

**Identifying Potential Cisco Refuge Lakes in Minnesota
under Future Climate Warming Scenarios**

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
Dec 10, 2016

Keywords: cisco, fish habitat, Minnesota lakes,
water quality model, temperature, dissolved oxygen

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Abstract

Fish habitat models were developed and applied to investigate the impacts of future climate change on cisco oxythermal habitat in Minnesota lakes. Cisco *Coregonus artedii* is the most common cold-water stenothermal fish species in lakes over the several northern states in USA. Daily water temperature (T) and dissolved oxygen (DO) profiles were simulated for different types of virtual lakes (surface area from 0.05 to 50 km²) representing cisco lakes in Minnesota and under the past climate conditions (1961–2008) and projected future climate scenarios. A process-oriented, dynamic and one-dimensional lake water quality model (MINLAKE2010/2012) was applied for the temperature and DO simulations using daily time steps. The parameters used to describe a lake in the model are surface area (A_s), maximum depth (H_{max}), and Secchi depth (as a measure of radiation attenuation and trophic state). Two projected future climate scenarios, predicted by the Canadian Centre of Climate Modeling and Analysis (CCCma) coupled general circulation model (CCCma CGCM 3.0) and the Model for Interdisciplinary Research on Climate (MIROC 3.2) were used. Both climate scenarios lead to a longer period of hypoxic hypolimnetic conditions in stratified lakes. The study was able to identify potential refuge lakes important for sustaining cisco habitat under climate warming scenarios. To project cisco's chances of survival under future warmer climate conditions, using simulated daily T and DO profiles in 74 virtual lakes, FishHabitat2013 model was developed with three oxythermal habitat modeling options: (1) constant lethal T and DO limits, (2) lethal-niche-boundary curve (variable lethal T and DO limits), and (3) an oxythermal habitat variable, TDO3, i.e., water temperature at DO = 3 mg/L. The fish habitat model implementing the first two options was validated against cisco mortality/habitable observations in 23 Minnesota cisco lakes of which 18 had cisco mortality while 5 had no cisco mortality in the unusually warm summer of 2006. Cisco lethal and habitable conditions in the 23

lakes simulated by the model had overall good agreement with observations in 2006. After model validation, T and DO in the 44 virtual lakes were first simulated under past and future climate scenarios to determine cisco lethal days. Polymictic shallow lakes with lake geometry ratio $A_s^{0.25}/H_{max} > 5.2 \text{ m}^{-0.5}$ (A_s in m^2 and H_{max} in m) were simulated to typically not support cisco habitat under past and future climate scenarios. Medium-depth lakes are projected to be most vulnerable to climate warming with most increase in the number of years with cisco kill. The mean daily TDO3 values over a 31-day fixed and variable benchmark periods were calculated for each of simulated years and then averaged over the simulation period for each of 30 virtual deep lakes. Projected increases of the multi-year average TDO3 (called AvgATD3) under the two future climate scenarios and relative to the past 47-year simulation period (1962–2008) had averages from 2.6 to 3.4 °C. Isopleths of AvgATD3 were interpolated for the 30 simulated virtual lakes on a plot of Secchi depth vs. lake geometry ratio used as indicators of trophic state and summer mixing conditions, respectively. Using their lake geometry ratios and Secchi depths as coordinates, existing 620 Minnesota cisco lakes were marked on the plot of AvgATD3, and this allowed to partition these 620 cisco lakes into the three tiers depending on where they fell between the isopleths: lakes with $\text{AvgATD3} \leq 11^\circ\text{C}$ (Tier 1 lakes) were selected to be most suitable for cisco; lakes with $11^\circ\text{C} < \text{AvgATD3} \leq 17^\circ\text{C}$ (Tier 2 lakes) had suitable habitat for cisco; and non-refuge lakes with $\text{AvgATD3} > 17^\circ\text{C}$ (Tier 3 lakes) would support cisco only at a reduced probability of occurrence or not at all. About 208 (one third) and 160 (one fourth) of the 620 Minnesota cisco lakes that were known to have cisco populations are projected to maintain viable cisco habitat under the two projected future climate scenarios using the fixed and variable benchmark periods, respectively. These selective lakes have a Secchi depth greater than 2.3 m (mesotrophic and oligotrophic lakes) and are seasonally stratified (geometry ratio less than $2.7 \text{ m}^{-0.5}$).

Acknowledgments

I would like to deeply thank my academic advisor, Dr. Xing Fang, for providing me the opportunity to pursue my PhD degree under his guidance. I really appreciate his support, continuous encouragement, patience and guidance he has shown towards me in accomplishing my goals. He is an excellent professional researcher as well a very good human being who will always remain as an inspiration throughout my life.

I am also equally thankful to my graduate committee members; Dr. T. Prabhakar Clement, Dr. Jose G. Vasconcelos, and Dr. Luke J. Marzen; University Reader Dr. James A. Stoeckel for their valuable time to review my dissertation and provide the insights and suggestions on my research problems and motivating me which substantially improved my research and study.

Finally, I would like to express my sincere gratitude and appreciation to my family who have supported me throughout my study period. Without their love, care, and encouragement I would not have been capable of completing this study.

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Chapter 1 **Introduction**

1.1 Background

The potential significance of future climate change for inland aquatic ecosystems (e.g., streams, lakes, and reservoirs) caught the attention of water resources professionals and scientists in the early 1990s. An increase of carbon dioxide (CO₂) and/or other greenhouse gases (methane, nitrous oxide, and ozone) in the atmosphere is projected to cause climate warming (NRC 1983; IPCC 2007), which would alter water temperature (T), ice/snow cover, and dissolved oxygen (DO) characteristics in lakes (Blumberg and Di Toro 1990; Stefan et al. 1996). These changes are in turn expected to have an effect on indigenous fish populations: cold-water, cool-water, and warm-water fish species (Coutant 1990; Magnuson et al. 1990; Chang et al. 1992; Stefan et al. 1995; De Stasio et al. 1996). Some basic information on effects of climate change on water quality and fish habitat for three fish guilds (8, 7, and 14 species of cold-water, cool-water, and warm-water fish guilds, respectively) in lakes in Minnesota and the contiguous USA have been summarized before (Fang and Stefan 2012). This study summarizes simulation results and model validation of cisco oxythermal habitat in Minnesota lakes that were used to identify cisco ‘refuge lakes’ under future climate scenarios in order to develop management strategies to protect these lakes. A ‘refuge lake’ in this study is a cisco lake that was identified to have cisco in netting assessments under the past climate conditions and is projected to provide suitable cold-water habitat under future climate scenarios.

Cisco *Coregonus artedii* is the most common cold-water stenothermal fish in northern lakes in Minnesota, Wisconsin, and other northern states, and it is a common forage fish for walleye *Sander vitreus* and northern pike *Esox lucius* among other prized sport fishes. The Minnesota (MN) Department of Natural Resources (DNR) has sampled cisco from 648 lakes in netting assessments

since 1946 (MN DNR files). These lakes are typically deeper and more transparent than average lakes in Minnesota (Fang et al. 2009). The lakes are scattered throughout much of the central and northern portions of the state (Figure 1.1) and cross several land uses (agricultural, urban, and forested). The wide distribution suggests that cisco is somewhat more eurythermal than other native, lentic cold-water stenotherms such as lake whitefish *Coregonus clupeaformis* (sampled in 155 Minnesota lakes), lake trout *Salvelinus namaycush* (124 Minnesota lakes) and burbot *Lota* (233 Minnesota lakes). Cisco physiologically require cold, well-oxygenated water to survive, grow, and reproduce (Cahn 1927; Frey 1955). The combination of a wide distribution (Figure 1.1) and a requirement for cold, oxygenated water (Frey 1955) makes cisco an excellent “canary in a mineshaft” species that is a sensitive indicator of ecological stresses such as eutrophication and climate warming. For example, eighteen lakes in north-central Minnesota experienced cisco mortality in the unusually hot summer of 2006 (Jacobson et al. 2008), and one example of cisco mortality is given in Figure 1.2.

The climate warming is projected to warm the water and increase hypolimnetic oxygen depletion during periods of stratification in lakes (Blumberg and Di Toro 1990; Fang and Stefan 1999, 2000; Fang and Stefan 2009a). Fish habitat is constrained by water temperature, available DO, food supply, human interference, and other environmental factors (Frey 1955; Fry 1971). In lakes, water temperature and DO are the two important water quality parameters that affect survival and growth of cold-water fishes (Magnuson et al. 1979; Coutant 1985b; Christie and Regier 1988; Coutant 1990; Jacobson et al. 2010; Fang et al. 2012b; Jiang et al. 2012). Therefore, projected changes of water temperature and DO characteristics due to climate warming have the potential to reduce cold-water fish habitat (such as cisco) in lakes (Magnuson et al. 1990; Schindler et al. 1996; Stefan et al. 1996; Fang et al. 2004a). Ciscoes have been declining in recent years in

Minnesota lakes, likely because of climate warming (Jacobson et al. 2012). Recently, Sharma et al. (2011) estimated that 30 to 70% of the cisco population in about 170 of Wisconsin's deepest and coldest lakes could become a climate change casualty and disappear from most of the Wisconsin cisco lakes by the year 2100.

The goal of the study was to simulate daily water temperature and DO profiles in different cisco lakes to project the quality of cold-water fish habitat in 620 known cisco lakes in Minnesota under future climate scenarios and to identify potential cisco refuge lakes and impacts of climate change on cisco habitat. To make projections of water quality and fish habitat in lakes under future climate scenarios, numerical simulation models of daily temperature and DO profiles are useful. It is infeasible to simulate all 620 cisco lakes in Minnesota using MINLAKE2010/2012 (Fang et al. 2012a). In this study, simulations of daily water temperature and DO profiles were made for the 30 deep virtual lakes (Fang et al. 2012b; Jiang et al. 2012) and 44 shallow, medium-depth, and deep virtual lakes (Fang et al. 2014; Jiang and Fang 2016) in Minnesota before cisco oxythermal habitat and lethal conditions were examined in these lakes. The overall modeling methodology for

