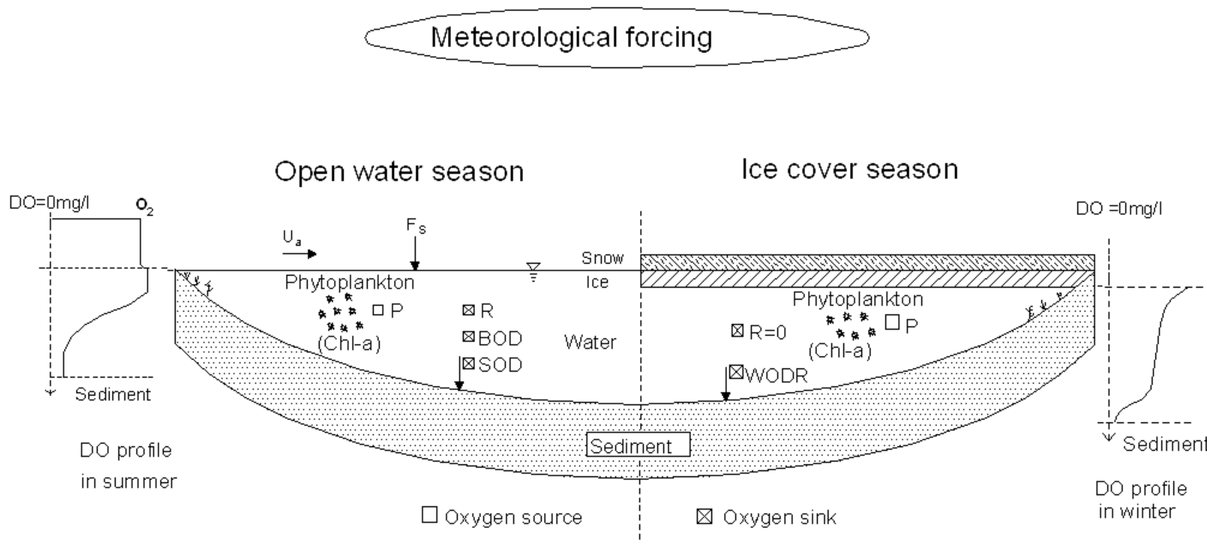

Figure 2.2 Schematic of a stratified lake showing dissolved oxygen source/sink terms and dissolved oxygen profiles in the open water season and in the ice cover period.

2.3 Model input requirements

2.3.1 *Previous lake classification*

Previous lake simulation studies focused on small lakes with surface area up to 10 km^2 and depth up to 24 m. To study the response of such lakes to climate change, a lake classification including 27 types of lakes (Table 2.1) was used previously (Stefan et al. 1992). A brief description of this lake classification is given below because it affected the selection of model parameter values used in previous studies. The 28 lakes selected for the cisco-study are significantly different from the previously used 27 lake classes; therefore, additional thought has to be given to the parameter value selection for the model calibration of the 28 lakes.

The lake geometry (bathymetry) is a model input and is specified by (a) a surface area A_s, (b) a maximum depth H_{max}, and (c) a function $A(z)/A_s$ in previous lake studies. A suitable bathymetry function derived for Minnesota lakes is

$$\frac{A(z)}{A_s} = a \exp(b \frac{z}{H_{max}}) + c \tag{2.4}$$

It characterizes the shape of the lake basin as a function of water depth z. A(z) is the horizontal area at depth z below water surface. Coefficients a, b, and c in equation (2.4) were determined by regression analysis from data for 122 Minnesota lakes (Hondzo and Stefan 1993b; Hondzo and Stefan 1993a), and are given in Table 2.2.

For the previous lake classification, lake surface areas A_S chosen were 0.2, 1.7 and 10.0 km^2 for small, medium, and large lakes, respectively; maximum depths H_{max} chosen were 4.0, 13.0 and 24.0 m for shallow, medium-depth, and deep lakes, respectively (Stefan et al. 1992). The lake classification was based on analysis of 3002 lakes in Schupp's data base for Minnesota (Hondzo and Stefan 1993a). More important than the individual numbers, is the observation that the likelihood of a strong or weak stratification in a lake can be related to the lake geometry ratio $A_S^{0.25}/H_{max}$ (Gorham and Boyce 1989). The above nine (9) types of lakes cover geometry ratios from 0.9 to 14.1. According to Gorham and Boyce (1989) polymictic lakes have the highest numbers, while strongly stratified lakes occur at the lowest numbers (Figure 2.3). The transition occurs between 3 and 5. Hence, the full range of stratification behavior is included in the 27 lake types. For the study of specific lakes with cisco habitat, the lake geometry provided by the MN DNR will be used.

Trophic state characterizes biological productivity and relates to plant density, especially phytoplankton, nutrient availability, photosynthetic oxygen production and respiratory consumption. All of these characteristics can be used to measure trophic status. In many, but not all lakes, trophic states are closely related to phytoplankton concentration and lake clarity. With this in mind, lakes were divided into three trophic states by the mean annual chlorophyll-a concentrations given in Table 2.1. Secchi depths (SD) of 1.2, 2.5, and 4.5 m were selected for eutrophic, mesotrophic, and oligotrophic lakes using Carlson's trophic state index (Carlson 1977), respectively.

Table 2.1 Physical parameters for 27 Minnesota lake classes [from Stefan et al. (1996)].

	Lake class				Lake geometry		
Key parameter	Descriptive term	Representative value used	Range	Cumulative frequency	A_s	H_{max}	$A_s : H_{max}$
Max depth, H_{max} (m)	Shallow	4.0	≤4.0	Lower 30%	0.2	4.0	5.3
	Medium	13.0	4.1–20.0	Central 60%	0.2	13.0	1.6
	Deep	24.0	20.1–45.0	Upper 10%	0.2	24.0	0.9
Surface area, A_s (km^2)	Small	0.2	≤0.4	Lower 30%	1.7	4.0	9.0
	Medium	1.7	0.5–5.0	Central 60%	1.7	13.0	2.8
	Large	10.0	5.1–40.0	Upper 10%	1.7	24.0	1.5
Secchi depth, Z_s (m)	Eutrophic	1.2	≤1.8	Lower 20–50%	10.0	4.0	14.1
	Mesotrophic	2.5	1.9–4.5	Central 20–50%	10.0	13.0	4.3
	Oligotrophic	4.5	4.6–7.0	Upper 0–10%	10.0	24.0	2.3

Table 2.2 Morphometric regression coefficients (from Hondzo and Stefan 1993a, 1993b).

Surface area	Coefficient a	Coefficient b	Coefficient c
Small (A_s = 0.2 km^2)	1.20	-1.76	-0.20
Medium (A_s = 1.7 km^2)	1.15	-2.10	-0.15
Large (A_s = 10.0 km^2)	1.10	-2.91	-0.10

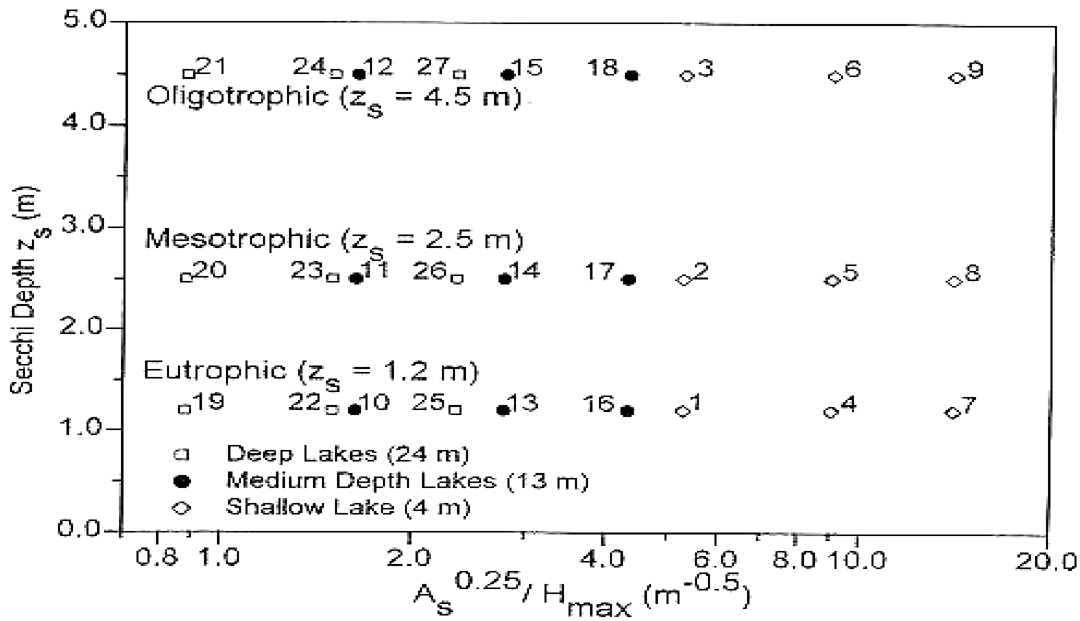

Figure 2.3 Distribution of 27 lake types on a plot with the lake geometry ratio $A_s^{0.25}/H_{max}$ as abscissa and Secchi depth z_s as ordinate.

The radiation attenuation in a lake is used to quantify how much of the solar energy reaching the water surface can penetrate through a water column to heat water below the surface, and to support photosynthesis of phytoplankton. Total attenuation coefficient, μ (m^{-1}), is given by

$$\mu = \mu_w + \mu_{ch}\,(Chl - a) \tag{2.5}$$

where μ_w (m^{-1}) is the attenuation coefficient of the lake water excluding chlorophyll-a, μ_{ch} [m^{-1} (g m^{-3} Chl-a)$^{-1}$] is the attenuation coefficient due to chlorophyll-a (Megard et al. 1979), and *Chl-a* is chlorophyll-a concentration (g m^{-3}). An alternative is to estimate total attenuation coefficient as function of Secchi depth (Hondzo and Stefan 1992) by the equation 2.6. The coefficient 1.84 is empirical, and other similar values have also been proposed.

$$\mu = \frac{1.84}{SD} \tag{2.6}$$

Table 2.3 gives total attenuation coefficient and the attenuation coefficient of the lake water for three regional lake classifications when μ_{ch} = 20 m^{-1} (g m^{-3} Chl-a)$^{-1}$ (Megard et al., 1979) is used.

Table 2.3 Trophic state values used in previous lake simulations.

Trophic state type	Chlorophyll-a Chl-a (mg m^{-3})	Secchi depth SD (m)	Total attenuation coefficient μ (m^{-1})	Attenuation coefficient of water μ_w (m^{-1})
Eutrophic	15.0	1.2	1.53	1.23
Mesotrophic	6.0	2.5	0.74	0.62
Oligotrophic	2.0	4.5	0.41	0.37

2.3.2 *Model input parameters and coefficients*

The hypsographic curve, or depth-area curve, has to be supplied as an input to the model MINLAKE96; it can be developed from hydrographic survey data, e.g., a depth contour map of a lake. If the surface area and the maximum depth of a lake are the only two known parameters, equation (2.4) can be used to estimate the depth-area curve.

A lake's trophic status has to be specified as a model input, and several other model parameters and model coefficients depend on it. The trophic status can be estimated from measurements of Secchi depth, mean summer chlorophyll-a concentration, or a total phosphorus concentration based on Carlson's trophic index.

Weather data have to be provided as model input and drive water temperature and DO dynamics calculated by the model over time. The meteorological data input is organized as daily weather data files, year by year. The weather data include daily average air temperature (^{o}F), dew point temperature (^{o}F), wind speed (mph), solar radiation (Langley), sunshine percentage, and precipitation including rainfall (cm) and snowfall (mm).

Required model coefficients developed previously and used in previous regional lake studies are given for water temperature modeling in Table 2.4 and for DO modeling in Table 2.5.

Table 2.4 Parameters and coefficient values used in the hydrothermal model (from Stefan et al. 1994).

Coefficients and symbols		Units	Range and references	Selected value
Open water season				
Radiation absorption for water	β_w	-	0.4[a]	0.4
Sediment specific heat	c_{psed}	kcal kg^{-1} $^oC^{-1}$	0.2 - 0.3[b]	0.28
Sediment thermal conductivity	k_{sed}	kcal day^{-1} $^oC^{-1}$ m^{-1}	8.64 - 51.8[b]	19.25
Radiation attenuation by Chl-a	μ_{chh}	m^2 g^{-1} Chl-a	0.2 - 31.5[c]	20.0
Radiation attenuation by water	μ_w	m^{-1}	0.33 - 1.03[d]	0.51
Sediment density	ρ_{sed}	kg m^{-3}	1650 - 2300[b]	1970
Wind sheltering	W_{str}	-	0.01 - 1.0[e]	varies
Winter ice cover				
Surface reflectivity for ice	α_i	-	0.55[h]	0.55
Surface reflectivity for snow	α_{sw}	-	0.4 - 0.95[l]	0.80
Radiation absorption for ice	β_i	-	0.17 - 0.32[f]	0.17
Radiation absorption for snow	β_{sw}	-	0.17 - 0.34[g]	0.34
Snow compaction	c_{sw}	-	0.125 - 0.5[l]	0.4
Ice thermal conductivity	k_i	kcal day^{-1} $^oC^{-1}$ m^{-1}	45.8[b]	53.6
Snow thermal conductivity	k_{sw}	kcal day^{-1} $^oC^{-1}$ m^{-1}	2.16[b]	5.57
Ice density	ρ_i	kg m^{-3}	920[b]	920.0
Snow density	ρ_{sw}	kg m^{-3}	100 - 400[l]	300.0
Radiation attenuation by ice	μ_i	m^{-1}	1.6 - 7.0[j]	1.6
Radiation attenuation by snow	μ_{sw}	m^{-1}	20 - 40[i]	40.0
Ice latent heat of fusion	λ_i	kcal kg^{-1}	80[k]	80.0
Snow latent heat of fusion	λ_{sw}	kcal kg^{-1}	80[k]	80.0

[a] Dake and Harleman (1969)
[b] Carslaw and Jaeger (1959)
[c] Bannister (1974)
[d] Megard et al. (1979)
[e] Riley and Stefan (1988)
[f] Wake and Rumer (1979)
[g] Scott (1964)
[h] Bolsenga (1977)
[I] Greene (1981)
[j] Pivovarov (1972)
[k] Ashton (1986)
[l] Lock (1990)

Table 2.5 Parameters and coefficient values in the dissolved oxygen model (from Stefan et al. 1994).

Coefficients and symbols		Units	Range and references	Selected value
Independent of trophic status				
BOD decay coefficient	k_b	day^{-1}	0.02-3.4[a]	0.1
Respiration rate coefficient	k_r	day^{-1}	0.05-0.5[a]	0.1
BOD temperature adjustment	θ_b	-	1.047[a]	1.047
Photosynthesis temperature adjustment	θ_p	-	1.066[e]	1.036
Respiration temperature adjustment	θ_r	-	1.045[c], 1.047[b]	1.047
Sediment temperature adjustment	θ_s	-	1.034-1.13[f]	1.065
Respiration ratio	YCHO2	-	0.0083[d]	0.0083
Water column oxygen demand during winter	WOD	$g\ m^{-3}\ day^{-1}$	0.01	0.01

Dependent on trophic status					
Coefficients and symbols		Units	Eutrophic	Mesotrophic	Oligotrophic
Oxygen equivalent	BOD	$mg\ l^{-1}$	1.0	0.5	0.2
Chlorophyll-a	Chl-a	$mg\ m^{-3}$	15	6	2
Sedimentary oxygen demand	S_{b20}	$g\ m^{-2}\ day^{-1}$	1.0 H_{max}=24 m	0.5 H_{max}=24 m	0.2 H_{max}=24 m
			1.5 H_{max} = 13m	0.75 H_{max} = 13m	0.4 H_{max} = 13m
			2.0 H_{max} = 4m	1.0 H_{max} = 4m	0.5 H_{max} = 4m
Sedimentary oxygen demand during winter	S_b	$g\ m^{-2}\ day^{-1}$	0.226	0.152	0.075

[a] QUAL2E (Brown and Barnwell 1987);
[b] MINLAKE (Riley and Stefan 1988)
[c] EUTR04 (Ambrose et al. 1988)
[d] (Stumm and Morgan. 1981)
[e] (Thomann and Mueller 1987)
[f] (Zison et al. 1978)

H_{max} = 4m = shallow lake H_{max} = 13m =medium depth H_{max} = 24m = deep lake

Chapter 3 Characteristics of 28 Study Lakes and Analysis of Field Data

In this chapter we discuss the selection of individual study lakes for the Minnesota cisco-lake study. These lakes were used for model calibration and application. The characteristic and model input parameters for these lakes were assembled. Field data such as measured Secchi depth, chlorophyll-a concentration, vertical temperature profiles and DO profiles were assembled.

3.1 Minnesota's cisco lakes

Information on Minnesota's cisco lakes needed for this study has been summarized and analyzed in SAFL Project Report No. 532 "Characteristics of Minnesota's Cisco Lakes" (Fang et al. 2009). There are other publications on Minnesota coldwater fish habitat that contain more detail than given in the report.

3.2 Selection of study lakes

In total, 28 Minnesota lakes were selected for calibration and application of the year-round water quality model MINLAKE2010 in order to simulate daily water temperature and dissolved oxygen profiles from which parameters can be extracted to identify potential coldwater refuge lakes for cisco in a warming Minnesota climate. The first 15 study lakes were selected and recommended in January 2009 by Peter C. Jacobson, Minnesota Department of Natural Resources (MN DNR), based on the availability of lake data and/or the presence of cisco. These 15 lakes are in the set of sentinel lakes selected by state agencies for intensive study. The 15 selected lakes include 8 cisco habitat lakes and 7 non-cisco habitat lakes. The eight cisco lakes are Lake Carlos, Cedar Lake, Lake Elk, Lake Kebekona, Lake South Twin, Ten Mile Lake, Lake Trout in Cook County, and White Iron Lake. The seven non-cisco lakes are Bear Head Lake, Lake Carrie, Lake Elephant, Hill Lake, Lake Madison, South Center Lake, and Lake St. Olaf. In the first phase of the study, MINLAKE2010 was calibrated and validated using these 15 lakes. Figure 3.1 shows the distribution of 558 cisco lakes, 15 study lakes, and the 27 regional lake classes used in previous studies on a plot using lake geometry ratio (GR = $A_s^{0.25}/H_{max}$) and Secchi depth (SD) as x- and y-axes. Cisco lakes without Secchi depth data from the 620 cisco lake database were not plotted on the graph. According to Gorham and Boyce (1989) polymictic lakes have the higher numbers on lake geometry ratio, while strongly stratified lakes occur at the lower numbers of GR (Figure 3.1). The transition occurs between 3 and 5. Figure 3.1 shows that six of the eight cisco habitat lakes are stratified mesotrophic or oligotrophic lakes (SD > 1.9 m, Table 2.2), and two cisco habitat lakes (South Twin and White Iron) are weakly stratified or polymictic lakes (GR > 4.0). The seven non-cisco lakes are either eutrophic lakes (SD < 1.9 m) or weakly stratified, polymictic lakes.

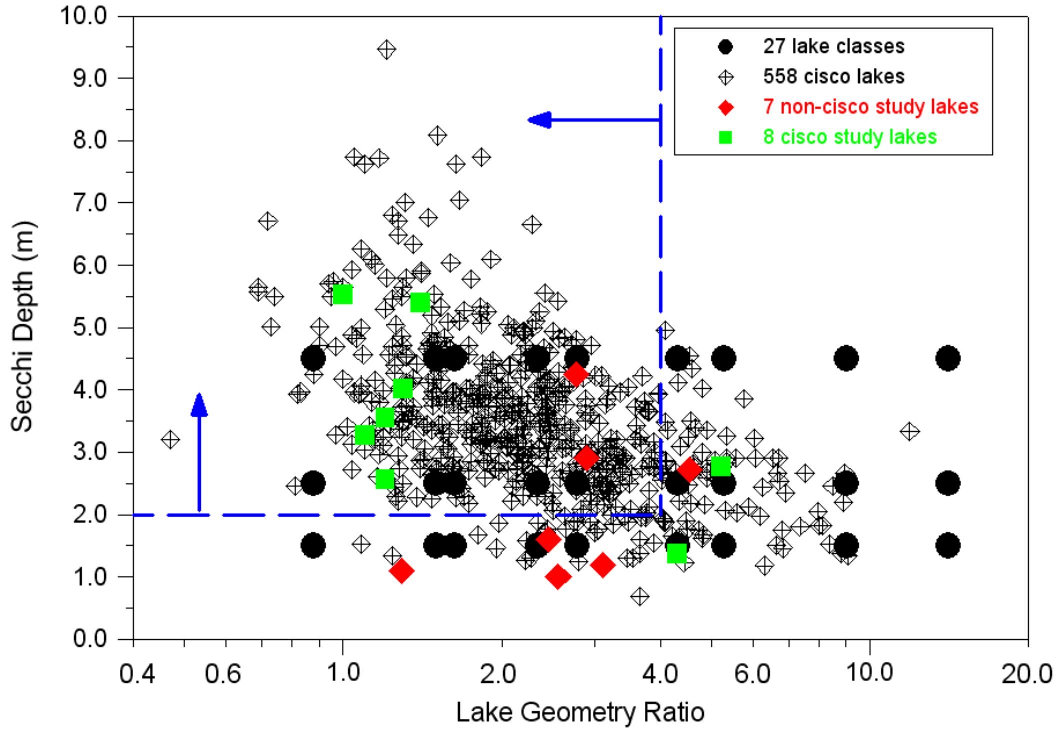

Figure 3.1 Distribution of 7 non-cisco and 8 cisco study lakes against 558 cisco lakes and the previously used 27 lake classes, on a plot of Secchi depth versus lake geometry ratio. The domain of interest is shown by the dashed boundary and arrows.

Figure 3.1 also shows that the eight cisco lakes cover only a small area of the plot and are not a representative sample of all 558 cisco lakes. During the discussion at the video conference with MN DNR in March 2010, it was therefore decided that model calibrations and simulations would be performed on an additional 12 or more cisco lakes in Minnesota. It was also agreed that additional lakes selected for further study should have Secchi depth greater than 2.0 m and lake geometry ratio less than 4.0. Blue dashed lines and arrows in Figure 3.1 indicate both limits. Accordingly, additional 13 cisco lakes were identified and selected for model calibration. These additional lakes were selected after review of existing databases because vertical temperature and DO profile data were collected on them for at least 4 days and are useful to model calibration. Therefore, a total 28 lakes in Minnesota, of which 21 lakes are cisco habitat lakes and seven are non-cisco habitat lakes, were selected for the study and were used for calibration and validation of the MINLAKE2010 model. Figure 3.2 gives the distribution of the 21 cisco lakes including 8 cisco lakes from the set of previously used 15 study lakes, and 10 regional lakes that satisfies the recommended criteria of consideration of potential refuge lakes for cisco (SD > 2.0 m and GR < 4.0 $m^{-0.5}$). Table 3.1 provides geographic information for all 28 study lakes and includes: (1) lake name, (2) MN DNR lake inventory number (DOW #), (3) primary county where a lake is located, (4) nearest town close to the lake, (5) latitude, and (6) longitude (negative number for longitude in West). Many Minnesota lakes have the same name, and there are two Little Sand Lakes and three Trout Lakes in the 620 cisco-lakes database; however, each lake has a unique inventory number (or lake ID). More information on individual lakes can be found on the MN DNR Lake Finder web site by using the lake name with primary county information or DOW number (lake ID) (URL: http://www.dnr.state.mn.us/lakefind/index.html). Latitude and longitude for each lake are given in decimal degrees (up to 4 decimal points), and anyone can use Google maps web site (http://maps.google.com/) and the lake's precise latitude longitude (given in Table 3.1) to find the lake's geographic location. Appendix A provides satellite images for all 28 study lakes and their surroundings using Google maps.

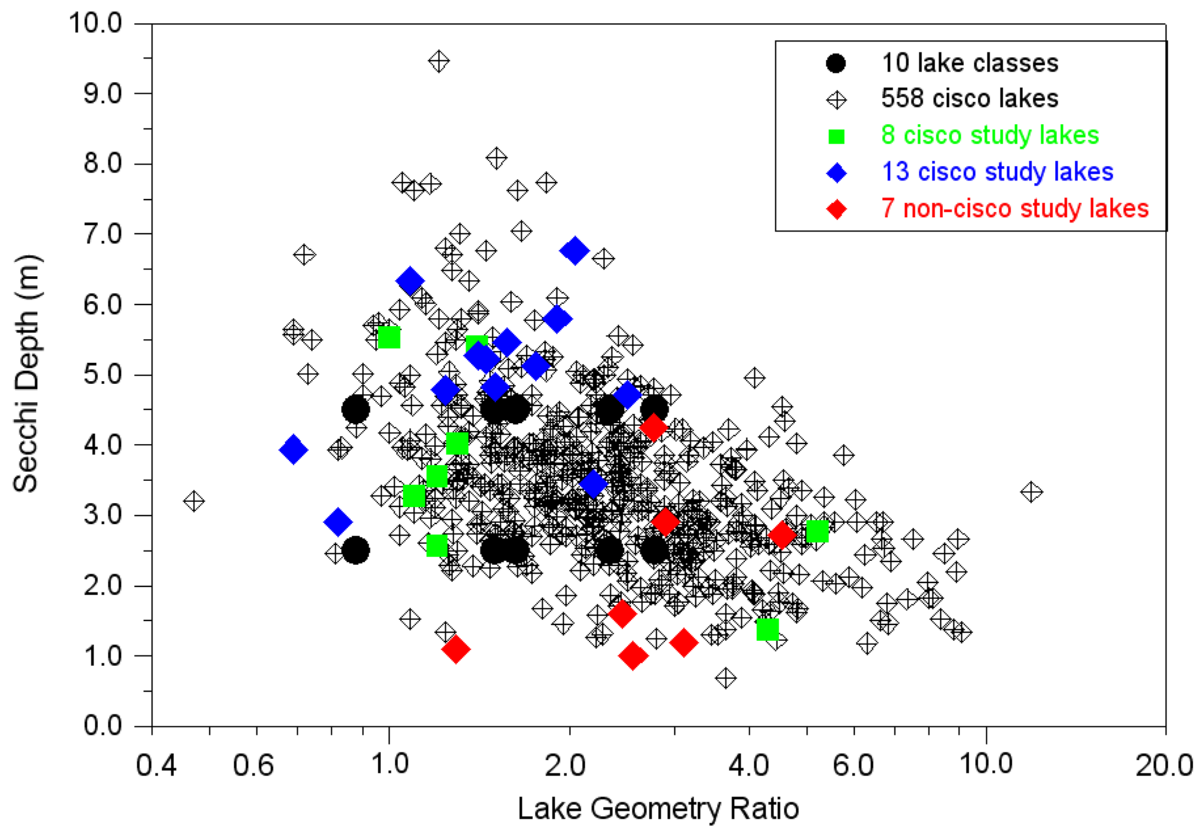

Figure 3.2 Distribution of 21 (8 + 13) cisco and 7 non-cisco study lakes against 558 cisco lakes and 10 of the previously used lake classes on a plot of Secchi depth versus lake geometry ratio.

Table 3.1 Lake inventory number (DOW) and geographic information for the 28 study lakes.

Lake name	DOW Number	County	Nearest city/town	Latitude	Longitude
Big Trout	18031500	Crow Wing	Manhattan Beach	46.7186	-94.1586
Blue	18021100	Crow Wing	Emily	46.7722	-93.9958
Burntside	69011800	St. Louis	Ely	47.9375	-92.0003
Carlos	21005700	Douglas	Carlos	45.9493	-95.3619
Cedar	49014000	Morris	Upsala	45.8133	-94.6356
Elk	15001000	Clearwater	Lake Itasca	47.1885	-95.2157
Fish Hook	29024200	Hubbard	Park Rapids	46.9578	-95.0622
Greenwood	16007700	Cook	Grand Marais	48.0069	-90.1719
Grindstone	58012300	Pine	Sandstone	46.1250	-93.0003
Kabekona	29007500	Hubbard	Laporte	47.1593	-94.7520
Little Sand	29015000	Hubbard	Dorset	46.9906	-94.9317
Little Trout	69068200	St. Louis	Crane lake	48.3972	-92.5227
Mukooda	69068400	St. Louis	Crane lake	48.3357	-92.4896
Siseebakwet	31055400	Itasca	Grand Rapids	47.1583	-93.6669
Six	56036900	Otter Tail	Frazee	46.7083	-95.7919
Snowbank	38052900	Lake	Ely	48.0000	-91.4169
South Twin	44001400	Mahnomen	Waubun	47.2250	-95.6461
Ten Mile	11041300	Cass	Hackensack	46.9782	-94.5655
Trout	16004900	Cook	Grand Marais	47.8705	-90.1668
Trout	69049800	St. Louis	Tower	47.9589	-92.3203
White Iron	69000400	St. Louis	Ely	47.8981	-91.7533
Non-cisco habitat lakes					
Bear Head	69025400	St. Louis	Tower	47.7845	-92.0794
Carrie	34003200	Kandiyohi	Atwater	45.0821	-94.7867
Elephant	69081000	St. Louis	Ash Lake	48.1931	-92.7441
Hill	01014201	Aitkin	Hill city	46.9833	-93.5947
Madison	07004400	Blue Earth	Madison lake city	44.1902	-93.8110
South Center	13002700	Chisago	Center City	45.3803	-92.8221
St. Olaf	810003000	Waseca	Mankato	43.9033	-93.4169

Figure 3.3 shows the geographic distribution of 21 cisco study lakes, 7 non-cisco study lakes, and 8 weather stations used. Two of seven non-cisco habitat lakes (Bear Head Lake and Elephant Lake) are relatively shallow (H_{max} = 9.1, and 14.0 m) mesotrophic lakes near the Canadian border, that do not support cisco habitat. Two of seven non-cisco habitat lakes (St. Olaf Lake and Madison Lake) are located south of Minneapolis/St. Paul where waters become too warm to support cisco habitat. Figure 3.4 shows the geographic distribution of all 620 cisco lakes in the MN DNR database. Cisco lakes are predominantly located in central and northern Minnesota.

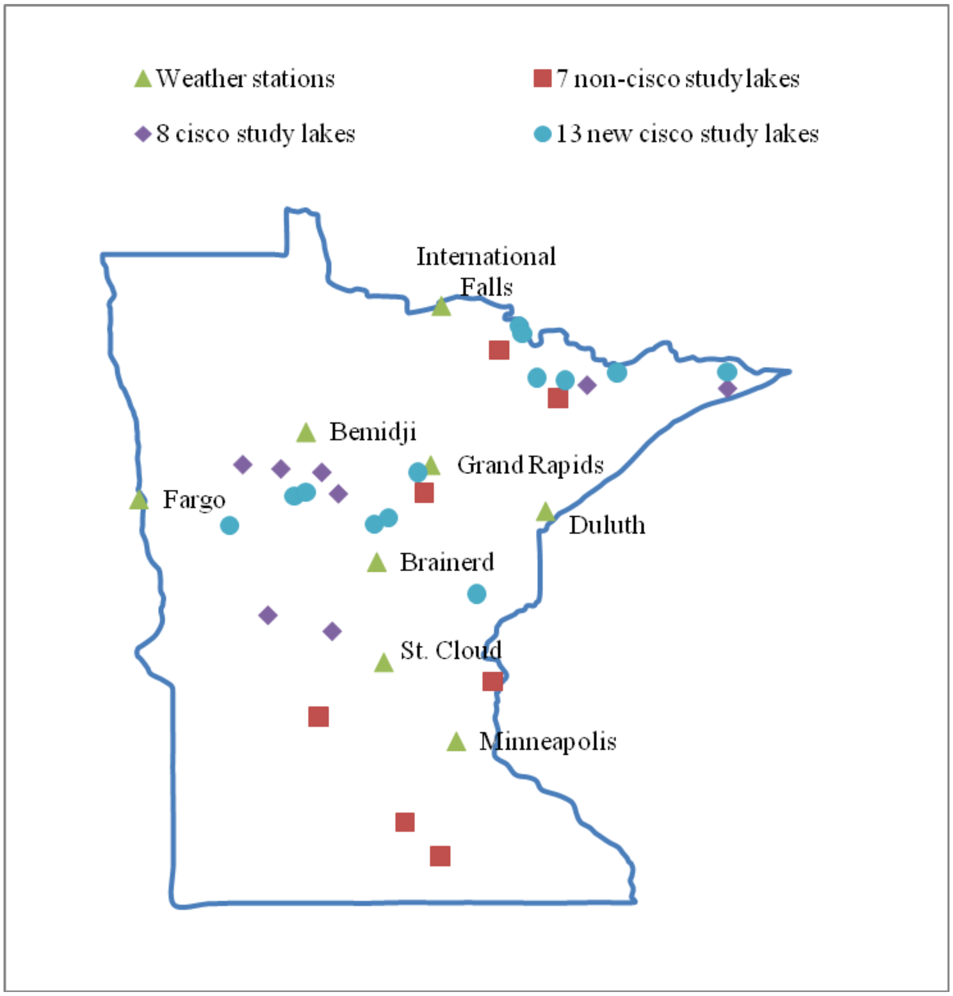

Figure 3.3 Locations of 28 study lakes and weather stations used for model simulations.

