Simulations of water quality and oxythermal cisco habitat in Minnesota lakes under past and future climate scenarios
Xing Fang, Shoeb R. Alam, Heinz G. Stefan, Liping Jiang, Peter C. Jacobson and Donald L. Pereira

ABSTRACT

A deterministic, process-oriented, dynamic and one-dimensional year-round lake water quality model, MINLAKE2010, was developed for water temperature (T) and dissolved oxygen (DO) simulations to study impacts of climate warming on lake water quality and cisco fish habitat. The DO model is able to simulate metalimnetic oxygen maxima in vertical DO profiles of oligotrophic lakes. The model was calibrated with profile data from the 28 study lakes in Minnesota; two-thirds of them are deep mesotrophic/oligotrophic lakes that support cisco, a coldwater fish species. The average standard error of estimate against measured data was 1.47 °C for T and 1.50 mg/L for DO. Oxythermal habitat parameter TDO3 (T at DO = 3 mg/L) was determined from simulated daily T and DO profiles under past and future climate scenarios in the 28 study lakes. Average annual maximum TDO3 (TDO3AM) for the 28 study lakes is projected to increase on the average of 3.2 °C under the MIROC 3.2 future scenario, while the occurrence day of TDO3AM is not much different under past and future climate scenarios. Both physical processes (mixing characteristics related to lake geometry ratio) and trophic status control temperature and DO characteristics and then affect cisco habitat in a lake.

Key words | climate change, dissolved oxygen, fish habitat, lakes, simulation model, water quality

INTRODUCTION

Water quality is a critical issue because of its direct influence on public health and biological integrity of natural resources. Water resources managers and professionals are concerned for the potential significance and impacts of climate change on inland aquatic ecosystems, i.e., streams, lakes, and reservoirs. To make projections of water quality and fish habitat in lakes under future climate scenarios, numerical simulation models are very useful, if not indispensable. To project potential effects of climate change on water quality and ecology of fresh water systems, deterministic simulation models have been developed and applied to the Laurentian Great Lakes (Blumberg & Di Toro 1990); reservoirs (Chang et al. 1992) and lakes in north-temperate regions (De Stasio et al. 1996; Stefan et al. 1996); and lakes in the contiguous USA (Fang & Stefan 2009).

The goal of the study described herein was to simulate daily water temperature (T) and dissolved oxygen (DO) profiles in cisco lakes in Minnesota, and then to project lake water quality conditions under projected future climate warming in order to identify cisco refuge lakes in Minnesota. A ‘refuge lake’ is a lake that has supported cisco under past (historical) climate conditions and is projected to provide cisco habitat under future climate scenarios. The Minnesota Department of Natural Resources (MN DNR) has sampled cisco from 648 lakes in netting assessments since 1946 (Minnesota DNR files). The cisco lakes are scattered throughout much of the central and northern USA.
portions of the state and cross several ecoregions (northern lakes and forests, north central hardwood forest, and prairie) and land uses (agricultural, urban, and forested). It was found that, on average, Minnesota cisco lakes are deeper, more transparent, and less productive than other lakes in Minnesota (Fang et al. 2009). A deterministic, process-oriented, unsteady, one-dimensional (vertical) year-round lake water quality model (Stefan et al. 1998), which has been successfully applied over a period of years to simulate hydrothermal and DO processes in individual lakes and regional lakes, was especially adapted for deep oligotrophic lakes in Minnesota as will be shown. An oxythermal fish habitat model was developed to determine TDO3, the water temperature at 3 mg/L of DO, from daily simulated habitat model to deep lakes, and its application to 28 Minnesota lakes under past and future climate scenarios are described and discussed in this paper.

**MATERIALS AND METHODS**

A year-round lake water quality model, MINLAKE2010, was developed from the MINLAKE96 model for small lakes (up to 10 km² surface area) in the contiguous USA; the original model framework came from the Minnesota Lake Water Quality Management Model – MINLAKE (Riley & Stefan 1988). The year-round model is run in daily time steps over multiple simulation years through both open-water seasons and ice-cover periods continuously, i.e., without re-initializing the simulations in each year. The one-dimensional model uses a stacked layer system; the layers consist of water and lake sediments during the open-water season and additional ice cover and snow cover layers for the winter period (Fang & Stefan 2009). The model simulates physical processes at the lake surface and within the lake (e.g., heat exchange, ice cover formation and melting, and wind mixing), and biological processes (e.g., photosynthesis and sedimentary oxygen uptake, SOU).

Several modifications and refinements were made to develop MINLAKE2010 from MINLAKE96.

1. The maximum number of horizontal layers in MINLAKE2010 was increased so that the model can handle much deeper lakes (up to 100 m maximum depth).
2. Several calibration parameters were activated or introduced in the program. Use of these parameters enhances the performance of the model significantly for the deep oligotrophic lakes as will be shown in the next section.
3. The model was 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 most recent global climate projection models.
5. The model was coded so that at the end of the winter ice-cover period when simulated water temperature increases to greater than 4 °C within 2 days, complete lake mixing (overturn) is enforced.
6. Various modifications were made in the program to make the input data files user friendly.