the study is discussed in detail in the next section (

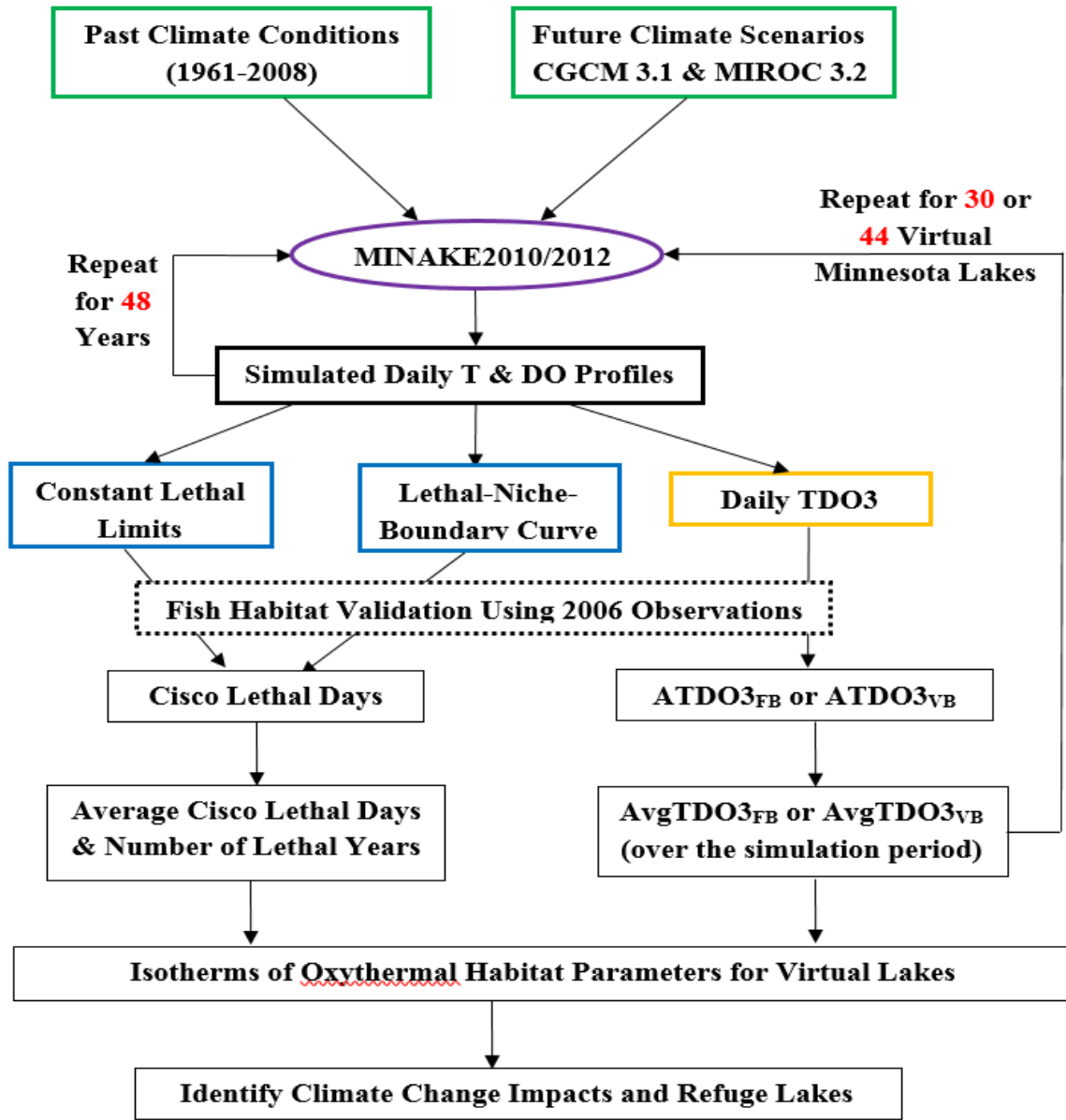
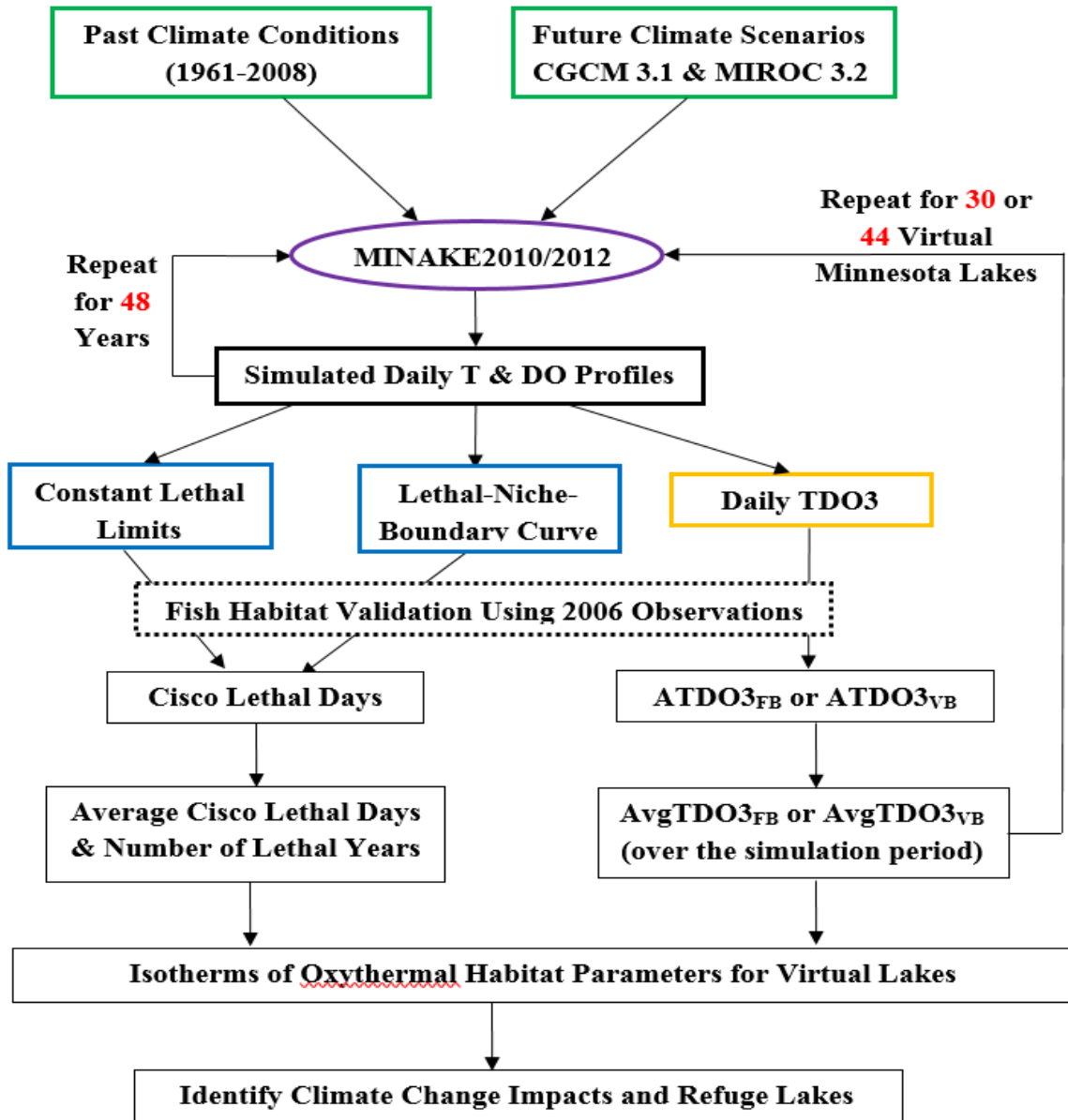


Figure 1.3).

In this study, cold-water oxythermal fish habitat was identified using three different methods



(Figure 1.3): (1) constant lethal limits (lethal temperature, LT and DO survival limit), (2) lethal-niche-boundary curve (Jacobson et al. 2008) (also called variable lethal limits), and (3) a single oxythermal habitat variable TDO3, temperature at 3 mg/L of DO (Jacobson et al. 2010). Depths at the good-growth temperatures and lethal limits and TDO3 values were calculated day by day from simulated daily lake water temperature and DO profiles obtained from the process-oriented, one-dimensional year-round water quality model MINLAKE2010/2012 (Fang et al. 2012a). The model

was run in daily time steps over a continuous 48-year simulation period for past (1961–2008) climate conditions, and for two projected future climate scenarios (CGCM 3.1 and MIROC 3.2). Monthly (31-day) fixed and variable benchmark periods (Jacobson et al. 2010; Jiang and Fang 2016) were used to identify future cold-water fish habitat in lakes based on projected future temperature and DO profiles.

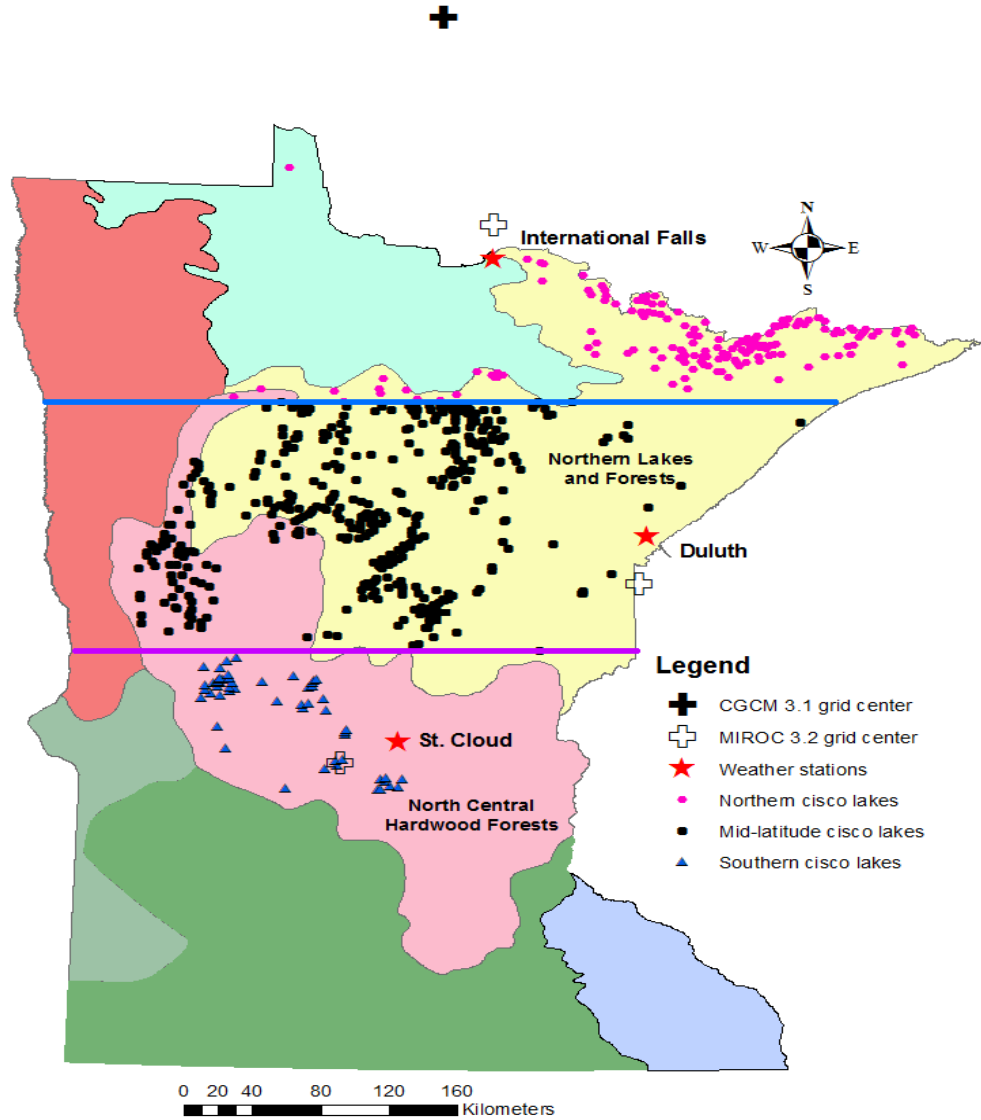


Figure 1.1 Geographic distribution of 620 cisco lakes grouped by latitude, three weather stations (stars) and associated grid center points (crosses) of CGCM 3.1 and MIROC 3.2 used for model

simulations. Background shades identify ecoregions of Minnesota. Cisco lakes are essentially in two ecoregions: (1) Northern Lakes and Forests, and (2) North Central Hardwood Forests.

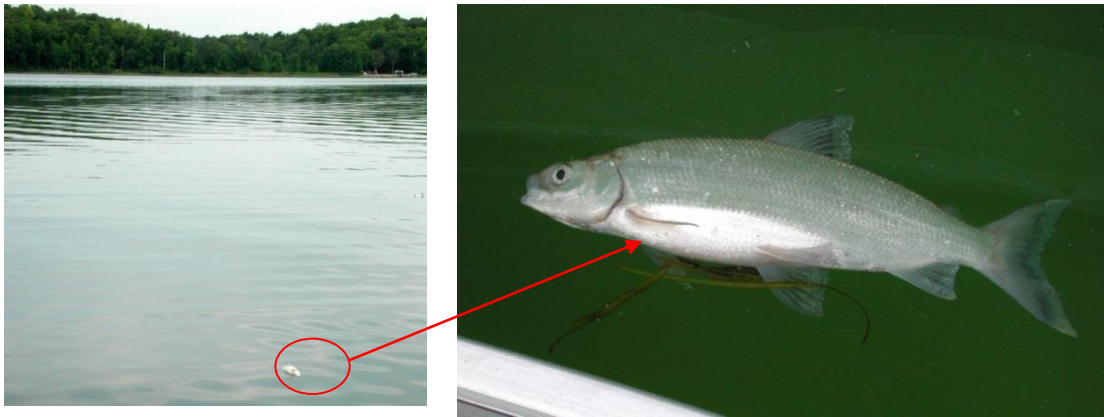


Figure 1.2 Lake Andrusia in Minnesota had cisco mortality in July 2006 (photo: Peter C. Jacobson, Minnesota Department of Natural Resources).