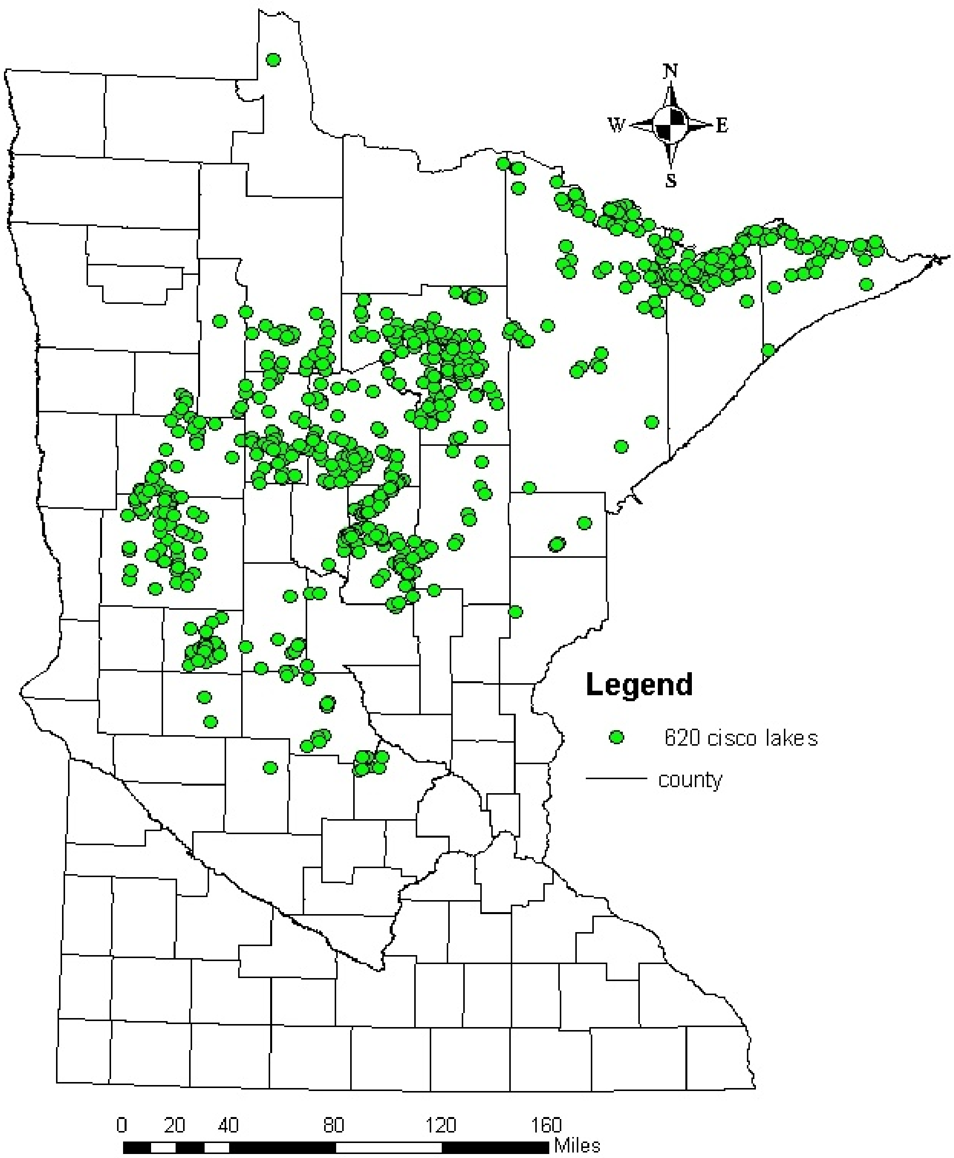

Figure 3.4 Locations of 620 cisco lakes in the MN DNR database.

3.3 Lake characteristics of study lakes

Lake characteristic parameter values and measurements (data) of lake water quality were needed for model calibration and validation. Such data were downloaded and assembled from the MN DNR Lake Finder website (http://www.dnr.state.mn.us/lakefind/index.html) for all 28 study lakes. Characteristics and data availability are summarized in Table 3.2. Data are presented for the twenty-one (21) cisco lakes first, and followed by the seven (7) non-cisco lakes. Table 3.2 lists lake name, surface area in km^2, maximum depth in m, lake geometry ratio (GR in $m^{-0.5}$), mean summer Secchi depth in m, mean summer chlorophyll-*a* concentration in mg/L, number of years with data on observed water temperature and DO profiles, total number of days with observed profile data, and total number of data pairs of observed profiles. Ranges of measured summer Secchi depths and chlorophyll-*a* concentrations for the 28 study lakes are given in Table 3.3. Mean summer values of Secchi depths and chlorophyll-*a* concentration reported in Tables 3.2 and 3.3 were calculated from downloaded field data.

Table 3.2 lists trophic status classification for all 28 study lakes based on mean summer Secchi depth and mean summer chlorophyll-*a* concentration and regional lake classification in Minnesota (Table 2.1). White Iron Lake is classified as a eutrophic lake based on mean summer Secchi depth (SD = 1.44 m < 1.8 m), but it can be classified as mesotrophic lake based on the range of measured summer chlorophyll-*a* concentrations (0.002 to 0.008 mg/L in Table 3.2). With the exception of White Iron Lake (SD = 1.44 m), mean summer Secchi depths for all other 20 cisco lakes range from 2.57 to 6.76 m, and these lakes are classified as mesotrophic and oligotrophic lakes in Minnesota (Table 2.1). Three of the seven non-cisco lakes are classified as eutrophic lakes, and another four are classified as mesotrophic lakes.

With the exception of Blue Lake (H_{max} = 14.6 m), South Twin Lake (H_{max} = 8.8 m), White Iron Lake (H_{max} = 14.3 m), all other 18 cisco lakes have a maximum depth greater than 20 meters (range from 23.0 to 50.0 m) and are classified as deep lakes in Minnesota (Table 2.1). With the exception of South Twin Lake (GR = 5.22) and White Iron Lake (GR = 4.26), lake the geometry ratios for the 19 cisco lake range from 0.69 to 2.5 $m^{-0.5}$, and these lakes are typically stratified or strongly stratified. Information on Minnesota's cisco lakes was presented in the first report (SAFL Report No. 532) on this project (Fang et al, 2009).

Available water temperature and DO profile data for the 21 cisco lakes, needed for model calibration, covered periods from 4 to 46 days and from 1 to 10 years (Table 3.2). In total, 80 years or 331 days with measured profiles, and 5608 total pairs of temperature and DO profiles in the 21 cisco lakes were available for model calibration. For the seven non-cisco lakes, a total of 25 years or 156 days with measured profiles data giving 1973 total data pairs were available.

Table 3.2 Study lake characteristics and availability of measured water temperature and dissolved oxygen profiles (table continued on the next page).

Lake	Surface area (km^2)	Maximum depth (m)	Geometry Ratio ($m^{-0.5}$)	Mean Secchi depth (m)	Mean chlorophyll a (mg/L)	Trophic status [1]	Years with data	Number of days of data	Number of data pairs
Big Trout	5.43	39.01	1.24	4.78	0.00336	O	86,92-02	46	916
Blue	0.71	14.63	2.04	6.76	0.00280	O	97,99,01,02	13	205
Burntside	28.90	38.40	1.91	5.80	0.00286	O	86,88,94,00	14	274
Carlos	10.20	50.00	1.13	3.27	0.00500	M	73, 77, 79, 80, 86, 90, 93, 94, 95, 96,	46	402
Cedar	0.98	26.80	1.17	3.56	0.00480	M	85, 86, 08	22	410
Elk	1.10	28.00	1.16	2.57	0.00480	M	85, 86, 07, 08	17	367
Fish Hook	6.61	23.16	2.19	3.44	0.00400	M	91	4	61
Greenwood	8.18	34.14	1.57	5.46	0.00255	O	83,84,85,86,06	14	222
Grindstone	2.13	46.63	0.82	2.88	0.00637	M	93	5	98
Kabekona	9.12	41.00	1.34	4.03	0.00320	M	90,94	6	129
Little Sand	1.56	24.38	1.45	5.22	0.00231	O	89,91	7	102
Little Trout	0.97	28.95	1.08	6.33	0.00073	O	97,06,07,08	11	281
Mukooda	3.05	23.77	1.76	5.12	0.00115	O	03,06,07	7	141
Siseebakwet	5.29	32.00	1.5	3.89	0.00205	M	92,93	6	122

(Table 3.2 continued)

Lake	Surface area (km^2)	Maximum depth (m)	Geometry Ratio ($m^{-0.5}$)	Mean Secchi depth (m)	Mean chlorophyll a (mg/L)	Trophic status [1]	Years with data	Number of days of data	Number of data pairs
Six	0.76	42.67	0.69	3.94	0.00445	M	97	4	70
Snowbank	17.30	45.72	1.41	5.28	0.00271	O	86,88	4	67
South Twin	4.52	8.80	5.22	2.78	0.00340	M	08	15	134
Ten Mile	18.90	63.00	1.05	5.54	0.00250	O	01, 02, 08	30	828
Trout (Cook)	1.04	23.00	1.39	5.40	0.00140	O	83,84,85,86,03, 08	23	349
Trout (St. Louis)	30.94	29.87	2.50	4.71	0.00247	O	06	5	89
White Iron	13.88	14.30	4.26	1.44	0.00520	E	95, 96, 00,07, 08	32	341
Non-cisco habitat lakes									
Bear Head	2.73	14.00	2.90	3.28	0.00450	M	08	16	209
Carrie	0.37	7.90	3.11	1.44	0.00630	M	08	15	121
Elephant	2.93	9.10	4.55	3.29	0.00470	M	08	13	135
Hill	2.66	14.60	2.77	3.99	0.00720	M	94, 08	21	281
Madison	4.50	18.00	2.56	0.88	0.05870	E	61, 70, 74, 79, 80, 86, 87, 89, 90, 93, 96, 06, 08	40	500
South Center	3.38	33.20	1.29	1.45	0.03160	E	86, 06, 08	19	413
St. Olaf	0.37	10.10	2.45	1.41	0.01840	E	86, 96, 01, 08	32	314

[1] E = Eutrophic, M = Mesotrophic, O = Oligotrophic.

3.4 Details of lake bathymetry and trophic state of study lakes

Information on the lake surface area (A_s), maximum depth (H_{max}), and bathymetric contour maps for the 28 study lakes were downloaded and assembled from the MN DNR Lake Finder web site. Lake bathymetry is a required model input and is provided as a data file giving lake horizontal areas, A(z), and cumulative lake volume, V(z), at different elevations (z) above the lake bottom. The procedure used to develop lake bathymetry data is given in Appendix A. As an example, Table 3.3 gives the bathymetry data for Carrie Lake developed from the contour map shown in Figure 3.5. Figure 3.6 gives the lake bathymetry curves, A(z) and V(z) versus elevation (z) above the deepest point in Carrie Lake. Appendix A provides depth contour maps (horizontal area and cumulative volume versus depth), and plots of bathymetry curves for all 28 study lakes (in alphabetical order of lake name).

Three dimensionless lake bathymetry curves, $A(z)/A_s$ versus z/H_{max}, were developed separately for lakes of small surface area (Figure 3.7), medium surface area (Figure 3.8), and large surface area (Figure 3.9). The Minnesota lake classification system (Table 2.1) was used to group lakes into small-area lakes with surface area $A_s \leq 0.4$ km^2, medium-area lakes with 0.5 km$^2 \leq A_s \leq 5.0$ km^2, and large-area lakes with surface area $A_s \geq 5.1$ km^2. In the set of 28 study lakes, there are 2 small-area lakes, 15 medium-area lakes, and 11 large-area lakes. The bathymetry of the 28 study lakes was compared with the curves previously developed for small-, medium- and large-area lakes in Minnesota (Hondzo and Stefan 1993a) and given by Equation 2.3 with coefficients from Table 2.2. The two small surface-area lakes (Figure 3.7) and the 15 medium-area lakes (Figure 3.8) selected for this study fitted the previously developed curves well, but 11 large-area lakes did not (Figure 3.9). A new representative bathymetry curve for the 11 large-area study lakes was therefore developed using regression fitting and is given by equation 3.1,

$$A(z)/A_s = 1.26 * \exp[-1.65*(1-z/H_{max})] - 0.26 \qquad (3.1)$$

The elevation z in equation 3.1 is from the lake bottom.

Table 3.3 Bathymetry of Carrie Lake (Elevation counted from lake bottom).

Elevation, z, (m)	Area, A(z), (m^2)	Cumulative Volume, V(z), (m^3)
0.00	0	0
0.28	1,931	270
1.80	36,549	29,592
3.33	81,480	119,532
4.85	110,125	265,537
6.38	143,244	458,605
7.90	369,276	849,150

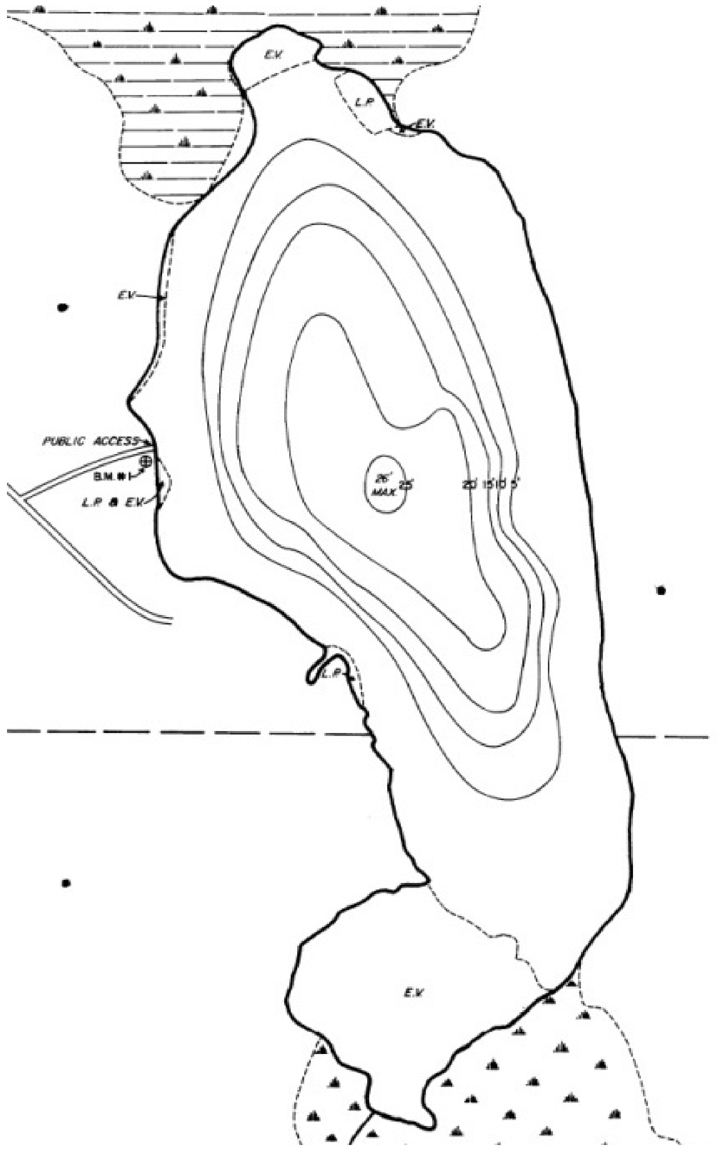

Figure 3.5 Contour map of Carrie Lake (source MN DNR website). Contours in increments of 5 feet.

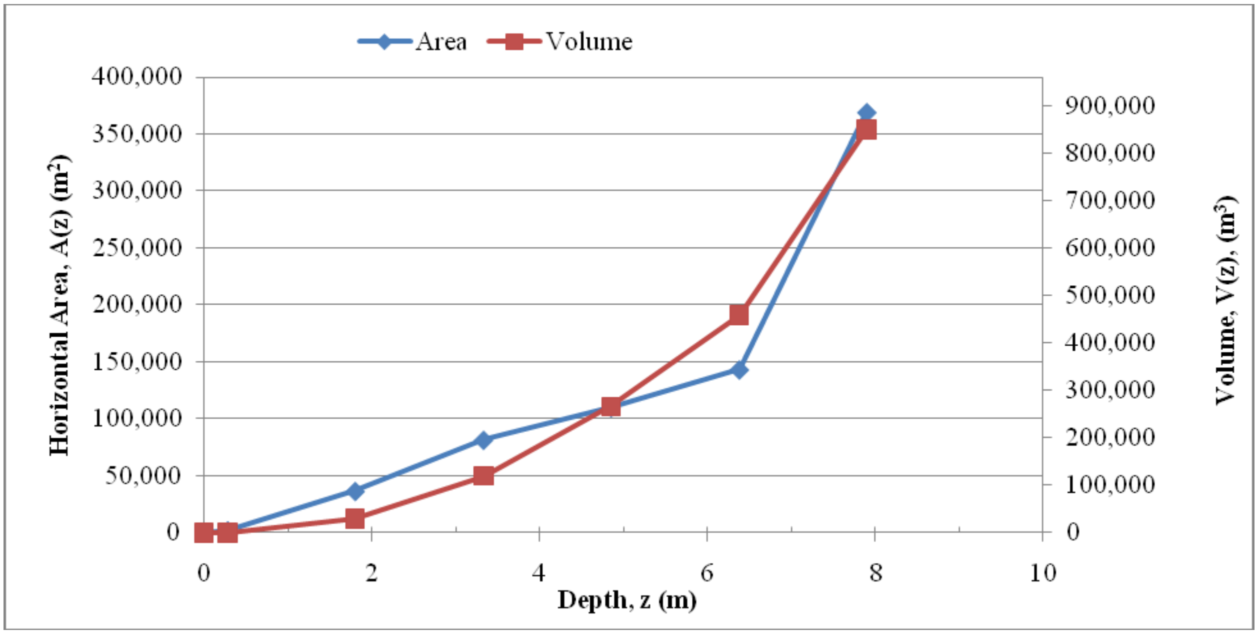

Figure 3.6 Lake bathymetry of Carrie Lake (horizontal area and cumulative volume versus elevation above the lake bottom).

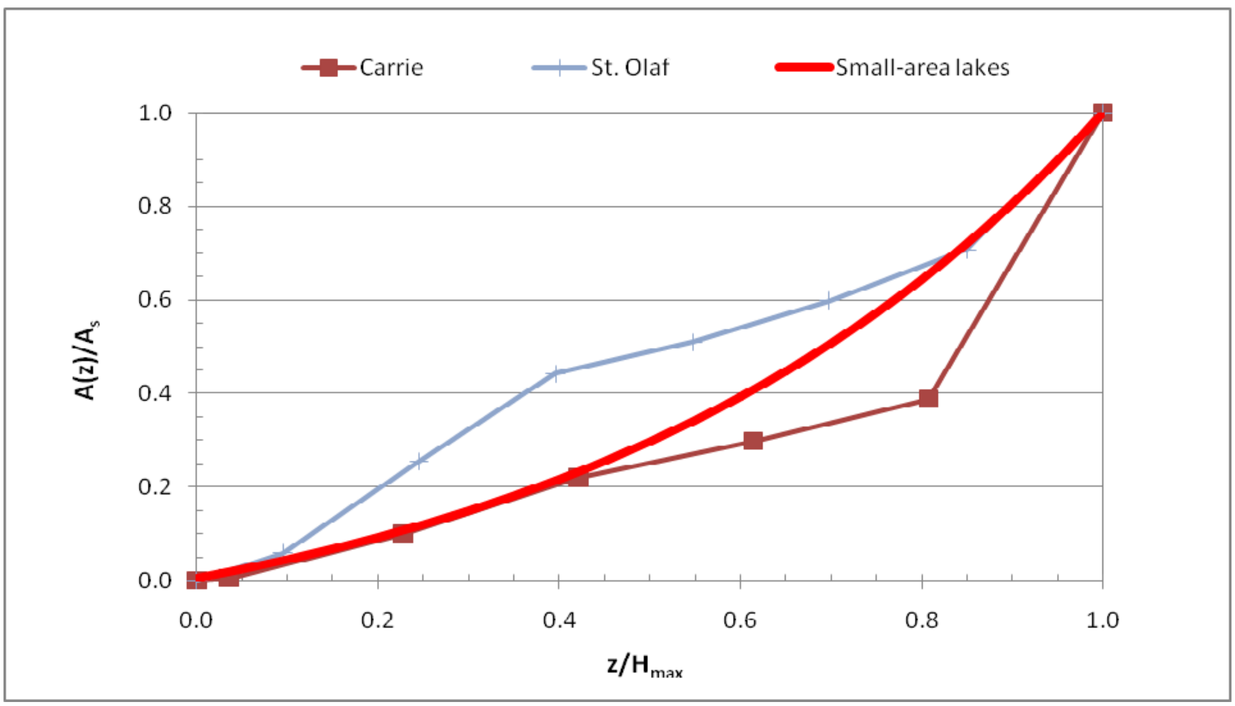

Figure 3.7 Dimensionless lake bathymetry curves for small-area study lakes ($A_s \leq 4.0$ km^2).

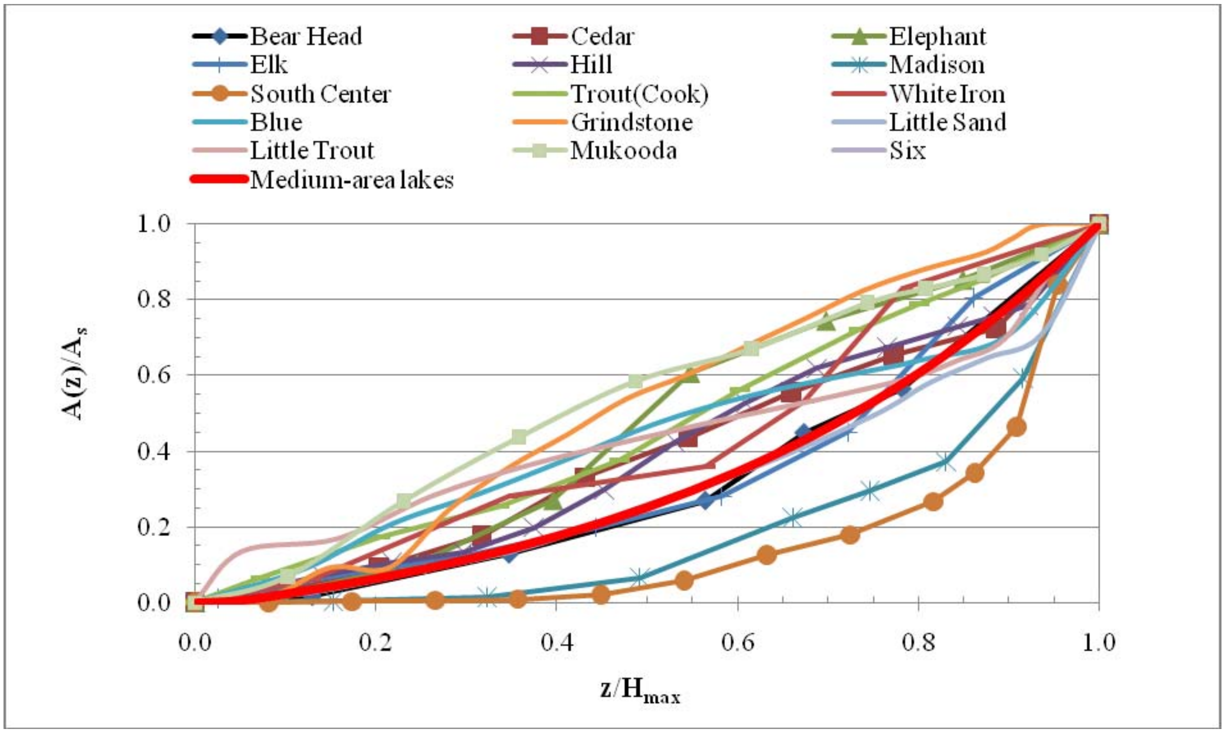

Figure 3.8 Dimensionless lake bathymetry curves for medium-area study lakes (0.5 km^2 ≤ A_s ≤ 5.0 km^2).

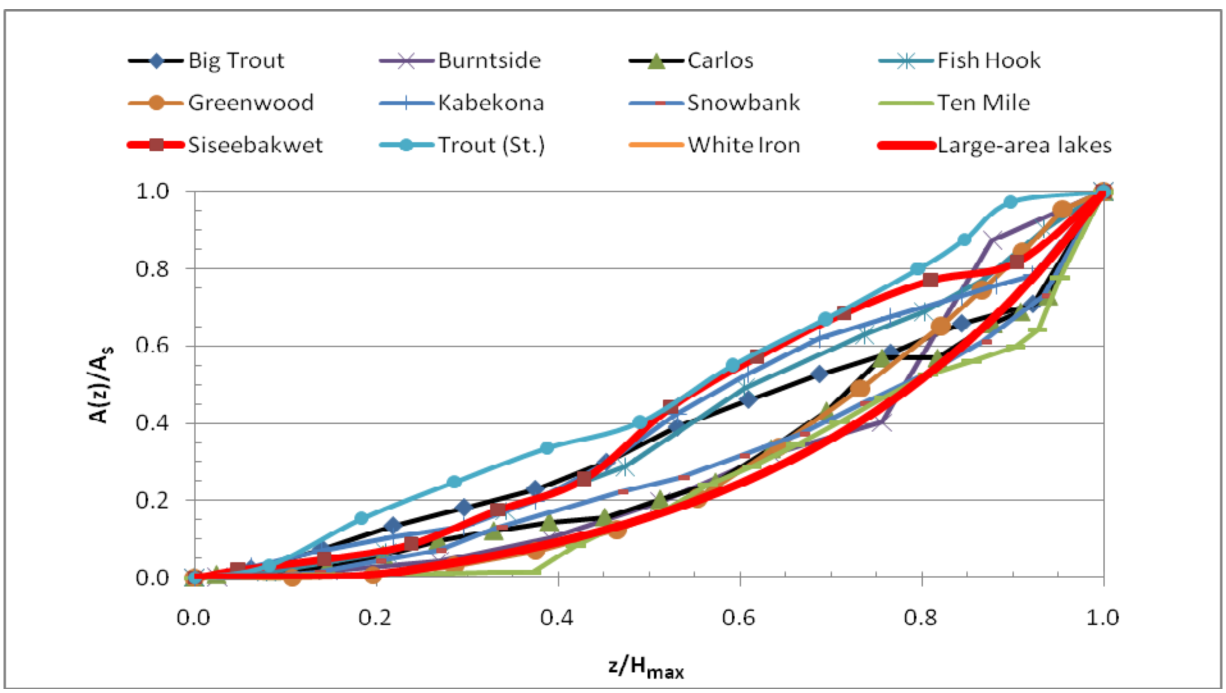

Figure 3.9 Dimensionless lake bathymetry curves for large-area study lakes (A_s ≥ 5.1 km^2).

3.5 Water quality data for study lakes

To accurately simulate daily water quality conditions in a lake, it is necessary to have information on the trophic status of the lake. In MINLAKE 96, summer averages of measured Secchi depth and chlorophyll-a concentration data are used to quantify a lake's trophic status. Table 3.4 summarizes summer means and ranges of Secchi depth and chlorophyll-*a* data in the 28 study lakes. Both mean values and ranges are calculated from the field data in the years when vertical temperature and DO profiles were measured ("years with data" in Table 3.1). The MN DNR Lake Finder web site reports the mean Secchi depth and the chlorophyll-*a* concentration calculated for all available data. These values are given in the last two columns of Table 3.4. For some lakes the mean summer chlorophyll-*a* is not reported on the web site and N/A is shown in Table 3.4. In the following sections the chlorophyll-*a* concentrations and Secchi depths observed in the first 15 study lakes that were selected by the MN DNR will be analyzed.

3.5.1 Seasonal progression of chlorophyll-a concentrations in study lakes

In the MINLAKE96 model a lake's trophic state is specified as model input of the summer mean chlorophyll-a concentration. In the program, the available chlorophyll-a field data are used to compute the summer mean value, and then a generic seasonal pattern is applied to compute the chlorophyll-a concentration for each simulation day. The seasonal pattern of phytoplankton biomass in temperate lakes is characterized by a pronounced spring bloom followed by lower levels through summer (summer depression) and a fall bloom; low chlorophyll-a levels through the winter are typical (Riley 1947; Hutchinson 1957; Goldman and Horne 1983; Taub 1984). As model input in the Minnesota cisco lakes project we use/specify measured field chlorophyll-a concentrations (measurements) on those days for which we also have measured temperature and dissolved oxygen (DO) profiles. For some days, we have temperature and DO profiles but we do not have a measured chlorophyll-*a* concentration; in that case long-term average chlorophyll-*a* concentration from all available data for those days is used.

To refine the temperature and DO model, we checked the seasonal progression of chlorophyll-a concentration as reflected in the field data. We assembled and examined all available measured chlorophyll-a concentrations in the 15 calibration lakes which were divided into three groups: eutrophic, mesotrophic, and oligotrophic lakes. We computed the summer mean of measured chlorophyll-a concentrations and the percent difference from the mean, year by year and lake by lake. A comparison of the results of this data analysis with the generic seasonal chlorophyll-a (biomass) pattern imposed in the original MINLAKE96 model is given in Figures 3.10 to 3.12. The pattern is given by the percent difference between the annual (summer) mean and the value on a specified day. It seems that the generic seasonal pattern used in the original MINLAKE96 model is well within the range of the field data. However, the patterns based on the data show large variations from year to year, and are limited to a few years. This does not allow us to propose a new generic seasonal pattern for the model, and leads to the conclusion that biomass growth varies significantly from year to year in the calibration lakes. Because there are only few data points (chlorophyll-a measurements) available within a year, the information provided by the field data does not justify a change of the imposed generic seasonal chlorophyll-*a* pattern. To capture yearly changes in biomass growth, a biomass growth kinetics model is available in MINLAKE (Riley and Stefan 1988), but in order to use it, external nutrient loading from the watershed and internal loading from the lake sediments have to be specified. This would have to be done on a lake by lake basis. The modeling effort to include runoff from the watershed of each lake is substantial and is beyond the scope of the current study.

Even though we see no need to propose a new seasonal pattern for chlorophyll-*a* in the model, we did test whether the use of measured chlorophyll-a concentrations in the model, as mentioned above, would change DO and T predictions significantly. We replaced daily chlorophyll-a concentrations of the generic pattern with measured field values on the day when the data were taken. On the days between the field measurement days chlorophyll-a values were linearly interpolated from the field data of the adjacent days. Figures 3.14 and 3.15 show the seasonal pattern we used previously and interpolated pattern from field data for Hill Lake and Madison Lake as two examples. We ran the model with this change for all the lakes. For a few lakes, the model gave better simulation results with the chlorophyll-*a* data input; for other lakes, the effect of this change was insignificant. Table 3.5 gives the average error parameters for all 15 lakes when simulations with either the generic seasonal chlorophyll-a pattern or the interpolated pattern based on field data was used in the model. Because the use of the field data did not significantly improve the DO and T results, and could not be used in lakes that have no field data available, we decided to use the generic seasonal pattern for the model simulations throughout the study.

3.5.2 Secchi depths in study lakes

In the MINLAKE96 model, the light (solar radiation) attenuation coefficients due to water (μ_w) and due to phytoplankton (μ_{chla}) are set as constant input parameters to the model (Stefan and Fang, 1994). The total attenuation coefficient due to water (μ_w) plus phytoplankton (μ_{chla} times chlorophyll concentration-a) is calculated as 1.84 m divided by the long-term average of measured Secchi depth (m). Even though the attenuation coefficients (μ_w and μ_{chla}) are constants, the total attenuation coefficient on each simulation day does change with the chlorophyll-a concentration that follows a seasonal pattern as discussed above. Although measured Secchi depths (SD) are in the model input files on the days when DO and temperature profiles are measured and available for model calibration, these measured Secchi depths were not used in the program to compute attenuation coefficient on that specific day. Instead, we assembled and examined all available measurements of Secchi depths in all 15 lakes and plotted Secchi depths versus calendar day to see whether there is a seasonal pattern for Secchi depth in each lake. We also plotted the annual mean and standard deviation of Secchi depths to identify the magnitude of variation within a year. These plots are presented in Appendix B.