**Year-round lake water temperature model**

The one-dimensional, unsteady heat transfer Equation (1) in a lake is solved to obtain daily vertical water temperature profiles.

\[
\frac{\partial T}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left( K_z A \frac{\partial T}{\partial z} \right) + \frac{H}{\rho C_p}
\]

where \(T(z, t)\) in °C is the water temperature in individual well-mixed horizontal layers, \(t\) in days is the time, \(A\) in m² is the horizontal area as function of depth \(z\) (m) based on a hypsographic curve (bathymetry), \(K_z\) in m²/day is the vertical turbulent heat diffusion coefficient, \(\rho C_p\) in J/(m³ °C) represents heat capacity per unit volume of water and is the density of water \((\rho)\) times heat capacity of water \((C_p)\), and \(H\) in J/(m³ day) is the internal heat source strength per unit volume of water. Solar radiation absorption in the water column is the main contributor to the heat source.
term during the open-water season. Heat exchange between the lake and the atmosphere (climate conditions) is treated as a source/sink term for the topmost water layer of a lake during the open-water season and for snow or ice covers during the ice-cover period. It includes incoming heat flux from net shortwave solar radiation and long-wave radiation and outgoing heat fluxes from back radiation, evaporation, and convection related to wind speed. The determination of source and sink terms has been discussed by Hondzo & Stefan (1993) among others. The heat budget components are linked to climate parameters that represent past or future climate.

MINLAKE2010 conjunctively uses a vertical eddy diffusion expression, mechanical energy balance (turbulent kinetic energy from wind and potential energy due to density difference) (Ford & Stefan 1980), and a convection algorithm for natural cooling, to distribute heat energy and predict well-mixed surface layer thickness and hypolimnetic water temperature profiles. The model uses calibration parameters and initial conditions linked to lake geometry and/or geographic location (Hondzo & Stefan 1993; Fang & Stefan 1998a). The eddy diffusion coefficient below the mixed layer \( K_z \) in cm²/s is a function of lake surface area \( A_s \) in km² and stability frequency \( N^2 = (\partial \theta^2 / \partial z) \rho / g \) in s⁻², where \( g \) is acceleration of gravity] (Hondzo & Stefan 1993):

\[
K_z = 8.17 \times 10^{-4} (A_s)^{0.56} (N^2)^{-0.43}
\]  

(2)

The maximum vertical hypolimnetic eddy diffusivity, \( K_{z,\text{max}} \), occurs under weakly stratified conditions that were defined as \( N^2 = 7.0 \times 10^{-5} \text{ s}^{-2} \) (Riley & Stefan 1988). A wind sheltering coefficient adjusts the wind speed for fetch over the lake in the direction of wind and is used to compute turbulent kinetic energy from a wind speed that is typically measured at an off-site weather station at 10-m elevation.

Projections of daily ice cover characteristics (Fang et al. 1996) use a full heat budget equation to estimate surface cooling, to quantify the effect of forced convective (wind) mixing, and include the latent heat removed by ice formation. Computations are made with a fine (0.02 m) spatial resolution near the water surface. Snow thickness is determined from snow accumulation, compaction, melting of snow by surface heat input (convection, rainfall, solar radiation) and transformation of wetted snow to ice when cracks in the ice cover allow water to spill onto the ice surface. In the model, ice growth occurs from the ice-water interface downward and from the ice surface upward. Ice decay occurs at the snow–ice interface, ice-water interface, and within the ice layer (Fang & Stefan 1996). Winter ice and snow cover models were calibrated against 128 ice/snow measurements over 8 years in Thrush Lake in Minnesota and Little Rock Lake in Wisconsin, and 198 observed freeze-over dates in another nine Minnesota lakes (Fang et al. 1996).

Heat exchange between lake sediment and water is calculated separately for each horizontal water layer and included as a source/sink term in the lake water temperature model. To determine heat flux between water and sediment, the one-dimensional (vertical), dynamic heat conduction equation is solved to simulate sediment temperature profiles down to 10 m below the lake bottom (Fang & Stefan 1998a).

Year-round lake dissolved oxygen model

The simulation model for daily DO profiles in a lake solves the one-dimensional, unsteady transport equation including oxygen sources (surface reaeration and photosynthesis of phytoplankton) and oxygen sinks (SOU, biochemical oxygen demand (BOD), and algal respiration): 

\[
\frac{\partial C}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left( AK_z \frac{\partial C}{\partial z} \right) + P_{\text{MAX}}^T \theta^T_{r-20} \text{Min} [L] \text{Chla} - \frac{S_b A}{A} \frac{\partial}{\partial z} \theta^s_{r-20} - k_0 \theta^T_{r-20} \text{BOD} - Y_{\text{O2CH}} k_r \theta^T_{r-20} \text{Chla}
\]

(3)

where \( C(z,t) \) is the DO concentration in mg/L as a function of depth and time, \( K_z(z,t) \) is the vertical turbulent diffusion coefficient for DO in m²/s, \( S_b \) is the coefficient for SOU at 20 °C in mg O₂/(m³ day), \( P_{\text{MAX}} \) is the maximum specific oxygen production rate by photosynthesis at 20 °C under saturating light conditions = 9.6 mg O₂/(mg Chla day), \( \text{Min} [L] \) is the light limitation determined by Haldane kinetics, \( \text{Chla} \) is the chlorophyll a concentration in mg/L, \( Y_{\text{O2CH}} \) is the yield coefficient that equals 120 mg O₂/(mg Chla), \( k_0 \) and \( k_r \) are the first order decay rate coefficient for BOD and algal respiration, respectively, and equal to 0.1 per day. The temperature adjustment coefficients \( \theta_1 = 1.065 \), \( \theta_0 = 1.036 \), \( \theta_c = 1.047 \) and \( \theta_r = 1.047 \) are for SOU, photosynthesis, BOD, and algal respiration, respectively. BOD is the
sum of carbonaceous and nitrogenous biochemical oxygen demands or uptakes that are mainly due to the aerobic microbial decomposition of particulate and dissolved organic matter in the lake. SOU varies with trophic status and maximum depth (Stefan & Fang 1994), e.g., 0.2 g/(m² day) in a deep oligotrophic lake and 2.0 g/(m² day) in a shallow eutrophic lake.