1.2 Overall Modeling Methodology

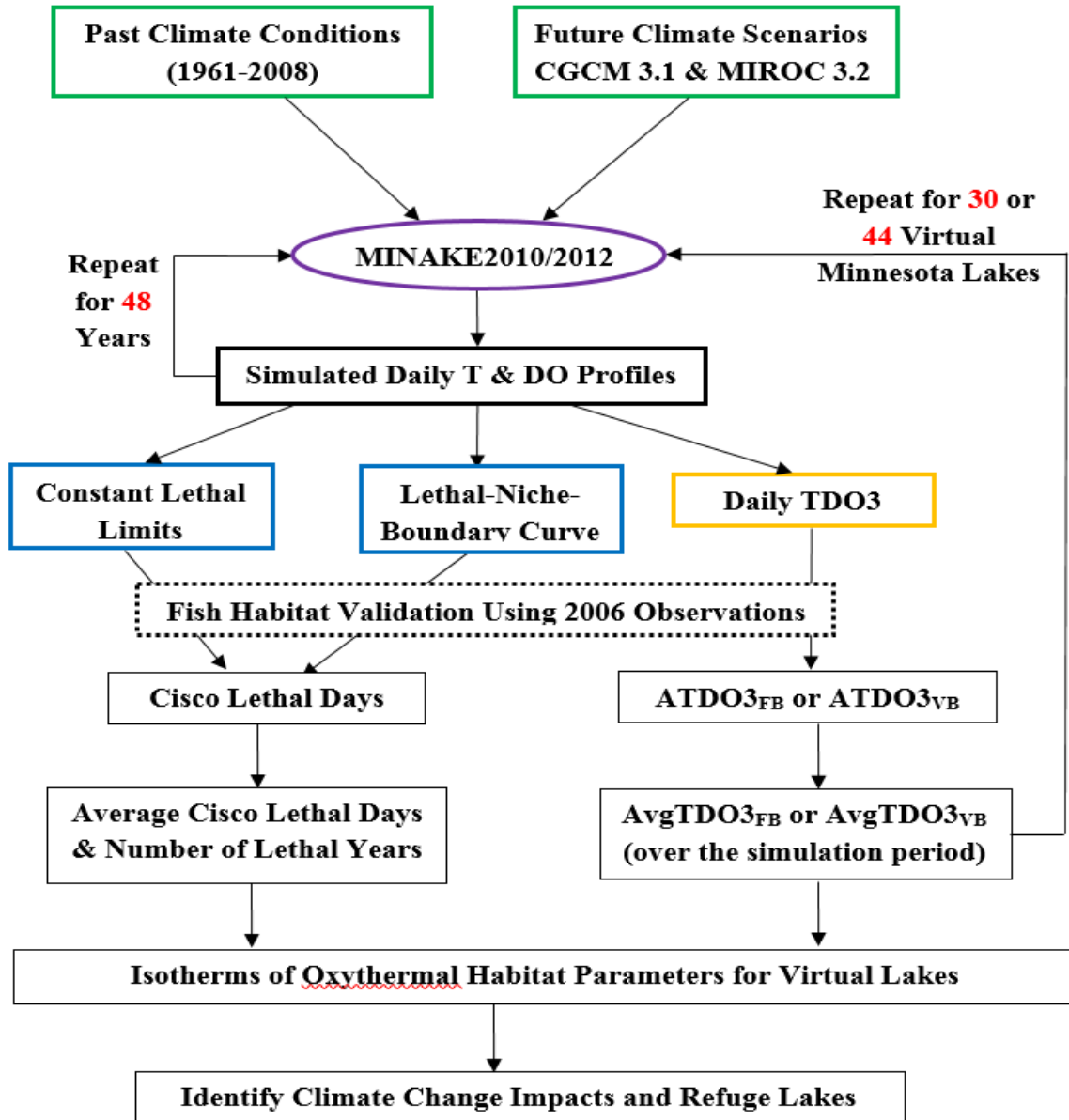


Figure 1.3 shows a flow chart of the study to project impacts of climate changes on cisco oxythermal habitat in Minnesota. Past climate conditions (1961 to 2008, 48 years) and two future climate scenarios at different weather stations were assembled and used as model inputs (atmospheric boundary conditions) to the deterministic, unsteady, one-dimensional (vertical) lake water quality model MINLAKE2010/2012 which can simulate T and DO profiles in cisco lakes continuously for 48 years over the open-water seasons and winter ice-cover periods.

A cisco habitat model with three different modeling options were developed, validated, and used for the study. The first option is to use the constant lethal limits to model cisco habitat in Minnesota lakes. The constant limits for fish survival (lethal) and good growth do not change with time and the method was previously used to project cold-water, cool-water, and warm-water fish habitat in small lakes in Minnesota and over the contiguous USA (Stefan et al. 2001). The constant lethal limits of cisco were calculated from the lethal-niche-boundary curve of adult cisco (Jacobson et al. 2008) and then determined through model validation in 23 Minnesota lakes using cisco mortality and survival data in the summer of 2006. The second option is to use a fitted regression

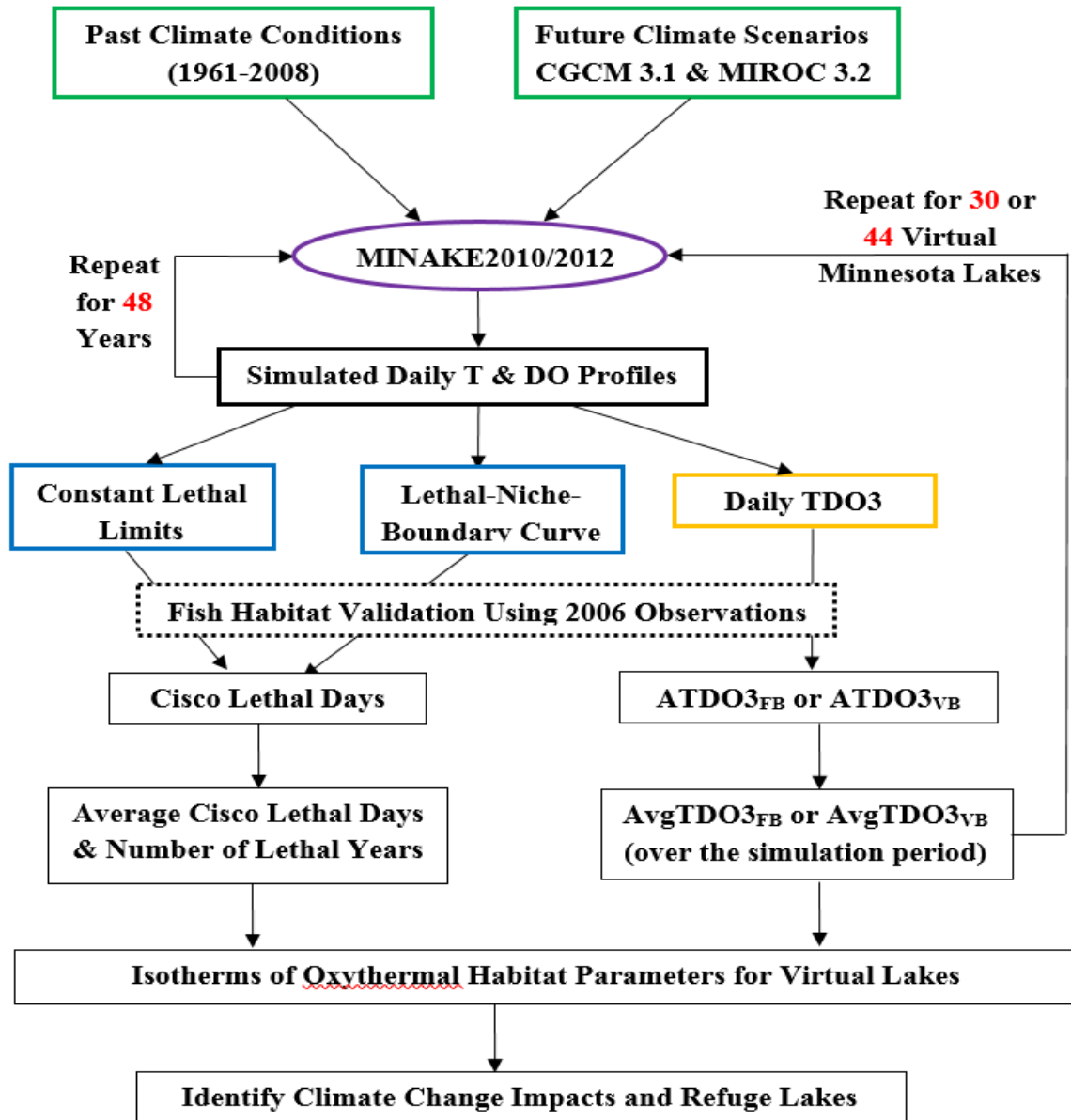


Figure 1.3 Flow chart of the study to project impacts of climate changes on cisco oxythermal habitat in Minnesota lakes.

equation as the lethal niche boundary of adult cisco. The equation was developed by Jacobson et al. (2008) and gives DO survival limits at different temperatures, which are temperature varying lethal limits. The third option is to use a single oxythermal variable TDO3 to identify cisco refuge

lakes (Fang et al. 2012b; Jiang et al. 2012). TDO3 has been a useful parameter for quantifying the oxythermal niche of cold-water fish (Jacobson et al. 2010). TDO3 was calculated from simulated daily T and DO profiles for every simulated day except days in 1961 to avoid effects of initial conditions. In the third option of cisco oxythermal habitat modeling, the daily TDO3 values were averaged over either the fixed benchmark (FB) period ($ATDO3_{FB}$) (Fang et al. 2012b) or the variable benchmark (VB) period ($ATDO3_{VB}$) (Jiang et al. 2012) for each simulated lake and year. Using the variable benchmark periods for each simulated year gave the maximum average TDO3 over a 31 day period in different years and different lake types (Jiang et al. 2012).

The oxythermal habitat options 1 and 2 determine which day lethal conditions can occur. In the first option, when the LT isotherm and the DO limit isopleth for cisco intersect in a particular day (Stefan et al. 2001; Fang et al. 2004a; Fang and Stefan 2012), the entire depth of a stratified lake is under lethal conditions on that day. The lethal conditions are because water temperature is higher than LT from the water surface to or below the intersecting depth and DO is lower than the DO limit from the lake bottom to or above the intersecting depth. In the second option, lethal conditions for cisco are assumed to occur if the simulated DO is less than the DO_{lethal} value in all water layers (from the lake water surface to the lake bottom) on that day when DO_{lethal} is calculated from simulated water temperature using the lethal-niche-boundary curve (Jacobson et al. 2008).

To understand climatic variability, the water quality model and fish habitat model were run using the weather data from 1961 to 2008 for the past climate conditions in 30 deep virtual lakes

(Table 1.2) and 44 shallow, medium-depth, and deep virtual lakes (Table 1.1) in Minnesota (

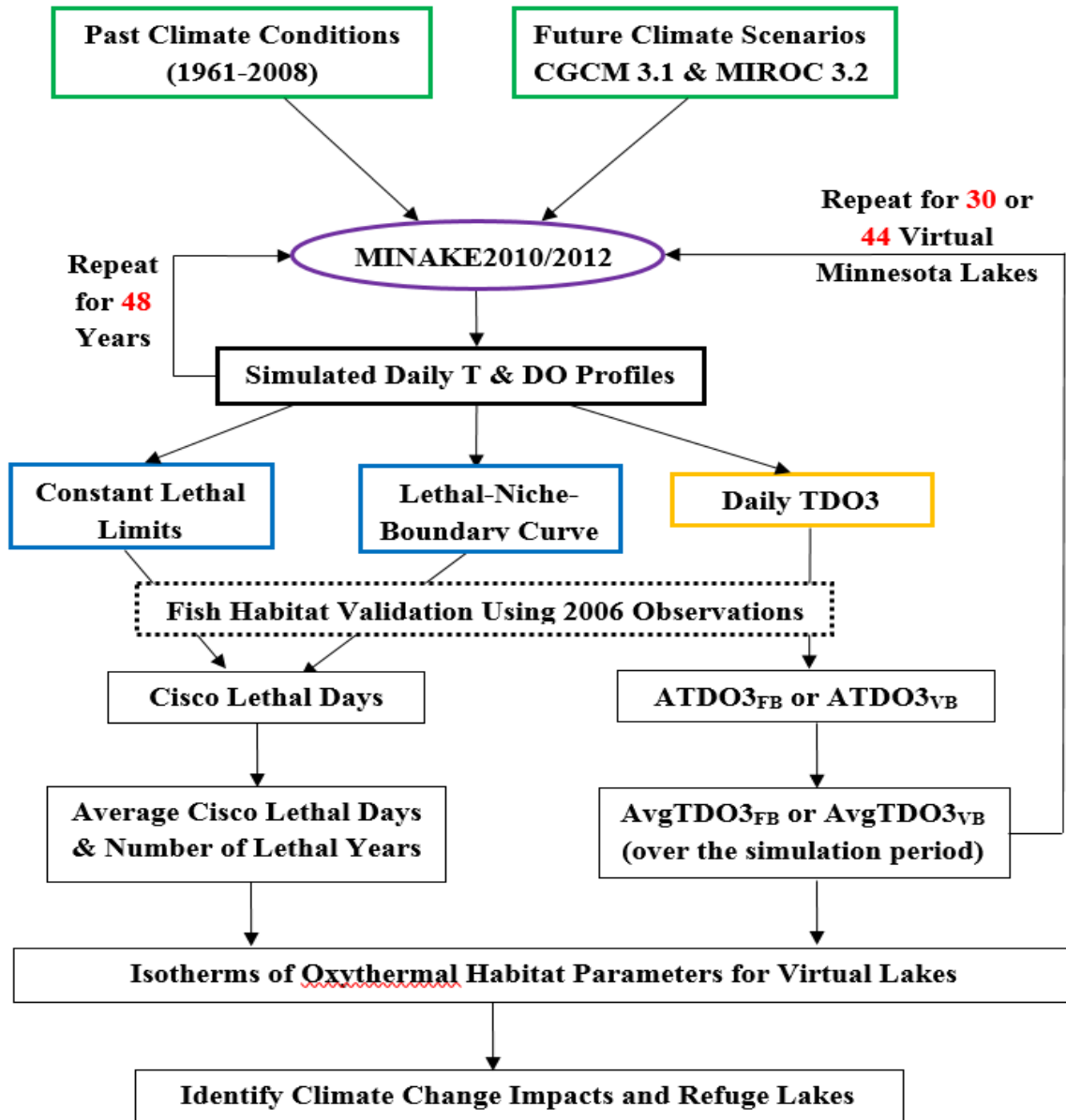


Figure 1.3). Number of years with cisco kill and number of cisco lethal days were determined during the simulation period for the habitat modeling options 1 and 2. The cisco kill was assumed to occur when the continuous lethal days of cisco last 3 or 7 days (Fang et al. 2014; Jiang and Fang 2016). To assess the quality of cisco habitat in a lake and identify refuge lakes, the 47-year averages of annual $ATDO3_{FB}$ and $ATDO3_{VB}$ values in the 1962–2008 simulation period (i.e., $AvgATD3_{FB}$ and $AvgATD3_{VB}$) were calculated in 30 deep virtual deep lakes (Table 1.2) and

compared to TDO3 limits (11°C and 17°C determined by the analysis of field data) to divide cisco lakes into three tiers: Tiers 1 and 2 refuge lakes, and Tier 3 non-refuge lakes (Fang et al. 2012b; Jiang et al. 2012).