Because measured Secchi depths are available for almost all days with measured temperature and DO profiles for model calibration, we were able to do two model tests regarding solar radiation attenuation that has a large effect on lake stratification.

(1) In the lake-modeling program, total radiation attenuation coefficients were computed from measured Secchi depths as 1.84 divided by measured Secchi depth (m). Attenuation coefficients

due to water (μ_w) change on the days when the field data (temperature and DO profiles) were collected. With time variable model input for (μ_w) we simulated temperature (T) and DO profiles of all 15 lakes and re-examined the error (parameters) between simulated and measured T and DO profiles. We found that this modified simulation procedure based on detailed Secchi depth measurements did not give any improvement in the simulated T and Do profiles as measured by the error parameters.

(2) We made additional adjustments to this procedure. We calculated the total attenuation coefficient not on the day when the field data was collected, but rather for the mid-day between two field data days. This revised procedure also did not give much improvement in model performance. We checked the temperature and DO profiles of all 15 lakes, and error parameters did not show any improvement from the regular procedure which we used before. Table 3.5 shows average error parameters of simulations in all 15 lakes when the original procedure and the above two additional procedures using Secchi depth measurements were tested.

A lake's classification with regard to trophic state affects our selection of appropriate values for certain model parameters, especially in the dissolved oxygen model. Both bio-chemical oxygen demand in the water column (BOD) and sedimentary oxygen demand (SOD) depend on trophic state classification. Information on Secchi depth or chlorophyll-*a* concentration for a lake can be and was used to classify a lake's trophic status. Carrie Lake and White Iron Lake were originally classified as eutrophic lakes, but based on the mean and range of chlorophyll-a concentrations, we reclassified them as mesotrophic lakes. In the Minnesota DNR 'lake finder' web site, both lakes are classified as eutrophic lakes. Elk Lake and Hill Lake are classified as mesotrophic lakes based on both Secchi depth and mean chlorophyll-a concentrations computed from the field data for the years with measured vertical T and DO profiles; however, the Minnesota DNR 'lake finder' web site classifies Elk Lake and Hill Lake as oligotrophic lakes based on mean Secchi depth computed from all available data. Elk Lake has Secchi depth data for 12 years (1985 – 2008) with annual mean Secchi depth from 2.5 m to 9.1 m and overall mean Secchi depth of 4.45 m. Annual mean Secchi depth in 2003 was 9.1 m (range from 4.87 m to 12.49 m); for all other years mean Secchi depths are less than 4.5 m. In our simulations, we treated Elk Lake and Hill Lake as mesotrophic.

Table 3.4 Summer means and ranges of Secchi depth and chlorophyll-*a* and attenuation parameters for model simulations in the 28 study lakes (table continued on the next page).

Lake name	Mean Secchi depth (m)	Range of Secchi depth (m)	Mean chlorophyll-*a* (mg/L)	Range of chlorophyll-*a* (mg/L)	μ (m^{-1})	μ_w (m^{-1})	DNR mean Secchi depth (m)	DNR Mean chlorophyll a (mg/L)
Big Trout	4.78	1.98 - 3.36	0.0034	0.0034 - 0.0034	0.39	0.32	4.40	0.0030
Blue	6.76	4.63 - 9.36	0.0028	0.0010 - 0.0050	0.27	0.22	7.43	N/A
Burntside	5.80	4.90 - 7.50	0.0029	0.0010 - 0.0043	0.32	0.26	6.34	N/A
Carlos	3.27	1.52 – 5.00	0.0050	0.0022 – 0.0097	0.56	0.46	3.20	0.0036
Cedar	3.56	2.20 -6.05	0.0048	0.0015 – 0.0093	0.52	0.42	3.41	N/A
Elk	2.57	2.13 – 3.80	0.0048	0.0022 – 0.0082	0.72	0.6	4.45	N/A
Fish Hook	3.44	2.90 - 4.70	0.004	0.0020 - 0.0061	0.53	0.45	3.30	0.0046
Greenwood	5.46	3.65 - 6.70	0.0025	0.0014 - 0.0042	0.34	0.29	5.30	0.0023
Grindstone	2.91	2.13 - 3.80	0.0064	0.0044 - 0.0083	0.63	0.5	3.68	N/A
Kabekona	4.03	2.90 – 4.60	0.0032	0.0022 – 0.0048	0.46	0.39	3.60	0.0029
Little Sand	5.22	3.50 - 8.69	0.0023	0.0008 - 0.0035	0.35	0.31	6.50	0.0019
Little Trout	6.33	4.93 - 7.40	0.0007	0.0007 - 0.0007	0.29	0.28	6.60	0.0007
Mukooda	5.12	3.90 - 6.10	0.0012	0.0010 - 0.0014	0.36	0.34	N/A	N/A
Siseebakwet	4.82	3.00 - 6.10	0.0012	0.0006 - 0.0025	0.38	0.36	3.60	0.0015

(Table 3.4 continued)

Lake name	Mean Secchi depth (m)	Range of Secchi depth (m)	Mean chlorophyll a (mg/L)	Range of chlorophyll a (mg/L)	μ [1] (m^{-1})	μ_w [2] (m^{-1})	DNR mean Secchi depth (m)	DNR mean chlorophyll a (mg/L)
Six	3.94	2.74 - 5.94	0.0026	0.0019 - 0.0031	0.47	0.42	5.70	0.0021
Snowbank	5.28	4.40 - 7.30	0.0027	0.0012 - 0.0043	0.35	0.29	6.10	N/A
South Twin	2.78	2.20 – 3.70	0.0034	0.0025 – 0.0044	0.66	0.59	2.90	N/A
Ten Mile	5.54	4.40 – 7.22	0.0025	0.0013 – 0.0042	0.33	0.28	5.97	0.0023
Trout (Cook)	5.40	3.65 – 7.20	0.0014	0.0005 - 0.0018	0.34	0.31	6.80	0.0010
Trout (St. Louis)	4.71	3.65 - 5.50	0.0025	0.0014 - 0.0037	0.39	0.34	4.40	0.0026
White Iron	1.37	0.90 – 1.68	0.0050	0.0020 – 0.0080	1.34	1.24	1.50	0.0055
Non-cisco habitat lakes								
Bear Head	3.28	3.00 – 3.50	0.0045	0.0026 – 0.0072	0.56	0.47	3.16	N/A
Carrie	1.44	0.76 – 2.10	0.0063	0.0028 – 0.0086	1.28	1.15	1.03	N/A
Elephant	3.29	2.30 – 4.30	0.0047	0.0025 – 0.0073	0.56	0.47	2.37	N/A
Hill	3.99	2.00 – 6.60	0.0072	0.0025 – 0.0135	0.46	0.32	2.98	N/A
Madison	0.88	0.50 – 1.70	0.0059	0.0051 – 0.0937	2.09	1.97	1.00	0.0500
South Center	1.45	0.60 – 3.35	0.0316	0.0067 – 0.0665	1.27	0.64	1.10	0.0485
St. Olaf	1.41	0.60 – 4.40	0.0184	0.0019 – 0.0515	1.3	0.94	1.60	0.0014

[1] μ is the total radiation attenuation coefficient

[2] μ_w is the water attenuation after chlorophyll-a (phytoplankton) has been filtered.

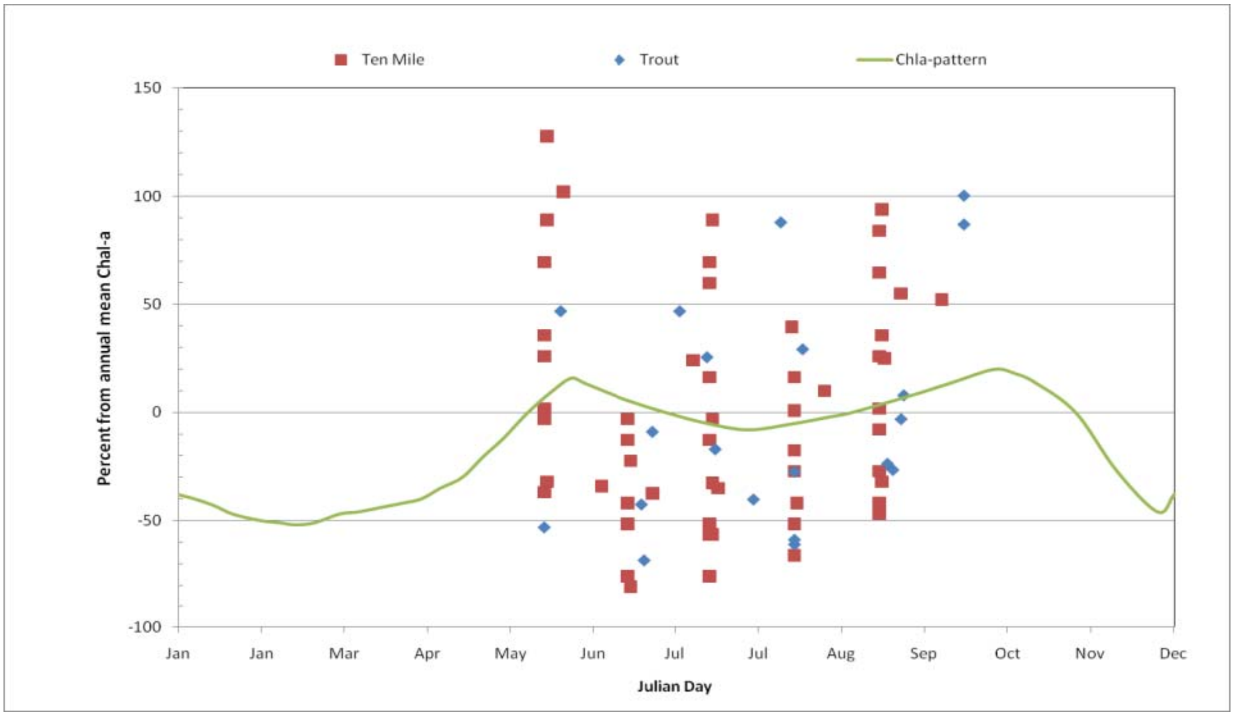

Figure 3.10 Seasonal chlorophyll-*a* distribution in oligotrophic lakes. Generic distribution and field data from two study lakes.

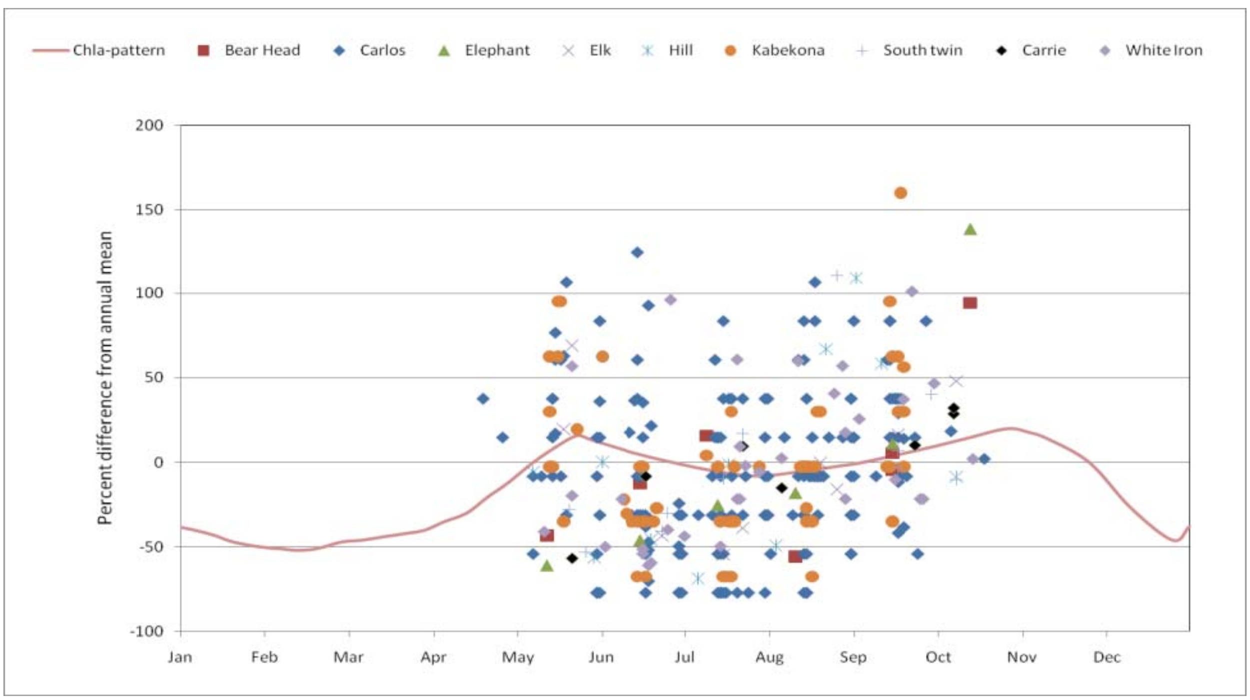

Figure 3.11 Seasonal chlorophyll-*a* distribution in mesotrophic lakes. Generic distribution and field data from nine study lakes.

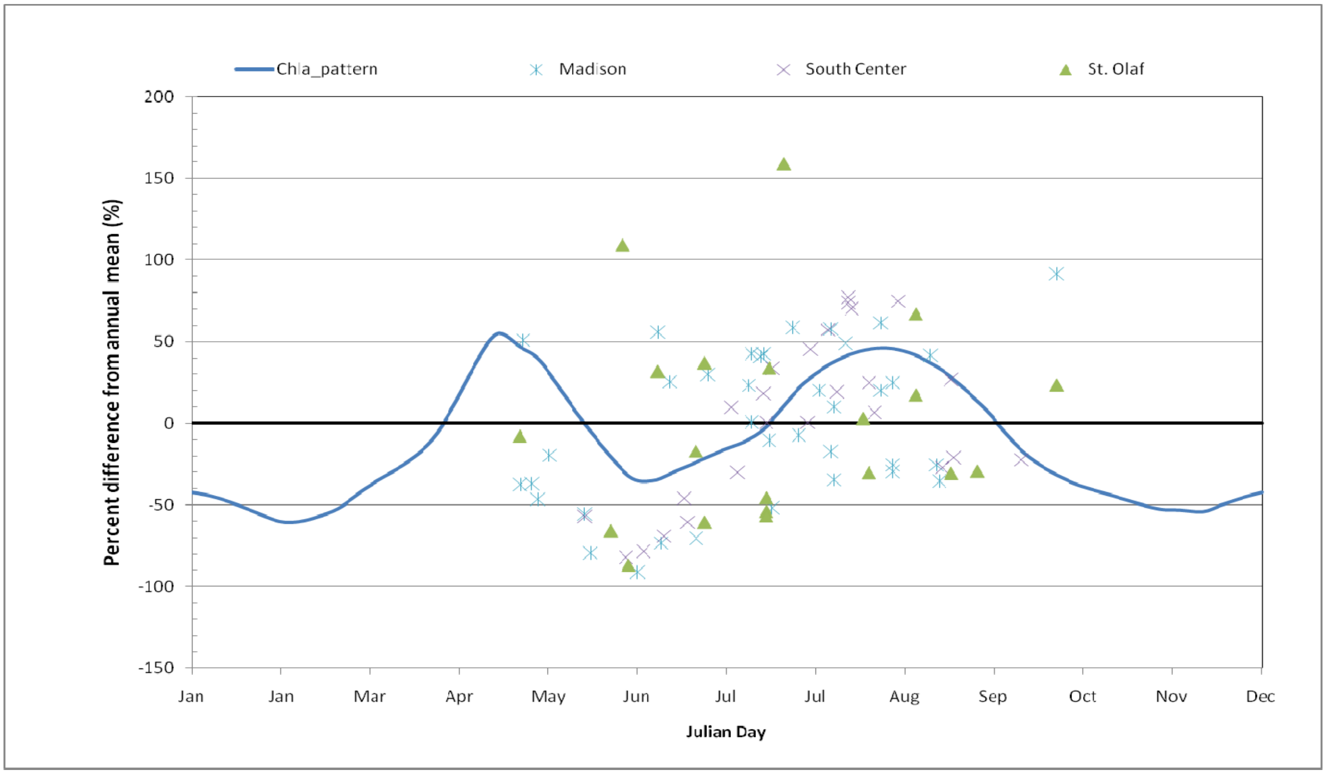

Figure 3.12 Seasonal chlorophyll-*a* distribution in eutrophic lakes. Generic distribution and field data from three study lakes.

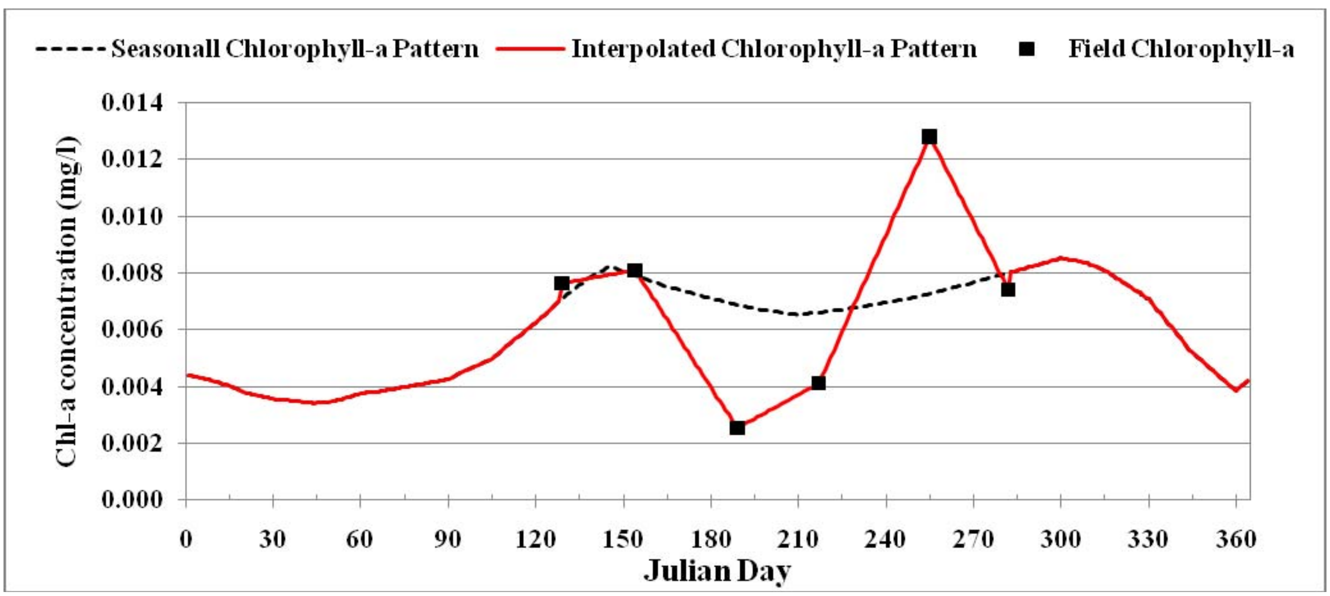

Figure 3.13 Seasonal distribution of chlorophyll-a used for Hill Lake: generic distribution from MINLAKE96 model and interpolated 2008 field data.

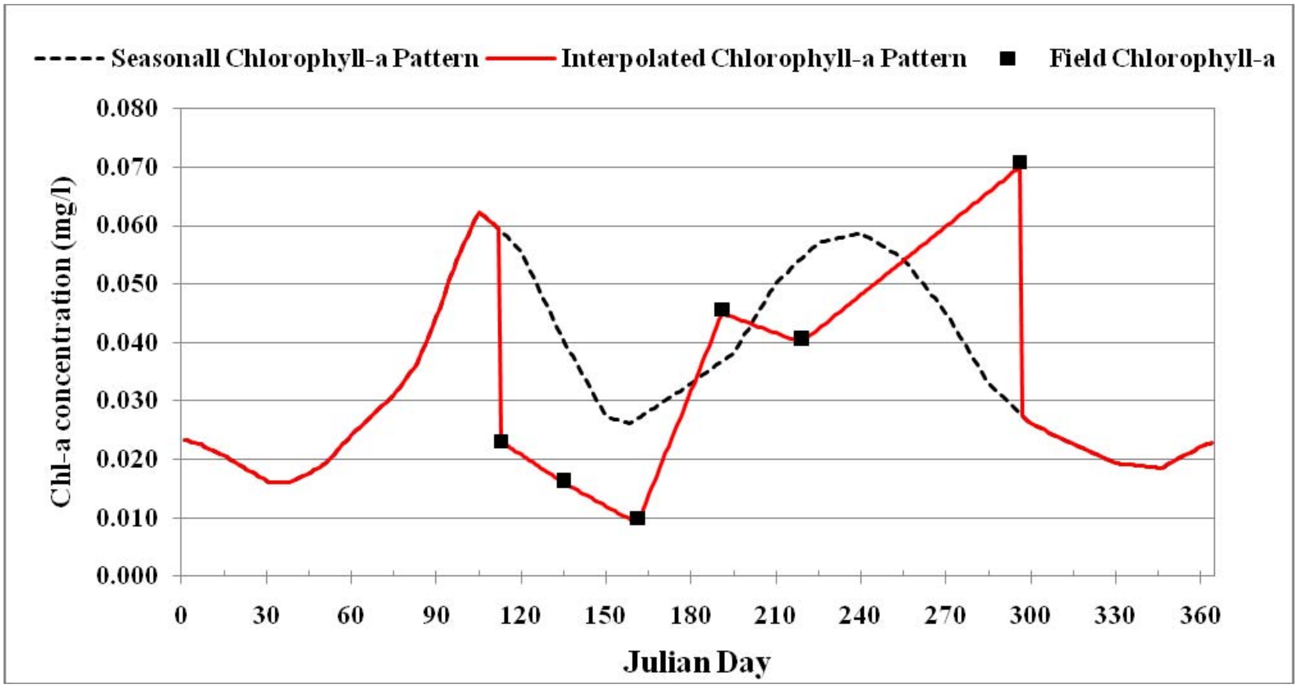

Figure 3.14 Seasonal distribution of chlorophyll-a used for Madison Lake: generic distribution from MINLAKE96 model and interpolated 2008 field data.

Table 3.5 Averages values of statistical error parameters for all 15 study lakes obtained with the generic seasonal distribution of chlorophyll-*a* concentrations and the interpolated chlorophyll-*a* concentrations using field data.

Seasonal chlorophyll-a concentration distribution used in the model simulations	Water Temperature			Dissolved Oxygen		
	RMSE (^oC)	R^2	S	RMSE (mg/L)	R^2	S
General seasonal pattern used	1.56	0.90	1.00	1.62	0.73	0.96
Interpolated patterns used	1.63	0.85	0.99	1.63	0.73	0.96

RMSE = root mean square error of estimate, R^2 = regression coefficient, and S = slope of model results to field data regression (Riley and Stefan, 1988).

Table 3.6 Averages values of statistical error parameters for all 15 lakes when three different methods were tested to calculate attenuation coefficients.

Method used to calculate solar radiation attenuation	Water Temperature			Dissolved Oxygen		
	RMSE (^oC)	R^2	S	RMSE (mg/L)	R^2	S
Long-term average of measured Secchi depth used (original MINLAKE model)	1.56	0.90	1.00	1.62	0.73	0.96
Attenuation coefficient calculated with SD value at field data dates	1.63	0.85	0.99	1.63	0.73	0.96
Attenuation coefficient calculated at the middle days between two field data dates	1.62	0.89	1.01	1.72	0.70	0.96

Chapter 4 Weather Data Input and Preparation

Daily weather data is the basic input data for modeling water quality dynamics in a lake using MINLAKE2010. Seven weather parameters, daily air temperature, dew point temperature, wind speed, solar radiation, percent of cloud cover or percent of sunshine, and precipitation as either rainfall or snowfall, are model inputs. Daily weather parameters are organized by weather station and year by year. Weather stations selected for this study include seven (7) stations in Minnesota, which are located at Duluth, Minneapolis/St. Paul, St Cloud, International Falls, Bemidji, Brainerd and Grand Rapid, and two stations beyond the border of Minnesota, which are Sioux Falls in South Dakota and Fargo in North Dakota (Table 4.1). Of these nine stations, six stations are National Weather Service (NWS) Class I stations and three, Bemidji, Brainerd and Grand Rapids are NWS Class II stations. Availability of weather data for the Class I stations (Table 4.2) is far better than for Class II stations. For each lake, we located the nearest weather station. Weather data from that station were used for simulations of that specific lake. It was found that no lake was near Sioux Falls; therefore, weather data for Sioux Falls, although assembled, were not used for model simulations.

4.1 Sources of weather data

Weather parameters were assembled in stages, from different sources and for different time periods. Weather data for the Class I stations were available from a previous project funded by US EPA, and purchased from the Solar and Meteorological Surface Observation Network (SAMSON) for the periods from 1961 to 1995. Weather data from 1995 to 2008 were downloaded from the web site of the National Climatic Data Center (NCDC) of the U.S. Department of Commerce, at Asheville, North Carolina (ftp://ftp.ncdc.noaa.gov/pub/data/gsod/) and the National Solar Radiation Data Base (NSRDB) (http://rredc.nrel.gov/solar/old_data/nsrdb /1991-2005/). For the Class II stations, weather data were collected from NCDC and NSRDB servers beginning with 1991, because solar radiation data are not available before 1991 for these stations, even though other weather parameters are available from as early as 1973 from the NCDC website. The solar radiation data from 2006 to 2008 were purchased from the NOAA Midwestern Regional Climate Center. Based on weather data availability, simulation periods were form 1991 to 2008 for the lakes nearest the Class II weather stations, and from 1961 to 2008 for the lakes nearest Class I weather stations.

Table 4.1 Weather stations and their locations.

Station Location	City	State	Latitude	Longitude	Data Period
Duluth International Airport	Duluth	MN	46.83 [1]	-92.22 [1]	1961-2008
International Falls International Airport	International Falls	MN	48.57	-93.40	1961-2008
Minneapolis/St. Paul International Airport	Minneapolis	MN	44.88	-93.23	1961-2008
St. Cloud Regional Airport	St. Cloud	MN	45.55	-94.05	1961-2008
Bemidji Municipal Airport	Bemidji	MN	47.50	-94.93	1991-2008
Brainerd	Brainerd	MN	46.40	-94.13	1991-2008
Grand Rapids	Grand Rapids	MN	47.22	-93.52	1991-2008
Sioux Falls Foss Field	Sioux Falls	SD	43.58	-96.75	1961-2008
Fargo Hector International Airport	Fargo	ND	46.93	-96.82	1961-2008

[1] Latitude and Longitudes are given in decimal degrees.

4.1.1 National Solar Radiation Data Base

The National Solar Radiation Data Base (NSRDB) website contains solar radiation data in two different datasets. The first dataset contains data at 239 weather stations in the USA and some stations in Guam and Puerto Rico. In this data set which was published in 1994, solar radiation data from 1961 to 1990 at six of our nine selected weather stations are available . The second dataset was published in 2007 and contains solar radiation data from 1991 to 2005 at 1454 locations in the USA and its territories.

The 1961-1990 dataset was assembled by the National Weather Service (NWS) over the past decades. The National Renewable Energy Laboratory (NREL) used Meteorological-Statistical (METSTAT) model (Maxwell 1998) to produce the solar radiation data. The METSTAT model was based on the solar radiation data collected by NWS from 1977 to 1980. The measured (7%) and modeled (93%) solar radiation data were combined with meteorological data (used by the solar energy industry) to form the NSRDB. The NSRDB contains a total of 56 primary and 183 secondary stations. Primary stations contain measured solar radiation data for at least a portion of the 30-year record while secondary stations are those which contain only modeled solar radiation data. All weather stations selected for our study fall in the group of secondary stations.

In the 1991-2005 dataset, data from the SUNY model in addition to METSTAT model were added to produce this updated database. The SUNY model was developed at the State University of New York (SUNY) at Albany, NY. Geostationary Operational Environmental Satellite (GOES) imagery was used to estimate solar radiation. In simple terms, this satellite model uses the inverse relationship between reflected irradiance (that reflected by clouds and the atmosphere back to space and the satellite sensor) and ground irradiance (that transmitted through the atmosphere to the Earth's surface). Based on simplicity and consistency, the SUNY model would have replaced the METSTAT model but for its limited period of record. The GOES imagery for the project was archived starting in 1998, leaving the period of 1991–1997 without coverage. Hence, a hybrid production effort uses both models.

The SUNY modeled data are available from 1998 to 2005 only; while METSTAT modeled data are available for all years from 1961 to 2005. We decided to use METSTAT modeled data for this study. The database has different categories of solar radiation data, and 'direct and diffuse solar radiation (METSTAT-modeled) on a horizontal surface' were selected to develop weather data input for this study.

4.1.2 National Climatic Data Center

Daily average air temperature, dew point temperature, wind speed, rainfall and snowfall were obtained (downloaded) from the NCDC web server (ftp://ftp.ncdc.noaa.gov/pub/data /gsod/). The input data used to build these daily summaries are the Integrated Surface Data (ISD), which includes global data obtained from the USAF Climatology Center. For the Class I stations, the quality of the data is satisfactory, but for the Class II stations there are many days with missing data. Especially snowfall data were not reported for the Class II stations (in most cases).

4.2 Estimation of missing weather data

Five weather parameters, daily air temperature, dew point temperature, wind speed, solar radiation and rainfall, were downloaded from the SAMSON, NCDC server and the NSRDB server for all stations for different time periods, depending on Class I and II stations. However, two other weather parameters, sunshine percentage and snowfall, were not available in most cases. To fill in the missing data we used estimation procedures for these two parameters.

All weather parameter data were reorganized station by station and year by year into weather input files using the format required by the MINLAKE model. For example, there are 48 weather input files of weather data for Minneapolis from 1961 to 2008.

4.2.1 Sunshine percentage data estimation

Only the SAMSON database provides sunshine percentage data. The NCDC web server does not. Therefore, for Class I weather stations we do not have any sunshine percentage data after 1995. For the Class II weather stations, we do not have sunshine percentage data either because all data were downloaded from the NCDC server; the exception is Brainerd, which has sunshine percentage data from 1995 to 2002 from a previous study. An estimation procedure was used to calculate the missing sunshine percentage information. Table 4.2 gives the years for which data were available and years for which values had to be estimated.

Table 4.2 Availability of sunshine percentage data

Location of weather station	Station Category	Data Period	Years at which sunshine % data not available
Duluth (MN)	Class I	1961- 2008	2003-2008
International Falls (MN)	Class I	1961- 2008	1996-2008
Minneapolis (MN)	Class I	1961- 2008	1996-2008
Saint cloud (MN)	Class I	1961- 2008	1996-2008
Fargo (ND)	Class I	1961- 2008	1996-2008
Sioux falls (SD)	Class I	1961- 2008	1996-2008
Brainerd (MN)	Class II	1991- 2008	2003-2008
Bemidji (MN)	Class II	1991- 2008	1991-2008
Grand Rapid (MN)	Class II	1991- 2008	1991-2008

The sunshine percentage was estimated from solar radiation data for those stations that had no sunshine percentage data. The literature indicates that there is a direct relationship between solar radiation and sunshine percentage; a set of equations that relates these two parameters was developed in other studies (Cole and Wells 2004). A portion of the FORTRAN program for the CEQUAL-W2 model computes sunshine percentage from solar radiation data. CE-QUAL-W2 is a two-dimensional, laterally averaged, hydrodynamic and water quality model for reservoirs. The CE-QUAL-W2 model simulates basic eutrophication processes (http://smig.usgs.gov/cgi-bin/SMIC/model_home_pages/model_home?selection=cequalw2). The CE-QUAL-W2 model uses a set of equation to compute values of solar radiation from cloud cover for the days when solar radiation data are not available. The program was modified to calculate cloud cover values form daily solar radiation. The sunshine percentage was calculated from estimated cloud cover values using equation 4.1.

$$\text{Sunshine percentage (decimal)} = 1 - \text{cloud cover} \tag{4.1}$$

4.2.2 Snowfall data estimation

For the Class II stations, precipitation data were collected from the NCDC server. The data is in inches of water (rainfall); snowfall is not given directly. Snowfall values were therefore estimated from adjacent first-class weather stations. We took a weighted average (on the basis of distance from the station) of the snowfall values of the nearest stations on both sides of the station with missing data and used those estimated values in the weather input files of the MINLAKE2010 model. For the Class I stations, snowfall is not given directly after 1995 (only

CD SAMSON has snowfall data from 1961 to 1995). Snowfall was estimated based on precipitation, air temperature, and relative humidity downloaded from NCDC web server. Snow can form at above freezing temperature (http://www.sciencebits.com/SnowAboveFreezing), and a relationship between snowfall and liquid equivalent (inches) of precipitation was used to estimate snowfall for the Class I stations.