In the model, chlorophyll a is specified by a mean annual value and a function that calculates typical seasonal chlorophyll cycles (Stefan & Fang 1994) based on data from 56 lakes or reservoirs in Europe and North America (Marshall & Peters 1989). In the model, the oxygen transfer through the water surface (reaeration) during the open-water season is used as an oxygen source or sink term in the topmost water (surface) layer of the lake, and surface oxygen transfer coefficient is calculated as a function of wind speed (Wanninkhof et al. 1993). For the DO simulations in a lake during the winter ice-cover period, modifications were made to account for the presence of an ice cover and low temperatures (Fang & Stefan 1997), e.g., reaeration is zero because the lake ice cover prevents any significant gas exchange between the atmosphere and the water body. DO concentrations were simulated after water temperature and ice covers had been simulated.

Model input data and calibration parameters

Input data for MINLAKE2010 provide the information necessary to begin the computation sequence to model water temperature and DO profiles in a lake. Model input data include:

1. Lake bathymetry (horizontal area and volume from lake bottom versus depth).
2. Lake specific model input data, e.g., coefficients for model calibration, initial conditions, light attenuation coefficient computed from mean summer Secchi depth, and annual mean chlorophyll a concentration in each simulation year.
3. Daily weather data (Fang et al. 2010a).

The year-round model simulation was started (initialized) at least 1 year before the start of observed water temperature and DO profiles used for model calibration, in order to eliminate the possible effects of assumed initial conditions which were uniform water temperature of 4 °C and DO of 10 mg/L on April 16 (near the spring overturn period). Weather data provide the atmospheric forcing in the model simulations and consist of daily air temperature, dew point temperature, wind speed, solar radiation, percentage sunshine, and precipitation (both rainfall and snowfall). For past climate, observed daily meteorological data from the closest weather station were used for model simulations. Five National Weather Service (NWS) Class I weather stations (Duluth, International Falls, Minneapolis, St. Cloud, MN, Fargo, ND) have weather data available from 1961 to 2008 and three NWS Class II weather stations (Bemidji, Brainerd, Grand Rapids, MN) have weather data available from 1991 to 2008 for model simulations (Table 1).

Projected future climate scenarios were based on the output of the Coupled Global Climate Model (CGCM), CCCma CGCM 3.1 (Kim et al. 2002, 2003), from the Canadian Climate Centre for Climate Modeling and Analysis (CC)ma), and the Model for Interdisciplinary Research on Climate, MIROC 3.2 (Hasumi & Emori 2004), developed in Japan. Monthly increments of air temperature, dew point temperature (computed from relative humidity), wind speed, solar radiation and precipitation from the closest GCM grid center point were applied to measured daily climate conditions (1961–2008) to generate the projected daily future climate scenario. Monthly increases of air temperature at International Falls were projected by CGCM 5.1 to be from 2.89 to 6.89 °C and by MIROC 3.2 from 3.55 to 5.15 °C. The highest change of air temperature was projected by CGCM 5.1 to be 8.09 °C in February at Duluth.

Six model calibration parameters were used in MINLAKE2010 for the deep and oligotrophic lakes: (1) wind sheltering coefficient; (2) BOD; (3) a multiplier for the diffusion coefficient in the metalimnion; (4) a multiplier of the diffusion coefficient in the hypolimnion; (5) a multiplier for chlorophyll a below the mixed layer; and (6) a multiplier for SOU below the mixed layer. The wind sheltering coefficient ($W_{st}$) was initially set as a function of lake surface area based on model calibrations of various Minnesota lakes (Hondzo & Stefan 1995) and then calibrated for each of the 28 study lakes when measured water temperature profiles were available. BOD is related to primary productivity represented as chlorophyll a; therefore, BOD was set as 1.0, 0.5, and 0.2 mg/L for eutrophic, mesotrophic, and oligotrophic lake in MINLAKE96 (Stefan & Fang 1994).
Chlorophyll $a$ concentrations were available as model input for all 28 lakes from measurements near the lake surface (epilimnion), but not in the metalimnion and hypolimnion; therefore, a multiplier for chlorophyll $a$ below the mixed layer was introduced as a calibration parameter.

### Oxythermal fish habitat model

Freshwater fish habitat is constrained by several physical and biological parameters that relate to water quality, food supply, and human interference. Channel geometry and streamflow are important to fish habitat in streams (Rundquist & Baldrige, 1994), respectively, but was further calibrated in MIN-LAKE2010. Chlorophyll $a$ concentrations were available as model input for all 28 lakes from measurements near the lake surface (epilimnion), but not in the metalimnion and hypolimnion; therefore, a multiplier for chlorophyll $a$ below the mixed layer was introduced as a calibration parameter.