To implement the above modeling approach, 44 shallow, medium-depth, and deep virtual lakes (Table 1.1,

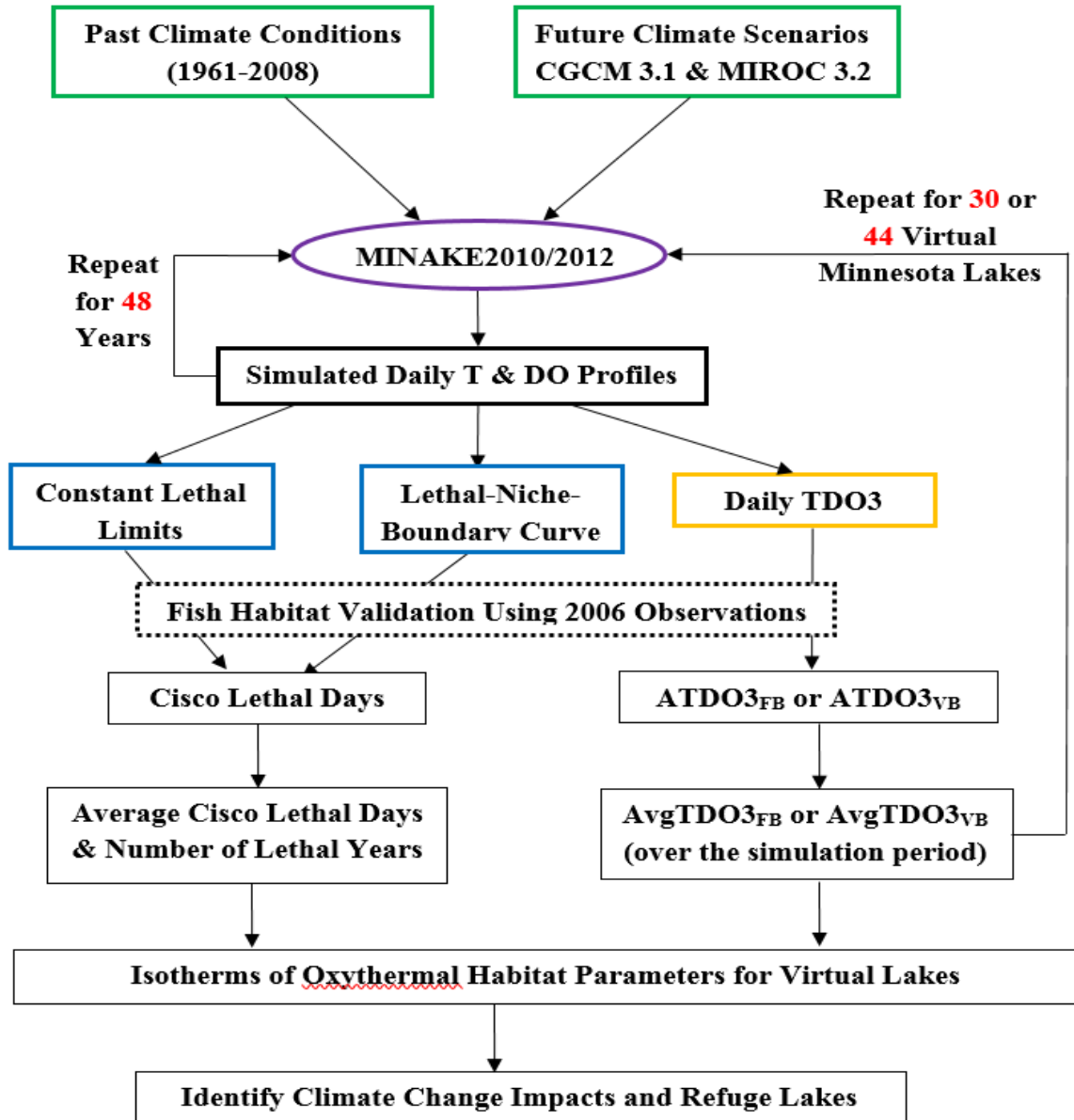


Figure 1.3) and 30 deep virtual lakes (Table 1.2,

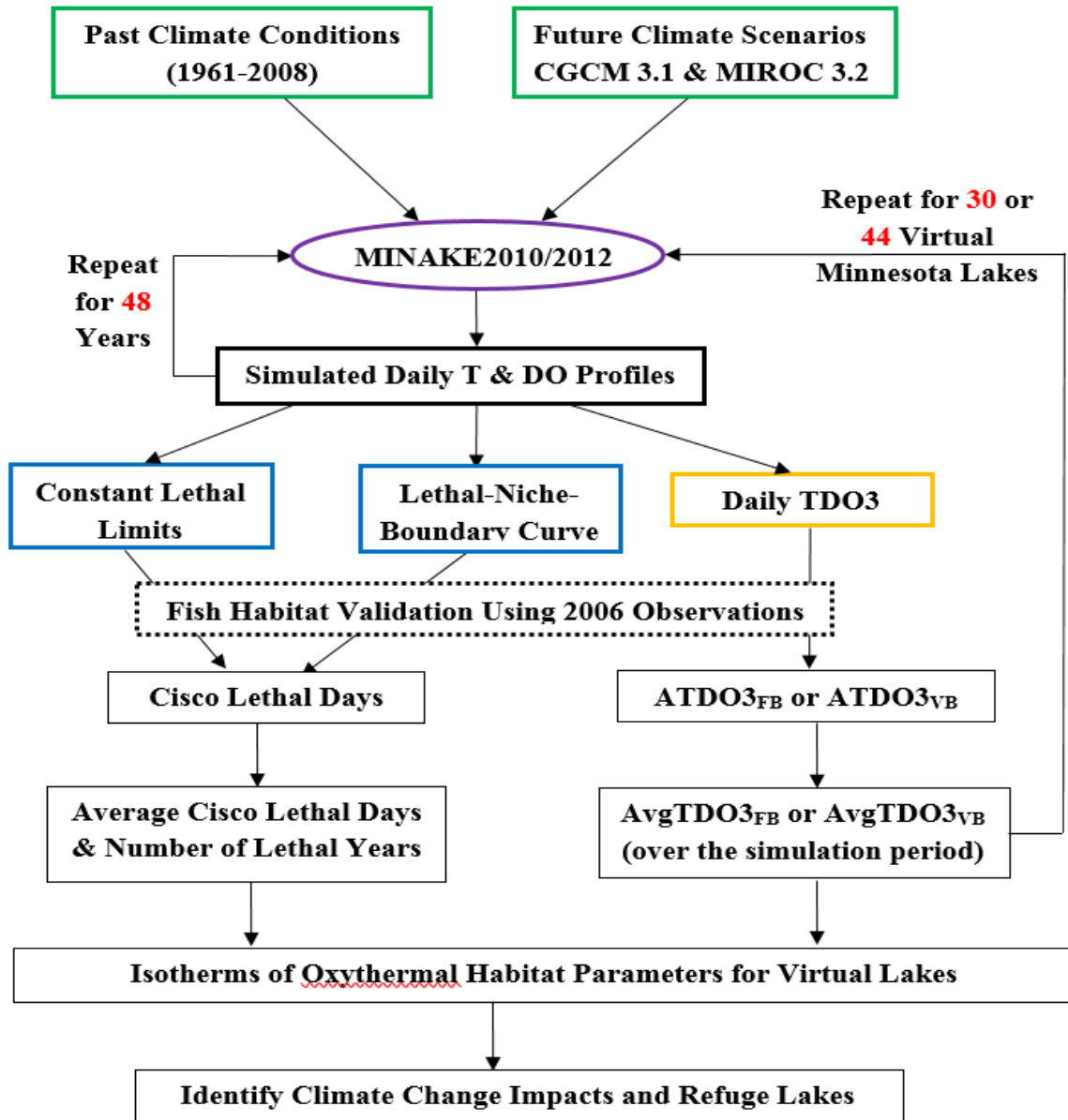


Figure 1.3) were chosen as representative of the entire set of Minnesota lakes in general and 620 cisco lakes, respectively; a similar approach using 27 ‘generic’ virtual lake types had been used to study climate warming impact on fish habitat in small lakes in Minnesota (Stefan et al. 1996) and in the contiguous USA (Stefan et al. 2001; Fang et al. 2004a), because it was not viable to run the deterministic model for all 620 cisco lakes over 47 years. To apply the oxythermal habitat results to the hundreds of cisco lakes that could not all be simulated, the virtual lakes had

to be characterized in a generic way. Following previous practice (Stefan et al. 2001; Fang et al. 2004a) two parameters were chosen for this purpose: a lake geometry ratio GR as an indicator of a lake's potential for strong or weak summer stratification (Gorham and Boyce 1989), and mean summer Secchi depth (SD) as an indicator of lake trophic state and transparency. These virtual lakes are described in detail in a separate section.

1.2.1 Cisco Lakes in Minnesota

The modeling analysis was conducted for 620 cisco lakes in Minnesota (Figure 1.1); the MN DNR had netting assessments for these lakes since 1946 where cisco was caught before. On average, Minnesota cisco lakes are deeper, more transparent (larger Secchi depth), and have lower chlorophyll-*a* concentrations than other lakes in Minnesota (Fang et al. 2009). The 620 cisco lakes vary in mean Secchi depth (SD) and lake geometry ratio (GR). The lake GR is defined as $A_s^{0.25}/H_{max}$ in $m^{-0.5}$ when surface area A_s is in m^2 and maximum depth H_{max} in m. The strength of the seasonal lake stratification is related to the GR (Gorham and Boyce 1989). Polymictic lakes such as large shallow lakes have the highest GR numbers, while strongly stratified lakes have the lowest GR numbers; the transition from weakly to strongly stratified lakes occurs when GR is between 3 and 5 (Gorham and Boyce 1989). Lake geometry ratios of Minnesota cisco lakes range from 0.47 to 22.7 $m^{-0.5}$ (Figure 1.4), and about 73% of these lakes have GR less than 3.0 $m^{-0.5}$ (Fang et al. 2009). Only 6% or 39 of these lakes have GR greater than 5.0 $m^{-0.5}$; these are very weakly stratified or unstratified lakes during the summer. Lake of Woods is located at the border of USA and Canada and has the largest surface area (3847.8 km^2) with the largest GR = 22.7 $m^{-0.5}$ and a maximum depth of 10.97 m. Mille Lacs Lake has the second largest GR = 11.9 $m^{-0.5}$ with a maximum depth of 12.8 m and surface area of 536.5 km^2 .

Maximum depths of the 620 cisco lakes range from 3.0 to 64.9 m, and 25% of these lakes have maximum depth greater than 24 m (Fang et al. 2009). For these 620 cisco lakes in Minnesota, there are 14 shallow lakes with $H_{max} < 5.0$ m, 385 medium-depth lakes (Figure 1.4 top) with $5.0 \text{ m} \leq H_{max} < 20.0$ m, and 221 deep lakes with $H_{max} \geq 20.0$ m (Figure 1.4 bottom) based on regional lake classification in Minnesota (Stefan et al. 1996). Surface areas of these lakes range from 0.04 to 3847.8 km² (Fang et al. 2009), and mean summer Secchi depths from 0.7 to 9.5 m. Nineteen percent and 81% of the 620 cisco lakes (Fang et al. 2009) have mean summer Secchi depth greater than 4.5 m (oligotrophic lakes) and 2.5 m (mesotrophic lakes), respectively, based on regional lake classifications in Minnesota (Stefan et al. 1993).

For modeling purposes, the 620 Minnesota cisco lakes were grouped by either shortest distance or latitude to associate with three Class I National Weather Service (NWS) weather stations in Minnesota (International Falls, Duluth, and St. Cloud; Figure 1.1). Weather data from only these three Class I NWS weather stations were useful and available for cisco lake long-term simulations for the period from 1961 to 2008. Three options (methods) were used to associate each lake with one of the three weather stations: (1) association by shortest distance (Fang et al. 2012b), (2) association by latitude (Jiang et al. 2012), (3) association of one single weather station with all lakes simulated (Fang et al. 2010b). Refuge lakes were determined using each of the three options (Fang et al. 2010b), but results were similar; simulation results by methods (1) and (2) are presented here.

1.2.2 Virtual Lake Types in Minnesota

Simulations of daily water temperature and DO profiles and oxythermal habitat parameters were made for 30 deep virtual lakes (Table 1.2) and 44 shallow, medium-depth, and deep virtual lakes (Table 1.1) in Minnesota before fish habitat was examined in 620 cisco lakes. The 44 virtual

lakes in Table 1.1 were expanded from the 27 virtual lake types used to study fish habitat in Minnesota (Stefan et al. 1996) and in the contiguous USA (Fang et al. 2004a). Lakes were classified by lake geometry (surface area A_s and maximum depth H_{max}) and trophic state as related to Secchi depth (SD) in Table 1.1 and Table 1.2. The representative surface areas chosen for the 27 lake types were 0.2, 1.7 and 10.0 km² for small, medium-size, and large lakes (Stefan et al. 1996; Fang et al. 2004a), respectively. The representative maximum depths chosen were 4, 13, and 24 m for shallow, medium-depth, and deep lakes (Stefan et al. 1996; Fang et al. 2004a), respectively. With these numbers for A_s and H_{max} , 9 lake types were obtained ranging from relatively large and shallow lakes to relatively small and deep lakes.