4.3 Characteristics of weather parameters

Table 4.3 lists the weather stations used for model simulations of the 28 study lakes. Years with available weather data and years with observed lake data (water temperature and DO profiles) are listed in Table 4.3. The weather data files are carefully inspected and checked using a computer program. Missing or wrong data from the original data sources were detected and corrected. For example, on some days dew point temperatures much higher than air temperatures were reported, or huge rainfall values were given. These were corrected using correlations with other weather stations. Figures 4.1 and 4.2 give an example of the daily and monthly weather data used, and the seasonal variability of weather in Minnesota. Averages (1961-2008) and variations (plus/minus standard deviation) of air temperature, dew point temperature, wind speed, and solar radiation at the Duluth weather station are plotted in Figures 4.1 and 4.2.

Table 4.3 Weather stations used and data availability for individual study lake simulations.

Lake name	Weather stations used	Years with available weather data	Years with field profile data
Big Trout	Brainerd	1991-2008	86,92-02
Blue	Grand Rapids	1991-2008	97,99,01,02
Burntside	Int'l Falls	1961-2008	86,88,94,00
Carlos	Saint Cloud	1961- 2008	79, 80, 86, 08
Cedar	Saint Cloud	1961- 2008	85, 86, 08
Elk	Bemidji	1991- 2008	07, 08
Fish Hook	Fargo	1961-2008	91
Greenwood	Duluth	1961-2008	83,84,85, 86,06
Grindstone	Brainerd	1991-2008	93
Kabekona	Bemidji	1991-2008	94
Little Sand	Fargo	1961-2008	89,91
Little Trout	International Falls	1961-2008	97,06,07,08
Mukooda	International Falls	1961-2008	03,06,07
Siseebakwet	Grand Rapids	1991-2008	92,93
Six	Grand Rapids	1991-2008	97
Snowbank	International Falls	1961-2008	86,88
South Twin	Bemidji	1991 2008	08
Ten Mile	Bemidji	1991-2008	01, 02, 08
Trout (Cook)	International Falls	1961-2008	83, 84, 85, 86, 03, 08
Trout (St. Louis)	International Falls	1961-2008	06
White Iron	Duluth	1961-2008	95, 96, 00, 06, 07, 08
Non-cisco habitat lakes			
Bear Head	Duluth	1961-2008	08
Carrie	Saint Cloud	1961-2008	08
Elephant	International Falls	1961-2008	08
Hill	Grand Rapids	1991–2008	94, 08
Madison	Minneapolis	1961-2008	80, 83, 86, 87, 89, 90, 93, 96, 06
South Center	Minneapolis	1961-2008	86, 06, 08
St. Olaf	Minneapolis	1991–2008	86, 96, 01, 08

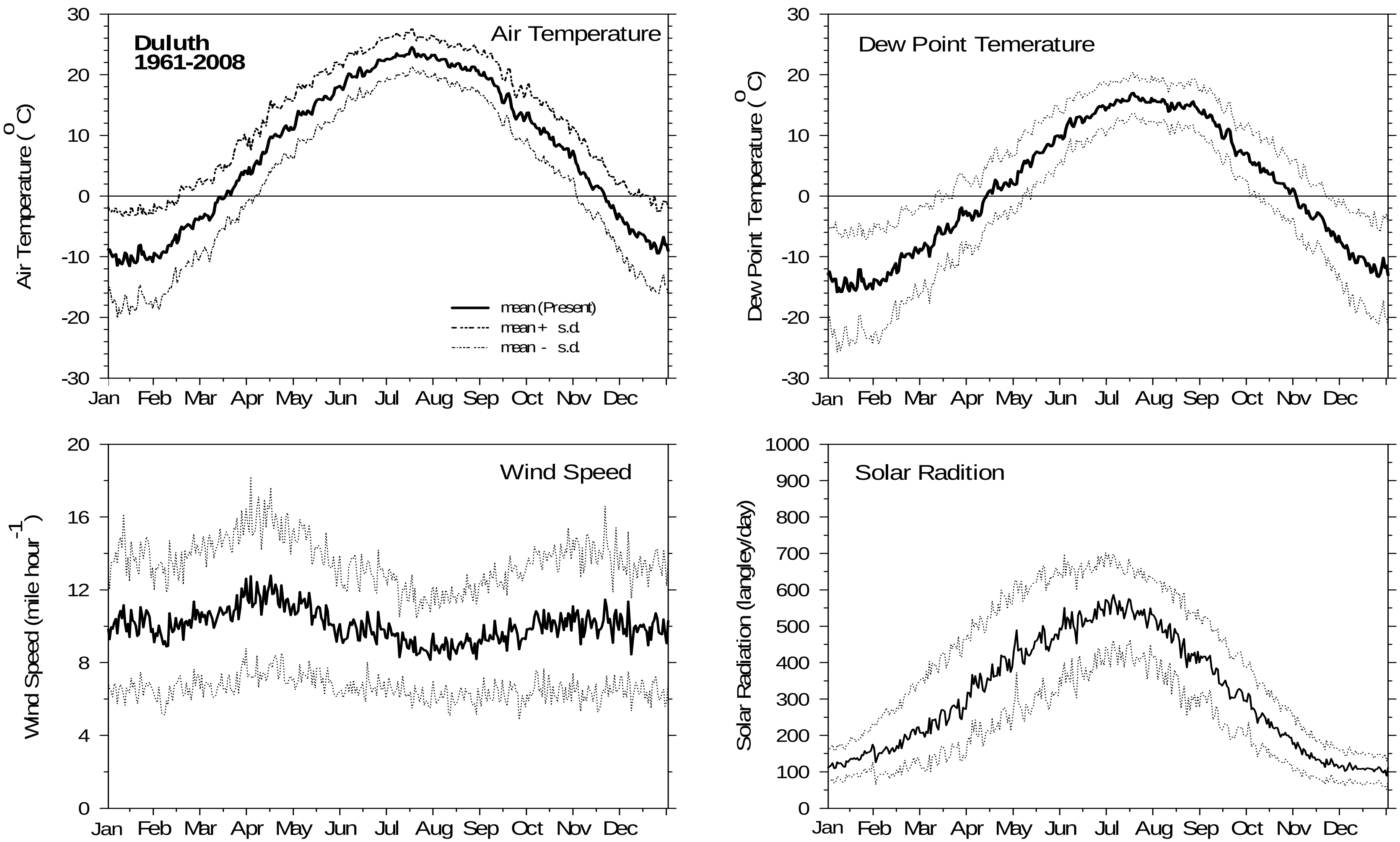

Figure 4.1 Example of seasonal weather variability in northern Minnesota. Daily averages (1961-2008) and variations (plus/minus standard deviation) of air temperature, dew point temperature, wind speed, and solar radiation at the Duluth weather station.

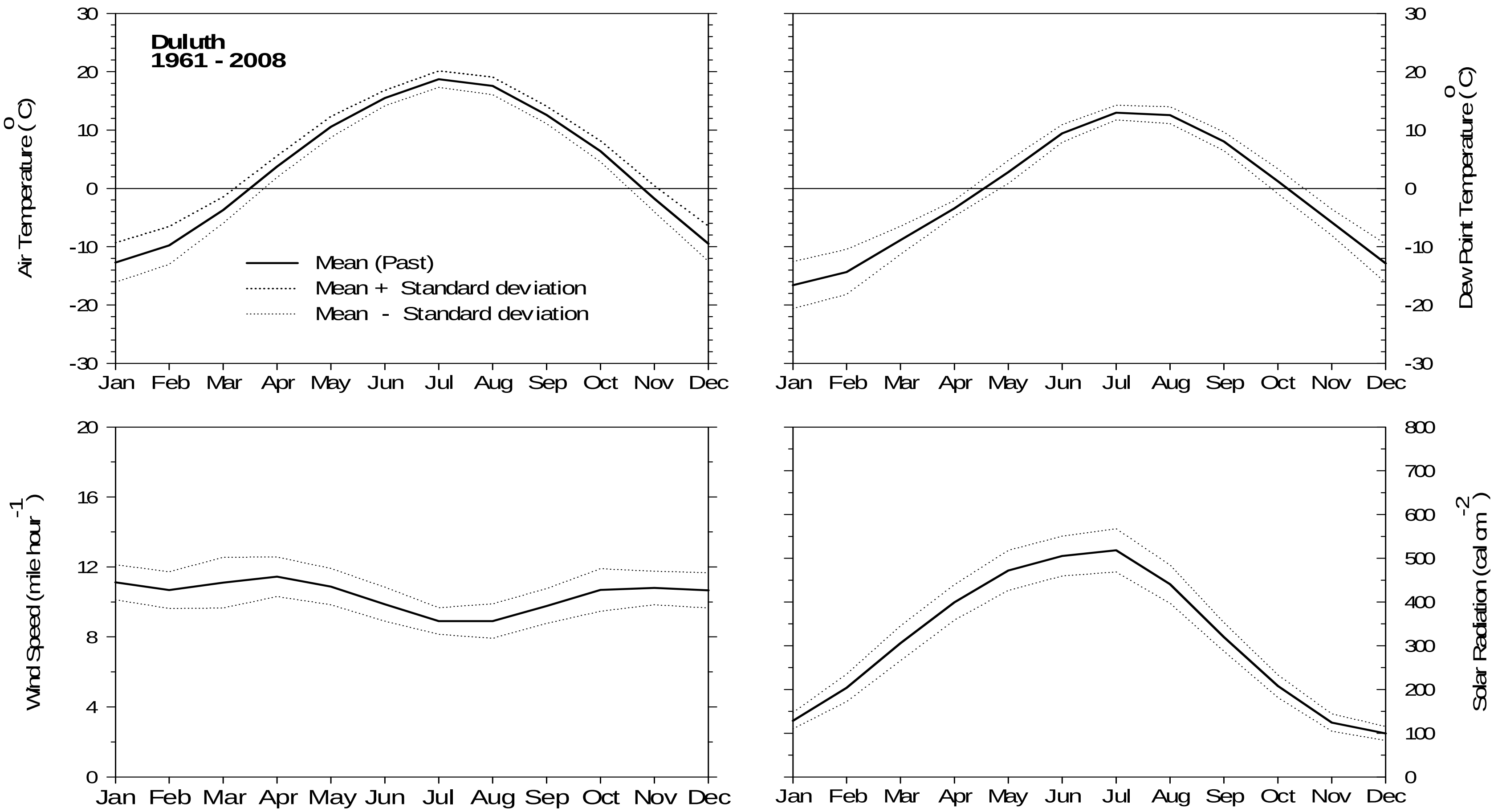

Figure 4.2 Monthly average (1961-2008) and variations (plus/minus standard deviation) of air temperature, dew point temperature, wind speed, and solar radiation at the Duluth weather station.

Chapter 5 Model Adaptation and Calibration Parameters

5.1. Adaptation and refinements of MINLAKE model

MINLAKE96 was developed from MINLAKE95, an earlier one-dimensional, regional, year-round water temperature and dissolved oxygen model (Stefan et al., 1994b). MINLAKE95 has been applied to simulate water temperature and dissolved oxygen (DO) characteristics of lakes in Minnesota and North Carolina under past and projected future climate scenarios (Stefan and Fang 1995; Rasmussen and Stefan 1996). MINLAKE95 was developed for typical Minnesota lakes which are often shallow and eutrophic. In order to more accurately predict water quality conditions in cisco lakes, which are typically deep and mesotrophic or oligotrophic lakes, various modifications and refinements were made in the program, particularly the simulation procedure and utility functions of the model. These changes were made at different stages of model development and calibration using the 28 study lakes during this study. The modified model, called MINLAKE2010, has shown the desired improved performance for deep lakes in many respects. The areas where modifications and refinements of the MINLAKE2010 model were made are as follows:

1. In previous earlier studies of 27 lake classes (Stefan et al. 1996) the maximum lake depth was 24 m. That is less than the maximum depth encountered in many Minnesota cisco study lakes. Some of the 28 study lakes are very deep (e.g., the maximum depth of Ten Mile Lake is 63 m). If the typical 1.0 m layer thickness is used in the model simulations, the maximum number of horizontal layers specified in the MINLAKE96 model (40 layers) is exceeded. The maximum number of horizontal layers in MINLAKE2010 was therefore increased to 80, so that the model can handle deeper lakes. The maximum depth of a lake can be up to 75 m if the 1.0 m layer thickness is used, because the first five layers near the water surface have thicknesses less than 1.0 m for winter ice-cover simulations.
2. Several new calibration parameters, such as EMCOE(1), EMCOE(2), EMCOE(4) and EMCOE(5), were activated or introduced in the program. Each calibration parameter will be discussed in the next section. Use of these parameters enhances the performance of the model significantly for some of the study lakes.
3. Some modifications and new coding were developed to estimate/determine the mixed-layer depths of the measured temperature and DO profiles. Now the model is coded to perform an error analysis between simulated and measured mixed-layer depths, and between simulated and measured temperature and DO in the mixed layers.
4. The model was expanded to read the output from two future climate projection models, CCC CGCM 3.1 (Kim et al. 2002; Kim et al. 2003) and MIRO 3.1 (Hasumi and Emori 2004). The model can therefore simulate lake responses to three future climate scenarios including the previous Canadian climate center's CCC CGCM 3.1 (Boer et al. 1992; McFarlane et al. 1992) output.
5. The model is coded so that at the end of winter ice cover period when simulated water temperature increases from less than to greater than $4^{o}C$ within two days, complete lake

mixing (overturn) is enforced. The previous model could miss complete spring mixing of a lake in cases when the lake warming was very fast.

6. Previously, the starting day of the simulations had to be on a date with known (measured) lake temperature and DO profiles. The program was not flexible enough to start the simulation from any day in relation to the field data collection dates. A refinement in the program now allows the model to run from any date, independent of the field data collection dates.
7. Various modifications were made in the program to make the input data files to be user-friendly, and this increased the model efficiency to model all 28 different lakes in the study. The modifications will also be of benefit to any future new users of the model.

5.2 Basic model input parameters

The MINLAKE2010 model reads model input data through the following ten (10) input files (file types):

(1) bathymetry data input file (Chapter 3; Section 3.3 and Table 3.3)
(2) weather data input files (Chapter 4; files are organized station by station and year by year)
(3) lake specific model parameter input file
(4) fixed model parameter input file
(5) file with long-term annual and January air temperatures for a list of weather stations
(6) weather station information file that gives elevations, longitudinal and latitude for all weather stations used
(7) dimensionless sediment temperature profile file (Fang and Stefan 1998)
(8) seasonal chlorophyll-a pattern file (Marshall and Peters 1989; Stefan and Fang 1994)
(9) path file directing the program to open model input files or save output files at different folders or locations in a computer
(10) future climate data files that have output data of GCM models (they will be described in the third project report).

Most of the input data files are common data files for model simulation of any lakes. Only three data files are created for a specific lake: the bathymetry data file, the lake specific model parameter input file, and the path file. Appendix C provides more information on these input files. Sediment temperatures at 10 meter below at sediment-water interfaces at different water layers are one of model input data (Fang and Stefan 1998). This 10-m sediment temperatures have been related to mean annual air temperatures (Todd 1980). Long-term air temperature in January is used in the model to specify whether the lake near that weather station would have ice cover during the winter or not (Fang and Stefan 1998). The station data file and the file with long-term air temperatures were previously developed for regional lake study in 209 weather stations over the contiguous United States. The corresponding data should be added if a new weather station beyond the original 209 stations is used for a lake simulation study, for example, the three Class II weather stations were used for the study and are not in the list of the 209 stations. Therefore, in addition to three lake specific input files mentioned early, the station data file and the file with long-term air temperatures were also updated. Model input parameters are organized and inputted in lake specific model parameter input file. Several basic but lake dependent model input parameters are as follows:

5.2.1 Attenuation coefficients (μ, μ_w , μ_{chla})

In MINLAKE2010, solar radiation attenuation coefficients due to the water (μ_w in m^{-1}) and due to phytoplankton ($\mu_{chla} \times$ Chla in m^{-1}) are set as constants over the entire simulation period of several years. "Chla" is daily chlorophyll-*a* concentration in the lake in mg/L and estimated from mean summer chlorophyll-*a* concentration and a seasonal pattern of chlorophyll-*a* (Marshall and Peters 1989) discussed in the section 3.3. The attenuation rate coefficient due to phytoplankton (μ_{chla}) is always set as constant [20 m^{-1}/(mg/L Chla)] in the model (Stefan and Fang, 1994). For each lake simulated, attenuation coefficient due to water is estimated by subtracting the attenuation coefficient due to phytoplankton from the result of equation 2.5 (1.84 divided by Secchi depth). Values of Secchi depth and chlorophyll-a concentration used in calculation of attenuation coefficient are long-term averages of available measurements. Even though these attenuation coefficients are constant, the total attenuation coefficient on each simulation day does change because the chlorophyll-*a* concentration follows a seasonal pattern as discussed above. Even Secchi depths (SD) are included in the model input file on the days when temperature and DO profiles were measured, these measured Secchi depths were not used in the program to compute attenuation coefficients as discussed in the section 3.3. Table 3.3 lists total attenuation coefficients and the attenuation coefficients due to water for all 28 study lakes. Total attenuation coefficients for 21 cisco lakes range from 0.27 to 0.72 m^{-1} with an average value of 0.43 m^{-1} after excluding White Iron Lake as an eutrophic lake. The total attenuation coefficients for seven non-cisco lakes are much higher and have an average of 1.07 m^{-1}.

5.2.2 Sedimentary oxygen demand (SOD)

SOD is quantified by the coefficient S_{b20} which is the value of sedimentary oxygen demand (S_b) at a temperature of 20^oC and is in grams of dissolved oxygen per bottom sediment surface area per day (g O_2 m^{-2} day^{-1}). Considering that the composition of lake bottom sediments in many Minnesota lakes is usually the result of the settling of mostly particulate organic matter such as phytoplankton, macrophytes, detritus and of a moderate amount of inorganic materials, different S_{b20} values need to be selected for lakes with different trophic states and maximum depths. S_{b20} values given in Table 2.5 were previously recommended and specified (Stefan et al. 1994a) for different trophic states, and deep, medium deep and shallow lakes in Minnesota. In this cisco lake study, the S_{b20} value was specified before the model calibration for each lake, depending on the trophic status and the maximum depth of a lake. The specified S_{b20} values for the 28 study lakes are summarized in Table 5.1.

5.2.3 Biochemical oxygen demand (BOD)

BOD is the sum of carbonaceous biochemical demand, CBOD and nitrogenous biochemical demand, NBOD. Since the lake model does not account for inflows from the watershed into a lake, it is assumed that there are no external (alochtonous) inflows of BOD to a lake. BOD is from the microbial decay of organic matter and dissolved organic carbon (DOC) in the lake. A relationship between primary productivity, represented as chlorophyll-*a* and BOD is hypothesized since chlorophyll-*a* is related to production of organic matter (measured as carbon) which in turn is related to detritus and BOD. The DO model developed for a previous study (Stefan et al. 1994a) suggested and recommended the values of total BOD for lakes with different trophic status given in Table 2.5. The ratio of carbon to chlorophyll-a (which is the basis for calculation of values of total BOD) had a wide range from 12 to 68 (Stefan and Fang 1994), suggesting that that total BOD should be calibrated for each lake to achieve better model results. The BOD value recommended before model calibration for each of the 28 study lakes depending on trophic status is given in Table 5.1.

5.2.4 Chlorophyll-a concentration (Chla)

In the MINLAKE model, summer mean values of chlorophyll-*a* concentration and deviations of daily chlorophyll-*a* concentrations from the mean are specified as model input. The specifications for lakes depend on different trophic status. Summer mean chlorophyll–*a* values were calculated for each lake using available measurements on the dates when vertical temperature and DO profiles were also measured. The summer mean chlorophyll-a concentrations are summarized in Table 5.1 for the 28 study lakes. The mean chlorophyll-*a* concentration is calculated by the MINLAKE program using measured chlorophyll-*a* concentrations as input (see Appendix C).

Table 5.1 lists cisco lakes and non-cisco lakes separately, and lakes are sorted by maximum depth classification, trophic status classification, and surface area classification to facilitate the comparison and generalization of model parameters in a later chapter of the report.

5.3 Calibration parameters

The lake water quality model MINLAKE2010 is calibrated first for water temperature and then for dissolved oxygen using measured profiles for both in individual lakes. In this study, we have introduced and used several calibration parameters as described in Table 5.2. The wind sheltering coefficient (W_{str}) was introduced in the original one-dimensional water temperature model (Ford and Stefan 1980) and was generalized by Hondzo and Stefan (1993b). BOD was used as a calibration parameter in the DO model for individual lakes and generalized for the regional DO model (Stefan and Fang 1994). A multiplier for chlorophyll–*a* in the hypolimnion was implicitly used based on detailed data analysis and enhancement of the DO model for oligotrophic Thrush Lake, Minnesota (Stefan et al. 1995a). A multiplier for SOD below the mixed layer was introduced in the MINLAKE96 program and used in testing and calibration of a few lakes. These four parameters were reactivated and calibrated for the 28 cisco study lakes. Two new calibration parameters, multipliers for diffusion coefficients, were introduced and used to improve simulation results in some deep lakes.

Table 5.1 Lake classification and basic model parameters before calibration.

Lake name	Lake Classification			Lake Specific Parameters		
	By H_{max}	By SD	By A_s	S_{b20}	BOD (mg/L)	Chl a (mg/L)
Cedar	Deep	Mesotrophic	Medium	0.50	0.50	0.0050
Elk	Deep	Mesotrophic	Medium	0.50	0.50	0.0094
Grindstone	Deep	Mesotrophic	Medium	0.50	0.50	0.0064
Six	Deep	Mesotrophic	Medium	0.50	0.50	0.0045
Carlos	Deep	Mesotrophic	Large	0.50	0.50	0.0039
Fish Hook	Deep	Mesotrophic	Large	0.50	0.50	0.0040
Kabekona	Deep	Mesotrophic	Large	0.50	0.50	0.0030
Siseebakwet	Deep	Mesotrophic	Large	0.50	0.50	0.0021
Little Sand	Deep	Oligotrophic	Medium	0.20	0.20	0.0023
Little Trout	Deep	Oligotrophic	Medium	0.20	0.20	0.0007
Mukooda	Deep	Oligotrophic	Medium	0.20	0.20	0.0012
Trout (Cook)	Deep	Oligotrophic	Medium	0.20	0.20	0.0011
Big Trout	Deep	Oligotrophic	Large	0.20	0.20	0.0034
Burntside	Deep	Oligotrophic	Large	0.20	0.20	0.0029
Greenwood	Deep	Oligotrophic	Large	0.20	0.20	0.0025
Snowbank	Deep	Oligotrophic	Large	0.20	0.20	0.0027
Ten Mile	Deep	Oligotrophic	Large	0.20	0.20	0.0023
Trout (St. Louis)	Deep	Oligotrophic	Large	0.20	0.20	0.0025
South Twin	Medium	Mesotrophic	Medium	0.75	0.50	0.0043
Blue	Medium	Oligotrophic	Medium	0.40	0.20	0.0028
White Iron	Medium	Eutrophic	Large	1.50	1.00	0.0055
Non-cisco habitat lakes						
South Center	Deep	Eutrophic	Medium	1.00	1.00	0.0485
Carrie	Medium	Eutrophic	Small	1.50	1.00	0.0066
St. Olaf	Medium	Eutrophic	Small	1.50	1.00	0.0137
Madison	Medium	Eutrophic	Medium	1.50	1.00	0.0500
Bear Head	Medium	Mesotrophic	Medium	0.75	0.50	0.0074
Elephant	Medium	Mesotrophic	Medium	0.75	0.50	0.0065
Hill	Medium	Mesotrophic	Medium	0.75	0.50	0.0115

H_{max} = lake maximum depth, A_s = lake surface area, SD = lake mean-summer Secchi depth as indicator for lake trophic status, and S_{b20} is in g $O_2/(m^2$ day).

Table 5.2 Calibration parameters for MINLAKE2010

Calibration parameter	Effect on model results	Description of the parameter
W_{str}	Temperature and DO profiles	Wind sheltering coefficient
BOD	DO Profiles	Biochemical oxygen demand depending on lake trophic status
EMCOE(1)	Temperature and DO Profiles	Multiplier for diffusion coefficient in the metalimnion
EMCOE(2)	DO Profiles	Multiplier for SOD below the mixed layer
EMCOE(4)	Temperature and DO Profiles	Multiplier for diffusion coefficient in hypolimnion
EMCOE(5)	DO Profiles	Multiplier for chlorophyll–a below the mixed layer

Note: EMCOE stands for EMpirical COEfficient. EMCOE is an array in the program. EMCOE(3) was used in the program for other purpose.

5.3.1 Wind sheltering coefficient (W_{str})

The wind sheltering coefficient (W_{str}) is an important model calibration parameter and represents the fraction of wind energy available for lake mixing (Riley and Stefan 1988). The wind sheltering coefficient for the model input file is calculated by equation 5.1 as function of lake surface area (Hondzo and Stefan 1993b).

$$W_{str} = 1.0 - \exp(-0.3 \times A_s) \tag{5.1}$$

where A_s is the lake surface area in km^2. The theoretical maximum value for the wind sheltering coefficient is 1.0, and the minimum is 0. Equation 5.1 indicates that for lakes with large surface area W_{str} is higher than for lakes with smaller surface area. A value of 1.0 indicates no wind sheltering, and a value of complete wind sheltering (no wind effects).

Actually, lakes with the same surface area can have different W_{str} values because the surroundings of a lake, in terms of tree canopies, buildings etc can have a significant effect on wind sheltering, especially for small lakes (Markfort et al. 2010). If a small lake is surrounded by tall and dense vegetation (forest) or buildings (residential area) wind sheltering is stronger in comparison to a lake with wide open space around its periphery. Even single rows of trees or buildings along the shoreline of a lake can shelter a larger portion of a small lake; hence W_{str} needs to be calibrated for individual lakes to simulate the wind mixing properly. The depth of the lake's surface mixed layer and the location of the thermocline will depend on it, and so will mixing in the hypolimnion. By comparison of simulated and measured temperature and DO profiles, an optimal W_{str} value was determined (calibrated) for each of the 28 study lakes. A bird's eye or aerial view of a lake's surroundings given on Bing maps (URL: http://www.bing.com/maps/) or Google maps (URL http://maps.google.com/maps) can be helpful to adjust wind sheltering coefficients for model calibration of individual lakes. Aerial views of the 28 study lakes from Google maps are present in appendix A. The wind sheltering effect of vegetation canopies on lakes and the associated reduction in wind sheltering coefficients has recently been studied in a wind tunnel and in the field (Markfort et al. 2010). The new method proposed for the initial, pre-calibration estimation of wind sheltering coefficients came too late for application in this cisco lake study.

5.3.2 Biochemical Oxygen Demand (BOD)

As discussed in section (5.2.3) of this report, BOD is an important parameter in the DO model. It can be specified *a priori* based on a lake's trophic state, but can then be refined by calibration to get better results on vertical DO profiles for each lake modeled. Table 3.12 shows the values of W_{str} and BOD before and after calibration in the 28 study lakes.

5.3.3 EMCOE(2)

EMCOE(2) is a new multiplier of sedimentary oxygen demand (SOD) below the mixed layer. SOD was previously quantified by the model parameter S_{b20} which was calibrated for the first 15 study lakes. During the process of improvement of the model performance a multiplier EMCOE(2), was activated and calibrated. This parameter is a multiplier for sedimentary oxygen demand below the mixed layer. After the temperature profiles had been calibrated, both BOD and EMCOE(2) were calibrated to obtain better model performance in the DO profile simulations. In Table 5.4 the EMCOE(2) values obtained by model calibration are summarized for each of the 28 study lakes. EMCOE(2) = 1.0 means that the rate of sedimentary oxygen demand in the epilimnion (the mixed layer) and below the mixed layer is the same. All 28 study lakes, except two lakes have EMCOE(2) values greater than 1.0 and up to 7.5.

5.3.4 EMCOE(5)

EMCOE (5) is a multiplier for chlorophyll–*a* concentration below the mixed layer, EMCOE(5), was introduced as a model calibration parameter before the start of the cisco study because measured vertical DO profiles in Thrush Lake had shown "metalimnetic oxygen maxima" (MOMs), i.e. DO peaks in the thermocline region (Stefan et al. 1995a). Measured chlorophyll-a concentrations from 1986 to 1991 in Thrush Lake were always fairly low and uniform in the epilimnion and much higher in the metalimnion and hypolimnion (Stefan et al. 1995a). However, the same values (time series) of chlorophyll-*a* concentrations in the epilimnion and in the hypolimnion were used in earlier studies for model simulations. The multiplier, EMCOE(5), was therefore introduced to increase chlorophyll-a concentration below the epilimnion when the model input file still has the same input values for the time series of chlorophyll-a concentrations in the epilimnion and below the epilimnion.

The multiplier EMCO(5) as a calibration parameter is easy to implement in the program and more user friendly than changing values of the chlorophyll-*a* concentration time series below the epilimnion (up to 46 values for the time series of the study lakes). After implementing the multiplier, better model performance was achieved for those lakes where MOMs were present. Table 5.4 lists the values of the EMCOE(5) calibration parameter for all 28 study lakes.

5.3.5 EMCOE (1) and EMCOE (4)

EMCOE(1) and EMCOE(4) are multipliers for metalimnetic and hypolimnetic diffusion coefficients, respectively. EMCOE(1) and EMCOE(4) are new calibration parameters introduced in this study to improve the model performance. When the simulated temperature profiles in a number of deep lakes were carefully examined and analyzed, it was found that in some cases metalimnetic and hypolimnetic diffusion rates determined from the model formula were higher or lower than indicated by the field temperature and DO profiles. Introduction of the two multipliers has improved the performance of the model. Table 5.4 lists the values of the two calibration parameters. During the calibration process, it became evident that EMCOE(1) has a relatively strong effect on temperature and DO profiles, while EMCOE(4) affects the profiles rather weakly.

Table 5.3 Calibration parameter values before and after calibration.

Lake name	Lake Classification			Before calibration		After calibration	
	By H_{max}	By Z_s	By A_s	W_{str} (-)	BOD (mg/L)	W_{str} (-)	BOD (mg/L)
Cedar	Deep	Mesotrophic	Medium	0.25	0.50	0.68	0.75
Elk	Deep	Mesotrophic	Medium	0.28	0.50	0.60	0.80
Grindstone	Deep	Mesotrophic	Medium	0.47	0.50	0.47	0.50
Six	Deep	Mesotrophic	Medium	0.20	0.50	0.10	0.50
Carlos	Deep	Mesotrophic	Large	0.95	0.50	1.00	0.50
Fish Hook	Deep	Mesotrophic	Large	0.86	0.50	0.30	0.50
Kabekona	Deep	Mesotrophic	Large	0.94	0.50	0.98	0.50
Little Sand	Deep	Oligotrophic	Medium	0.37	0.20	0.30	0.20
Little Trout	Deep	Oligotrophic	Medium	0.25	0.20	0.25	0.20
Mukooda	Deep	Oligotrophic	Medium	0.60	0.20	0.60	0.40
Trout (Cook)	Deep	Oligotrophic	Medium	0.27	0.20	0.10	0.25
Big Trout	Deep	Oligotrophic	Large	0.80	0.20	0.80	0.20
Burntside	Deep	Oligotrophic	Large	1.00	0.20	1.00	1.00
Greenwood	Deep	Oligotrophic	Large	0.91	0.20	0.50	0.20
Siseebakwet	Deep	Oligotrophic	Large	0.80	0.20	1.00	0.40
Snowbank	Deep	Oligotrophic	Large	0.99	0.20	0.99	1.00
Ten Mile	Deep	Oligotrophic	Large	1.00	0.20	1.00	0.50
Trout (St. Louis)	Deep	Oligotrophic	Large	1.00	0.20	1.00	1.15
White Iron	Medium	Eutrophic	Large	0.98	1.00	1.00	0.25
South Twin	Medium	Mesotrophic	Medium	0.74	0.50	0.74	0.50
Blue	Medium	Oligotrophic	Medium	0.19	0.20	0.40	1.25
Non-cisco habitat lakes							
South Center	Deep	Eutrophic	Medium	0.64	1.00	0.64	1.50
Carrie	Medium	Eutrophic	Small	0.10	1.00	0.70	1.00
St. Olaf	Medium	Eutrophic	Small	0.10	1.00	0.50	1.90
Madison	Medium	Eutrophic	Medium	0.74	1.00	1.00	2.50
Bear Head	Medium	Mesotrophic	Medium	0.56	0.50	0.45	1.00
Elephant	Medium	Mesotrophic	Medium	0.58	0.50	0.90	1.00
Hill	Medium	Mesotrophic	Medium	0.55	0.50	0.65	1.75

Table 5.4 Calibrated values for four model parameters.