<table>
<thead>
<tr>
<th>Lake name</th>
<th>$A_s$ (km$^2$)</th>
<th>$H_{max}$ (m)</th>
<th>GR$^a$ (m$^{-1/2}$)</th>
<th>Secchi depth (m)</th>
<th>Data (days /data pairs)</th>
<th>S.E. for temp (°C)</th>
<th>S.E. for DO (mg/L)</th>
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</thead>
<tbody>
<tr>
<td>Big Trout$^b$</td>
<td>5.43</td>
<td>39.01</td>
<td>1.24</td>
<td>4.78</td>
<td>46/916</td>
<td>1.65</td>
<td>1.52</td>
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<td>Blue$^b$</td>
<td>0.71</td>
<td>14.63</td>
<td>1.98</td>
<td>6.76</td>
<td>13/205</td>
<td>1.70</td>
<td>1.80</td>
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<td>Burntside</td>
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<td>38.40</td>
<td>1.91</td>
<td>5.80</td>
<td>14/274</td>
<td>1.72</td>
<td>1.37</td>
</tr>
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<td>Carlos</td>
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<td>50.00</td>
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<td>5.27</td>
<td>16/366</td>
<td>1.70</td>
<td>1.52</td>
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<td>Cedar</td>
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<td>1.40</td>
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<td>28.00</td>
<td>1.16</td>
<td>2.57</td>
<td>17/312</td>
<td>1.47</td>
<td>1.03</td>
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<td>Fish Hook</td>
<td>6.61</td>
<td>23.16</td>
<td>2.19</td>
<td>3.44</td>
<td>4/61</td>
<td>2.06</td>
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<td>Greenwood</td>
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<td>34.14</td>
<td>1.57</td>
<td>5.46</td>
<td>14/222</td>
<td>1.76</td>
<td>1.36</td>
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<td>46.63</td>
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<td>2.88</td>
<td>5/98</td>
<td>1.67</td>
<td>1.83</td>
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<tr>
<td>Kabekonab</td>
<td>9.12</td>
<td>41.00</td>
<td>1.54</td>
<td>4.03</td>
<td>5/104</td>
<td>1.37</td>
<td>0.89</td>
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<td>Little Sand</td>
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<td>24.38</td>
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<td>5.22</td>
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<td>1.76</td>
<td>1.28</td>
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<td>3.89</td>
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<td>5.54</td>
<td>30/828</td>
<td>1.68</td>
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<td>23/349</td>
<td>1.24</td>
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<tr>
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<td>2.73</td>
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<td>Carrie$^c$</td>
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<td>7.90</td>
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<td>Hill$^b,c$</td>
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<td>14.60</td>
<td>2.77</td>
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<td>South Center$^c$</td>
<td>3.38</td>
<td>32.20</td>
<td>1.33</td>
<td>1.45</td>
<td>19/413</td>
<td>1.47</td>
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<td>St. Olaf$^c$</td>
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<td>10.10</td>
<td>2.44</td>
<td>1.41</td>
<td>32/314</td>
<td>1.34</td>
<td>2.05</td>
</tr>
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</table>

Overall number of data and average standard errors:

$^a$GR = lake geometry ratio $= A_s^{0.25} H_{max}$ where $A_s$ is in m$^2$ and $H_{max}$ in m.

$^b$NWS Class II weather station data from 1991 to 2008 were used for model simulations.

$^c$Non-cisco lakes.

$^d$Total days or pairs of measurements.

$^e$Average standard error (S.E.).
In lakes, water temperature and DO concentration are two of the most significant water quality parameters affecting survival and growth of fish (Fry 1971; Christie & Regier 1988). The oxythermal habitat approach commonly used in coldwater fish niche modeling (Dillon et al. 2003) defines an upper boundary for temperature (e.g., lethal temperature) and a lower boundary for DO concentration. These oxythermal habitat models determine the water volume or layer thickness in a stratified lake between the upper temperature and lower DO bound that represent either optimal thermal habitat (Dillon et al. 2003) or non-lethal/useable habitat (Stefan et al. 2001). Jacobson et al. (2010) proposed a single variable to quantify oxythermal habitat that allows for comparison across several coldwater fish species (lake trout, cisco, lake whitefish, and burbot) that have different requirements for cold, oxygenated water. The single generalized oxythermal habitat variable is defined as the water temperature at 3 mg/L of DO, known as TDO3. A higher TDO3 value represents higher oxythermal stress for the fish. The TDO3 can be determined by interpolating the temperature of water at the DO concentration of 3 mg/L from measured or simulated data. When non-monotonic profiles generate low oxygen concentrations with more than one TDO3 value, the coldest TDO3 is used (Jacobson et al. 2010). In this study, a fish habitat model was developed to compute the oxythermal habitat parameter TDO3 using simulated daily water temperature and DO profiles in lakes over periods of many years. The annual maximum TDO3 (TDO3AM), the occurrence day of TDO3AM, and mean daily TDO3 over a fixed 31-day benchmark period (ATDO3FB) were calculated for each simulated year. The benchmark period is the period of greatest oxythermal stress for freshwater fish, i.e., it is the period with the highest values of TDO3. For stratified lakes (lake geometry ratio GR < 5.0) in Minnesota, the 31-day benchmark period extends from the day of year (DOY or calendar date) 209 to DOY 239, which is from July 28 to August 27 (Jacobson et al. 2010).