Secchi (disk) depth SD is a common limnological parameter to measure transparency of a lake (Hutchinson 1957; Horne and Goldman 1994). It was used in previous fish habitat studies (Stefan et al. 1996; Fang et al. 2004a) to represent both trophic state (primary productivity of biomass or photosynthesis of plants) and solar radiation attenuation in a lake, which is used to quantify how much solar energy reaching the water surface can penetrate through a water column to heat water and to support photosynthesis of aquatic plants. Lake turbidity from suspended inorganic sediment is relatively rare in Minnesota, and total phosphorus or chlorophyll-*a* in most Minnesota lakes are well correlated with SD (Stefan and Fang 1994a). Therefore, SD is a representative parameter to characterize trophic state of each of the 620 cisco lakes in the database. Contours (isotherms or isopleths) on plots with SD versus GR as axes have been previously used successfully by the authors to give/present generic, but regional, patterns or variations of different characteristic parameters in lakes, e.g., maximum surface water temperatures, maximum lake bottom temperatures, minimum DO at the sediment/water interface, and various fish habitat parameters in lakes (Stefan et al. 1996; Fang and Stefan 1997; Fang and Stefan 1999).

The representative Secchi depths of 1.2, 2.5, and 4.5 m were previously selected for eutrophic, mesotrophic, and oligotrophic Minnesota lakes (Stefan et al. 1996; Fang et al. 2004a), respectively, using Carlson's trophic state index (Carlson 1977). Ten percent or 62 lakes of 620 cisco lakes have mean summer Secchi depths of 5.0–9.5 m. Therefore, the fourth Secchi depth of 7.0 m was added creating 9 new representative or virtual lake types for the study. A set of virtual cisco lakes (Table 1.2) with SD = 7.0 m was first used to study cisco refuge lakes in Minnesota (Jiang et al. 2012). Therefore, the first 36 virtual lake types (Table 1.1) were characterized by a 3×3×4 matrix consisting of (a) three different lake surface areas, (b) three lake maximum depths, and (c) four Secchi depths.

The first 28 shallow and medium-depth lakes in Table 1.1 and the 30 deep virtual lakes in Table 1.2 were used for fish habitat modeling of the constant lethal limits method (Fang et al. 2014). Four medium-depth lakes LakeR37–R40 were added to have a lake geometry ratio of 1.15 to reflect some of the medium-depth cisco lakes with smaller GR (Jiang and Fang 2016). Four deep lakes (LakeR41–R44) were added to have the same geometry ratio as four medium-depth lakes LakeR10–R12 and LakeR31 to compare fish habitat parameters in these two groups of lakes (Fang et al. 2014). With above 8 additional virtual lakes, there are total 44 virtual lakes (Table 1.1 and Figure 1.4 top) used for cisco habitat modeling in Minnesota. Forty virtual lakes, i.e., 44 virtual lakes excluding LakeR37–R40 in Table 1.1, were used for fish habitat modeling of the lethal niche-boundary curve method (Fang et al. 2014).

The representative or regional values for each lake parameter (Table 1.1) were selected from the data analysis of these parameters in the Minnesota Lakes Fisheries Database containing lake survey data for 3002 lakes (Hondzo and Stefan 1993a) and 620 cisco lakes (Fang et al. 2009). The lake bathymetry of these 44 virtual lakes (the shape of the lake basin as part of model input data)

is characterized by three functions $A(z)/A_s$ versus z/H_{max} for small, medium-size, and large lakes; which are regression equations developed from 122 Minnesota lakes by Hondzo and Stefan (1993b). More important than the geometric characteristics of each virtual lake type is the likelihood of relating a strong or weak stratification in a lake to the lake's geometry ratio $GR = A_s^{0.25}/H_{max}$ (Gorham and Boyce 1989). The above 44 lake types cover geometry ratios from 0.88 to $14.06 \text{ m}^{-0.5}$ (Table 1.1). Polymictic lakes, i.e., large shallow lakes have the highest geometric ratio, while strongly stratified, i.e., small deep lakes have the lowest geometry ratio. Hence, these 44 lake types selected for the study include the full range of stratification behavior.

The set of 30 deep virtual lakes (Figure 1.4 bottom) comprised lakes with five different SD values (1.2 m, 2.5 m, 4.5 m, 7.0 m and 8.5 m) and six different surface areas (0.1 km^2 , 0.5 km^2 , 1.5 km^2 , 5.0 km^2 , 13.0 km^2 , and 50 km^2). The maximum depth of all 30 deep virtual lakes was set at 24 m (Fang et al. 2009; Fang et al. 2012b; Jiang et al. 2012). Combinations of the maximum depth and surface areas gave six different geometry ratios for the 30 deep virtual lakes, i.e., $0.74 \text{ m}^{-0.5}$, $1.11 \text{ m}^{-0.5}$, $1.46 \text{ m}^{-0.5}$, $1.97 \text{ m}^{-0.5}$, $2.50 \text{ m}^{-0.5}$, and $3.50 \text{ m}^{-0.5}$ (Table 1.2). Twenty of the 30 deep virtual cisco lake types were strongly stratified with $GR < 2 \text{ m}^{-0.5}$; the other ten lake types were relatively weakly stratified (Table 1.2). The 30 deep virtual cisco lakes (Table 1.2) do not include any polymictic lakes because they likely would not provide suitable cold-water habitat in Minnesota after climate warming. For example, Fang et al. (2012a) studied the oxythermal habitat variable TDO3 in 21 cisco lakes in Minnesota and found that two cisco lakes with $GR > 4.0 \text{ m}^{-0.5}$ (White Iron Lake and South Twin Lake) had high annual maximum TDO3 values indicating unfavorable conditions for cisco survival and growth. Values of TDO3 extracted from observed temperature and DO profiles were lowest in lakes with small geometry ratios ($GR < 2 \text{ m}^{-0.5}$); a geometry ratio of $4 \text{ m}^{-0.5}$ effectively marked the transition between stratified and unstratified lakes

(Jacobson et al. 2010). Thirty virtual lakes were used for fish habitat modeling for variable benchmark period and fixed benchmark period methods.

Even though the lake bathymetry (surface area and maximum depth) and Secchi depth of the 30 deep virtual cisco lakes were subjective, the selected values were representative of most of the 620 Minnesota cisco lake database (Fang et al. 2009). The 30 deep virtual cisco lakes were all stratified lakes based on geometry ratio, and included eutrophic to oligotrophic lakes (Table 1.2). The 30 deep virtual lakes were more or less uniformly distributed on the plot of SD vs GR (Figure 1.4 bottom) (Fang et al. 2012b). None of the 30 deep virtual lakes in Table 1.2 have the same lake surface areas as 44 virtual lakes in Table 1.1. These two groups of virtual lake classes (types) were

used in the different fish habitat modeling options (

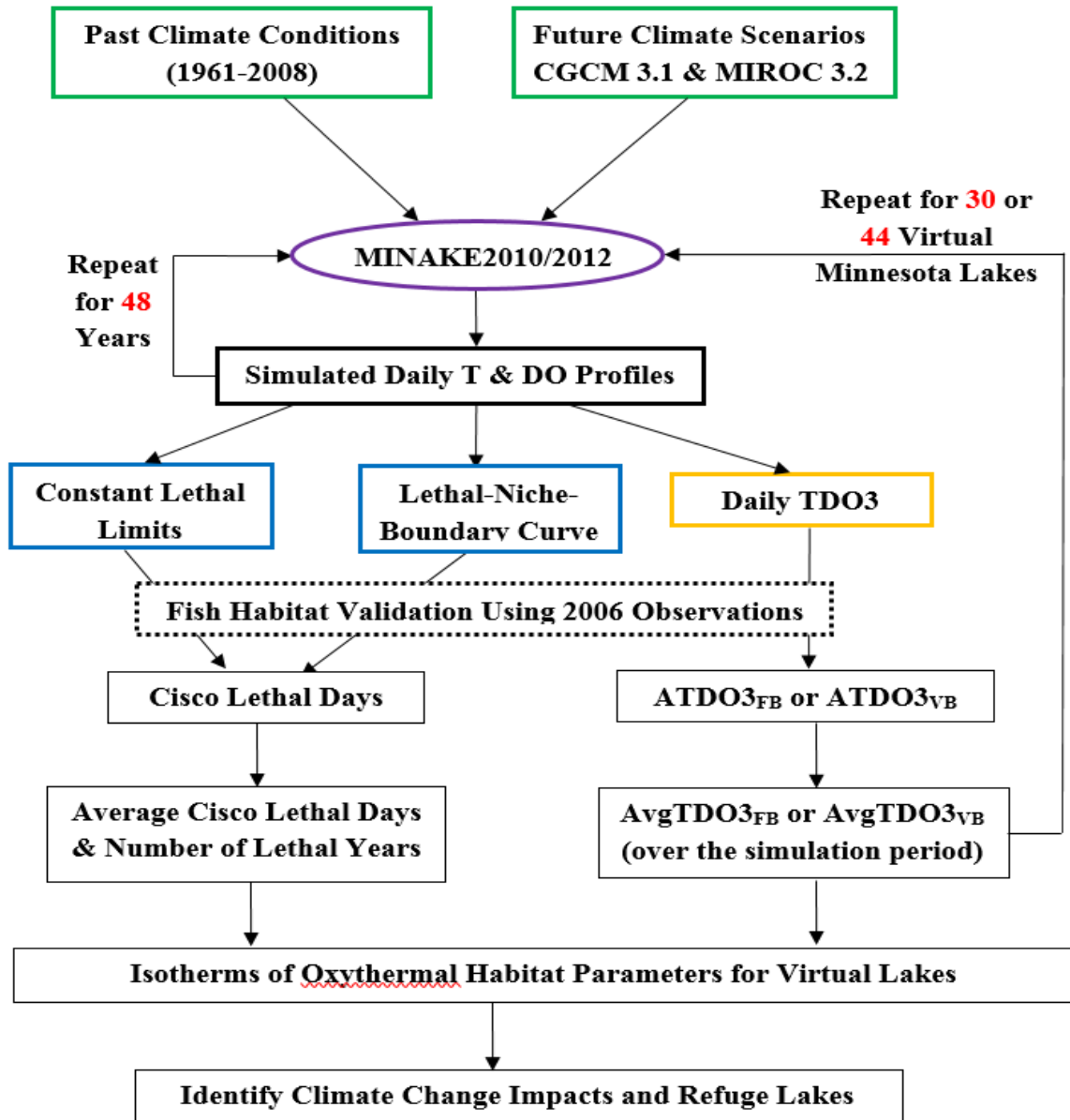


Figure 1.3): 44 shallow, medium-depth, and deep virtual lakes for the oxythermal model options 1 and 2 using lethal limits (Figure 1.4) and 30 deep virtual lakes for the model option 1

(constant lethal limits) and the model option 3 using TDO3 (

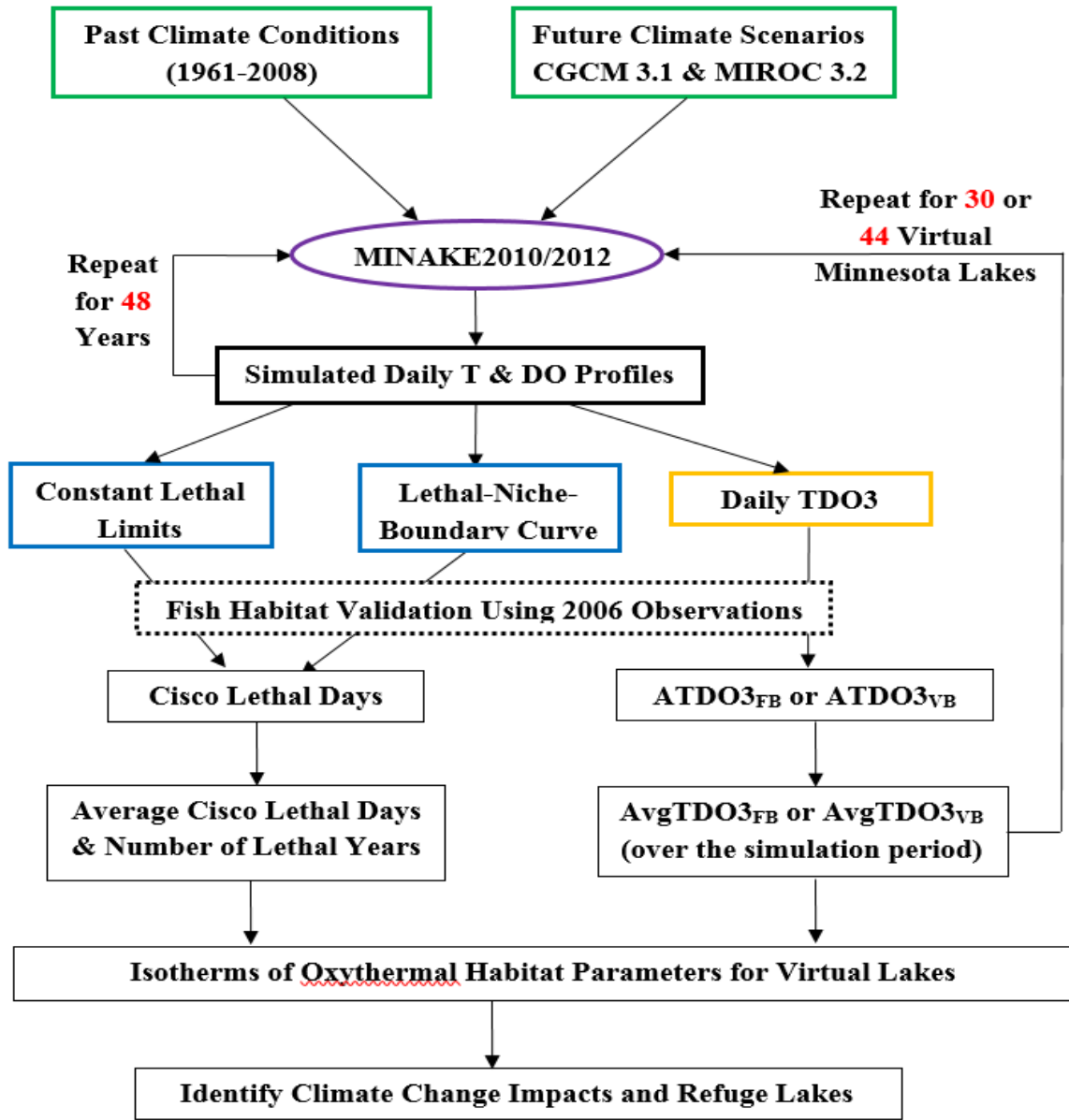


Figure 1.3) during different study periods.