Lake name	Lake Classification			Calibrated Values			
	By H_{max}	By Z_s	By A_s	EMCOE(2)	EMCOE(1)	EMCOE(4)	EMCOE(5)
Cedar	Deep	Mesotrophic	Medium	3.00	1.00	1.00	1.00
Elk	Deep	Mesotrophic	Medium	3.50	0.80	1.50	1.00
Grindstone	Deep	Mesotrophic	Medium	0.45	1.25	1.00	1.00
Six	Deep	Mesotrophic	Medium	3.75	0.10	0.10	1.10
Carlos	Deep	Mesotrophic	Large	2.20	1.50	1.00	1.00
Fish Hook	Deep	Mesotrophic	Large	2.50	0.75	1.00	1.00
Kabekona	Deep	Mesotrophic	Large	2.75	1.00	1.00	1.00
Siseebakwet	Deep	Mesotrophic	Large	1.75	1.50	1.00	2.00
Little Sand	Deep	Oligotrophic	Medium	7.50	0.10	1.00	1.75
Little Trout	Deep	Oligotrophic	Medium	7.50	0.05	1.00	2.25
Mukooda	Deep	Oligotrophic	Medium	5.00	0.50	1.00	2.00
Trout (Cook)	Deep	Oligotrophic	Medium	2.00	0.35	4.00	1.00
Big Trout	Deep	Oligotrophic	Large	8.00	0.80	1.00	1.00
Burntside	Deep	Oligotrophic	Large	0.75	0.20	1.50	1.00
Greenwood	Deep	Oligotrophic	Large	6.00	0.20	1.00	1.00
Snowbank	Deep	Oligotrophic	Large	1.25	0.40	1.00	1.50
Ten Mile	Deep	Oligotrophic	Large	6.50	0.70	6.00	1.00
Trout (St Louis)	Deep	Oligotrophic	Large	4.00	0.25	1.00	1.00
White Iron	Medium	Eutrophic	Large	1.20	1.75	1.00	1.00
South Twin	Medium	Mesotrophic	Medium	1.50	1.50	3.00	1.00
Blue	Medium	Oligotrophic	Medium	2.40	0.10	1.00	1.35
Non-cisco habitat lakes							
South Center	Deep	Eutrophic	Medium	1.00	0.70	1.00	1.0
Carrie	Medium	Eutrophic	Small	1.00	2.00	1.00	1.0
St. Olaf	Medium	Eutrophic	Small	1.60	1.00	1.00	1.6
Madison	Medium	Eutrophic	Medium	2.00	1.00	1.00	1.0
Bear Head	Medium	Mesotrophic	Medium	1.45	0.65	1.00	1.0
Elephant	Medium	Mesotrophic	Medium	1.00	0.75	1.00	1.0
Hill	Medium	Mesotrophic	Medium	6.00	0.60	1.00	1.0

EMCOE(1) = multiplier of diffusion coefficient in the metalimnion,
EMCOE(2) = multiplier of SOD below the mixed layer
EMCOE(4) = multiplier of diffusion coefficient in the hypolimnion,
EMCOE (5) = multiplier of chlorophyll a concentration below the epilimnion.

Chapter 6 Model Calibration Results and Discussion

6.1 Calibration procedure and measures of success

The model calibration was conducted by (1) comparing statistical error parameter values calculated from simulated and measured data pairs of water temperatures and DO concentrations at all depths and dates when measured profiles of water temperature and DO were available and (2) comparing the profile plots and time series plots of simulated and measured temperature and DO values. Profile plots for all 28 study lakes are presented in Appendix D, and time series of plots for the first 15 study lakes are presented in Appendix E.

Calibration parameters were varied until the best fit between observations and model predications was achieved. The reliability and accuracy of the model were evaluated by using the following statistical error parameters calculated from observed and simulated data pairs: (1) standard error of prediction (S.E.), (2) the slope of regression (*S*), and (3) the coefficient of determination or regression coefficient (R^2). The S.E. (S_e symbol is used in equation 6.1) is commonly called the root mean square of error (RMSE) between simulated value and observed (measured) data and is computed as

$$S_e^2 = \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{n} \qquad (6.1)$$

where y_i is the observed value (temperature, DO concentration, or mixed layer depth from measured profiles), x_i is the predicted or simulated value, and n is the number of pairs of observed and simulated data. The objective of model calibration is to reduce S_e to an acceptable value, and smaller S_e means better match between simulated and observed values.

The slope of the regression (*S*) indicates if the model is over predicting (slope < 1.0) or under predicting (slope > 1.0) observed data. *S* is defined and calculated by equation 6.2.

$$S = \frac{\sum_{i=1}^{n} y_i x_i}{\sum_{i=1}^{n} (x_i)^2} \qquad (6.2)$$

The objective value of *S* is 1.0 when, overall, the simulated values are in perfect agreement with the observed values.

The regression coefficient is the ratio of the variance between measured (observed) and predicted (simulated) values to the total variance in the field data. It is given by equation 6.3

$$R^2 = 1 - \frac{S_e^2}{\sigma^2} \tag{6.3}$$

where σ is standard deviation of the mean of field (observed) data and calculated as

$$\sigma^2 = \frac{\sum_{i=1}^{n} \left(y_i - \overline{y}\right)^2}{n} \tag{6.4}$$

$$\overline{y} = \frac{\sum_{i=1}^{n} y_i}{n} \tag{6.5}$$

$\overline{y}$ is the mean of the measured (observed) data or the observed mean. The calibration objective is that R^2 approaches 1.0 and S.E. goes to 0.0. In hydrological modeling simulation, the regression coefficient R^2 is called the Nash-Sutcliffe coefficient (N_r) or model efficiency (E) (Nash and Sutcliffe 1970).

The value of R^2 can vary from $-\infty$ to 1. The ideal value is one ($R^2 = 1$) which indicates a perfect match of simulated values and observed data. A coefficient of value zero ($R^2 = 0$) indicates that the model predictions are no better than that obtained using the simple average of observed data (when $S_e = \sigma$). When the coefficient is less than zero ($R^2 < 0$), it means that $S_e > \sigma$, the standard error of prediction is greater than the standard deviation from the mean of observed data. When there are small amount of observed data with small variations, the standard deviation (σ) can be very small to make R^2 less than zero even though S_e and S are acceptable.

6.2 Calibration and validation results in selected lakes

We carefully examined all model parameters given in Tables 2.4 and 2.5, and used in previous year-round simulations of daily water temperature and DO dynamics in Minnesota lakes. Basic model input parameters and model coefficients for MINLAKE2010 were specified using guidance and experience developed in previous lake studies (Hondzo and Stefan 1993a; Stefan et al. 1994b). Table 5.4 gives lake classifications for the 28 study lakes by maximum depth, surface area, and trophic status using previous lake classification criteria from Table 2.1. It lists the initial values of lake specific model parameters before calibration, sedimentary oxygen demand (S_{b20}) and biochemical oxygen demand (BOD), for the 28 study lakes based on previous lake model parameters given in Table 2.5. The last column in Table 5.1 gives summer mean chlorophyll-a concentration (Chla) calculated from measured Chla data for the 28 study lakes. Mean summer chlorophyll-*a* concentrations for eutrophic, mesotrophic, and oligotrophic lakes were previously specified as 2.0, 6.0, 15.0 μg/L as shown in Table 2.1, but were not used for individual lake simulations in this cisco study. Mean summer Secchi depth and mean summer chlorophyll-*a* concentration for each lake was used to specify (classifying) a lake's trophic status (Table 3.2). Both information on Secchi depth and chlorophyll a concentration for a lake was used in classifying the lake trophic status (Table 3.2). Lake Carlos was originally classified as eutrophic lakes, but based on mean and range of chlorophyll-a concentrations, we reclassified the lake as mesotrophic lakes. In Minnesota DNR Lake Finder web site, this lake is classified as eutrophic lakes. Lake Elk and Hill Lake are classified as mesotrophic lakes based on both Secchi depth and mean chlorophyll-a concentration computed from the data for those years with vertical profiles (Table 3.2), but Minnesota DNR Lake Finder web site classifies them as oligotrophic lakes based on mean Secchi depth computed from all available data. For example, Lake Elk has Secchi depth data for 12 years (1985 – 2008) with annual mean Secchi depth ranges from 2.5 to 9.1 m and overall mean Secchi depth as 4.45 meters. Annual mean Secchi depth in 2003 is 9.1 meters (ranging from 4.87 to 12.49 meters), and for all other years they are less than 4.5 meters.

In this section, the MINLAKE2010 model was calibrated using part of measured profiles in the first few years and validated using remaining part of measured profiles in the last several years. This is typical model calibration and validation process if there are many years of measured data available. The data record was divided into two parts; one period was used to calibrate the model, and the other period was used to validate the calibrated model. Model calibration and validation results for six selected lakes are reported here. Lakes selected are Blue Lake, Burntside Lake, Little Trout Lake, Trout Lake (Cook County), St. Olaf Lake, and White Iron Lake. These lakes have field data for several (3 to 5) years. In this study, some of the study lakes have only one or two years of data available, therefore, the MINLAKE2010 model was first calibrated for all 28 study lakes using all available measured temperature and DO profiles, and calibration results are summarized in the next section.

Three simulation runs were made using MINLAKE2010 for each of the six lakes. The first run was for the first few years of field measurements (see third column of Table 6.1) and used default model parameters. The second run was performed for the same period, but model parameters were calibrated to this period; this is the 'model calibration run'. The third run was performed for the last few years of field measurements (last column of Table 6.1) and using the calibrated model parameters; this is the 'model validation run'. Table 6.1 shows years with available field data, years or simulation period used for model calibration and validation.

Table 6.2 gives quantitative measures of success of simulations for water temperature (^oC) and dissolved oxygen (mg/L) – error parameters (standard error S.E., model efficiency R^2, regression slope S) for the three model runs for each of the six lakes. Table 6.2 shows that all measures of success (error parameters) for the calibration run were better than for the run using default model parameters. If the third model run (validation run) has satisfactory results (similar or better values of error parameters), it is assumed that the model validation is successful for that lake. By this standard, the model was successfully validated for all the six lakes as shown by the error parameter values in Table 6.2.

The numerical values of the six calibration parameters obtained in the calibration process were compared with those obtained in the original model calibration with the all data record. The six calibrated model parameters were very similar to those obtained with the all data record and given in Tables 6.3 and 6.4.

Table 6.1 Years of data used for validation purpose

Lake Name	Years with available field data	Years of field data used for calibration	Years of field data used for validation
Blue	1997, 99, 2001, 2002	1987, 99	2001, 02
Burntside	1986, 88, 94, 2000	1986, 88	1994, 2000
Little Trout	1997, 2006, 07, 08	1997, 2006	2007, 08
Trout (Cook)	1983, 84, 85, 86	1983, 84	1985, 86
St. Olaf	1986, 2001, 2008	1986, 01	2008
White Iron	1995, 96, 2000, 06, 07	1995, 96, 2000, 06	2007

Table 6.2 Quantitative measures of success of simulations of water temperature (°C) and dissolved oxygen (mg/L) for model calibration and validation runs.

Lake	Years	Runs	Temperature			DO		
			S.E. (°C)	R^2	S	S.E. (mg/L)	R^2	S
Blue	1987, 99	1st run	2.31	0.79	0.49	3.02	0.49	0.44
	1987,99	calibration run	1.77	0.89	0.97	1.68	0.91	0.97
	2001, 02	validation run	1.82	0.83	0.98	1.55	0.71	0.99
Burntside	1986, 88	1st run	2.79	0.45	.67	4.02	0.34	0.65
	1986, 88	calibration run	1.82	0.91	0.92	1.41	0.94	1.03
	1994, 00	validation run	1.67	0.91	1.01	1.44	0.99	1.03
Little Trout	1997, 06	1st run	2.61	0.74	0.52	3.02	0.49	0.44
	1997, 06	calibration run	1.77	0.89	0.97	1.68	0.91	0.97
	2007, 08	validation run	1.82	0.83	0.98	1.55	0.71	0.99
Trout (Cook)	1983, 84	1st run	2.79	0.45	.67	4.02	0.34	0.65
	1983,84	calibration run	1.82	0.91	0.92	1.41	0.94	1.03
	1985,86	validation run	1.67	0.91	1.01	1.44	0.99	1.03
St. Olaf	1986, 96	1st run	2.44	0.79	0.69	3.24	0.59	0.54
	1986, 96	calibration run	1.77	0.89	0.97	1.98	0.81	0.92
	2001,08	validation run	1.29	0.83	0.98	1.89	0.79	0.92
White Iron	1995, 96	1st run	3.21	0.55	0.81	3.71	0.54	0.75
	1995, 96	calibration run	1.52	0.96	0.99	1.81	0.90	1.08
	2006, 07	validation run	1.49	0.92	1.02	1.64	0.99	1.02

6.3 Overall model performance after calibration

The model performance after calibration of the 28 study lakes is summarized in Table 6.3. The average standard error of estimate (SE) between simulation and measurements for all 28 study lakes is 1.47^{o}C for water temperature (range from 0.8 to 2.06^{o}C) and 1.50 mg/L for DO (range from 0.88 to 2.76 mg/L). The average regression coefficient (R^2) (in hydrological modeling called Nash-Sutcliffe coefficient or coefficient of determination or modeling efficiency) is 0.92 for water temperature (range from 0.84 to 0.97) and 0.75 for DO (range from 0.12 to 0.91). For reference, R^2 = 1 is the best possible model performance. The average slope (S) for the model to field data regression is 1.00 for water temperature (range from 0.93 to 1.05) and 0.97 for DO (range from 0.85 to 1.07). For reference, if the model is over-predicting the slope is less than 1.0, if the model is under-predicting the slope is greater than 1.0. Table 6.3 lists cisco lakes and non-cisco lakes separately. The average standard error of estimate for the 21 cisco lakes is 1.51^{o}C for water temperature (range from 0.8 to 2.06^{o}C) and 1.39 mg/L for DO (range from 0.88 to 2.38 mg/L). The average standard error of estimate for the 7 non-cisco lakes is 1.34^{o}C for water temperature (range from 0.97 to 1.72^{o}C) and 1.50 mg/L for DO (range from 1.06 to 2.05 mg/L). MINLAKE96 was calibrated on nine Minnesota lakes and one oligotrophic lake, Thrush Lake; the average SE between simulations and measurements for 5,976 data pairs for dissolved oxygen was 1.94 mg/L with a range from 1.61 to 2.59 mg/L (Fang and Stefan 1997).

Figures 6.1 to 6.4 show measured versus simulated water temperature and dissolved oxygen for each of the 28 study lakes, and include a solid lines (1:1) that would indicate perfect agreement between model and field data. Figure 6.5 shows measured versus simulated water temperature and DO for all 28 study lakes in a single plot.

6.3.1 Error parameters for surface mixed layer

The surface mixed layer depth, and the water temperature and DO concentration in the surface mixed layer were not extracted from measured water temperature and DO profiles in earlier versions of the MINLAKE model. For this cisco lake study, MINLAKE2010 was coded to estimate the mixed layer depth, temperature, and DO concentration from measured temperature and DO profiles. There is an option in the program to calculate the error parameters between simulated and measured values of mixed layer depth, temperature and DO concentration. It should be mentioned that measured water temperatures and DO concentrations within the mixed layer are typically not really identical, but have some small differences, because the surface mixed layer is fully mixed only during short windy periods, and tends to restratify between such periods. It is therefore difficult to accurately determine the mixed layer depth. The MINLAKE2010 model predicts and reports one mixed layer depth for simulated water temperature and DO profiles, but measured temperature and DO profiles do show and have different mixed-layer depths on many days with profile measurements. The calculation of the mixed layer depth starts from the water surface and checks the difference between measured temperature at a depth and average temperature at three depths above. If the difference is greater than a specified limiting value, then the mixed layer is taken to be at the mid-point of the last two depths where the difference exceeds the specified limit. By extensive calibration of the algorithm, the specified limit was determined to have a value between 0.4 and 1.0°C (or mg/L for the DO profile) and can be computed as 1/10th of the maximum temperature difference in the profile (1/5th when the maximum difference is less than 5 during weak stratification periods). The model determines a mixed layer depth from both the measured temperature and DO profiles, and the average value of the two mixed layer depths is reported and used for comparison with the simulated mixed layer depth, and error parameter generation.

Quantitative measures (error parameters) for depth, temperature and DO in the mixed layer in all 28 lakes are given in Table 6.4. Average SE (standard error of estimate) for water temperature in the mixed layer is 1.53°C (range from 0.41 to 2.97°C), and average SE for dissolved oxygen in the mixed layer is 1.09 mg/L (range from 0.44 to 3.21 mg/L). The error parameters are listed separately for cisco and non-cisco lakes. The average standard error of estimate for the 21 cisco lakes is 1.47°C for water temperature (range from 0.74 to 2.97°C) and 1.01 mg/L for DO (range from 0.44 to 3.21 mg/L) in the mixed layer. The average standard error of estimate for the 7 non-cisco lakes is 1.72°C for water temperature (range from 0.89 to 4.5°C) and 1.32 mg/L for DO (ranging from 0.69 to 2.32 mg/L) in the mixed layer. The largest error of DO concentration in the mixed layer occurred in Cedar Lake (3.21 mg/L). On 22 days measured data are available for Cedar Lake. Most of the error is generated by simulations for August 15, 1985, September 12, 1985 and May 11, 2008 where the model highly overpredicted or underpredicted DO concentrations in the epilimnion (Figure D.19). For the other 19 days the model predicted DO concentration in the mixed layer with reasonable accuracy (Figure D.19). Overall, reasonable simulations for the mixed layer temperature were obtained, but South Center Lake (S.E. = 4.50°C), Grindstone Lake (S.E. = 2.97 °C) and Six Lake (S.E. = 2.24 °C) had relatively large errors. For South Center Lake it seems that surface reaeration is too small. A major contribution to the error for Grindstone Lake comes from one profile in early spring, May 4, 1993 (Figure D.29). the average SE for mixed layer depth is 2.96 m (range from 0.85 to 8.60 m). Overall, it is difficult to estimate the mixed layer depth from vertical profiles of measured water temperature and/or DO. For example, on October 24, 1984, October 23, 1985 and October 29, 1986 the model predicts more or less fully mixed conditions in Greenwood Lake based on profiles of water temperature, but the field data are available only up to 12 m depth. The average standard error for the mixed layer depths in Greenwood Lake is 2.89 m ranging from 0.85 to 8.29 m. There are some negative regression coefficients for mixed layer DO and depth. Only one mixed layer depth or DO concentration is estimated for each day with a measured profile. With very limited data available for the estimation of error parameters in the mixed layer (for example, only on 4 days were profiles in Snowbank Lake measured), the standard deviation from the observed mean can be very small and R^2 can become less than zero.

Table 6.3 Quantitative measures of the success of the water temperature (^oC) and dissolved oxygen (mg/L) simulations in the 28 study lakes.

Lake Name	Field data used in simulation			Water Temperature			Dissolved Oxygen		
	Years	Days	Data	S.E.	R^2	S	S.E.	R^2	S
Big Trout	86,92-02	46	916	1.65	0.91	1.01	1.52	0.68	1.02
Blue	97,99,01,02	13	205	1.70	0.92	1.05	1.80	0.77	0.99
Burntside	86,88,94,00	14	274	1.72	0.90	0.97	1.37	0.12	0.95
Carlos	79, 80, 86, 08	16	366	1.70	0.93	1.00	1.32	0.86	1.04
Cedar	85, 86, 08	22	410	1.34	0.96	1.00	1.40	0.88	0.97
Elk	07, 08	17	312	1.47	0.94	1.05	1.03	0.93	0.99
Fish Hook	91	4	61	2.06	0.84	1.01	1.10	0.91	1.06
Greenwood	83,84,85,86,06	14	222	1.76	0.87	0.93	1.36	0.69	0.95
Grindstone	93	5	98	1.67	0.91	1.01	1.83	0.15	0.91
Kabekona	94	5	104	1.37	0.93	1.05	0.89	0.90	0.95
Little Sand	89,91	7	102	1.76	0.92	1.01	1.28	0.86	0.96
Little Trout	97,06,07,08	11	281	1.46	0.95	0.96	1.44	0.84	1.04
Mukooda	03,06,07	7	141	1.13	0.96	0.99	1.56	0.78	1.03
Siseebakwet	92,93	6	122	1.66	0.92	1.02	1.47	0.86	1.07
Six	97	4	70	1.72	0.93	0.92	2.38	0.76	0.85
Snowbank	86,88	4	67	0.92	0.97	0.98	0.88	0.56	1.00
South Twin	08	15	126	1.42	0.80	1.06	1.33	0.59	1.02
Ten Mile	01, 02, 08	30	828	1.68	0.92	1.04	1.04	0.80	0.96
Trout (Cook)	83, 84, 85, 86,	23	349	1.24	0.94	0.96	1.63	0.51	0.93
Trout (St. Louis)	06	5	89	0.80	0.97	0.99	0.95	0.83	0.95
White Iron	95, 96, 00, 06,	21	342	1.43	0.84	0.99	1.63	0.46	0.98
Total or Average (cisco lakes)		289 [1]	5485 [1]	1.51	0.92	1.00	1.39	0.70	0.98
Non-cisco habitat lakes									
Bear Head	08	16	193	0.97	0.95	0.98	1.06	0.90	0.94
Carrie	08	15	121	1.22	0.89	1.02	1.57	0.82	1.10
Elephant	08	13	135	1.24	0.94	0.98	1.62	0.66	0.94
Hill	94, 08	21	267	1.41	0.92	1.02	1.83	0.78	0.92
Madison	80, 86, 87, 88,	34	456	1.72	0.90	1.02	2.76	0.55	0.83
South Center	86, 06, 08	19	413	1.47	0.94	0.99	1.77	0.83	0.83
St. Olaf	86, 96, 01, 08	32	314	1.34	0.94	1.02	2.05	0.80	0.96
Total or Average (non cisco lakes)		150 [1]	1899 [1]	1.34	0.93	1.00	1.81	0.76	0.93
Total or Average (all lakes)		439 [1]	7384 [1]	1.47	0.92	1.00	1.50	0.72	0.97

[1] – These are total number of days or data pairs and are not average.

Table 6.4 Quantitative measures of the success of simulations of mixed layer depth, mixed layer temperature and dissolved oxygen.

Lake Name	Mixed layer depth			Mixed layer temperature			Mixed layer DO		
	S.E.	R^2	S	S.E.	R^2	S	S.E.	R^2	S
Big Trout	6.23	-3.98	0.64	1.96	0.81	0.97	1.61	0.10	1.03
Blue	1.36	0.56	0.92	2.20	0.52	1.07	0.50	-1.83	0.97
Burntside	3.78	0.33	1.18	0.77	0.94	0.99	1.59	-3.02	0.86
Carlos	4.14	0.75	1.20	1.85	0.92	0.96	0.83	0.65	0.99
Cedar	2.03	-6.09	0.54	1.24	0.95	1.00	3.21	-0.20	0.90
Elk	2.77	-1.20	0.77	1.37	0.93	1.05	1.04	-0.01	1.01
Fish Hook	1.75	0.57	0.83	1.93	0.54	0.97	0.61	0.15	1.06
Greenwood	8.29	-3.65	0.62	1.88	0.88	0.91	0.86	0.58	0.94
Grindstone	4.30	-1.31	1.45	2.97	0.70	0.92	1.93	-0.85	0.85
Kabekona	2.20	-1.55	0.86	0.80	0.91	1.03	0.74	0.60	0.96
Little Sand	0.89	0.77	0.93	1.66	0.85	1.03	0.53	0.34	0.96
Little Trout	0.96	0.86	1.00	0.88	0.94	1.00	0.44	0.51	0.97
Mukooda	0.85	0.91	1.06	1.12	0.95	0.97	1.01	0.35	1.01
Siseebakwet	8.60	0.07	1.54	1.06	0.98	0.97	0.77	0.52	1.04
Six	2.23	-0.37	1.28	2.24	0.85	0.91	1.22	-0.77	0.91
Snowbank	3.43	0.27	1.28	0.74	-0.32	0.97	0.54	-	0.95
South Twin	2.84	-2.80	0.63	1.41	0.84	1.04	0.62	0.45	1.05
Ten Mile	3.13	0.26	0.90	1.32	0.92	1.05	0.70	0.47	0.96
Trout (Cook)	2.35	0.65	1.08	1.60	0.91	0.93	0.58	0.56	0.98
Trout (St. Louis)	2.29	0.00	1.08	0.41	0.99	0.98	0.99	0.13	0.91
White Iron	4.27	-1.08	0.69	1.43	0.89	1.01	0.96	0.23	0.98
Average (cisco)	3.27	-0.76	0.98	1.47	0.80	0.99	1.01	-1.60	0.97
Non-cisco habitat lakes									
Bear Head	1.56	0.62	0.85	0.89	0.96	1.01	0.69	0.16	0.94
Carrie	1.08	0.61	0.85	1.71	0.83	1.01	1.21	-3.94	1.14
Elephant	1.83	-0.39	0.84	1.09	0.96	0.99	0.95	0.22	0.98
Hill	2.87	-0.65	0.74	1.17	0.94	1.04	0.99	-0.39	0.95
Madison	4.00	-0.31	0.66	1.47	0.94	0.99	1.66	0.27	0.96
South Center	1.26	0.57	1.16	4.50	-0.49	0.83	2.32	-2.08	0.85
St. Olaf	1.61	-0.71	0.80	1.23	0.93	1.00	1.45	0.32	1.01
Average (non cisco)	2.03	-0.04	0.84	1.72	0.72	0.98	1.32	-0.78	0.98
Average (all lakes)	2.96	-0.58	0.94	1.53	0.78	0.99	1.09	-1.39	0.97

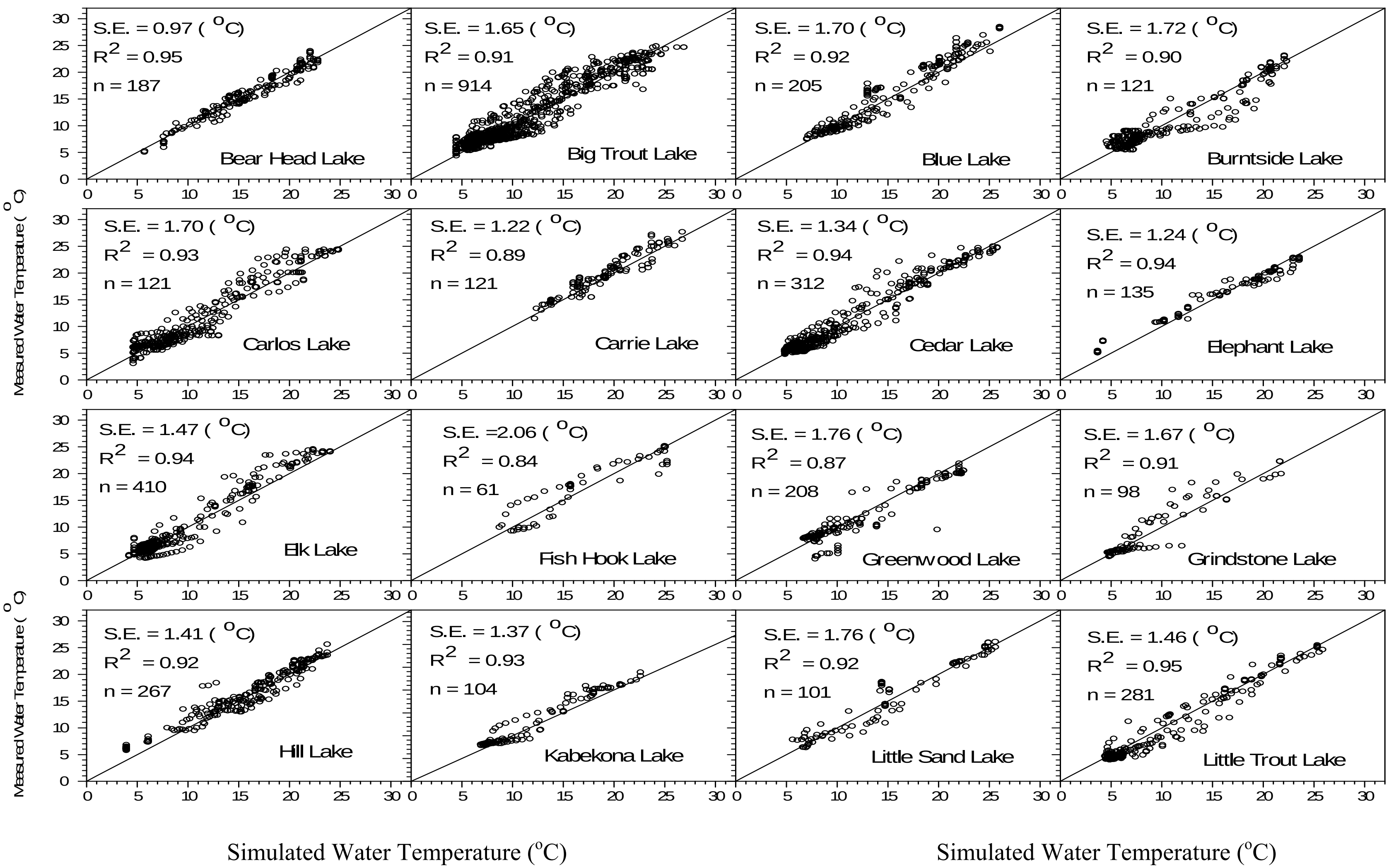

Figure 6.1 Simulated versus measured water temperatures (°C) in 16 of the 28 calibration lakes. The solid line (1:1) would indicate perfect agreement.