RESULTS AND DISCUSSION

Water temperature and DO simulations

In this study, 21 cisco lakes and seven non-cisco lakes (Table 1) were selected for model calibration based on multi-year data availability. About 70% of the 28 lakes have a maximum depth ($H_{max}$) greater than 23.0 m, and 23 of the 28 lakes are either mesotrophic or oligotrophic lakes. Figure 1 shows the distribution of the 28 study lakes on a plot of lake geometry ratio ($GR = A_s^{0.25}/H_{max}^{0.5}$ when $A_s$ is in m$^2$ and $H_{max}$ in m) versus mean-summer Secchi depth (m). High GR corresponds to relatively large and shallow lakes, and low GR to relatively small and deep lakes. The strength of the seasonal lake stratification is related to the lake geometry ratio (Gorham & Boyce 1989). Lakes with the highest GR numbers have many mixing periods and are polymictic lakes, while lakes with the lowest GR numbers are strongly stratified dimictic lakes; lakes with GR between 3 and 5 are at the transition of the mixing regimes (Gorham & Boyce 1989). Figure 1 shows that 17 of the 21 cisco lakes are strongly stratified lakes with GR < 2, two (Fish Hook Lake and Lake Trout in St. Louis County) have GR between 2 and 3, and another two (South Twin Lake and White Iron Lake) have GR > 4.0 (Table 1) and are labeled as weakly stratified lakes in Figure 1. Chlorophyll $a$ concentration that represents biomass or phytoplankton in MINLAKEx2010 is related to Secchi depth by the Carlson trophic index (Carlson 1977). Lake geometry ratio and Secchi depth are two representative parameters to characterize each of the 620 cisco lakes in the database, and Figure 1 is an example for the 28 study lakes. These two parameters were also used to identify ‘refuge’ cisco lakes in Minnesota (Fang et al. 2010b), i.e., lakes that would be able to maintain and provide cisco habitat under future climate scenarios. Figure 1 suggests that lakes without suitable cisco habitat are typically either

![Figure 1](https://iwaponline.com/wqrj/article-pdf/47/3-4/375/163545/375.pdf)
eutrophic or relatively shallow with relatively large GR values.

Basic lake characteristic parameters and quantitative measures of the success of the water temperature (°C) and DO (mg/L) simulations in the 28 study lakes are listed in Table 1; 439 lake-days with measured water temperature and DO profiles (7,384 data pairs) were used for model calibration. After calibration the average standard error (S.E. in Table 1) of estimate against measured data for all 28 lakes was 1.47 °C for water temperature (range from 0.8 to 2.06 °C) and 1.50 mg/L for DO (range from 0.88 to 2.76 mg/L).

There were no weather stations that have long-term and high resolution meteorological data at or near the study lakes. Available data from the closest weather station were used for model simulations in each of the 28 study lakes. The distance from a lake to the closest weather station ranged from 15 to 199 km (average distance is 84 km). Meteorological data were used for simulations with no adjustments or adaption, except wind speed. A wind sheltering coefficient is a model calibration parameter that adjusts wind speed to account for sheltering effects of the vegetation, topography or buildings along the shoreline of a lake and also indirectly compensates for the distance from the weather station to the study lake. With this model calibration against observed temperature and DO profiles, the distance between a lake and the closest weather station may not directly affect model performance. For example, Greenwood Lake and Trout Lake (St. Louis County) are about 190 km away from Duluth (the closest weather station) and standard errors for temperature and DO simulations are smaller than or similar to average standard errors for all 28 lakes (Table 1).

Figure 2 shows examples of observed and simulated temperature and DO profiles (after model calibration) in Little Trout Lake, which has a maximum depth of 29 m (Table 1) and mean summer Secchi depth of 6.3 m (oligotrophic lake). Temperature profiles in the summers of 1997 and 2008 show very strong stratification, e.g., the temperature difference between lake surface and lake bottom was 19 °C on 6 August 1997. Both measurements and simulation results show metalimnetic oxygen maxima in the DO profiles (Figure 2). DO concentrations in the metalimnion were up to 12.6 mg/L but only 8.6 mg/L in the surface mixed layer on July 13, 2008. This creates favorable habitat conditions for coldwater fish species such as cisco. Figure 3 illustrates the seasonal change of simulated water temperature and DO (after model calibration) in the epilimnion (1.0 m) and hypolimnion (45.0 m) in Ten Mile Lake, which has a maximum depth of 63 m (Table 1) and mean summer Secchi depth of 5.5 m (oligotrophic lake). Measured and simulated water temperatures near the lake surface respond to variations of weather with season every year; a strong thermal stratification develops in Ten Mile Lake every summer (simulation for 2 years and available data for 1 year are shown in Figure 3). Measured and simulated water temperatures near the lake bottom vary from 4 °C in winter to about 7 °C in summer; they have much smaller variations with season (Figure 3) than surface waters because of the attenuation of solar radiation with water depth and lack of vertical mixing.

Six model parameters were calibrated for each of 28 study lakes. Individual model calibration parameter values were analyzed, and generalized model calibration parameter values were developed for use in cisco lakes without data.
The model performance using generalized calibration parameter values was only marginally lower than with calibration parameter values based on data (Fang et al. 2010a). Daily temperature and DO profiles over 48 years under past and future climate scenarios in 30 virtual cisco lakes without measured data were simulated using generalized model parameters; results were used to examine changes of cisco fish habitat due to climate change and to identify cisco refuge lakes, but these results are presented elsewhere (e.g., Fang et al. 2010b, 2011).