Table 1.1 Morphometric characteristics and 'names' of the 44 virtual lake types in Minnesota simulated with the MINLAKE2010/MINLAKE2012 model.

Maximum Depth (m)	Surface Area A_S (km ²)	Secchi Depth, SD (m)				Geometry Ratio (GR)
		1.2	2.5	4.5	7.0	$A_S^{0.25}/H_{max}$
$H_{max} = 4$ m (shallow)	0.2	LakeR01 ¹	LakeR02	LakeR03	LakeR28	5.29 m ^{-0.5}
	1.7	LakeR04	LakeR05	LakeR06	LakeR29	9.03 m ^{-0.5}
	10	LakeR07	LakeR08	LakeR09	LakeR30	14.06 m ^{-0.5}
$H_{max} = 13$ m (medium-depth)	0.05	LakeR37	LakeR38	LakeR39	LakeR40	1.15 m ^{-0.5}
	0.2	LakeR10	LakeR11	LakeR12	LakeR31	1.63 m ^{-0.5}
	1.7	LakeR13	LakeR14	LakeR15	LakeR32	2.78 m ^{-0.5}
$H_{max} = 24$ m (deep)	10	LakeR16	LakeR17	LakeR18	LakeR33	4.33 m ^{-0.5}
	0.2	LakeR19	LakeR20 ²	LakeR21	LakeR34	0.88 m ^{-0.5}
	1.7	LakeR22	LakeR23	LakeR24	LakeR35	1.50 m ^{-0.5}
	10	LakeR25	LakeR26	LakeR27	LakeR36	2.34 m ^{-0.5}
	2.32	LakeR41 ³	LakeR42	LakeR43	LakeR44	1.63 m ^{-0.5}

Note: ¹ The first 28 shallow and medium-depth lakes were used for fish habitat modeling of the constant lethal limits method. ² These highlighted lakes are strongly stratified mesotrophic and oligotrophic deep lakes used for fish habitat modeling of the lethal-niche-boundary curve method. ³ These four deep lakes (LakeR41–R44) have the same geometry ratio as four medium-depth lakes LakeR10–R12 and LakeR31 for comparison study.

Table 1.2 Morphometric characteristics and “names” of the 30 virtual deep cisco lakes simulated with the MINLAKE2010/MINLAKE2012 model (Maximum lake depth $H_{max} = 24$ m).

Surface Area A_S (km ²)	Secchi Depth SD (m)					Geometry Ratio, $GR = A_S^{0.25}/H_{max}$
	1.2	2.5	4.5	7.0	8.5	
0.1	LakeC01	LakeC02	LakeC03	LakeC04	LakeC05	0.74
0.5	LakeC06	LakeC07	LakeC08	LakeC09	LakeC10	1.11
1.5	LakeC11	LakeC12	LakeC13	LakeC14	LakeC15	1.46
5.0	LakeC16	LakeC17	LakeC18	LakeC19	LakeC20	1.97
13.0	LakeC21	LakeC22	LakeC23	LakeC24	LakeC25	2.50
50.0	LakeC26	LakeC27	LakeC28	LakeC29	LakeC30	3.50

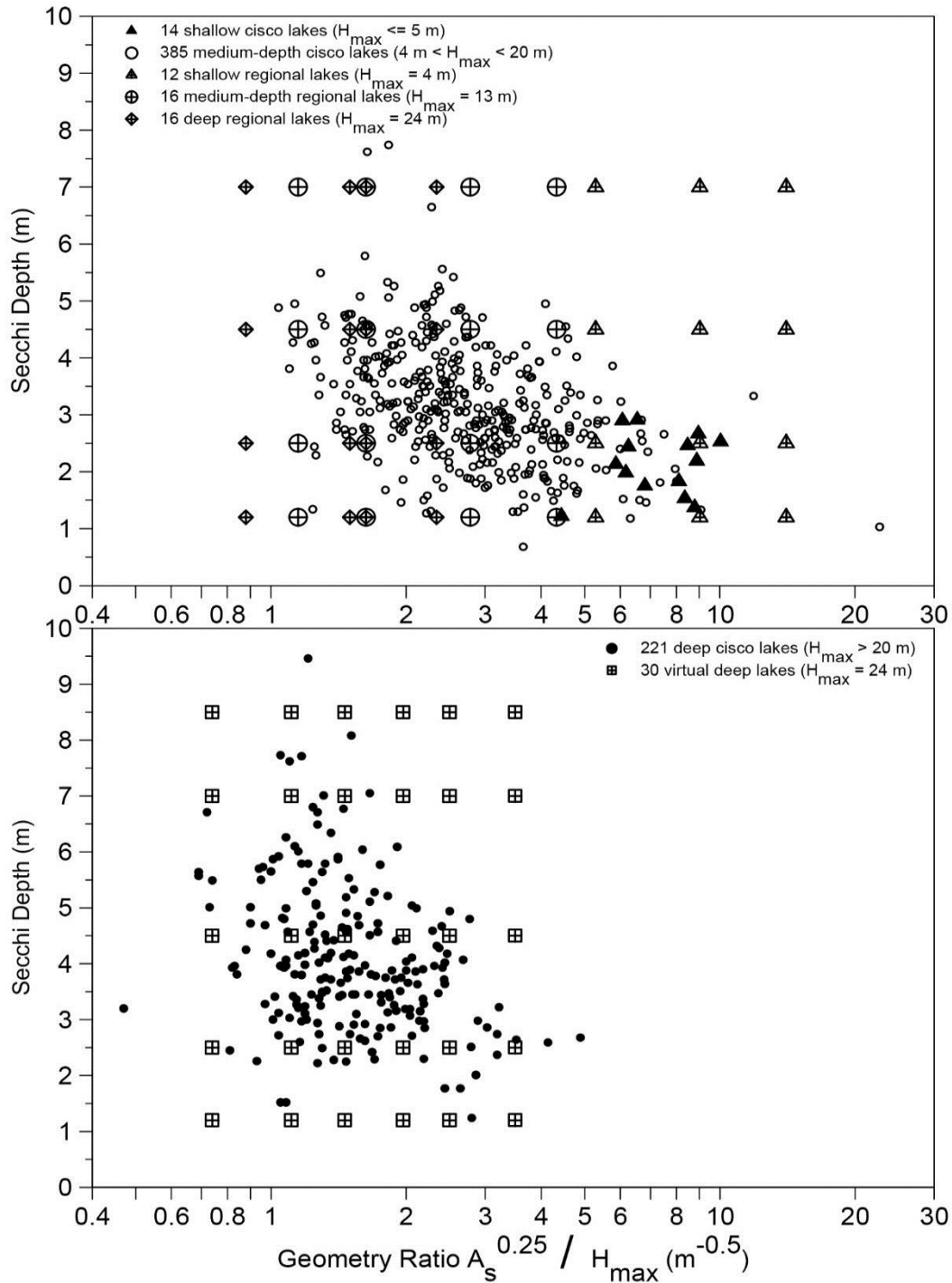


Figure 1.4 Distribution of 14 shallow and 385 medium-depth cisco lakes (top) and 221 deep cisco lakes (bottom) from 620 cisco lakes in Minnesota including 44 regional or virtual lakes (Table 1.1) and 30 virtual deep lakes (Table 1.2) plotted using Secchi depth and lake geometry ratio as axes.

1.2.3 Past Climate and Future Climate Scenarios

Climate conditions control water temperature and DO distribution in a lake. Climate scenarios are model inputs of MINLAKE2010/MINLAKE2012 for producing water temperature and DO concentration scenarios for the simulated lakes (Table 1.1 and Table 1.2), which are used to assess potential changes in cisco habitats in these lakes. To identify refuge lakes, we need to project whether a lake that currently has a cisco population can support cisco habitat under future climate scenarios, i.e. after climate warming. To make the projection, the model outputs from two Coupled General Circulation Models (CGCMs) of the earth's atmosphere and oceans (*i.e.*, CGCM 3.1 and MIROC 3.2) were used as input to the MINLAKE2010 model to calculate a range of future water quality conditions.

Forty-eight years (1961–2008) of recorded daily weather data, which were obtained from the Solar and Meteorological Surface Observation Network (SAMSON) and Midwestern Regional Climate Center, were used to describe past climate conditions for Minnesota lakes. Weather data used for lake modeling consist of daily air temperature (°F), dew point temperature (°F), wind speed (mph), solar radiation (Langley), percent sunshine, and precipitation (both rainfall and snowfall).

The CGCM 3.1 (Kim et al. 2002; Kim et al. 2003) is the third generation of CGCMs from the Canadian Centre for Climate Modeling and Analysis (CCCma). The CCCma CGCM 3.1 uses the ocean component from the earlier Second Generation CGCM (McFarlane et al. 1992) and applies a substantially updated atmospheric component – the third Generation Atmospheric General Circulation Model. Output of the CGCM 3.1 model with a coarse global surface grid resolution of roughly 3.75 degrees latitude and longitude or approximately 410 km in Minnesota was used for the study because it was available to be downloaded from the Intergovernmental Panel on

Climate Change (IPCC) data center in 2008. When CGCM 3.1 is used for the study, there is one grid center point within Minnesota and another grid center point in Canada that is the closest grid point to the International Falls weather station (Figure 1.1).

The MIROC 3.2 (Hasumi and Emori 2004) was developed by the Center for Climate System Research, University of Tokyo; the National Institute for Environmental Studies; and the Frontier Research Center for Global Change – Japan Agency for Marine-Earth Science and Technology. Output of the MIROC 3.2 model with a high spatial surface grid resolution of roughly 1.12 degrees latitude and longitude or approximately 120 km in Minnesota was used. The MIROC 3.2 model has 17 grid center points in Minnesota, and Figure 1.1 shows three grid center points from MIROC 3.2 that are the closest to three weather stations (St. Cloud, Duluth, and International Falls) used for the model study.

At all CGCM grid center points, the differences or ratios known as "change fields" were produced and reported at a monthly interval. The 2070–2099 change field data, 30 year averages compatible with the Third Assessment Report of the IPCC (IPCC 2007), were downloaded from the IPCC's website and used in the study. These monthly climate parameter differences or ratios predicted by CGCM models were then applied to measured daily climate conditions (1961–2008) month by month to produce the projected daily future climate scenario. Monthly increments from the grid center point closest to a weather station were used to specify the future climate. For the MIROC 3.2 future climate scenario, each of the three Class I NWS weather stations (International Falls, Duluth and St. Cloud) used for the study had a closest grid center point (Figure 1.1); for the CGCM 3.1 future climate scenario, Duluth and St. Cloud used the grid center point in Minnesota (Figure 1.1), and International Falls used a grid center point in Canada (Figure 1.1).

Monthly air temperature increases projected by MIROC 3.2 range from 3.53 °C to 4.70 °C with annual averages of 4.00 to 4.24 °C for the three weather stations (Table 1.3); CGCM 3.1 projection has a range from 2.89 °C to 8.09 °C with annual averages of 4.07 to 4.14 °C for the three weather stations (Fang et al. 2010b). The average monthly increases in air temperature range from 3.6 °C to 4.7 °C (3.6–3.8 °C from July–September) in Bemidji, Minnesota, which was also used for the oxythermal habitat option 2 (lethal-niche-boundary curve).

1.3 Organization of the dissertation

This dissertation is organized into six chapters. Chapters two, three, four and five are organized using journal paper format prepared for British Journal of Environment & Climate Change (BJECC), Water, Ecological Modelling, and Transaction of the American Fisheries Society, respectively. These four papers are already published. Literature review for each part of the study is given in each chapter. Therefore, they are some repetitions of entrained information in different chapters since these chapters are related to each other. The summary and conclusion of the whole study and suggestions for future related study are given in Chapter six. The reviews of different numerical models for water quality and fish habitat simulations in lakes are given in Appendix A and Appendix B, respectively. The references quoted in all chapters and appendixes were combined, sorted, and listed at the end of the dissertation.