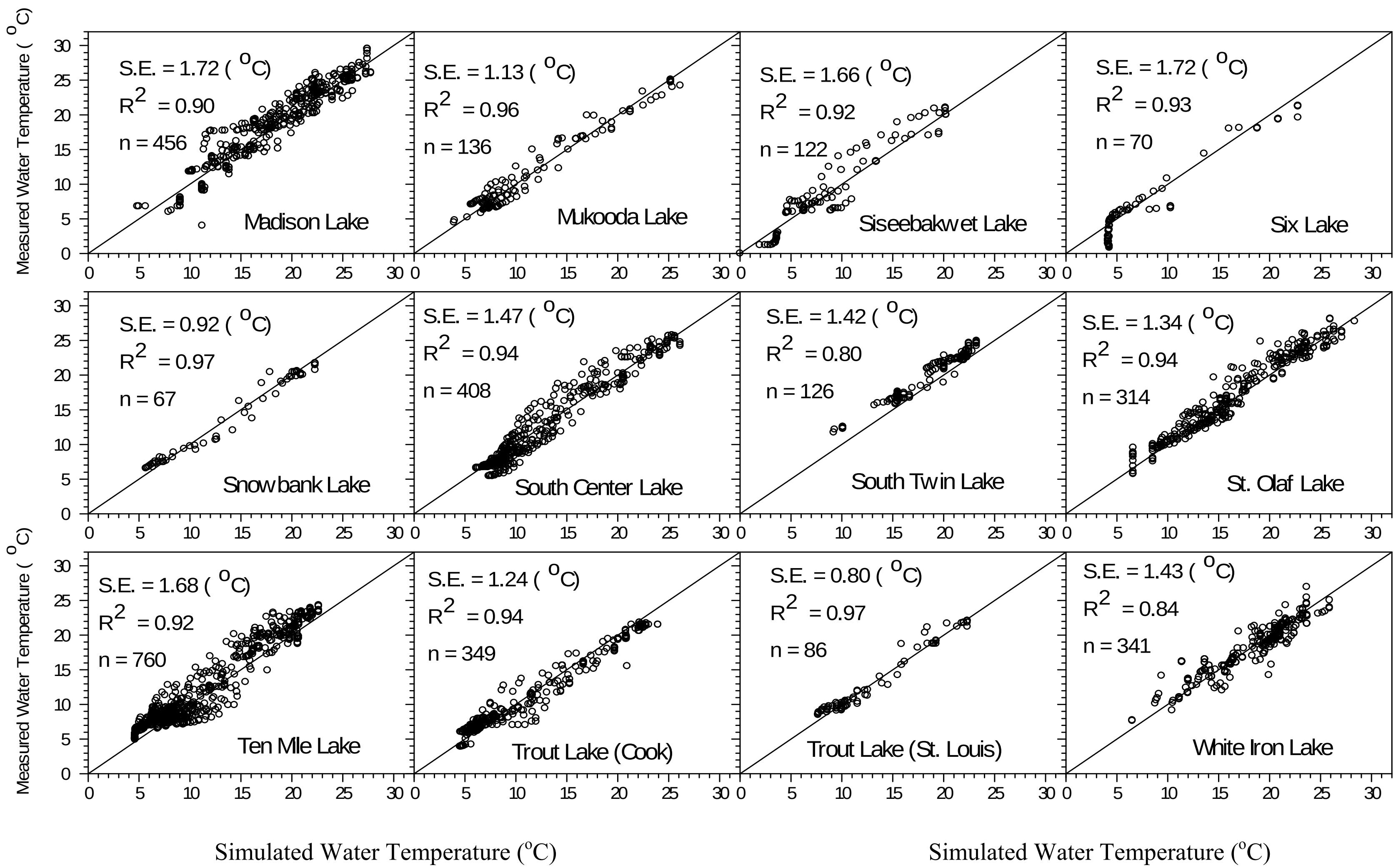

Figure 6.2 Simulated versus measured water temperatures (°C) in 12 of 28 calibration lakes. The solid line (1:1) would indicate perfect agreement.

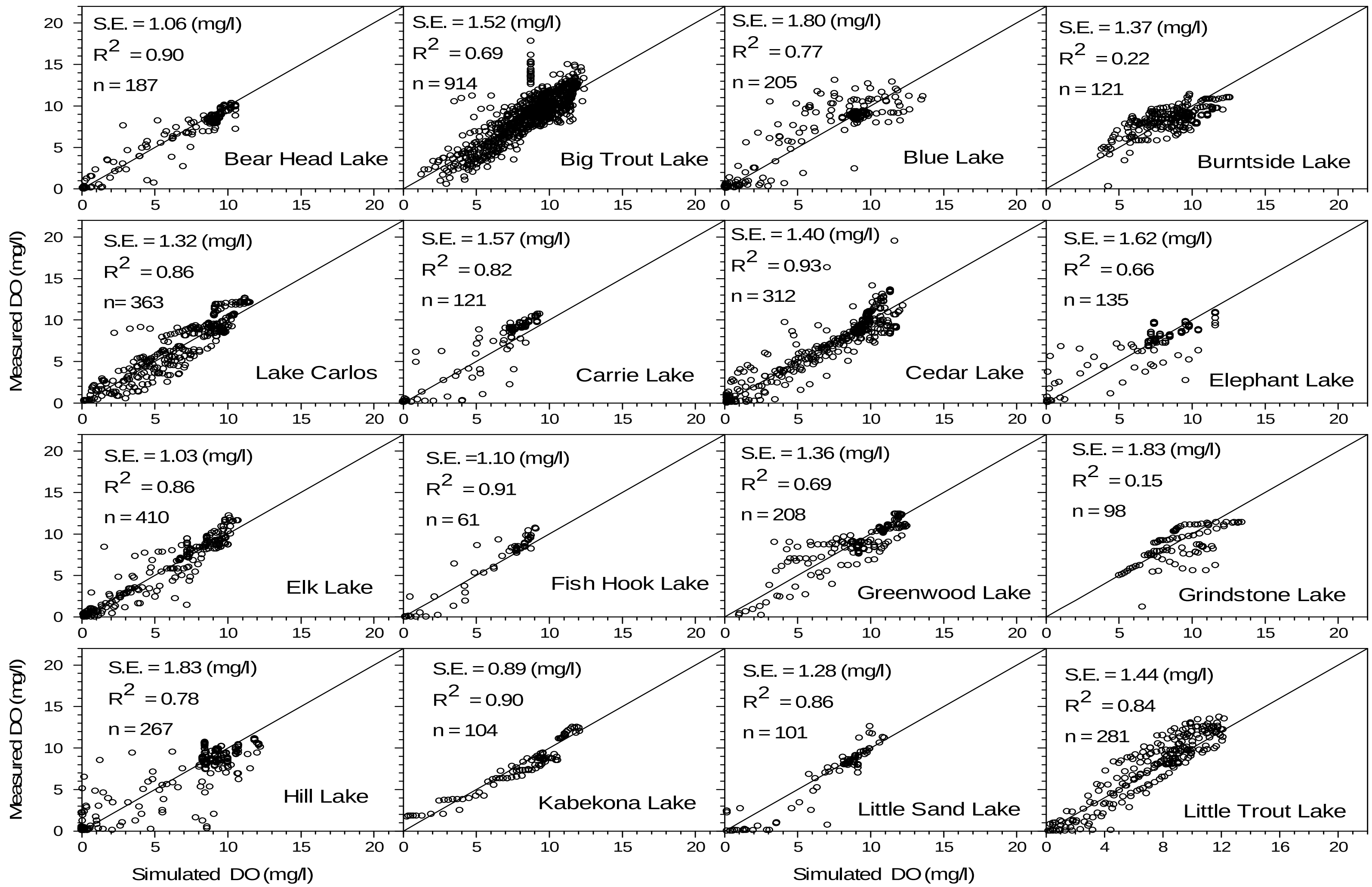

Figure 6.3 Simulated versus measured dissolved oxygen (DO) in 16 calibration lakes. The solid line (1:1) would indicate perfect agreement.

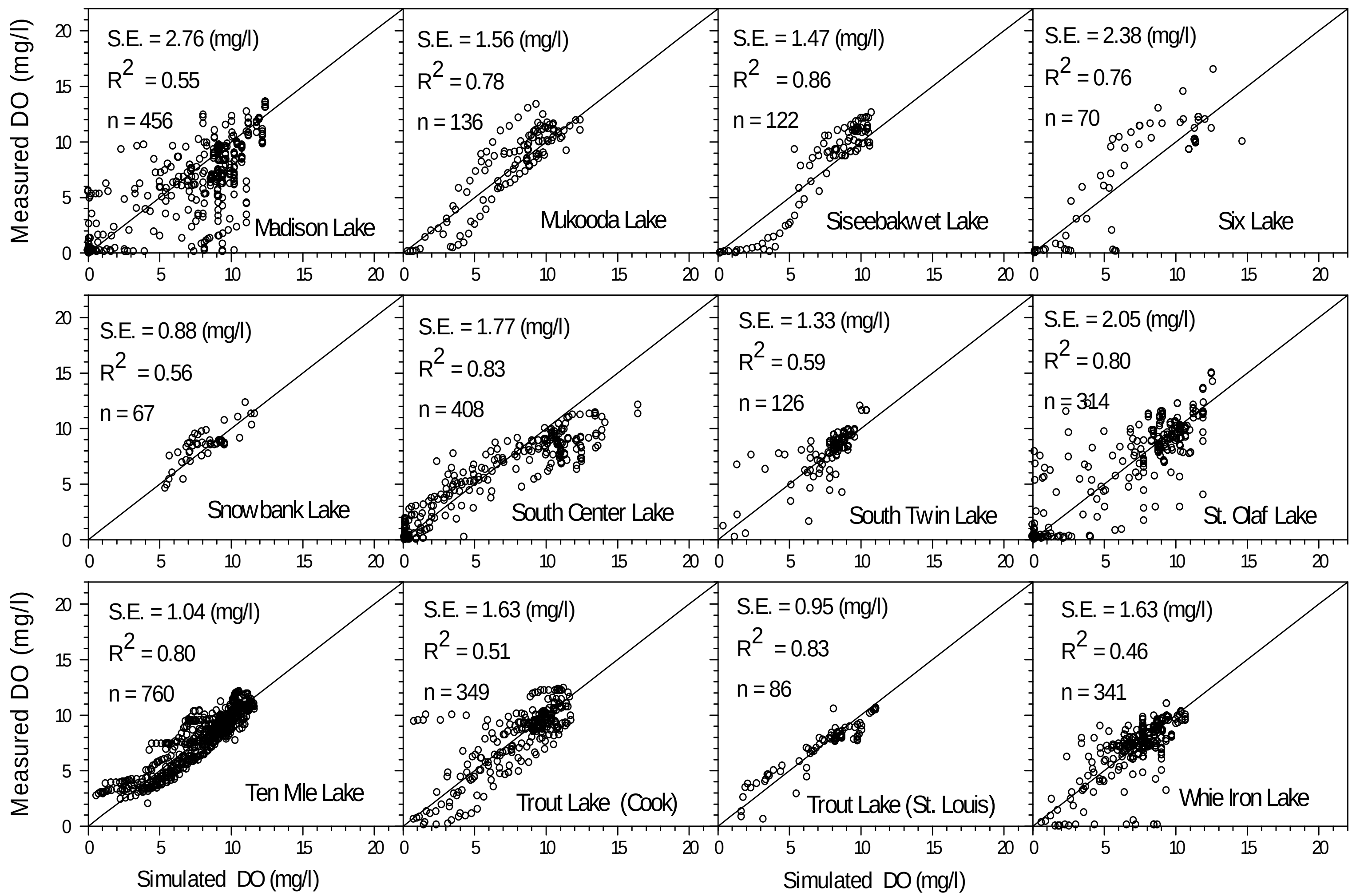

Figure 6.4 Simulated versus measured dissolved oxygen (DO) in 12 calibration lakes. The solid line (1:1) would indicate perfect agreement.

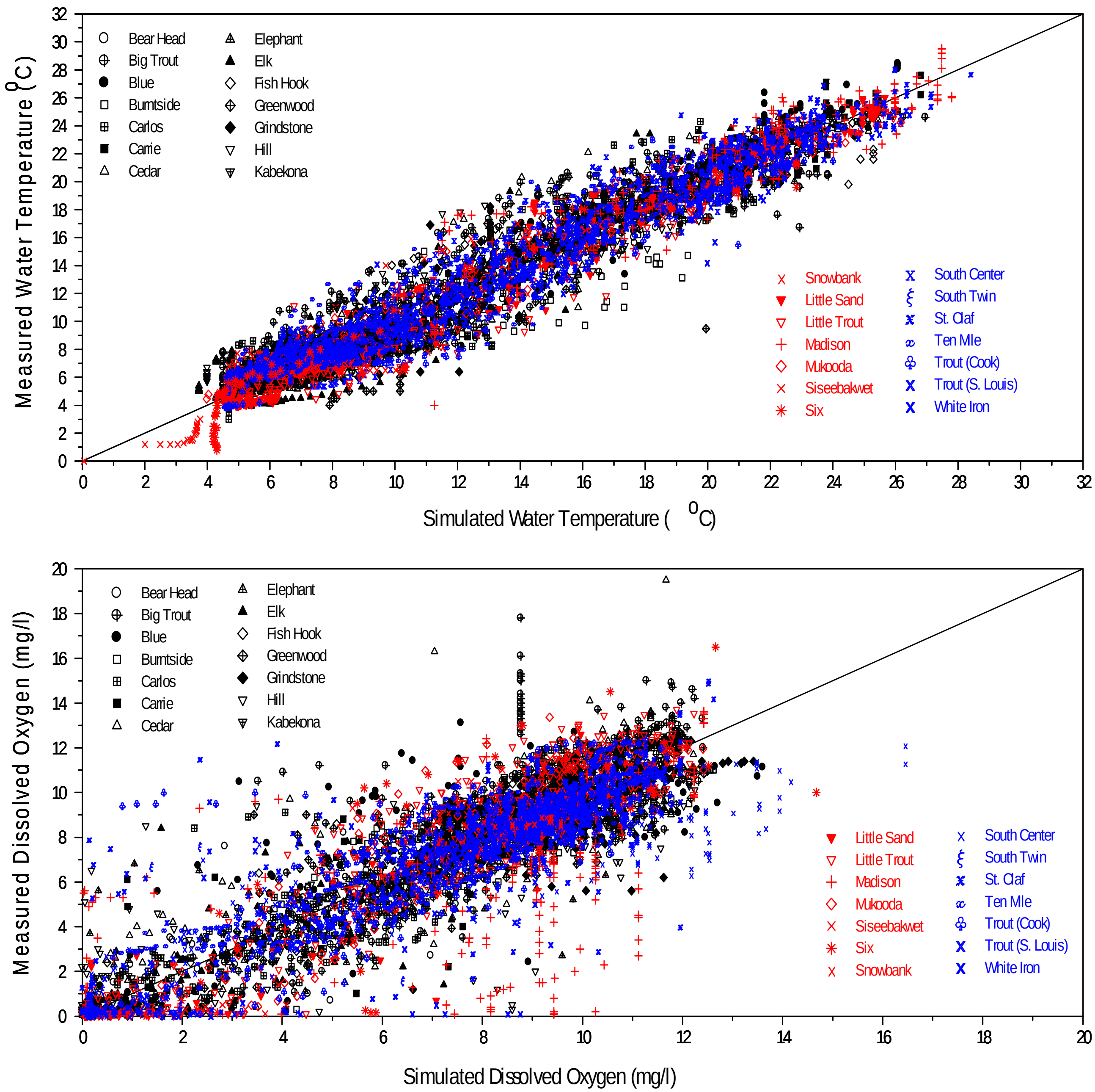

Figure 6.5 Simulated versus measured temperature and dissolved oxygen (DO) in 28 calibration lakes. The solid line (1:1) would indicate perfect agreement.

6.4 Model calibration results for individual lakes

The average standard error of estimate is 1.47°C for temperature and 1.50 mg/L for dissolved oxygen. There are few lakes with errors higher than overall average errors for either temperature or DO. When temperature and DO profiles were inspected lake by lake it was found that in many cases the error becomes higher when the model fails to predict the profile(s) from the surface to the bottom on one or two days out of many days. The larger error on those one or two days results in an overall high error for that lake. In some cases it was found that the model predicted spring overturn (in late April or early May) or fall overturn (in October or November), while the measured profiles show a weak stratification, and vice versa. Lack of field data is another reason of high error in some of lakes. The measured profiles make it evident that there were warm water intrusions or cold water intrusions in some of the lakes. The model does not include any physical process to simulate intrusions, and the model failed to match the observed profiles in those cases. There are no winter data for the study lakes available, except one single case – one winter profile in Siseebakwet Lake (January 20, 1993). The model was not calibrated for winter ice-cover periods, and this may affect the model predictions in early spring.

The following paragraphs provide some information and discussion of model calibration results for the individual 28 study lakes. The 7 non-cisco lakes will be presented first, and then the 21 cisco lakes. The information will be presented in alphabetical order of lake name.

6.4.1 Model calibration results in seven non-cisco lakes

Bear Head Lake (DNR ID 69025400, latitude 47°77'48" N, and longitude 92°08'08"E) is located at 1 mile south and 10 mile east of city of Tower in St. Louis County and has a surface area of 674 acres (2.73 km^2) and maximum depth of 46 ft (14.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 2.90 and is classified as a stratified medium-depth lake. It has a mean Secchi depth of 9.5 ft (2.9 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Duluth weather data; and Figures D.1 and D.2 show simulated and measured water temperature and DO profiles in 2008. The standard error between simulated and measured water temperatures is 0.97 °C and 1.06 mg/L for DO after model calibration. Overall, simulated water temperature and DO profiles agree well with measured profiles on 16 days in 2008 (193 data pairs). The model slightly overpredicted bottom DO from May to middle of June in 2008. Time series of simulated temperature and DO at five different depths (1.0, 4.0, 7.0, 10.0, 13.0 m) in 2007 and 2008 are given in Figures E.1 and E.2 and agree well with measurements over time.

Carrie Lake (DNR ID 34003200, latitude 45°04'55" N, and longitude 94°47'12"E) is located at Water city in Kandiyohi County and has a surface area of 91 acres (0.37 km^2) and maximum depth of 26 ft (7.9 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 3.11 and is classified as a weakly stratified medium-depth lake. It has a mean Secchi depth of 3.9 ft (1.2 m) and is classified as an eutrophic lake (Table 2.1). Water temperature and DO profiles were simulated using St. Cloud weather data; and Figures D.13 and D.14 show simulated and measured water temperature and DO profiles in 2008. The standard error between simulated and measured water temperatures is 1.22 °C and 1.57 mg/L for DO after model calibration. Overall, simulated water temperature and DO profiles agree reasonably well with measured profiles on 15 days in 2008 (121 data pairs). Time series of simulated temperature and DO at five different depths (1.0, 2.5, 4.0, 5.5, 7.0 m) in 2007 and 2008 are given in Figures E.7 and E.8 and agree reasonably well with measurements over time. This weakly stratified lake shows dynamic mixing in summer as indicated by time series of DO at 5.5 and 7.0 m.

Elephant Lake (DNR ID 69081000, latitude 48°11'35" N, and longitude 92°44'39"E) is located at east of Ash Lake in St. Louis County and has a surface area of 724 acres (2.93 km^2) and maximum depth of 30 ft (9.1 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 4.55 and is classified as a weakly stratified medium-depth lake. It has a mean Secchi depth of 8.9 ft (2.7 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using International Falls weather data; and Figures D.17 and D.18 show simulated and measured water temperature and DO profiles in 2008. The standard error between simulated and measured water temperatures is 1.24 ^oC and 1.62 mg/L for DO after model calibration. For Elephant Lake, there are measured profiles on 13 days in 2008 (135 data pairs). Simulated water temperature and DO profiles agree well with measured profiles for the most days. Only during the spring overturn and fall overturn (May 13, 2008 and Nov 10, 2008) simulated values were under estimated and over estimated respectively by 1-2 degree Celsius for temperature profile and 1-2 mg/L for DO profile. There were no or very weak stratification in temperature profiles in October and November, but much strong stratification exist in measured DO profiles. The largest error in DO profiles occurs at the bottom depth on October 13, 2008. Time series of simulated temperature and DO at five different depths (1.0, 2.5, 4.0, 6.5, 8.0 m) in Elephant Lake are given in Figures E.13 and E.14 and agree well with measurements over time (2007 to 2008). Time series of DO shows anoxic condition over bottom depths at the end of winter ice cover period and the model predicted well dynamic mixing in June and July in 2008 in this weakly stratified lake.

Hill Lake (DNR ID 10142010, latitude 46°58'59" N, and longitude 93°35'40"E) is located at Hill city in Aitkin County and has a surface area of 657 acres (2.66 km^2) and maximum depth of 48 ft (14.6 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 2.77 and is classified as a stratified medium-depth lake. It has a mean Secchi depth of 8.9 ft (2.7 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Duluth weather data; and Figures D.29 and D.30 show simulated and measured water temperature profiles, and Figures D.31 and D.32 show simulated and measured DO profiles in 1994 and 2008. The standard error between simulated and measured water temperatures is 1.41 ^oC and 1.83 mg/L for DO after model calibration. For Hill Lake, there are measured profiles on 21 days in 1994 and 2008 (267 data pairs). Overall, simulated water temperature and DO profiles agree well with measured profiles for the most days. On the two days in June 2008 (June 18 and June 30), hypolimnion temperature was not in agreement with measured data. The model underpredicted hypolimnetic temperatures for those two days and other four days in July 2008. Measured profiles show unusual warm water intrusions at the hypolimnion during these days. The model overpredicted DO profiles in the epilimnion for three days in 1994 and in early summer days in 2008. The model overpredicted the mixed layer depth on September 11, 2008, and this results in very larg error in DO profile on that day (Figure D.31) because of strong DO stratification. Time series of simulated temperature and DO at five different depths (1.0, 4.0, 7.0, 10.0, 14.0 m) in Hill Lake are given in Figures E.17 and E.20 and agree well with measurements over time (1994 to 1995 and 2007 to 2008).

Madison Lake (DNR ID 70044000, latitude 44°11'24" N, and longitude 93°48'39"E) is located at city of Madison Lake in East Blue County and has a surface area of 1,113 acres (4.50 km^2) and maximum depth of 59 ft (18.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 2.56 and is classified as a stratified medium-depth lake. It has a mean Secchi depth of 3.3 ft (1.0 m) and is classified as a eutrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Minneapolis weather data; and Figures D.39 to D.42 show simulated and measured water temperature and DO profiles in 1980, 1986, 1987, 1989, 1990, 1993, 2006, and 2008. The standard error between simulated and measured water temperatures is 1.72 °C and 2.76 mg/L for DO after model calibration. There are measured profiles on 34 days in the years stated above (455 data pairs). Overall, simulated temperature profiles agree reasonably well with the measured profiles in the most cases. Simulated DO profiles produced the largest standard error of the DO model errors in the 28 study lakes. The model overpredicted the mixed layer depths (fall overturn) on August 24, 1987 and September 12, 2006, but measured DO profiles on these two days have strong stratification. Simulated temperature profile on May 17, 2006 (Figure D.40) agrees well with measured one, but measured DO profile on that day is very unusual – much strong stratification that shows much large oxygen demand in this eutrophic lake. Measured DO profile on May 14, 2008 has total different DO distribution in comparison to one on May 17, 2006. The model overpredicted mixed layer depths on July 14 and August 3, 1987 and August 11, 1988 and resulted in large error in DO profiles on these days. Time series of simulated temperature and DO at five different depths (1.0, 5.0, 9.0, 13.0, and 27.0 m) in Madison Lake are given in Figures E.23 and E.26 and agree reasonably well with measurements over time (1979 to 1993 and 2005 to 2006).

South Center Lake (DNR ID 13002700, latitude 45°22'49" N, and longitude 92°49'20" E) is located at Center City in Chisago County and has a surface area of 835 acres (3.38 km^2) and maximum depth of 109 ft (33.2 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.29 and is classified as a stratified deep-depth lake. It has a mean Secchi depth of 3.6 ft (1.1 m) and is classified as a eutrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Minneapolis weather data; and Figures D.50 to D.53 show simulated and measured water temperature and DO profiles in 1986, 2006 and 2008. The standard error between simulated and measured water temperatures is 1.47 °C and 1.77 mg/L for DO after model calibration. There are measured profiles on 19 days in those three years (407 data pairs). Simulated water temperature profiles agree reasonably well with measured profiles. The model overpredicted DO concentrations in the epilimnion at many days (maybe due to large oxygen demand in this eutrophic lake). Measured DO profiles after the middle of July showed anoxic conditions over large portion of the lake, and the model predicted well in hypolimnion DO for these days. Time series of simulated temperature and DO at five different depths (1.0, 6.0, 11.0, 16.0, 22.0 m) in South Center Lake are given in Figures E.27 and E.30 and agree well with measurements over time (1985 to 1986 and 2005 to 2008).

St. Olaf Lake (DNR ID 81000300, latitude 43°54'11" N, and longitude 93°25'01"E) is located at New Richland in Waseca County and has a surface area of 91 acres (0.37 km^2) and maximum depth of 33 ft (10.1 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 2.45 and is classified as a stratified medium-depth lake. It has a mean Secchi depth of 5.3 ft (1.6 m) and is classified as a eutrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Duluth weather data; and Figures D.56 to D.59 show simulated and measured water temperature and DO profiles in 1986, 1996, 2001 and 2008. The standard error between simulated and measured water temperatures is 1.34 ^oC and 2.05 mg/L for DO after model calibration. There are measured profiles on 32 days in those four years (313 data pairs). Simulated water temperature profiles agree well with measured profiles on all days. Simulated DO profiles agree reasonably well with measured profiles in the most days. Simulated DO profile on Jun 24, 1996 created large errors on DO profiles; on that day, measured DO profile had a metalimnion oxygen maximum (MOM) which is unusual in a relative eutrophic lake, but the model did not predict it. On September 25, 1996, April 22 and May 02, 2008, the model predicted complete mixing (fall or spring overturn periods), but measured DO profiles had some stratification. Time series of simulated temperature and DO at five different depths (1.0, 3.0, 5.0, 7.0, 9.0 m) in St. Olaf Lake are given in Figures E.33 to E.36 showing stratification along depths and agree well with measurements over time (1985 to 1986 and 2000 to 2008).

6.4.2 Model calibration results in twenty-one cisco lakes

Big Trout Lake (DNR ID 18031500, latitude 46^{o}43'07" N, and longitude 94^{o}09'30"E) is located west of Manhattan Beach (nearest town) in Crow Wing County and has a surface area of 1343 acres (5.43 km^2) and maximum depth of 128.0 ft (39.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.24 and is classified as a stratified deep lake. It has a mean Secchi depth of 15.7 ft (4.8 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Brainerd weather data; and Figures D.3 to D.6 show simulated and measured water temperature and DO profiles from 1992 to 2002 (Table 3.1 shows that there are measured profiles in 1986 but weather data at Brainerd are only available from 1991). The standard error between simulated and measured water temperatures is 1.65 ^oC and 1.52 mg/L for DO after model calibration. There are measured profiles on 46 days from 1992 to 2002 (914 data pairs). Overall, simulated water temperature profiles agree well with measured profiles on almost all days; and errors are because of slightly mismatch on metalimnion in some of the days (where temperature gradients are very strong). Measured DO profiles show metalimnetic oxygen maxima in many days in this deep oligotrophic lake, and the model predicted reasonably well the most of oxygen peaks in the metalimnion. There is a very unusual DO profile on May 15, 1996, and the model underpredicted it (large percent of the total error is due to that profile alone) and simulated temperature profile agrees well with measured data at that day.

Blue Lake (DNR ID 18021100, latitude 46^{o}46'19" N, and longitude 93^{o}59'45"E) is located at city of Emily in Crow Wing County and has a surface area of 175 acres (0.71 km^2) and maximum depth of 48 ft (14.6 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.98 and is classified as a stratified medium-depth lake. It has a mean Secchi depth of 22.2 ft (6.8 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Grand Rapids weather data; and Figures D.7 and D.8 show simulated and measured water temperature and DO profiles in 1997, 1999, 2000 and 2002. The standard error between simulated and measured water temperatures is 1.70 ^oC and 1.80 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree reasonably well with measured profiles on 13 days in those years (205 data pairs). The model overpredicted the mixed layer depths on September 23, 1999 and September 27, 2001. Measured DO profiles show metalimnetic oxygen maxima during summer in every year and the model missed MOM in three simulation days because the general seasonal pattern in oligotrophic lake (Fig. 3.10) may not reflect chlorophyll-a variation in Blue Lake for those days.

Burntside Lake (DNR ID 69011800, latitude 47°56'15" N, and longitude 92°00'01"E) is located at 3 mile northwest of Ely in St. Louis County and has a surface area of 7142 acres (28.90 km^2) and maximum depth of 126 ft (38.4 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.91 and is classified as a stratified deep lake. It has a mean Secchi depth of 19.0 ft (5.8 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using International Falls weather data; and Figures D.9 and D.10 show simulated and measured water temperature and DO profiles in 1986, 1988, 1994, and 2000. The standard error between simulated and measured water temperatures is 1.72 °C and 1.37 mg/L for DO after model calibration. There are measured profiles on 14 days in those four years (274 data pairs). Overall, simulated water temperature profiles agree reasonably well with measured profiles on all the days; and measured temperature profiles show some irregular changes/jumps in hypolimnion. Measured DO profiles show very unusual and irregular vertical distributions in hypolimnion; and have metalimnetic oxygen minimum and metalimnetic/hypolimnetic maximum at the same day. Even though the standard error for DO simulations is reasonable (1.37 mg/L) but the model does not capture these minor variations. The model overpredicted DO concentrations in the epilimnion in 2000.

Lake Carlos (DNR ID 21005700, latitude 45°56'57" N, and longitude 95°21'43"E) is located at 2 miles west of Carlos (nearest town) in Douglas County and has a surface area of 2520 acres (10.20 km^2) and maximum depth of 164 ft (50.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.13 and is classified as a stratified deep depth lake. It has a mean Secchi depth of 11.2 ft (3.4 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Saint Cloud weather data from 1978 to 2008; and Figures D.15 and D.16 show simulated and measured water temperature and DO profiles in 1979, 1980, 1986 and 2008. The standard error between simulated and measured water temperatures is 1.70 °C and 1.32 mg/L for DO after model calibration. There are measured profiles on 46 days in those years (402 data pairs). Simulated water temperature and DO profiles agree reasonably well with measured profiles; and the model underpredicted mixed layer depths on May 20 and 21, 2008 due to much warmer temperature simulated in the epilimnion (maybe due to either solar radiation or wind speed data). Overall prediction of the model for DO profiles is satisfactory except that there are some days (August 22, 1979, August 28, 1980, July 08, 1986, August 11, 1986, July 24, 2008 and August 07, 2008) where measured profiles show metalimnion oxygen minima, while the model could not predict them. Time series of simulated temperature and DO at five different depths (1.0, 10.0, 20.0, 30.0, 48.0 m) in Lake Carlos are given in Figures E.3 to E.6 and agree well with measurements over time.

Cedar Lake (DNR ID 49014000, latitude 45°48'48" N, and longitude 94°38'08"E) is located at city of Upsala in Morris County and has a surface area of 242 acres (0.98 km^2) and maximum depth of 88 ft (26.8 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.17 and is classified as a stratified deep lake. It has a mean Secchi depth of 11.2 ft (3.4 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Saint Cloud weather data from 1984 to 2008; and Figures D.17 to D.20 show simulated and measured water temperature and DO profiles in 1985, 1986 and 2008. The standard error between simulated and measured water temperatures is 1.34 °C and 1.40 mg/L for DO after model calibration. Overall, simulated water temperature and DO profiles agree well with measured profiles in 22 days over these three years (410 data pairs). Time series of simulated temperature and DO at five different depths (1.0, 6.0, 11.0, 16.0, 22.0 m) in Cedar Lake are given in Figures E.9 and E.12 and agree well with measurements over time (1984 to 1986 and 2007 to 2008).

Elk Lake (DNR ID 15001000, latitude 47°11'18" N, and longitude 95°12'56"E) is located at 5 miles south of Lake Itasca (nearest town) in Clear Water County and has a surface area of 272 acres (1.10 km^2) and maximum depth of 92 ft (28.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.16 and is classified as a stratified deep lake. It has a mean Secchi depth of 8.2 ft (2.5 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Bemidji weather data from 1984 to 2008; and Figures D.21 and D.22 show simulated and measured water temperature and DO profiles in 1985, 1986, 2007 and 2008. The standard error between simulated and measured water temperatures is 1.47 °C and 1.03 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree reasonably well with measured profiles in 16 days in these four years (367 data pairs). Time series of simulated temperature and DO at five different depths (1.0, 7.5, 14.0, 20.5, 27.0 m) in Elk Lake are given in Figures E.15 and E.16 and agree reasonably well with measurements over time (2007 to 2008).

Fish Hook Lake (DNR ID 29024200, latitude 46°57'28" N, and longitude 95°03'44"E) is located at 2 miles north of Park Rapids (nearest town) in Hubbard County and has a surface area of 1633 acres (6.61 km^2) and maximum depth of 76 ft (23.2 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 2.19 and is classified as a stratified deep lake. It has a mean Secchi depth of 11.3 ft (3.4 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Fargo weather data from 1990 to 1991; and Figures D.23 and D.24 show simulated and measured water temperature and DO profiles in 1991. The standard error between simulated and measured water temperatures is 2.06 °C and 1.10 mg/L for DO after model calibration. Simulated DO profiles agree well with measured profiles on 4 days in 1991 (61 data pairs), but simulated temperature profile could not predict well on one of the four days (June 14, 1991, an unusual temperature profile). The model overpredicted the mixed layer depth on September 19, 1991.