Figure 4 shows example plots of simulated water temperature and DO profiles for sensitivity analysis on: (a) BOD = 0.2, 0.5, and 1.0 mg/L for simulations in Trout Lake (St. Louis), (b) a multiplier EMCOE(1) = 1.0, 0.5, and 0.2 for the diffusion coefficient in the metalimnion for simulations in Burnside Lake; and (c) a multiplier EMCOE(2) = 1.0, 5.0, and 6.0 for SOU below the mixed layer for simulations in Greenwood Lake. For each sensitivity analysis run, only one parameter was changed and other model parameters were fixed and equal to calibrated values. Dots in Figure 4 show available measurements for comparison. Generalized BOD values for MINLAKE2010 determined by calibration were set at 1.5, 0.75, and 0.5 mg/L for eutrophic, mesotrophic, and oligotrophic lakes, respectively. Trout Lake in St. Louis County is an oligotrophic lake; the recommended BOD for regional lake study (Stefan & Fang 1994) was 0.2 mg/L and the standard error of the DO simulations was 2.46 mg/L. Calibrated BOD was 1.0 mg/L in Trout Lake with a standard error of 1.08 mg/L (Figure 4(a)).

The multiplier EMCOE(2) for the diffusion coefficient in the metalimnion was determined by calibration to be 0.5 for deep lakes and 1.0 for medium-deep and shallow lakes. For the hypolimnion, the multiplier of the diffusion coefficient was determined by calibration to be 1.0 for all lakes regardless of maximum depth. This means that the eddy diffusion coefficient (Equation (2)) is valid for shallow and medium-deep lakes but too large for deep lakes. Burnside Lake is a deep lake with maximum depth of 28.9 m. When EMCOE(1) = 1.0 was used (Figure 4(b)), it means that the eddy diffusion coefficient below the mixed layer was computed from Equation (2) recommended for regional lakes and for MINLAKE96 model, and the standard error of the water temperature simulations in Burnside Lake was 3.28 °C. Calibrated EMCOE(1) for Burnside Lake was 0.2 with a standard error of 1.73 °C (Figure 4(b)).

The multiplier for chlorophyll $a$ below the mixed layer was determined by calibration to be 1.5 for oligotrophic lakes (mean summer Secchi depth greater than 4.5 m) and 1.0 for mesotrophic and eutrophic lakes. Higher chlorophyll $a$ concentrations in the metalimnion matched observations.
in Thrush Lake (Stefan et al. 1996), and are key inputs for simulations of metalimnetic oxygen maxima occurring in oligotrophic lakes, such as Little Trout Lake (Figure 1). SOU below the mixed layer depends on both maximum depth and trophic status (Table 2). The $S_{b20}$ values, SOU at 20°C in g O$_2$/m$^2$ day, were adopted from the regional DO model (Stefan & Fang 1994). The proposed multiplier EMCOE(2) for SOU was found by calibration to be typically greater than 1.0, i.e., SOU in deeper lakes is larger than the values used for the regional lake model, especially for oligotrophic and mesotrophic lakes. Sensitivity analysis of DO profiles on EMCOE(2) is given in Figure 4(c) for simulations in Greenwood Lake, a deep oligotrophic lake (Table 1) as an example. When EMCOE(2) = 1.0 was used, the $S_{b20}$ value at 20°C was 0.2 g O$_2$/m$^2$ day) recommended previously for regional lakes, and the standard error of the DO simulations was 3.44 mg/L. Calibrated EMCOE(2) was equal to 6.0 or $S_{b20} = 1.2$ g O$_2$/m$^2$ day) in Greenwood Lake (Figure 4(c)) with a standard error of 1.37 mg/L. Long-term accumulation on the lake bottom of organic matter from the death of phytoplankton and from the surrounding watershed is the source of SOU below the mixed layer. The influence of the long-term accumulation of organic sediment on SOU in the hypolimnion or areal hypolimnetic oxygen depletion rate (AHOD) is called ‘sediment memory effect’ (Matzinger et al. 2010). This is because the degradation of the refractory part of deposited organic matter to reduced substances can take decades to centuries (Carignan & Lean 1991); there is

![Figure 4](https://iwaponline.com/wqrj/article-pdf/47/3-4/375/163545/375.pdf)

**Figure 4** Examples of simulated water temperature and DO profiles for sensitivity analysis on: (a) BOD for simulations in Trout Lake (St. Louis County), (b) the multiplier EMCOE(1) for the diffusion coefficient in the metalimnion for simulations in Burnside Lake; and (c) the multiplier EMCOE(2) for SOU below the mixed layer for simulations in Greenwood Lake. Dots show available measurements.

**Table 2** Generalized (calibrated) values of the multiplier EMCOE(2) for SOU below the mixed layer

<table>
<thead>
<tr>
<th>Lake maximum depth</th>
<th>Eutrophic</th>
<th>Mesotrophic</th>
<th>Oligotrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average of values after model calibration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMCOE(2) \times S_{b20} [g O_2/(m^2 day)]</td>
<td>Deep (all lakes)</td>
<td>1.00 (1)$^a$</td>
<td>1.30 (7)</td>
</tr>
<tr>
<td></td>
<td>Deep (cisco lakes)</td>
<td>– (0)</td>
<td>1.30 (7)</td>
</tr>
<tr>
<td></td>
<td>Medium (all lakes)</td>
<td>1.98 (4)</td>
<td>2.05 (4)</td>
</tr>
<tr>
<td></td>
<td>Medium (cisco lakes)</td>
<td>1.80 (1)</td>
<td>1.13 (1)</td>
</tr>
<tr>
<td>Proposed values of EMCOE(2) \times S_{b20} [g O_2/(m^2 day)]</td>
<td>Deep</td>
<td>1.50</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1.95</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>2.20</td>
<td>1.90</td>
</tr>
<tr>
<td>Generalized EMCOE(2) values</td>
<td>Deep</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>1.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Recommended S_{b20} [g O_2/(m^2 day)]</td>
<td>Deep</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1.5</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Shallow</td>
<td>2.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$^a$Only one deep eutrophic lake used.  
$^b$Only one medium-depth oligotrophic lake used.
relatively slow diffusion-controlled flux of reduced substances (e.g., CH4, NH4+) from the sediment (Lorke et al. 2003; Bryant et al. 2010).