Table 1.3 Monthly changes of air temperature (T_{air} , °C) and solar radiation (S_{RAD} , Langley/day) projected by MIROC 3.2 and CGCM 3.1 for the three principal Minnesota weather stations.

Station	International Falls		Duluth		St. Cloud	
Month	T_{air}^1	S_{RAD}^2	T_{air}	S_{RAD}	T_{air}	S_{RAD}
Jan	5.15/6.89 ³	-20.34/-5.69	4.67/4.84	-15.92/-7.49	4.35/4.84	-4.60/-7.49
Feb	4.70/5.07	-25.36/-9.51	4.67/8.09	-23.42/-38.21	4.17/8.09	-9.13/-38.21
Mar	4.64/3.90	-24.84/1.83	4.53/6.25	-15.75/-55.05	4.08/6.25	0.35/-55.05
Apr	4.52/4.31	-3.32/-18.77	3.89/3.60	0.78/-25.99	3.88/3.60	9.80/-25.99
May	4.37/4.12	-4.43/-29.39	4.21/3.47	-15.22/-19.96	4.33/3.47	2.45/-19.96
Jun	3.62/4.59	-3.82/9.63	3.59/3.28	-3.92/2.28	3.67/3.28	0.36/2.28
Jul	3.53/3.80	-5.38/14.43	3.68/3.25	10.36/14.78	3.67/3.25	17.08/14.78
Aug	3.75/3.30	-0.49/7.63	3.82/3.32	0.52/3.66	3.92/3.32	3.64/3.66
Sep	3.80/3.49	16.57/10.69	3.81/3.34	19.27/0.34	3.87/3.34	24.14/0.34
Oct	4.46/3.19	-2.76/3.94	4.29/3.39	3.03/-1.18	4.30/3.39	9.87/-1.18
Nov	4.10/2.89	-4.22/-1.82	3.89/3.06	3.03/-2.16	3.87/3.06	5.79/-2.16
Dec	4.18/4.14	-12.80/-4.86	3.99/2.91	-9.24/-1.32	3.92/2.91	-3.16/-1.32
Average	4.24/4.14	-7.60/-1.82	4.09/4.07	-3.87/-10.86	4.00/4.07	4.71/-10.86

¹ Conversion of temperature changes: 1.0 °C = 1.8 °F

² stands for solar radiation, 1.0 Langley/day = 0.484 Watts/m²

³ The first value is for MIROC 3.2 and the second value is for CGCM 3.1

Chapter 2 **Simulation and Validation of Cisco Habitat in Minnesota Lakes Using the Lethal-Niche-Boundary Curve**

2.1 Abstract

Fish survival in lakes is strongly influenced by water temperature and dissolved oxygen (DO) concentration. A one-dimensional (vertical) lake water quality model MINLAKE2012 was calibrated in 23 Minnesota lakes and used to simulate daily water temperature and DO concentrations in 36 representative lake types under past (1992–2008) climate conditions and a future climate scenario (MIROC 3.2). The 36 representative Minnesota lake types were developed based on three maximum depths ($H_{max} = 4, 13, \text{ and } 24 \text{ m}$), three surface areas ($A_s = 0.2, 1.7, 10 \text{ km}^2$), and four Secchi depths ($SD = 1.2, 2.5, 4.5, \text{ and } 7 \text{ m}$, from eutrophic to oligotrophic lake). A fish habitat model using the lethal-niche-boundary curve of adult cisco (*Coregonus artedii*, a cold-water fish species) was then developed to evaluate cisco oxythermal habitat and survival in Minnesota lakes. The fish habitat model was validated in the 23 Minnesota lakes of which 18 had cisco mortality while 5 had no cisco mortality in the unusually warm summer of 2006. Cisco lethal and habitable conditions in the 23 lakes simulated by the model had an overall good agreement with observations in 2006. After model validation, cisco lethal days in the 36 lake types were modeled using simulated daily temperature and DO profiles from MINLAKE2012. Polymictic shallow lakes with lake geometry ratio $A_s^{0.25}/H_{max} > 5.2 \text{ m}^{-0.5}$ were simulated to typically not support cisco oxythermal habitat under past climate conditions and the future climate scenario. Medium-depth lakes are projected to be most vulnerable to climate warming with most increase in the number of years with cisco kill (average increase 13 years out of 17 simulation years). Strongly stratified mesotrophic and oligotrophic deep lakes are possible to support cisco habitat

under both past and future climate conditions, and these deep lakes are good candidates for cisco refuge lakes that should be protected against water quality deteriorations.

2.2 Introduction

The increase of CO₂ and other greenhouse gases in the atmosphere is projected to cause climate warming, which will lead to increase in water temperature and hypolimnetic oxygen depletion during longer periods of summer stratification in lakes (Blumberg and Di Toro 1990; Fang and Stefan 2009a). Fish habitat is constrained by water temperature, available dissolved oxygen (DO), food supply, human interference, and other environmental factors. In lakes, temperature and DO are the two most significant water quality parameters that affect survival and growth of cold-water fishes (Fry 1971; Magnuson et al. 1979; Christie and Regier 1988). Therefore, projected changes in water temperature and DO concentrations are expected to have an effect on indigenous fish populations (Magnuson et al. 1990; De Stasio et al. 1996; Stefan et al. 2001).

MINLAKE2012 used in the study was derived from a regional lake water quality model MINLAKE96, which was originally developed for Minnesota lakes and then applied to 27 lake types at 209 locations over the contiguous US in studying the response of temperature, DO, and fish habitat in the lakes to future climate changes. These lakes were simulated for a continuous 19-year period under past (1961-1979) climate and projected 2xCO₂ climate scenarios (McFarlane et al. 1992). Not all these lake types actually exist at all 209 locations investigated in the contiguous USA (Stefan et al. 2001). In many locations, they are hypothetical lakes. The generic approach, however, provides a good picture of how different lake types may behave in different parts of the country, especially under future climate scenarios for which there are no lake data.

Cisco *Coregonus artedii* is the most common cold-water stenothermal fish in Minnesota lakes. The Minnesota (MN) Department of Natural Resources (DNR) has sampled cisco from 648 lakes

in netting assessments since 1946. These lakes are scattered throughout much of the central and northern portions of Minnesota. Cisco physiologically require cold, well-oxygenated water to survive, grow, and reproduce (Cahn 1927; Frey 1955). Cisco is a sensitive indicator of ecological stresses such as eutrophication and climate warming. For example, 18 lakes (Table 2.1) in north-central Minnesota experienced cisco mortality (Figure 2.1) in the unusually hot summer of 2006 (Jacobson et al. 2008).

The physiological response of adult populations of different fish species to water temperature and DO levels has been the subject of numerous laboratory and field studies. Several fish habitat studies described, e.g., by Coutant (Coutant 1990), McCormick et al. (McCormick et al. 1972), and Hokanson et al. (Hokanson et al. 1977), attempted to correlate fish survival, growth, and reproduction to chronic temperature and DO exposure. The oxythermal habitat approach commonly used lethal boundaries for temperature and DO in cold-water fish niche modeling (Dillon et al. 2003). Both upper (i.e. lethal) temperature and lower DO survival limits are constants and do not vary with time in those studies. These oxythermal habitat models determine the water volume or layer thickness in a stratified lake between the upper temperature and lower DO limits that represent either optimal thermal habitat (Dillon et al. 2003) or non-lethal/useable habitat (Stefan et al. 2001; Fang et al. 2004a). To study fish habitats in small lakes over the contiguous USA, the constant lethal temperature used for cold-water species was 23.4 °C and the constant DO limit was 3 mg/L (Eaton et al. 1995). Recently, Jiang et al. (Jiang et al. 2012) used a single variable to quantify oxythermal habitat of cisco in Minnesota lakes, and the variable TDO3 was originally proposed by Jacobson et al. (Jacobson et al. 2010). TDO3 is defined as the water temperature at 3 mg/L of DO, and the 3 mg/L was selected as a benchmark oxygen concentration that is probably lethal or nearly so for many cold-water species (Frey 1955; EPA 1986; Fang et al. 2004a).

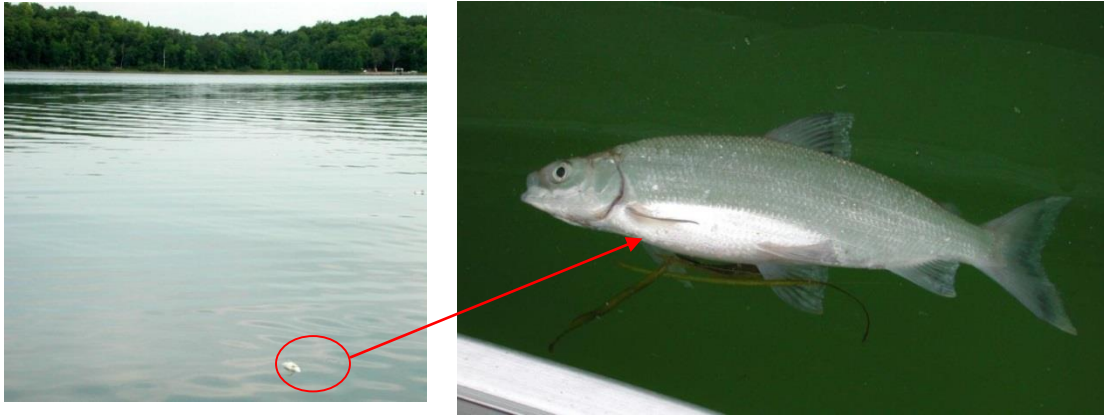


Figure 2.1 Lake Andrusia in Minnesota had cisco mortality in July 2006 (photo: Peter C. Jacobson, Minnesota Department of Natural Resources)

In this study, the fish habitat model for cisco uses a fitted regression equation as the lethal niche boundary of adult cisco. The equation was developed by Jacobson et al. (Jacobson et al. 2008) in 2008. It mapped the temperatures and DO concentrations from the profiles measured in 16 Minnesota lakes that experienced cisco mortality in July and August 2006 (Table 2.1). First, the fish habitat model was validated in 23 Minnesota lakes and then used to project cisco lethal conditions in 36 representative lake types under past (1992–2008) climate conditions and a future climate scenario (MIROC 3.2). Based on the number of years with cisco kill and the number of annual cisco lethal days, lake types that most likely could not support cisco were identified, and lake types that can support cisco under both the past climate and the future climate scenario were identified as potential cisco refuge lakes.

2.3 Materials and Methods

2.3.1 Simulation Models for Year-Round Water Quality

To make projections of water quality and fish habitat in small lakes under future climate scenarios, numerical simulation models of daily temperature and DO profiles are indispensable. The one-dimensional (vertical) year-round lake water quality model MINLAKE96 was developed

to run continuously over many simulation years for both the open-water season and the ice-cover period (Fang and Stefan 1996a). The model uses a stacked layer system (Figure 2.2); the layers consist of lake water and lake sediments during the open-water season and additional ice cover and snow cover during the winter ice-cover period (Fang and Stefan 2009a). It simulates daily water temperature profiles in a lake using daily weather data as input. Figure 2.2 is a schematic of a stratified lake including heat transfer components for the year-round water temperature model and typical temperature profiles in the summer and winter (Fang and Stefan 1996b).

A lake is divided into a series of well-mixed horizontal water layers (Figure 2.1) because the horizontal variations of water quality parameters are typically much smaller than the vertical variations in a small stratified lake. The one-dimensional, unsteady heat transfer equation in a lake was solved for daily vertical water temperature profiles (Hondzo and Stefan 1993b):

$$\frac{\partial T}{\partial t} = \frac{1}{A} \frac{\partial}{\partial z} \left(K_{zT} A \frac{\partial T}{\partial z} \right) + \frac{H_w}{\rho C_p} \quad 2.1$$

where $T(z, t)$ ($^{\circ}\text{C}$) is the water temperature in a horizontal layer, t (day) is the time, $A(z)$ (m^2) is the horizontal area as a function of depth z (m) based on lake bathymetry input data, K_{zT} ($\text{m}^2 \text{ day}^{-1}$) is the vertical turbulent heat diffusion coefficient, ρc_p ($\text{J m}^{-3} \text{ }^{\circ}\text{C}^{-1}$) is the density of water (ρ) times heat capacity of water (c_p) and represents heat capacity per unit volume, and H_w ($\text{J m}^{-3} \text{ day}^{-1}$) 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 (Stefan and Ford 1975). Heat exchange with the bottom sediment layer included in MINLAKE96 can be important in the shallow water layers and during the winter ice-cover periods (Fang and Stefan 1996c).

Heat exchange between the lake and the atmosphere is treated as a source or sink term (Figure 2.2) for the topmost water layer of a lake during the open-water season [$H_w(I)$ in Eq. (1) = $A_s/V(I) \times (H_{SN} + H_A - H_{BR} - H_E - H_C)$, where A_s is the lake surface area and $V(I)$ is the volume of the topmost/first water layer] due to the surface wind mixing. It includes surface heat fluxes in $J m^{-2} day^{-1}$ such as incoming heat from short-wave solar radiation (H_{SN}) and long-wave radiation (H_A) and outgoing heat from back radiation (H_{BR}), evaporation (H_E), and convection (H_C) related to wind speed (U). The computation of above surface heat fluxes and the internal heat source term (H_w) using daily weather input data has been discussed by Hondzo and Stefan (Hondzo and Stefan 1993b) among others. During the ice-cover period (Fang and Stefan 1996b), the model first simulates snow/ice thicknesses and sediment temperature profiles (heat conduction equation), then determines the heat source/sink terms, and finally solves the heat transfer equation to obtain water temperature profiles below the ice. The heat budget components through the water surface are directly linked to climate parameters that are related to future climate changes.