Greenwood Lake (DNR ID 16007700, latitude 48°00'25" N, and longitude 90°10'19"E) is located at city of Grand Marais in Cook County and has a surface area of 2022 acres (8.18 km^2) and maximum depth of 112 ft (34.1 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.57 and is classified as a stratified deep lake. It has a mean Secchi depth of 17.9 ft (5.5 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Duluth weather data from 1982 to 2006; and Figures D.25 and D.26 show simulated and measured water temperature and DO profiles in 1983, 1984, 1985, 1986 and 2006. The standard error between simulated and measured water temperatures is 1.76 °C and 1.36 mg/L for DO after model calibration. There are measured profiles on 14 days in those five years (222 data pairs). The model underpredicted the mixed layer depth on October 6, 1983, even though measured profile data are available only up 16 meters. The model overpredicted water temperature profile (about three degrees) on May 15, 1984, which could be caused by winter simulation (e.g., too early of ice out date). Overall, simulated water temperature and DO profiles agree reasonably well with measured profiles.

Grindstone Lake (DNR ID 58012300, latitude 46°07'30" N, and longitude 93°00'01"E) is located at city of Sandstone in Pine County and has a surface area of 526 acres (2.13 km^2) and maximum depth of 153 ft (46.6 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 0.82 and is classified as a stratified deep lake. It has a mean Secchi depth of 9.5 ft (2.9 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Brainerd weather data from 1992 to 1993; and Figures D.27 and D.28 show simulated and measured water temperature and DO profiles on five days in 1993. The standard error between simulated and measured water temperatures is 1.67 °C and 1.83 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree reasonably well with measured profiles on 5 days in 1993 (98 data pairs). The model predicted much warmer and thin epilimnion on May 4, 1993, which could be due to unrepresentative weather condition.

Kabekona Lake (DNR ID 29007500, latitude 47°09'33" N, and longitude 94°45'07"E) is located at city of Laporte in Hubbard County and has a surface area of 2254 acres (9.12 km^2) and maximum depth of 134 ft (41.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.34 and is classified as a stratified deep lake. It has a mean Secchi depth of 12.1 ft (3.7 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Bemidji weather data from 1993 to 1994; and Figures D.33 and D.34 show simulated and measured water temperature and DO profiles on five days in 1994. The standard error between simulated and measured water temperatures is 1.37 °C and 0.89 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree well with measured profiles on 5 days in 1994 (129 data pairs). Time series of simulated temperature and DO at five different depths (1.0, 4.0, 7.0, 10.0, 13.0 m) in Kabekona Lake are given in Figures E.21 and E.22 and agree well with measurements over time (2007 to 2008).

Little Sand Lake (DNR ID 29015000, latitude 46°59'26" N, and longitude 94°55'54"E) is located at city of Dorset in Hubbard County and has a surface area of 386 acres (1.56 km^2) and maximum depth of 80 ft (24.4 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.45 and is classified as a stratified deep lake. It has a mean Secchi depth of 17.1 ft (5.2 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Fargo weather data from 1988 to 1991; and Figures D.35 and D.36 show simulated and measured water temperature and DO profiles in 1989 and 1991. The standard error between simulated and measured water temperatures is 1.76 °C and 1.28 mg/L for DO after model calibration. There are measured profiles on 7 days in 1989 and 1991 (102 data pairs). The model overpredicted the mixed layer depths on September 13, 1989 and September 19, 1991, and this resulted underpredicted water temperature in the epilimnion. Simulated water temperature and DO profiles agree well with measured profiles on all other days.

Little Trout Lake (DNR ID 69068200, latitude 48°23'49" N, and longitude 92°31'22"E) is located at city of Crane Lake in St. Louis County and has a surface area of 239 acres (0.97 km^2) and maximum depth of 95 ft (29.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.08 and is classified as a stratified deep lake. It has a mean Secchi depth of 20.8 ft (6.3 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using International Falls weather data; and Figures D.37 and D.38 show simulated and measured water temperature and DO profiles in 1997, 2006, 2007 and 2008. The standard error between simulated and measured water temperatures is 1.46 ^{o}C and 1.44 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree well with measured profiles on 11 days in these four years (281 data pairs).

Mukooda Lake (DNR ID 69068400, latitude 48^{o}20'09" N, and longitude 92^{o}29'23"E) is located at city of Crane in St. Louis County and has a surface area of 754 acres (3.05 km^2) and maximum depth of 78 ft (23.8 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.76 and is classified as a stratified deep lake. It has a mean Secchi depth of 16.8 ft (5.1 m) and is classified as an oligotrophic (Table 2.1). Water temperature and DO profiles were simulated using International Falls weather data; and Figures D.43 and D.44 show simulated and measured water temperature and DO profiles in 2003, 2006 and 2008. The standard error between simulated and measured water temperatures is 1.13 ^{o}C and 1.56 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree well with measured profiles on 7 days in these three years (141 data pairs). The model underpredicted DO profile on July 24, 2007, which could be due to seasonal chlorophyll-a pattern.

Siseebakwet Lake (DNR ID 31055400, latitude 47^{o}09'30" N, and longitude 93^{o}40'01"E) is located at city of Grand Rapids in Itasca County and has a surface area of 1307 acres (5.19 km^2) and maximum depth of 105 ft (32.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.50 and is classified as a stratified deep lake. It has a mean Secchi depth of 12.8 ft (3.9 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Grand Rapids weather data; and Figures D.45 and D.46 show simulated and measured water temperature and DO profiles in 1992 and 1993. The standard error between simulated and measured water temperatures is 1.66 ^{o}C and 1.47 mg/L for DO after model calibration. There are measured profiles on 6 days in 1992 and 1993 (122 data pairs). There is one measured profile during winter ice-covered period (January 20, 1993). The model predicted temperature of 4 ^{o}C at 6 m and deeper on that day, and measured temperatures are 1 to 2 ^{o}C less than simulated ones. Simulated and measured DO profiles on January 20, 1993, have the same vertical distribution pattern, but the model underpredicted DO values about 2 mg/L. The model predicted typical increase of hypolimnetic water temperature during the summer, but measured profiles indicates almost no change at all in hypolimnetic water temperatures, which indicate some groundwater intrusion or thermal heat sources in the hypolimnion.

Six Lake (DNR ID 56036900, latitude 46^{o}42'30" N, and longitude 95^{o}47'31"E) is located at city of Frazee in Otter Tail County and has a surface area of 188 acres (0.76 km^2) and maximum depth of 140 ft (42.7 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 0.69 and is classified as a stratified deep lake. It has a mean Secchi depth of 12.9 ft (3.9 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Grand Rapids weather data; and Figures D.47 and D.48 show simulated and measured water temperature and DO profiles on 4 days in 1997 (70 data pairs). The standard error between simulated and measured water temperatures is 1.72 ^{o}C and 2.38 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree well with measured profiles in the epilimnion and metalimnion in summer, but measured temperature profiles had very unusual temperature drop from 16 m – water temperatures in hypolimnion are below 4 ^{o}C. This may indicate some groundwater intrusion with low DO or anoxic water, which can be seen from measured DO profiles on May 20 and June 18, 1997. This creates the largest standard error for

DO in the 21 cisco lakes simulated in this study. This also may indicate that Six Lake is a meromictic lake, and there is no spring and fall overturns to mix hypolimnetic water. A meromictic lake may form for a number of reasons: (1) the basin is unusually deep and steep-sided compared to the lake's surface area, and (2) the lower layer of the lake is highly saline and denser than the higher levels of water (from http://en.wikipedia.org/wiki/Meromictic_lake). Six Lake has the small geometry ratio in the 28 study lakes; small surface area in comparison to the maximum depth. In 620 cisco lake database, there is only one lake, LaSalle Lake, having geometry ratio equal to 0.47 which is less than 0.69 for Six Lake and Gun Lake; and the smallest geometry ratio for the 27 regional lakes is 0.88 for a small depth lake (0.2 km^2 and 24 m deep). Figures A.59 and A.60 show that the deep part of the lake has relative small horizontal area.

Snowbank Lake (DNR ID 38052900, latitude 48^{o}00'008" N, and longitude 91^{o}25'01"E) is located at city of Forest Center in Lake County and has a surface area of 4275 acres (17.30 km^2) and maximum depth of 150 ft (45.7 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.41 and is classified as a stratified deep lake. It has a mean Secchi depth of 17.3 ft (5.3 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using International Falls weather data; and Figures D.49 and D.50 show simulated and measured water temperature and DO profiles on 4 days in 1986 and 1988. The standard error between simulated and measured water temperatures is 0.92 ^{o}C and 0.88 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree well with measured profiles on those four days (67 data pairs).

South Twin Lake (DNR ID 44001400, latitude 47^{o}13'30" N, and longitude 95^{o}38'46"E) is located at city of Waubun in Mahnomen County and has a surface area of 1118 acres (4.52 km^2) and maximum depth of 29 ft (8.8 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 5.22 and is classified as a weakly stratified medium-depth lake. It has a mean Secchi depth of 9.5 ft (2.9 m) and is classified as a mesotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Bemidji weather data; and Figures D.50 to D.53 show simulated and measured water temperature and DO profiles in 2008. The standard error between simulated and measured water temperatures is 1.42 ^{o}C and 1.33 mg/L for DO after model calibration. Overall, simulated water temperature and DO profiles agree reasonably well with measured profiles on 15 days in 2008 (134 data pairs).

Ten Mile Lake (DNR ID 11041300, latitude 46^{o}58'42" N, and longitude 94^{o}33'56"E) is located at city of Hackensack in Cass County and has a surface area of 4670 acres (18.90 km^2) and maximum depth of 207 ft (63.0 m, the deepest lake of the 28 study lakes). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.05 and is classified as a stratified deep lake. It has a mean Secchi depth of 18.2 ft (5.5 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Bemidji weather data; and Figures D.60 to D.63 show simulated and measured water temperature and DO profiles in 2001, 2002 and 2008. The standard error between simulated and measured water temperatures is 1.68 ^{o}C and 1.04 mg/L for DO after model calibration. There are very strong temperature gradients in the metalimnion where the model has some under- or over-predictions. Simulated temperature and DO variations (gradients along depth) in the hypolimnion are slightly larger than measured ones (more or less well mixed in hypolimnetic temperature and DO below 30 m). Overall, simulated water temperature and DO profiles agree well with measured profiles on 30 days in 2001, 2002 and 2008 (828 data pairs). Time series of simulated temperature and DO at five different depths (1.0, 15.0, 30.0, 45.0, 55.0 m) in Ten Miles Lake are given in Figures E.37 and E.38 and agree well with measurements over time (2000 to 2008).

Trout Lake (DNR ID 16004900, latitude 47°57'32" N, and longitude 92°19'13"E) is located at city of Grand Marais in Cook County and has a surface area of 257 acres (1.04 km^2) and maximum depth of 76 ft (23.0 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 1.39 and is classified as a stratified deep lake. It has a mean Secchi depth of 20.7 ft (6.3 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using International Falls weather data; and Figures D.67 to D.70 show simulated and measured water temperature and DO profiles in 1983, 1984, 2003 and 2008. The standard error between simulated and measured water temperatures is 1.24 °C and 1.63 mg/L for DO after model calibration. There are measured profiles on 23 days in these four years (349 data pairs). On May 15, 1984, the model overpredicted water temperature at the epilimnion. On 29 October 1986 and October 31, 2008 model, the model underpredicted the mixed layer depths but measured temperature and DO profiles showed the fall overturns. From June to August, 2008 the model overpredicted water temperatures in the epilimnion. Time series of simulated temperature and DO at five different depths (1.0, 6.0, 12.0, 18.0, 22.0 m) in Trout Lake are given in Figures E.39 and E.41 and agree well with measurements over time (1982 to 1986 and 2000 to 2008).

Trout Lake (DNR ID 69049800, latitude 47°57'32" N, and longitude 92°19'13"E) is located at city of Tower in St. Louis County and has a surface area of 7644 acres (30.9 km^2) and maximum depth of 98 ft (29.9 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 2.50 and is classified as a stratified deep lake. It has a mean Secchi depth of 15.5 ft (4.7 m) and is classified as an oligotrophic lake (Table 2.1). Water temperature and DO profiles were simulated using International Falls weather data; and Figures D.71 and D.72 show simulated and measured water temperature and DO profiles in 2006. The standard error between simulated and measured water temperatures is 0.80 °C and 0.95 mg/L for DO after model calibration. Simulated water temperature and DO profiles agree well with measured profiles on 5 days in 2006 (89 data pairs). There are several data points of measured DO concentration that are incorrect or inconsistent with general vertical profile.

White Iron Lake (DNR ID 69000400, latitude 47°53'53" N, and longitude 91°45'12"E) is located at city of Ely in St. Louis County and has a surface area of 3429 acres (13.9 km^2) and maximum depth of 47 ft (14.3 m). It has a geometry ratio ($A_s^{0.25}/H_{max}$) of 4.26 and is classified as a weakly stratified medium-depth lake. It has a mean Secchi depth of 4.9 ft (1.5 m) and is classified as an eutrophic lake (Table 2.1). Water temperature and DO profiles were simulated using Duluth weather data; and Figures D.73 to D.76 show simulated and measured water temperature and DO profiles in 1995, 1996, 2000, 2006, and 2007. The standard error between simulated and measured water temperatures is 1.43 °C and 1.63 mg/L for DO after model calibration. There are measured profiles on 21 days in these four years (341 data pairs). On June 21 and July 30, 1995, and July 02, 1996 the model overpredicted temperature in the hypolimnion. On June 03, 1996 the model underpredicted temperature in the epilimnion. Simulated temperature profiles agree reasonably well with measured profiles on other days. On June 03, 1996, June 12, 2000, September 19, 2000 and May 23, 2006 the model overpredicted and on July 18, 2000 the model underpredicted the DO profiles, and for the most cases the difference is only about 1-2 mg/L. Simulated DO profiles agree well with measured profiles on other days.

Chapter 7 Generalization of Model Parameters

7.1. Analysis and generalization of model calibration parameters

Six model parameters were used for model calibration to enhance the performance of the model. These parameters were calibrated for each of the 28 study lake individually, with the results given in Tables 5.3 and 5.4. As can be seen, many different values for each parameter were found. Model calibration is a time consuming and tedious process. An analysis of model calibration parameters was therefore performed in order to see if they correlate with basic lake characteristic parameters. If successful, generalized calibration parameters make the calibration of individual lakes superfluous. Table 7.1 lists the six model calibration parameters as well as lake parameters that may relate to each calibration parameter. Default values for the four multipliers [EMCOE(1), EMCOE(2), EMCOE(4), and EMCOE(5)] are equal to 1.0 which means no increase and no decrease of diffusion coefficients, SOD, and chlorophyll-a concentrations relative to the default values. An analysis of each calibration parameter and a proposed generalization is presented in the next subsections.

Table 7.1 Calibration parameters and related lake characteristic parameters.

Calibration parameters	**Related lake characteristics**
Wind sheltering coefficient (W_{Str})	Lake area and presence of vegetation along the shore line.
Biochemical oxygen demand (BOD)	Trophic status of lakes
Multiplier for diffusion coefficient in the metalimnion -EMCOE (1)	Maximum depth
Multiplier for SOD below mixed layer - EMCOE (2)	Maximum depth and trophic status
Multiplier for diffusion coefficient in the hypolimnion - EMCOE (4)	Maximum depth
Multiplier for chlorophyll–a below the mixed layer - EMCOE (5)	Trophic Status

7.1.1 Wind Sheltering Coefficient

As discussed in section 5.3, the wind sheltering coefficient (W_{str}) depends on the surface area of a lake and on the vegetation or buildings along the shoreline of a lake. W_{str} was calibrated based on the model predictions of a lake's surface mixed layer depth. The mixed layer depths of simulated and observed temperature and DO profiles for a study lake were compared, and then W_{str} was adjusted (increased or decreased) for the lake. A lake's surroundings as shown on Bing maps or Google maps were checked to see whether the change of W_{str} could be justified. Table 7.2 lists W_{str} – values, either calibrated or calculated using Equation 5.1 that was developed for previous lake studies. Values of W_{str} determined by calibration for 17 of the 28 study lakes; are different from calculated values.

Figure 7.1 is a plot of calibrated W_{str} values versus lake surface area and a curve generated from Equation (5.1). W_{str} values calculated from Equation (5.1) were used for model calibration runs in 11 study lakes (Table 7.2 and Fig. 7.1). The differences between calibrated and calculated W_{str} values for 28 lakes are listed in the last column of Table 7.2; for ten of the 28 lakes the absolute difference in the wind sheltering coefficient is greater than 0.10. There are seven lakes with an absolute difference greater than 0.25, a relatively large adjustment from the calculated W_{str}. Table 7.4 and Figure 7.1 indicate that lakes with surface area greater than 10 km^2 can be simulated with a wind sheltering coefficient equal to 1.0, i.e. vegetation and buildings along the shoreline have no effect on the overall wind mixing in the lake. When the lake surface area becomes smaller than 10 km^2 wind sheltering depends more on vegetation and buildings surrounding the lake. For the same vegetation or buildings along the periphery of a lake, the sheltered lake area can be a large portion of the total lake surface in a small lake, but only a small portion in a large lake. When a small lake is located in wide open and flat terrain, wind sheltering can be smaller or W_{str} can be larger than would be estimated from Equation (5.1). This situation seems to occur in St. Olaf Lake, Carrie Lake, Elk Lake, and Cedar Lake (Fig. 7.1). Of the 15 study lakes with surface area larger than 3.0 km^2, only 6 lakes had to be calibrated for W_{str}, and of the 13 study lakes with surface area less than 3.0 km^2, 11 lakes had be calibrated for W_{str}.

W_{str} values used for model calibration and simulation also include the uncertainty of wind speed used. The wind speed data used are typically measured at airports that are surrounded by flat terrain whereas study lakes may be many kilometers away and surrounded by different terrain. The calibrated W_{str} for Greenwood Lake is much smaller than the W_{str} calculated from Equation (5.1); Greenwood Lake is located in the northeastern corner of Minnesota and the weather data used for model simulation come from the Duluth airport – far away from Greenwood. There are four other cases similar to Greenwood Lake: Trout Lake in Cook County using weather data from International Falls, Six Lake using weather data from Grand Rapids, and Lake Madison and St. Olaf Lake using weather data from Minneapolis. For one or two lakes, it was found that making W_{str} greater than 1.0 can give better simulation results. All of these examples indicate the same problem – how well the wind speed from a weather station at an airport represents the wind speed at a far away lake site.

Considering the differences between calculated and calibrated W_{str} values, a new regression equation fitted to calibrated W_{str} values was developed. It is given as Equation (7.1) and is plotted as a dashed line in Figure 7.1. Equation (7.1) is just slightly different from Equation (5.1).

$$W_{str} = 1.0 - \exp(-0.383 \times A_s) \qquad (7.1)$$

Table 7.2 Calibrated and calculated values of wind sheltering coefficient.

Lake Name	Surface area (km^2)	W_{str} (Calculated using eqn.	W_{str} (Calibrated)	W_{str} (Markfort et al., 2010)	Difference W_{str} *(Calib.)* - W_{str} *(Calc.)*
Trout (St. Louis)	30.94	1.00	1.00		0
Burntside	28.90	1.00	1.00		0
Ten Mile	18.90	1.00	1.00		0
Snowbank	17.30	0.99	0.99		0
White Iron	13.88	0.98	1.00		0.02
Carlos	10.20	0.95	1.00		0.05
Kabekona	9.12	0.94	0.98		0.04
Greenwood	8.18	0.91	0.50		-0.41
Fish Hook	6.61	0.86	0.86		0
Big Trout	5.43	0.80	0.80		0
Siseebakwet	5.29	0.80	1.00		0.20
South Twin	4.52	0.74	0.74		0
Madison	4.50	0.74	1.00		0.26
South Center	3.38	0.64	0.64		0
Mukooda	3.05	0.60	0.60		0
Elephant	2.93	0.58	0.90		0.32
Bear Head	2.73	0.56	0.45		-0.11
Hill	2.66	0.55	0.65		0.10
Grindstone	2.13	0.47	0.47		0
Little Sand	1.56	0.37	0.30		-0.07
Elk	1.10	0.28	0.60		0.32
Trout (Cook)	1.04	0.27	0.10		-0.17
Cedar	0.98	0.25	0.68		0.43
Little Trout	0.97	0.25	0.25		0
Blue	0.79	0.21	0.19		-0.02
Six	0.76	0.20	0.10		-0.10
Carrie	0.37	0.10	0.70		0.60
St. Olaf	0.37	0.10	0.50		0.40

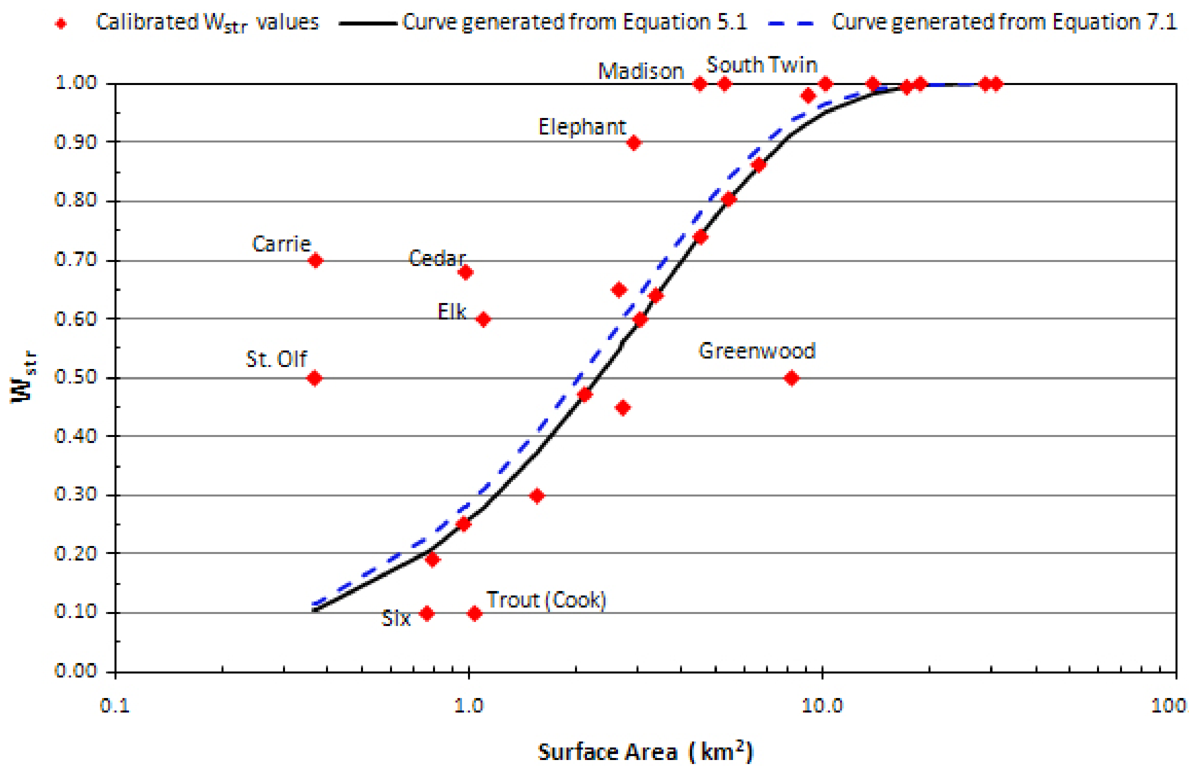

Figure 7.1 Calibrated wind sheltering coefficient W_{str} vs. lake surface area, and plots of equations (5.1) and (7.1).

7.1.2 Biochemical oxygen demand (BOD)

BOD was used as a calibration parameter in previous lake studies (Stefan and Fang 1994). BOD was specified for each lake depending on lake trophic status, and Table 7.3 lists values of BOD that would be recommended similarly for the 28 study lakes based on trophic status. Recommended BOD values were 1.0, 0.5, and 0.2 mg/L for eutrophic (E), mesotrophic, (M) and oligotrophic (O) lakes, respectively. BOD values obtained by calibration of the MINLAKE2010 model and previously listed in Table 6.1 are also reproduced in Table 7.3 for comparison. The recommended BOD values were used in 13 of the 28 study lakes after model calibration. Higher BOD values were used in 14 of the 28 study lakes after model calibration, and a lower value was used in only one lake (White Iron) to improve model performance.

Table 7.4 gives model performance (standard error SE) for four sample lakes when recommended or calibrated values of BOD are used as input. Table 7.4 shows that using higher values of BOD improved the model performance to a satisfactory level. Figure 7.2 gives examples of measured and simulated DO profiles on four days in Trout Lake (St. Louis County). DO profiles were obtained with either recommended or calibrated BOD values as input. Figure

7.2 shows that with the recommended value of BOD (0.2 mg/L) DO was overpredicted in both the epilimnion and hypolimnion, and after calibration with a higher BOD value (1.15 mg/L) the model simulations agree reasonably well with observed profiles. The calibrated average BOD values in eutrophic, mesotrophic, and oligotrophic study lakes are listed in Table 7.5, and the recommended BOD values for cisco lakes are also listed.

Table 7.3 Values of BOD recommended based on trophic status and values of BOD obtained by calibration of the 28 study lakes.

Lake Name	Trophic Status	Recommended BOD	Calibrated BOD
Carrie	Eutrophic	1.00	1.00
Madison	Eutrophic	1.00	2.50
South Center	Eutrophic	1.00	1.50
St. Olaf	Eutrophic	1.00	1.90
White Iron	Eutrophic	1.00	0.25
Bear Head	Mesotrophic	0.50	1.00
Carlos	Mesotrophic	0.50	0.50
Cedar	Mesotrophic	0.50	0.75
Elephant	Mesotrophic	0.50	1.00
Elk	Mesotrophic	0.50	0.80
Fish Hook	Mesotrophic	0.50	0.50
Grindstone	Mesotrophic	0.50	0.50
Hill	Mesotrophic	0.50	1.75
Kabekona	Mesotrophic	0.50	0.50
Siseebakwet	Mesotrophic	0.50	0.50
Six	Mesotrophic	0.50	0.50
South Twin	Mesotrophic	0.50	0.50
Big Trout	Oligotrophic	0.20	0.20
Blue	Oligotrophic	0.20	1.25
Burntside	Oligotrophic	0.20	1.00
Greenwood	Oligotrophic	0.20	0.20
Little Sand	Oligotrophic	0.20	0.20
Little Trout	Oligotrophic	0.20	0.20
Mukooda	Oligotrophic	0.20	0.40
Snowbank	Oligotrophic	0.20	1.00
Ten Mile	Oligotrophic	0.20	0.50
Trout (St. Louis)	Oligotrophic	0.20	1.15
Trout (Cook)	Oligotrophic	0.20	0.25

Table 7.4 Quantitative measures of success of simulations of dissolved oxygen (mg/L) using recommended BOD and calibrated BOD in four lakes.

Lake Name	Trophic Status	Recommended BOD (mg/L)	S.E. (mg/L) with recommended BOD	Calibrated BOD (mg/L)	S.E. (mg/L) with calibrated BOD
Madison	Eutrophic	1.00	2.99	2.50	2.76
Hill	Mesotrophic	0.50	2.43	1.75	1.83
Blue	Oligotrophic	0.20	4.60	1.25	1.80
Trout [1]	Oligotrophic	0.20	3.00	1.15	0.95

[1] – Lake Trout in St. Louis County

Table 7.5 Average values of BOD and proposed BOD values for regional cisco lakes.

Parameters	Eutrophic	Mesotrophic	Oligotrophic
Average BOD (all lakes)	1.43	0.71	0.58
Number of lakes	5	12	11
Average BOD (cisco lakes)	0.25	0.53	0.58
Number of cisco lakes	1	9	11
Proposed BOD	1.50	0.75	0.50

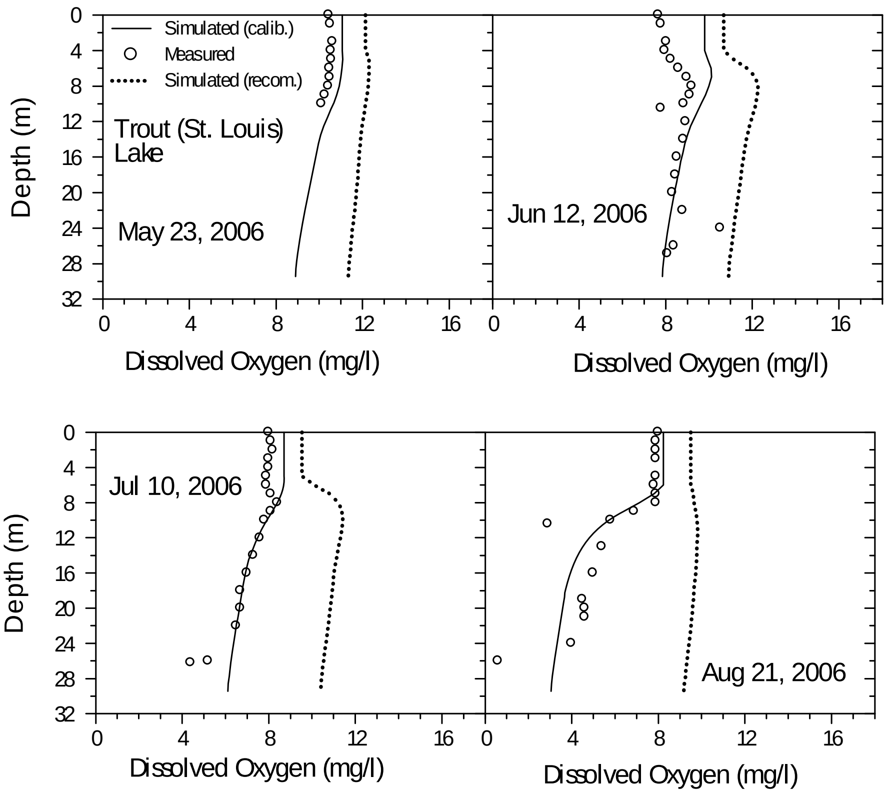

Figure 7.2 Measured and simulated DO profiles in Trout Lake (St. Louis County) using recommended (based on trophic state) and calibrated BOD values.

7.1.3 EMCOE(1) and EMCOE(4)

EMCOE(1) and EMCOE(4) are multipliers of the diffusion coefficients in the metalimnion and hypolimnion, respectively. Model calibration indicates that these two parameters are dependent on the maximum depth of a lake. Table 7.6 lists calibrated values of EMCOE(1) and EMCOE(4) for the 28 study lakes ordered by decreasing maximum depth. These are two new calibration parameters introduced in this study, and their default values are 1.0 for the previous regional lake model MINLAKE96. The model calibration shows that the model performance in deep lakes was sensitive to EMCOE(1). Table 7.7 and Table 7.8 list standard errors of estimate (SE) of temperature and DO simulations in three study lakes before and after calibration of EMCOE(1) and EMCOE(4). The calibration parameter EMCOE(1) improved the performance of the model to a satisfactory level (Table 7.7), and, by comparison, EMCOE(4) is not effective. Figure 7.3 shows measured and simulated temperature and DO profiles in Burntside Lake on four days. Temperature and DO profiles were simulated using uncalibrated and calibrated parameter values. Figure 7.3 shows that when calibration is not done with EMCOE (1) the model overpredicted temperature and underpredicted DO in the hypolimnion. After calibration both simulated temperature and DO profiles agree well with observed profiles.

Table 7.6 shows EMCOE(1) was calibrated, i.e. different from 1.0 for 25 lakes out of 28 lakes. Because EMCOE(4) does not have much effect on the simulation, it was calibrated for only 5 deep lakes and one medium lake, and set as EMCOE(4) = 1.0 for all other lakes. Table 7.11 lists average values of calibrated EMCOE(1) and EMCOE(4) for the 28 study lakes and proposed values of these two parameters for regional cisco lakes. It is proposed that EMCOE (1) is equal to 0.5 for deep lakes and 1.0 for all other lakes, and EMCOE (4) is equal to 1.0 for all lakes.

Table 7.6 Calibrated values of EMCOE (1) and EMCOE (4) for the 28 study lakes grouped on the maximum depth classification.

Lake Name	EMCOE(1)	EMCOE (4)	Depth
South Center	0.70	1.00	Deep
Carlos	1.50	1.00	Deep
Cedar	1.00	1.00	Deep
Elk	0.80	1.50	Deep
Fish Hook	0.75	1.00	Deep
Grindstone	1.25	1.00	Deep
Kabekona	1.00	1.00	Deep
Six	0.10	0.10	Deep
Big Trout	0.80	1.00	Deep
Burntside	0.20	1.50	Deep
Greenwood	0.20	1.00	Deep
Little Sand	0.10	1.00	Deep
Little Trout	0.05	1.00	Deep
Mukooda	0.50	1.00	Deep
Siseebakwet	1.50	1.00	Deep
Snowbank	0.40	1.00	Deep
Ten Mile	0.70	6.00	Deep
Trout (Cook)	0.25	1.00	Deep
Trout (St. Louis)	0.35	4.00	Deep
Carrie	2.00	1.00	Medium
Madison	1.00	1.00	Medium
St. Olaf	1.60	1.00	Medium
White Iron	1.75	1.00	Medium
Bear Head	0.65	1.00	Medium
Elephant	0.80	1.00	Medium
Hill	0.60	1.00	Medium
South Twin	1.50	3.00	Medium
Blue	0.10	1.00	Medium

Table 7.7 Quantitative measures of success of simulations of dissolved oxygen (mg/L) before and after calibrating EMCOE (1) in three lakes.