Simulations of oxythermal cisco habitat

Figure 5 shows an example of the oxythermal habitat parameter TDO3 values determined from observed temperature (circles) and DO (triangles) profiles on 17 July 1991 in Fish Hook Lake, which has a maximum depth of 23 m (Table 1) and mean summer Secchi depth of 3.4 m (mesotrophic lake). TDO3 determined on 17 July 1991 was 15.4 °C. Plot (c) in Figure 5 gives a time series plot of daily TDO3 values determined from simulated water temperature and DO profiles in Fish Hook Lake in 1984 and for the MIROC 3.2 future climate scenario. The annual maximum TDO3, TDO3_{AM}, was 19.0 °C in 1984 and occurred on DOY 235 (August 21); TDO3_{AM} ranged from 15.6 to 21.4 °C and occurred on DOY 216 to DOY 259 (with an average of DOY 241 or August 29) over the simulation period from 1962 to 2008 (Fang et al. 2010b). The average TDO3 over the fixed benchmark period (DOY 209 to 239) was 17.5 °C in 1984 (Figure 5) and ranged from 11.2 to 20.5 °C for the simulation period (1962–2008) when weather data from Fargo, ND, were used (Fang et al. 2010b). The average of mean TDO3 over the fixed benchmark period in the simulation period (1962–2008) was 16.1 °C in Fish Hook Lake (Figure 6) and is called AvgATDO3_{FB}. It was used to identify ‘refuge’ cisco lakes (Fang et al. 2010b, 2011). Temperature and DO profiles simulated for the first year (1961 or 1991) were not used to extract TDO3 values in order to avoid possible effects of assumed initial conditions.
The average day of occurrence (DOY) of TDO₃_AM, the average TDO₃_AM value, and the AvgATDO₃_FB in the simulation periods 1991–2008 or 1961–2008 (depending on the weather station used) are shown in Figure 6 for the 28 study lakes. Lakes in Figure 6 are sorted separately for cisco and non-cisco study lakes by DOY of TDO₃_AM under past climate conditions. With the exception of two lakes (South Twin Lake and White Iron Lake), the average DOY for the occurrence of the TDO₃_AM ranged from DOY 240 to 312 for the 21 cisco study lakes (August 28 to November 8) under past climate conditions as shown in Figure 6(a). These dates are later than the average DOY in...
Non-cisco lakes. Average DOY for TDO3AM in seven non-cisco lakes (Bear Head, Carrie, Elephant, Hill, Madison, South Center, and St. Olaf) ranged from 210 to 223 (July 29 to August 11) (Figure 6(a)). South Twin Lake and White Iron Lake are classified by MN DNR as cisco lakes but are shallow and weakly stratified mesotrophic and eutrophic lakes (Table 1), respectively. They also have the largest lake geometry ratios GR of all 28 study lakes (Table 1). Average TDO3AM values over the simulation period (Figure 6(b)) for the 28 study lakes ranged from 5.7 to 24.2 °C. Higher values (average of 22.3 °C) were found for the seven non-cisco lakes and the two shallow cisco lakes (South Twin Lake and White Iron Lakes). Average TDO3AM values over the simulation period for the remaining 19 cisco lakes were typically smaller (from 5.7 to 17.9 °C) under past climate conditions.

From the data in Figure 6(a) and (b) for the 28 study lakes under past climate conditions, it was derived that the average TDO3AM value over the simulation period is in inverse proportion to the average DOY of occurrence of TDO3AM (DOYTDO3AM):

\[
TDO3AM = -0.187 \times DOYTDO3AM + 62.44 (R^2 = 0.96) \quad (4)
\]

The earlier occurrence of TDO3AM is associated with a higher TDO3AM. The AvgATDO3FB in the simulation periods for the 28 study lakes follows a similar pattern to the average TDO3AM. The AvgATDO3FB (Figure 6(c)) in the 28 study lakes ranged from 4.6 to 21.4 °C, and had higher values (average of 20.1 °C) in the seven non-cisco lakes and the two shallow cisco lakes (South Twin Lake and White Iron Lakes). The AvgATDO3FB in the other 19 cisco lakes were typically smaller (from 4.6 to 16.1 °C) under past climate conditions.