Lake Name	Lake Maximum Depth	Calibrated value of EMCOE(1)	Not Calibrated		Calibrated	
			S.E. (^oC) (Temperature)	S.E. (mg/L) (DO)	S.E. (^oC) (Temperature)	S.E. (mg/L) (DO)
Burntside	Deep	0.20	3.26	1.60	1.72	1.37
Ten Mile	Deep	0.70	1.83	1.03	1.68	1.04
Trout (St. Louis)	Deep	0.35	2.57	1.12	0.80	0.95

Table 7.8 Quantitative measures of success of simulations on dissolved oxygen (mg/L) before and after calibrating EMCOE (4) in three lakes.

Lake Name	Lake Maximum Depth	Calibrated value of EMCOE(4)	Not calibrated		Calibrated	
			S.E. (^oC) (Temperature)	S.E. (mg/L) (DO)	S.E. (^oC) (Temperature)	S.E. (mg/L) (DO)
Burntside	Deep	1.50	1.74	1.37	1.72	1.37
Ten Mile	Deep	6.00	1.76	0.99	1.68	1.04
Trout (St. Louis)	Deep	4.00	0.84	0.94	0.80	0.95

Table 7.9 Average and proposed values of EMCOE(1) and EMCOE(4) for regional cisco lakes.

Parameter		Deep	Medium	Shallow
EMCOE (1)	Average (all lakes)	0.64 (19)	1.11(9)	-
	Average (cisco lakes)	0.64(18)	1.12(3)	-
	Proposed Refined	0.50	1.0	1.0
EMCOE (4)	Average (all lakes)	1.43(19)	1.22 (9)	-
	Average (cisco lakes)	1.45 (18)	1.67(3)	
	Proposed Refined	1.0	1.0	1.0

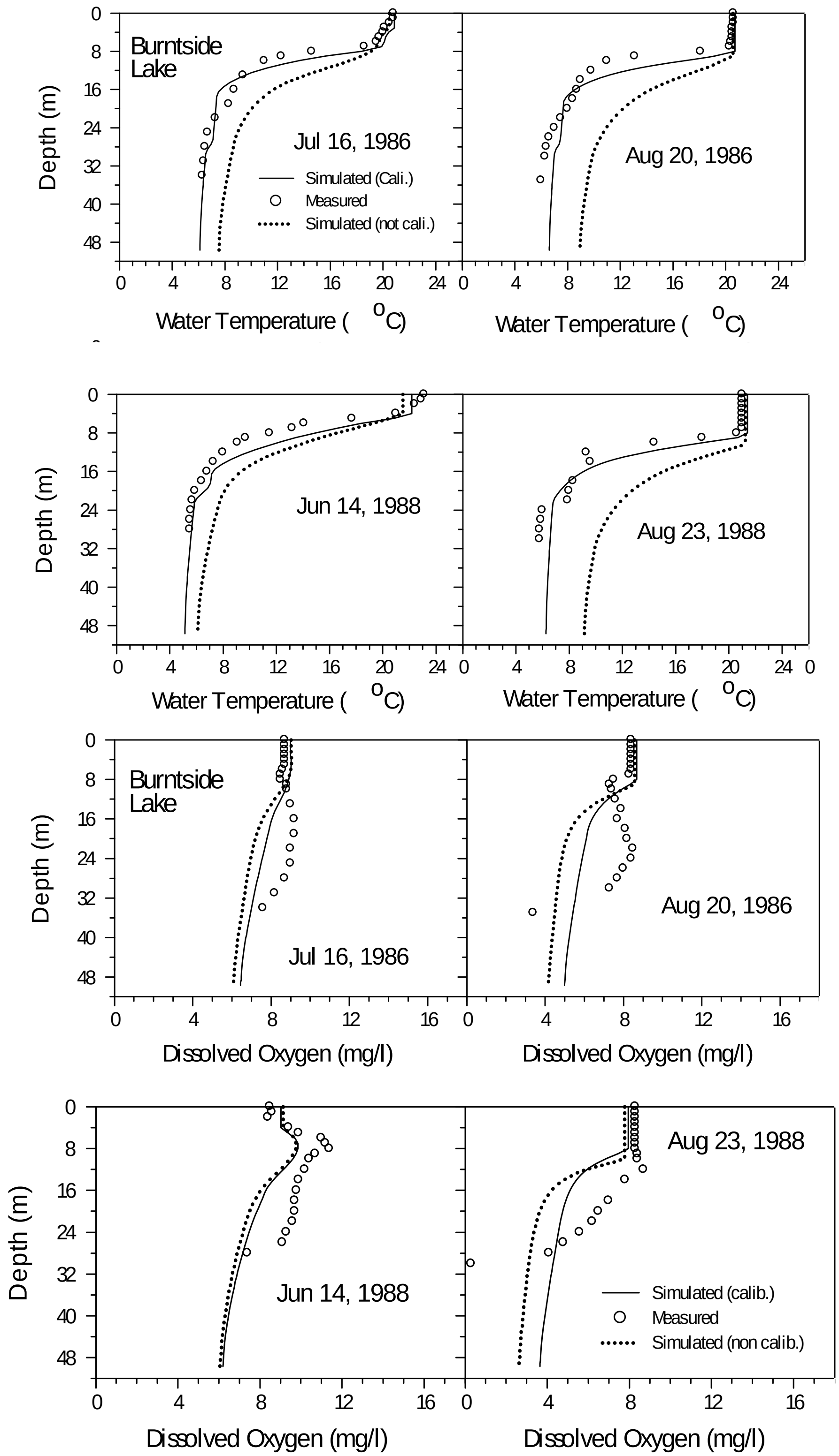

Figure 7.3 Effect of calibration of EMCOE(1) on temperature and dissolved oxygen profiles in Burntside Lake on four days. Simulated profiles are drawn with and without calibration of EMCOE(1).

7.1.4 EMCOE (2)

EMCOE (2) is the multiplier for SOD below the mixed layer and depends on both maximum depth and trophic status. When EMCOE(2) is equal to 1.0 (default or uncalibrated value for the MINLAKE96 model), the rates of SOD are the same in the mixed layer (epilimnion) and below the mixed layer (metalimnion and hypolimnion). Table 7.10 lists the standard error of estimate (S.E.) used to quantify the success of the model simulations in five study lakes with and without calibration of EMCOE(2). When EMCOE(2) was calibrated the model performance was improved to a satisfactory level (Table 7.11). Figure 7.4 shows DO profiles in Greenwood Lake on four days, simulated without and with calibration of EMCOE(2). Figure 7.4 shows that without calibration of EMCOE(2), the model overpredicted DO profiles in both epilimnion and hypolimnion. After calibrating EMCOE(2) simulated profiles agree well with observed ones.

The effect of EMCOE(2) is strong, especially in the hypolimnion. EMCOE(2) had to be calibrated for all lakes, except one (South Center Lake), to get better DO simulation results. Table 7.11 lists calibrated values of EMCOE(2) for the 28 study lakes listed according to trophic status and maximum depth. Table 7.11 also includes values of S_{b20}, which is the rate of SOD used in the epilimnion, and EMCOE(2) × S_{B20}, which is the rate of SOD in the metalimnion and hypolimnion (below the mixed layer). Table 7.11 and Figure 7.5 show that EMCOE(2) x S_{b20} values are lower for deeper lakes and lower for clearer lakes, a trend which is the same as for S_{b20} values (Table 3.1). Table 7.12 lists the average calibrated values and proposed values of EMCOE(2) x S_{b20} , i.e. the rate of SOD below the mixed layer. Proposed EMCOE(2) values for future studies are also given in Table 7.12 and vary with lake maximum depth and trophic status. EMCOE(2) is set to be 1.0 for shallow lakes until further study on shallow lakes provides more information on it because there are no shallow lakes in the 28 study lakes.

Table 7.10 Quantitative measures of success of simulations of dissolved oxygen (mg/L) before and after calibrating EMCOE(2) in five sample lakes.

Lake Name	Lake Trophic status	Lake Maximum Depth	Calibrated value of EMCOE(2)	S.E. (mg/L) when EMCOE(2) = 1.0.	S.E. (mg/L) using calibrated EMCOE(2)
Six	Mesotrophic	Deep	3.75	4.02	2.38
Greenwood	Oligotrophic	Deep	6.00	3.44	1.36
Ten Mile	Oligotrophic	Deep	6.50	2.19	1.04
Trout (St. Louis)	Oligotrophic	Deep	2.00	1.04	0.95
Hill	Mesotrophic	Medium	6.00	2.43	1.85

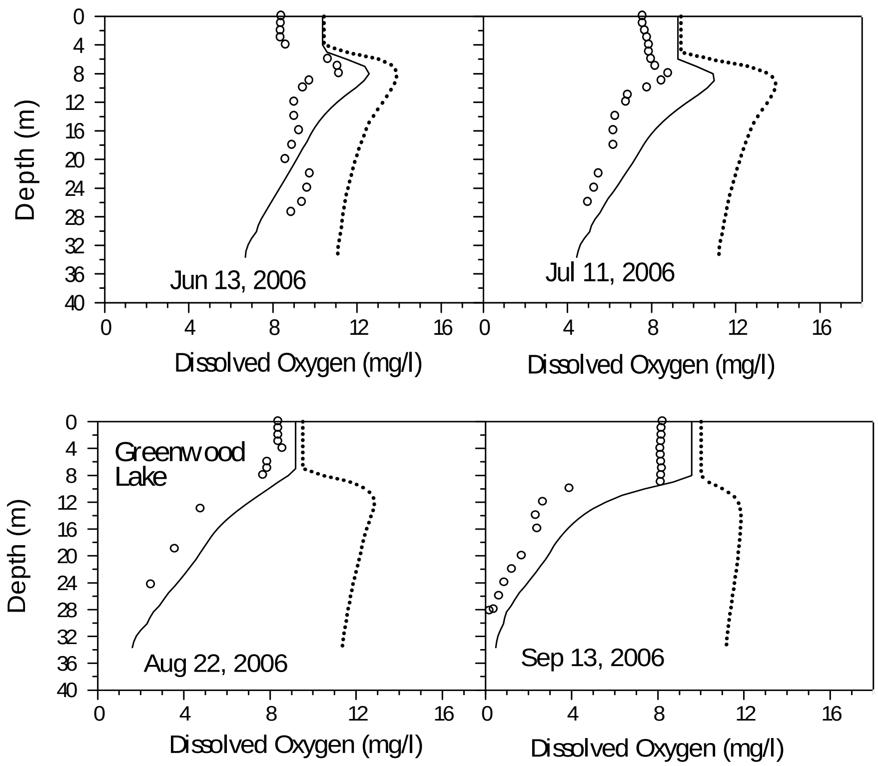

Figure 7.4 Effect of EMCOE (2) calibration on dissolved oxygen profiles of four days on Greenwood Lake, where profiles are drawn for both with and without calibration.

Table 7.11 Calibrated values of EMCOE (2) for the 28 study lakes listed by trophic status and maximum depth.

Lake Name	S_{b20}	Trophic Status	Maximum Depth	EMCOE (2)	EMCOE(2) × S_{B20}
South Center	1.00	Eutrophic	Deep	1.00	1.00
Carrie	1.50	Eutrophic	Medium	0.82	1.23
Madison	1.50	Eutrophic	Medium	2.00	3.00
St. Olaf	1.50	Eutrophic	Medium	1.25	1.88
White Iron	1.50	Eutrophic	Medium	1.20	1.80
Carlos	0.50	Mesotrophic	Deep	2.20	1.10
Cedar	0.50	Mesotrophic	Deep	3.00	1.50
Elk	0.50	Mesotrophic	Deep	3.50	1.75
Fish Hook	0.50	Mesotrophic	Deep	2.50	1.25
Grindstone	0.50	Mesotrophic	Deep	0.45	0.23
Kabekona	0.50	Mesotrophic	Deep	2.75	1.38
Six	0.50	Mesotrophic	Deep	3.75	1.88
Bear Head	0.75	Mesotrophic	Medium	1.45	1.09
Elephant	0.75	Mesotrophic	Medium	2.00	1.50
Hill	0.75	Mesotrophic	Medium	6.00	4.50
South Twin	0.75	Mesotrophic	Medium	1.50	1.13
Big Trout	0.20	Oligotrophic	Deep	8.00	1.60
Burntside	0.20	Oligotrophic	Deep	0.75	0.15
Greenwood	0.20	Oligotrophic	Deep	6.00	1.20
Little Sand	0.20	Oligotrophic	Deep	7.50	1.50
Little Trout	0.20	Oligotrophic	Deep	7.50	1.50
Mukooda	0.20	Oligotrophic	Deep	5.00	1.00
Siseebakwet	0.20	Oligotrophic	Deep	6.00	1.20
Snowbank	0.20	Oligotrophic	Deep	1.25	0.25
Ten Mile	0.20	Oligotrophic	Deep	6.50	1.30
Trout (Cook)	0.20	Oligotrophic	Deep	4.00	0.80
Trout (St.	0.20	Oligotrophic	Deep	2.00	0.40
Blue	0.4	Oligotrophic	Medium	2.40	0.96

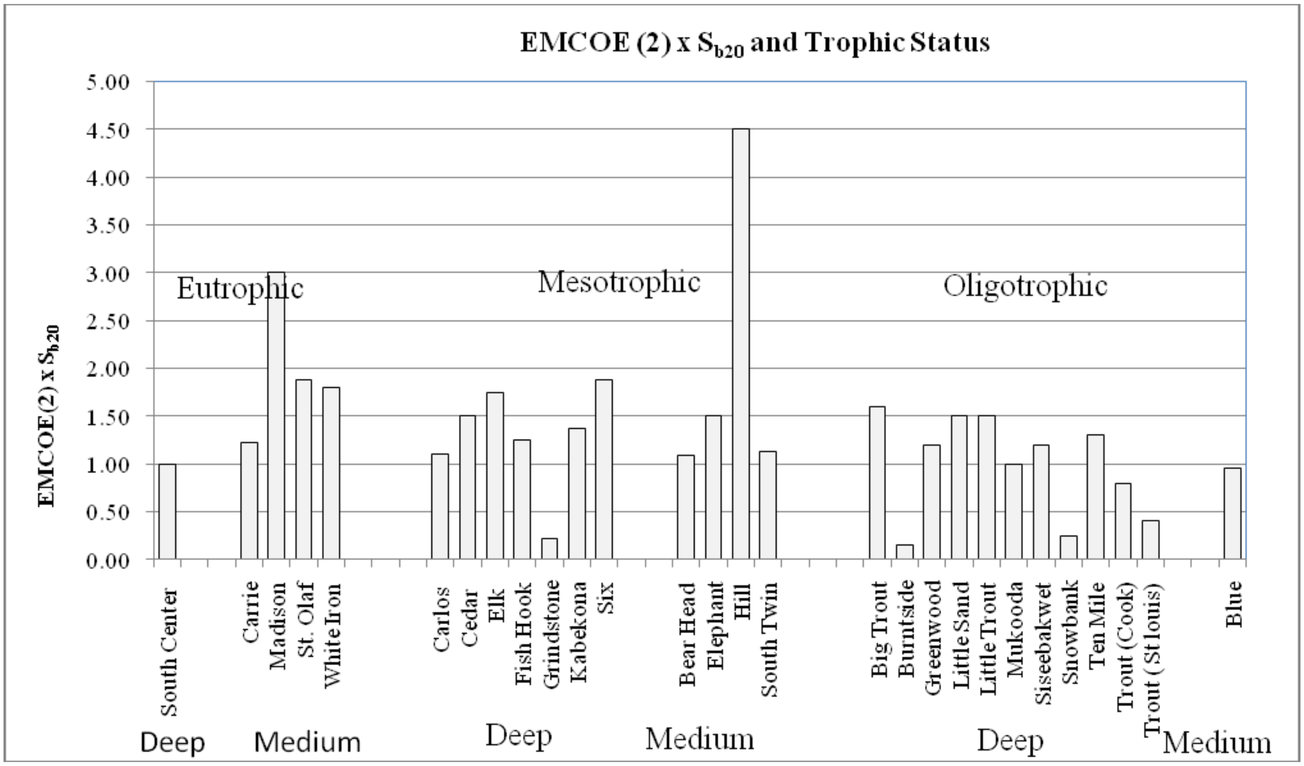

Figure 7.5 EMCOE(2) x S_{b20} and trophic status

Table 7.12 Average and refined values of EMCOE (2).

EMCOE (2) /EMCOE (2) × S_{B20}		Eutrophic	Mesotrophic	Oligotrophic
Average of values used in input files EMCOE (2) × S_{b20}	Deep (all lakes)	1.00 (1) [1]	1.30(7)	0.99(11)
	Deep (cisco lakes)	- (0)	1.30 (7)	0.99 (11)
	Medium (all lakes)	1.98(4)	2.05(4)	0.96 (1) [2]
	Medium (cisco lakes)	1.80 (1)	1.13 (1)	0.96 (1)
Proposed values of EMCOE (2) × S_{b20}	Deep	1.50	1.25	1.00
	Medium	1.95	1.75	1.20
	Shallow	2.20	1.90	1.25
Proposed EMCOE (2) values	Deep	1.5	2.5	5.0
	Medium	1.3	2.3	3.0
	Shallow	1.1	1.9	2.5
Recommended S_{b20} (g O_2 m^{-2} day^{-1})	Deep	1.0	0.5	0.2
	Medium	1.5	0.75	0.4
	Shallow	2.0	1.0	0.5

[1] – only one deep eutrophic lake used, [2] – only one medium-depth oligotrophic lake used

7.2.5 EMCOE (5)

EMCOE(5) is the multiplier for chlorophyll–*a* concentration below the mixed layer. When EMCOE(5) = 1 (default value), chlorophyll-*a* concentrations in the epilimnion and below are the same. Table 7.13 lists calibrated values of EMCOE(5) for the 28 study lakes grouped on the basis of trophic status. It was found that for eutrophic and mesotrophic lakes, calibrated EMCOE(5) values were 1.0 except 1.10 in Six Lake. This indicates that an increase of chlorophyll-*a* concentration below the epilimnion is not necessary; this is consistent with what was used in previous lake models (MINLAKE95 and MINLAKE96). Table 7.13 shows that calibrated values of EMCOE(5) were greater than 1.0 in six oligotrophic lakes and equal to 1.0 in the remaining six oligotrophic lakes. Table 7.14 gives average calibrated values and proposed values of EMCOE(5) in the 21 cisco lakes grouped by trophic status. It is proposed that the EMCOE(5) value be set equal to 1.50 for oligotrophic lakes and 1.0 for eutrophic and mesotrophic lakes. It means that chlorophyll-*a* concentrations below the epilimnion are about 50% larger than in the epilimnion.

Table 7.13 Values of EMCOE (5) for lakes listed according to trophic status

Lake Name	Trophic status	EMCOE(5)
Carrie [1]	Eutrophic	1.00
Madison [1]	Eutrophic	1.00
South Center [1]	Eutrophic	1.00
St. Olaf [1]	Eutrophic	1.00
White Iron	Eutrophic	1.00
Bear Head [1]	Mesotrophic	1.00
Carlos	Mesotrophic	1.00
Cedar	Mesotrophic	1.00
Elephant [1]	Mesotrophic	1.00
Elk	Mesotrophic	1.00
Fish Hook	Mesotrophic	1.00
Grindstone	Mesotrophic	1.00
Hill [1]	Mesotrophic	1.00
Kabekona	Mesotrophic	1.00
Six	Mesotrophic	1.10
South Twin	Mesotrophic	1.00
Big Trout	Oligotrophic	1.00
Blue	Oligotrophic	1.35
Burntside	Oligotrophic	1.00
Greenwood	Oligotrophic	1.00
Little Sand	Oligotrophic	1.75
Little Trout	Oligotrophic	2.25
Mukooda	Oligotrophic	2.00
Siseebakwet	Oligotrophic	2.00
Snowbank	Oligotrophic	1.50
Ten Mile	Oligotrophic	1.00
Trout (St. Luis)	Oligotrophic	1.00
Trout (Cook)	Oligotrophic	1.00

[1] – Non-cisco habitat lakes

Table 7.14 Average calibrated values and proposed values of EMCOE (5) in cisco lakes.

EMCOE(5)	Eutrophic	Mesotrophic	Oligotrophic
Average of calibrated values (all lakes)	1.00 (5)	1.01(11)	1.40 (12)
Average of calibrated values (cisco lakes)	1.00 (1)	1.01 (8)	1.40 (12)
Proposed values	1.00	1.00	1.50

7.3 Model performance with generalized calibration parameters

In the previous section six calibration parameters, W_{str}, BOD, EMCOE(1), EMCOE(2), EMCOE(4), and EMCOE(5) were analyzed and for each parameter a generalized value was proposed. Simulation runs using the MINLAKE2010 model were made with these generalized calibration parameters as model input. The simulations were made for the 21 study lakes that are known to have cisco habitat, to check model performance. Table 7.15 lists the error parameters generated by these model runs with generalized calibration parameters for the 21 cisco lakes. Table 7.16 lists the error parameters obtained with the calibration parameters determined by the calibration of each lake individually. In Table 7.15 values of the generalized calibration parameters suitable for each cisco lakes are listed, while in Table 7.16 values of the individually calibrated parameters for each cisco lake are listed. A comparison of generalized and calibrated model parameters can therefore be easily made.

The MINLAKE2010 model performance with generalized calibration parameters is as good as the performance that was found with calibration parameters fitted to individual lake data. The average standard error of estimate or S.E. for the 21 cisco lakes using the generalized model parameters is 1.87^{o}C for water temperature (range from 1.0 to 2.67 ^{o}C) and 1.77 mg/l for DO (range from 0.85 to 3.24 mg/l). The average regression coefficient (R^2) is 0.88 for water temperature (range from 0.79 to 0.97) and 0.49 for DO (range from -1.66 to 0.92). The average slope (S) for the model to field data regression is 1.00 for water temperature (range from 0.89 to 1.13) and 1.00 for DO (range from 0.80 to 1.20). Results in Tables 7.15 and 7.16 illustrate that the average standard error of estimate of both temperature and DO simulations for the 21 cisco lakes are only slightly higher when generalized calibration parameters are used than those when individually calibrated parameters are used. The model performance is satisfactory and average S.E. values are acceptable for both temperature and DO simulation. The average SE = 1.77 mg/L for DO using the generalized model parameters is smaller than the S.E. = 1.94 mg/L using the MINLAKE96 model (Fang and Stefan 1997) with calibrated parameters.

Table 7.15 Error parameters for model runs with generalized calibration parameters for 21 cisco lakes.

Lake name	Generalized calibration parameters						Water temperature			Dissolved oxygen		
	W_{str}[1]	BOD (mg/L)	EMCOE (2)	EMCOE (1)	EMCOE (4)	EMCOE (5)	S.E. (°C)	R^2	S	S.E. (mg/L)	R^2	S
Big Trout	0.88	0.50	5.00	0.50	1.00	1.5	1.82	0.90	1.04	1.88	0.53	1.03
Blue	0.26	0.50	3.00	1.00	1.00	1.5	2.58	0.82	0.99	2.93	0.40	0.80
Burntside	1.00	0.50	5.00	0.50	1.00	1.5	2.29	0.83	0.92	1.71	-0.37	0.88
Carlos	0.98	0.75	2.50	0.50	1.00	1.0	2.67	0.82	1.06	1.89	0.72	1.12
Cedar	0.31	0.75	2.50	0.50	1.00	1.0	2.07	0.90	1.06	1.83	0.79	0.91
Elk	0.34	0.75	2.50	0.50	1.00	1.0	2.04	0.89	1.13	1.24	0.91	0.98
Fish Hook	0.92	0.75	2.50	0.50	1.00	1.0	2.04	0.84	0.97	1.17	0.90	1.08
Greenwood	0.96	0.50	5.00	0.50	1.00	1.5	2.23	0.79	0.89	1.31	0.71	0.95
Grindstone	0.56	0.75	2.50	0.50	1.00	1.0	2.21	0.84	1.03	3.24	-1.66	1.11
Kabekona	0.97	0.75	2.50	0.50	1.00	1.0	1.53	0.92	1.07	0.82	0.92	1.01
Little Sand	0.45	0.50	5.00	0.50	1.00	1.5	2.54	0.83	0.96	1.68	0.76	0.96
Little Trout	0.31	0.50	5.00	0.50	1.00	1.5	1.83	0.92	0.94	2.56	0.48	1.20
Mukooda	0.69	0.50	5.00	0.50	1.00	1.5	1.10	0.96	1.00	1.69	0.74	1.09
Siseebakwet	0.87	0.50	5.00	0.50	1.00	1.5	2.11	0.87	1.07	2.10	0.73	1.19
Six	0.25	0.75	2.50	0.50	1.00	1.0	1.94	0.91	0.89	1.99	0.83	0.95
Snowbank	1.00	0.50	5.00	0.50	1.00	1.5	1.00	0.97	0.98	0.85	0.58	0.93
South Twin	0.82	0.75	2.50	1.00	1.00	1.0	1.46	0.80	1.06	1.76	0.28	1.07
Ten Mile	1.00	0.50	5.00	0.50	1.00	1.5	1.89	0.90	1.08	1.46	0.62	0.90
Trout(Cook)	0.33	0.50	5.00	0.50	1.00	1.5	1.42	0.92	0.93	1.59	0.63	1.02
Trout(St. Louis)	1.00	0.50	5.00	0.50	1.00	1.5	1.04	0.96	0.97	1.62	0.49	0.84
White Iron	1.00	1.50	1.30	1.00	1.00	1.0	1.37	0.86	1.00	1.92	0.27	1.05
Average Error Parameters							1.87	0.88	1.00	1.77	0.49	1.00

[1] $W_{str} = 1-\exp(-0.383 \times A_s)$

Table 7.16 Error parameters for model runs with calibration parameters determined for individual cisco lakes (21 lakes).

Lake name	Lake specific calibration parameters						Water temperature			Dissolved oxygen		
	W_{str}[1]	BOD (mg/L)	EMCOE (2)	EMCOE (1)	EMCOE (4)	EMCOE (5)	S.E. (°C)	R^2	S	S.E. (mg/L)	R^2	S
Big Trout	0.80	0.20	8.00	0.80	1.00	1.00	1.65	0.91	1.01	1.52	0.68	1.02
Blue	0.19	1.25	2.40	0.10	1.00	1.35	1.70	0.92	1.05	1.80	0.77	0.99
Burntside	1.00	1.00	0.75	0.20	1.50	1.00	1.72	0.90	0.97	1.37	0.12	0.95
Carlos	1.00	0.50	2.20	1.50	1.00	1.00	1.70	0.93	1.00	1.32	0.86	1.04
Cedar	0.68	0.75	3.00	1.00	1.00	1.00	1.34	0.96	1.00	1.40	0.88	0.97
Elk	0.60	0.50	3.50	0.80	1.50	1.00	1.47	0.94	1.05	1.03	0.93	0.99
Fish Hook	0.86	0.50	2.50	0.75	1.00	1.00	2.06	0.84	1.01	1.10	0.91	1.06
Greenwood	0.50	0.20	6.00	0.20	1.00	1.00	1.76	0.87	0.93	1.36	0.69	0.95
Grindstone	0.47	0.50	0.45	1.25	1.00	1.00	1.67	0.91	1.01	1.83	0.15	0.91
Kabekona	0.98	0.50	2.75	1.00	1.00	1.00	1.37	0.93	1.05	0.89	0.90	0.95
Little Sand	0.30	0.20	7.50	0.10	1.00	1.75	1.76	0.92	1.01	1.28	0.86	0.96
Little Trout	0.25	0.20	7.50	0.05	1.00	2.25	1.46	0.95	0.96	1.44	0.84	1.04
Mukooda	0.60	0.40	5.00	0.50	1.00	2.00	1.13	0.96	0.99	1.56	0.78	1.03
Siseebakwet	1.00	0.50	1.75	1.50	1.00	2.00	1.66	0.92	1.02	1.47	0.86	1.07
Six	0.10	0.50	3.75	0.10	0.10	1.10	1.72	0.93	0.92	2.38	0.76	0.85
Snowbank	0.99	1.00	1.25	0.40	1.00	1.50	0.92	0.97	0.98	0.88	0.56	1.00
South Twin	0.74	0.50	1.50	1.50	3.00	1.00	1.42	0.80	1.06	1.33	0.59	1.02
Ten Mile	1.00	0.50	6.50	0.70	6.00	1.00	1.68	0.92	1.04	1.04	0.80	0.96
Trout(Cook)	0.10	0.25	4.00	0.25	1.00	1.00	1.24	0.94	0.96	1.63	0.51	0.93
Trout(St. Louis)	1.00	1.15	2.00	0.35	4.00	1.00	0.80	0.97	0.99	0.95	0.83	0.95
White Iron	1.00	0.25	1.20	1.75	1.00	1.00	1.43	0.84	0.99	1.63	0.46	0.98
Average Error Parameters							1.51	0.92	1.00	1.39	0.70	0.98

[1] $W_{str} = 1 - \exp(-0.3 \times A_s)$

Chapter 8 Summary and Conclusions

This report starts with a brief review of the year-round water quality model used for previous regional lake modeling over the contiguous United States. In order to more accurately predict water quality conditions in cisco lakes, which are typically deep mesotrophic or oligotrophic lakes, various modifications and refinements were made in the MINLAKE96 program by changing the simulation procedure and utility functions of the model. The improved model is called MINLAKE2010. The report summarizes model calibration and simulation results for 28 lakes in Minnesota. Twenty-one cisco lakes and seven non-cisco habitat lakes were selected for model calibration and refinement of the model. Lake bathymetry data and measured water quality data (water temperature and dissolved oxygen profiles, Secchi depths, chlorophyll-a concentrations) were assembled and analyzed. Available water temperature and DO profile data for the 21 cisco lakes, needed for model calibration, covered periods from 4 to 46 days in specific years, and from 1 to 10 years (Table 3.2). In total, 80 years or 331 days with measured profiles, and 5608 total pairs of temperature and DO data in the 21 cisco lakes were available for model calibration. For the seven non-cisco lakes, a total of 25 years or 156 days with measured profiles data giving 1973 total data pairs were available. Measured chlorophyll-a concentrations on the dates with measured profiles were used as model input parameters to represent lake trophic conditions. Because there were only limited chlorophyll-a measurements available within a year, the information provided by the field data did not justify a change of the imposed generic seasonal chlorophyll-*a* pattern. In the MINLAKE2010 model, the light (solar radiation) attenuation coefficients due to water (μ_w) and due to phytoplankton (μ_{chla}) were set as constant input parameters to the model. Weather data are necessary model input data and drive water temperature, and DO dynamics simulated by the model over time. Weather data from nine stations were assembled for the period 1961 to 2008 for the Class I stations and 1991 to 2008 for Class II stations.

The model simulations in the 28 lakes were calibrated using six model calibration parameters (wind sheltering coefficient, W_{str}; biochemical oxygen demand, BOD; a multiplier for chlorophyll–*a* in the hypolimnion, a multiplier for SOD below the mixed layer, and multipliers for diffusion coefficient in the metalimnion and hypolimnion. The average standard error of estimate (S.E.) against measured data for all 28 lakes is 1.47 ^oC for water temperature (ranging from 0.8 to 2.06 ^oC) and 1.50 mg/L for DO (ranging from 0.88 to 2.76 mg/L). The average regression coefficient (R^2) is 0.92 for water temperature (ranging from 0.84 to 0.97) and 0.75 for DO (ranging from 0.12 to 0.91). Simulation results are presented as profile plots and time-series plots. Model calibration parameters were analyzed and suggested values were proposed for cisco lakes in Minnesota. The model performance using proposed calibration parameter values were examined and the average standard errors were acceptable. Therefore, the MINLAKE2010 can be applied to other cisco lakes in Minnesota with or without measured profiles to simulate water temperature and DO conditions and to further analyze fish habitat and identify refuge lakes for cisco.

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