Based on an analysis of observed temperature and DO profiles in Minnesota lakes, Jacobson et al. (2010) found that cisco were present in lakes with a broad range of ATDO3FB values, with central species response borders of ATDO3FB from 4.0 to 16.9 °C. A 17 °C reference line was selected and drawn on the plot of AvgATDO3FB for the 28 study lakes (Figure 6(c)). AvgATDO3FB = 17 °C was used to identify cisco refuge lakes in Minnesota (Fang et al. 2010b). The 17 °C reference line relative to the AvgATDO3FB values in Figure 6 indicates that the seven non-cisco lakes, plus South Twin Lake and White Iron Lake, do not have favorable conditions to support cisco habitat in comparison to the other 19 cisco lakes. Transferring the information to Figure 1, a boundary was drawn to separate lakes with favorable and non-favorable cisco habitat. Non-favorable lakes (Figure 1) have either a large lake geometry ratio (weakly stratified) or low Secchi depth (more eutrophic). Both physical process (mixing characteristics) and trophic status (Secchi depth) control temperature and DO characteristics that affect fish habitat characterized by the TDO3 parameter.

**Projections for future climate scenarios**

Besides lake bathymetry and trophic status, meteorological conditions control water temperature and DO distribution in a lake. In this paper impacts of future climate changes on water quality and cisco habitat were examined by assuming no changes in lake geometry and trophic status (Secchi depth). To study the changes of water quality and trophic status in response to climate change is beyond the scope of this paper. The sensitivity of cisco habitat to trophic state (Secchi depth) is presented elsewhere (e.g., Fang et al. 2010b, 2011).

Figures 2 and 3 give examples of projected temperature and DO profiles and time series under two future climate scenarios. Surface temperatures were projected to increase by about 3 °C and hypolimnetic temperature less than 1 °C (Figure 2). Surface DO concentrations were projected to decrease by about 0.5 mg/L and hypolimnetic DO concentrations by more than 1 ~2 mg/L (Figure 2), largely because of the increase of water temperature and the earlier onset of stratification (see time series at 45.0 m in Figure 3). The model projects ice-out to be on April 14 under the MIROC 3.2 future climate scenario in Ten Mile Lake (Figure 3). The model predicts ice-cover formation on December 15, 2008, but projects no ice formation by December 31 under the MIROC 3.2 future climate scenario in Ten Mile Lake (Figure 3). Ice-in is projected to occur later and ice-out earlier, under the future climate scenarios, i.e. ice cover periods are projected to be shorter (Fang & Stefan 1998b).

The oxythermal habitat parameter TDO3 determined from simulated temperature (solid line) and DO (dashed line) profiles for Fish Hook Lake under the MIROC 3.2
future climate scenario is projected to be 18.5 °C on July 17 (Figure 5(b)). The occurrence day of TDO$_3$AM in Fish Hook is projected to range from DOY 215 to DOY 255, with an average DOY of 236 (August 24) under the MIROC 3.2 future scenario. The average DOY for TDO$_3$AM over the simulation periods for the 28 study lakes is projected to range from DOY 210 to 325 (July 29 to November 21) under the MIROC 3.2 future scenario (Figure 6(a)). This is similar to past climate conditions. The difference of average DOY for TDO$_3$AM between future and past climate scenarios is only up to 12 days (Figure 6(a)). The average TDO$_3$AM (annual maximum) for the 28 study lakes is projected to increase by 0.5 to 4.6 °C (average increase of 3.2 °C) under the MIROC 3.2 future climate scenario (Figure 6(b)).

The AvgATDO$_3$FB (mean TDO$_3$ over the fixed 31-day benchmark period) is projected to increase by 0.0 to 4.4 °C (average increase of 2.4 °C) for the 28 study lakes under the MIROC 3.2 climate scenario (Figure 6(c)). Five current cisco lakes (South Twin, White Iron, Elk, Fish Hook, and Blue) are projected to lose their favorable cisco habitat under the MIROC 3.2 future climate scenario (Figure 6(c)). Blue Lake has a large mean Secchi depth (6.8 m, Table 1), but the maximum depth is only 14.6 m (the third shallowest lake of the 21 cisco study lakes), and 13 observed temperature and DO profiles from 1997 to 2002 in Blue Lake had low or zero DO near the lake bottom that resulted in higher TDO$_3$ (Fang et al. 2010a). AvgATDO$_3$FB in Blue Lake was 13.7 °C over the 1991–2008 simulation period and is projected to be 17.6 °C under the MIROC 3.2 future scenario. This information indicates that lake maximum depth (related to total DO content after the spring overturn) does affect DO concentration in the hypolimnion and fish habitat during the summer.

CONCLUSIONS

A one-dimensional year-round lake water quality model, MINLAKE2010, was developed and calibrated with more than 7,000 measurements for water temperature and DO simulations in order to study the potential impact of climate warming on lake water quality and cisco fish habitat in relatively deep and mesotrophic/oligotrophic lakes in Minnesota. It is projected that lake surface water temperature will increase by about 5 °C and hypolimnetic DO will decrease by about 1–2 mg/L. Oxythermal habitat parameter TDO$_3$ was determined from simulated daily water temperature and DO profiles under past and future climate scenarios in the 28 study lakes. The average TDO$_3$AM (annual maximum TDO$_3$) (Figure 6(b)) for the 28 study lakes is projected to increase by 0.5–4.6 °C (average increase of 3.2 °C) under the MIROC 3.2 future climate scenario. The occurrence day of TDO$_3$AM is not much different between past and future climate scenarios. Both physical processes (mixing characteristics related to lake geometry ratio) and trophic status (Secchi depth) control temperature and DO characteristics and then affect cisco habitat (e.g., TDO$_3$ parameter) in a lake. It is projected that five of the 21 study lakes in Minnesota with documented cisco populations may lose their cisco habitat under the MIROC 3.2 climate scenario.

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