Dissolved oxygen concentration is viewed as one of the most important lake water quality parameters which indicate a lake's overall ecological health. The vertical DO profiles in the lake are computed from a balance between oxygen sources (surface reaeration and photosynthesis, Figure 2.2) and oxygen sinks (sedimentary oxygen demand SOD, biochemical oxygen demand BOD, and plant respiration R). The numerical simulation model for daily DO profiles in a lake solves the one-dimensional, unsteady transport equation:

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

In Equation (2.2), $C(z, t)$ is the DO concentration in mg L^{-1} as a function of depth (z) and time (t), $K_z(z, t)$ is the DO vertical turbulent diffusion coefficient in $\text{m}^2 \text{day}^{-1}$, and S_b is the coefficient for SOD at 20°C in $\text{mg O}_2 \text{m}^{-2} \text{day}^{-1}$. P_{MAX} is the maximum specific oxygen production rate by aquatic plants at 20°C under saturating light conditions in $\text{mg O}_2 (\text{mg Chla})^{-1} \text{day}^{-1}$. $Min[L]$ is the light limitation determined by Haldane kinetics (Megard et al. 1984). $Chla$ is the chlorophyll-a concentration in mg L^{-1} to represent the biomass of aquatic plants in a lake. $YCHO2$ is the yield coefficient, i.e., the ratio of mg chlorophyll-a to mg oxygen. The first-order decay rate coefficients are k_b and k_r for BOD and plant respiration (day^{-1}), respectively. The temperature adjustment coefficients for SOD, photosynthesis, BOD, and plant respiration are θ_s , θ_p , θ_b , and θ_r , respectively. BOD is in mg L^{-1} . Diffusive oxygen flux at the lake bottom is set equal to zero as a boundary condition.

Oxygen production is related to chlorophyll-a concentration and limitation of available light determined by Haldane kinetics. In the model, chlorophyll-a is specified by a mean annual value which depends on the specified trophic state of a lake and a function that calculates typical seasonal chlorophyll cycles (Stefan and Fang 1994b) based on observational data from 56 lakes and reservoirs in Europe and North America (Marshall and Peters 1989). In the model, the oxygen transfers 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 after the reaeration is multiplied by the surface area and divided by the layer volume, and the surface oxygen transfer coefficient is calculated as a function of wind speed. SOD is treated as a sink term for each water layer because each water layer is in contact with sediments. BOD occurs in the water column along all water depths, and plant respiration for all water layers is a function of chlorophyll-a concentration.

For the DO simulations in a lake during the ice-cover period (Figure 2.2), modifications must be made to account for the presence of an ice cover and low temperatures. For example, reaeration is zero because the lake ice cover prevents any significant gas exchange between the atmosphere and the water body. The water column oxygen demand (WOD in Figure 2.2) is $0.01 \text{ g O}_2 \text{ m}^{-3}$ per day. DO concentrations were simulated after water temperature and snow/ice covers had been simulated. Equations (1) and (2) are solved numerically for time steps of one day and layer thicknesses from 0.02 m (near the water surface and the ice-water interface) to 1.0 m (when $z > 1.0$ m) for small lakes using an implicit finite difference scheme and a Gaussian elimination method. Model parameters and detailed formulations of the year-round DO model (Equation 2.2) have been described elsewhere by Fang and Stefan (Stefan and Fang 1994b; Fang and Stefan 1997).

Several modifications and refinements were made to develop MINLAKE2010 from MINLAKE96 for relative deep cisco lakes in Minnesota and have been reported elsewhere (Fang et al. 2012a). MINLAKE2012 used in this study is a spreadsheet model developed from MINLAKE2010 (Fang et al. 2012a). The most important upgrades of MINLAKE2012 compared to MINLAKE2010 are the conversion to a user-friendly Excel spreadsheet (for data input and displaying basic graphic results) and the introduction of variable temporal resolution, allowing the model to run at hourly and daily time step. The MINLAKE model was calibrated and validated against extensive Minnesota lake data: first using 5,378 water temperature and DO measurements for 48 lake years in 9 lakes for MINLAKE96 (Fang and Stefan 1996b) and then using 7,384 water temperature and DO measurements for 439 lake years in 28 lakes for MINLAKE2010 (Fang et al. 2012a).

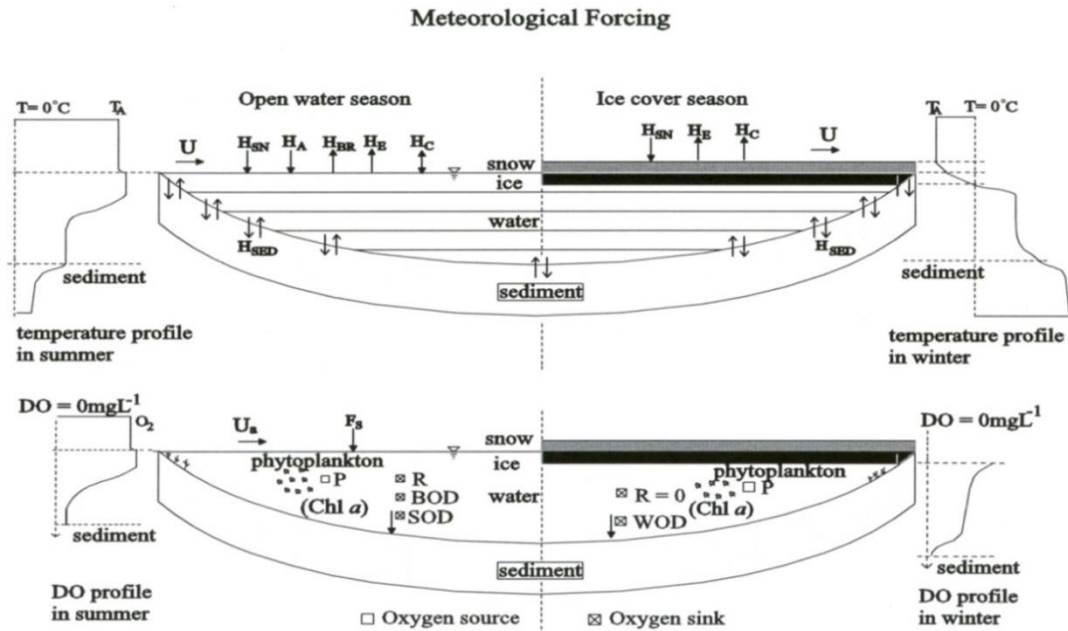


Figure 2.2 Schematic of a stratified lake showing heat transfer components, oxygen sources and sinks for the year-round water temperature and DO model MINLAKE96/2010/2012, and typical temperature and DO profiles in summer (left) and winter (right)

2.3.2 Fish Habitat Projection Model

In lakes, water temperature and DO concentrations are two of the most important water quality parameters that affect the survival and growth of cold-water fishes (Christie and Regier 1988). In this study, the fish habitat model for cisco uses a fitted regression equation as the lethal-niche-boundary of adult cisco developed by Jacobson et al. (Jacobson et al. 2008) in 2008. The equation mapped the DO concentrations and water temperatures from the profiles measured in 16 Minnesota lakes that experienced cisco mortality in 2006 (Table 2.1). One profile was measured in each of the 16 lakes on the same day or a few days after reported mortality. The shifted exponential function given in Equation (3) is a fit of the 99th quartile nonparametric regression line bracketed

the lethal combinations of observed oxygen and temperature in 16 lakes with midsummer (July 19 to August 6) mortality events in 2006 (Jacobson et al. 2008).

$$DO_{lethal} = 0.40 + 0.0000060 e^{0.59T_{lethal}} \quad 2.3$$

where DO_{lethal} and T_{lethal} are the DO concentrations (in mg/L) and the water temperatures (in °C), respectively, which define the lethal niche boundary (Jacobson et al. 2008). The computed DO_{lethal} is the required minimum DO concentration at a given water temperature T_{lethal} for cisco to survive. For the regression equation (2.3), the coefficients 0.40 and 0.0000060 are in mg/L and the coefficient 0.59 is in °C⁻¹.

Equation (2.3) indicates the DO survival limit for adult cisco is not constant but depends on water temperature. The lethal-niche-boundary curve for cisco (Equation 3) was plotted in Figure 2.3 for three Minnesota lakes (Pine Mountain Lake, Itasca Lake, and Woman Lake). In comparison with the previous constant lethal temperature for cold-water fish species, i.e., 23.4 °C (Eaton et al. 1995), the lethal temperature from Equation (2.3) is only 22.0°C when 3.0 mg/L is used as the DO survival limit (Jacobson et al. 2008). In this study, the required DO concentration DO_{lethal} was computed from the simulated water temperature in each water layer of a lake for each simulated day using Equation (2.3). The computed DO_{lethal} value was then compared with the simulated DO concentration in the same layer; lethal conditions for cisco were assumed to occur if the simulated DO was less than the DO_{lethal} value in all water layers (from the lake water surface to the lake bottom) on that day. In Figure 2.3, simulated DO was plotted against simulated temperature for three selected days in each of the three lakes. On July 28, 2006 in Pine Mountain Lake, all simulated temperature-DO data points (shown by the crosses) are located at the right side

of or below the lethal-niche-boundary curve when simulated DO concentrations were below computed DO_{lethal} values at simulated temperatures at all water depths. The same situation of cisco lethal conditions was predicted to occur on July 31, 2006 in Itasca Lake and August 20, 2003 in Woman Lake.

If simulated DO concentrations are less than the DO_{lethal} values in only some of the water layers, lethal conditions for cisco are not assumed to occur on that day because cisco can swim to other water layers having suitable DO and temperature condition. These days with habitat at some depths are shown as filled triangles on Figure 2.3. When simulated DO concentrations are greater than the DO_{lethal} values in all water layers, fish can live in any depth of the lake, i.e., filled circles in Figure 2.3.

2.3.3 Representative Lake Types in Minnesota

It is infeasible to simulate more than 600 cisco lakes in Minnesota using MINLAKE2012. In this study, simulations of daily water temperature and DO profiles were made for 36 representative lake types in Minnesota before fish habitat was examined in these lakes. The 36 representative lake types was expanded from the 27 lake types used to study fish habitat in Minnesota (Stefan et al. 1996) and in the contiguous USA (Fang et al. 2004a). Lakes were classified by lake geometry (surface area A_s and maximum depth H_{max}) and trophic state as related to Secchi depth (SD in Table 2.2). The representative surface areas chosen were 0.2, 1.7 and 10.0 km² for small, medium-size, and large lakes, respectively. The representative maximum depths chosen were 4, 13, and 24 m for shallow, medium-depth, and deep lakes, respectively. With these numbers, 9 lake types are obtained ranging from relatively large and shallow lakes to relatively small and deep lakes. More important than the geometric characteristics of each lake type is the likelihood of relating a strong or weak stratification in a lake to the lake's geometry ratio GR defined as $A_s^{0.25}/H_{max}$ (Gorham and

Boyce 1989), where A_s is in m^2 and H_{max} in m. The above 9 lake types cover geometry ratios from 0.88 to 14.06 $m^{-0.5}$ (Table 2.2). Polymictic lakes, i.e., large shallow lakes have the highest geometric ratio, while strongly stratified, i.e., small deep lakes have the lowest geometry ratio. The transition of stratification occurs when GR is between 3 and 5 $m^{-0.5}$ (Stefan et al. 1996). Hence, these nine lake types selected for the study include the full range of stratification behavior.

Secchi (disk) depth is a common limnological parameter to measure transparency of a lake (Hutchinson 1957; Horne and Goldman 1994). It was used in previous fish habitat studies (Stefan et al. 1996; Fang et al. 2004a) to represent both trophic state (primary productivity of biomass or photosynthesis of plants) and radiation attenuation in a lake, which is used to quantify how much solar energy reaching the water surface can penetrate through a water column to heat water and to support photosynthesis of aquatic plants. The representative Secchi depths of 1.2, 2.5, and 4.5 m were previously selected for eutrophic, mesotrophic, and oligotrophic Minnesota lakes (Stefan et al. 1996), respectively, using Carlson's trophic state index (Carlson 1977). Minnesota cisco lakes are generally deeper, more transparent, and less trophic than other lakes in Minnesota (Fang et al. 2009). For example, 10% of 620 cisco lakes have mean Secchi depths of 5.0–9.5 m. Therefore, the fourth Secchi depth of 7.0 m was added creating 9 new representative lake types for the study. A set of virtual cisco lakes with $SD = 7.0$ m was used before to study cisco refuge lakes in Minnesota (Jiang et al. 2012). Therefore, the 36 representative lake types (Table 2.2) were characterized by a $3 \times 3 \times 4$ matrix consisting of (a) three different lake surface areas, (b) three lake maximum depths, and (c) four Secchi depths. These representative values for each parameter (Table 2.2) were selected from the data analysis of these parameters in the Minnesota Lakes Fisheries Database containing lake survey data for 3002 lakes (Hondzo and Stefan 1993a) and 620 cisco lakes (Fang et al. 2009).

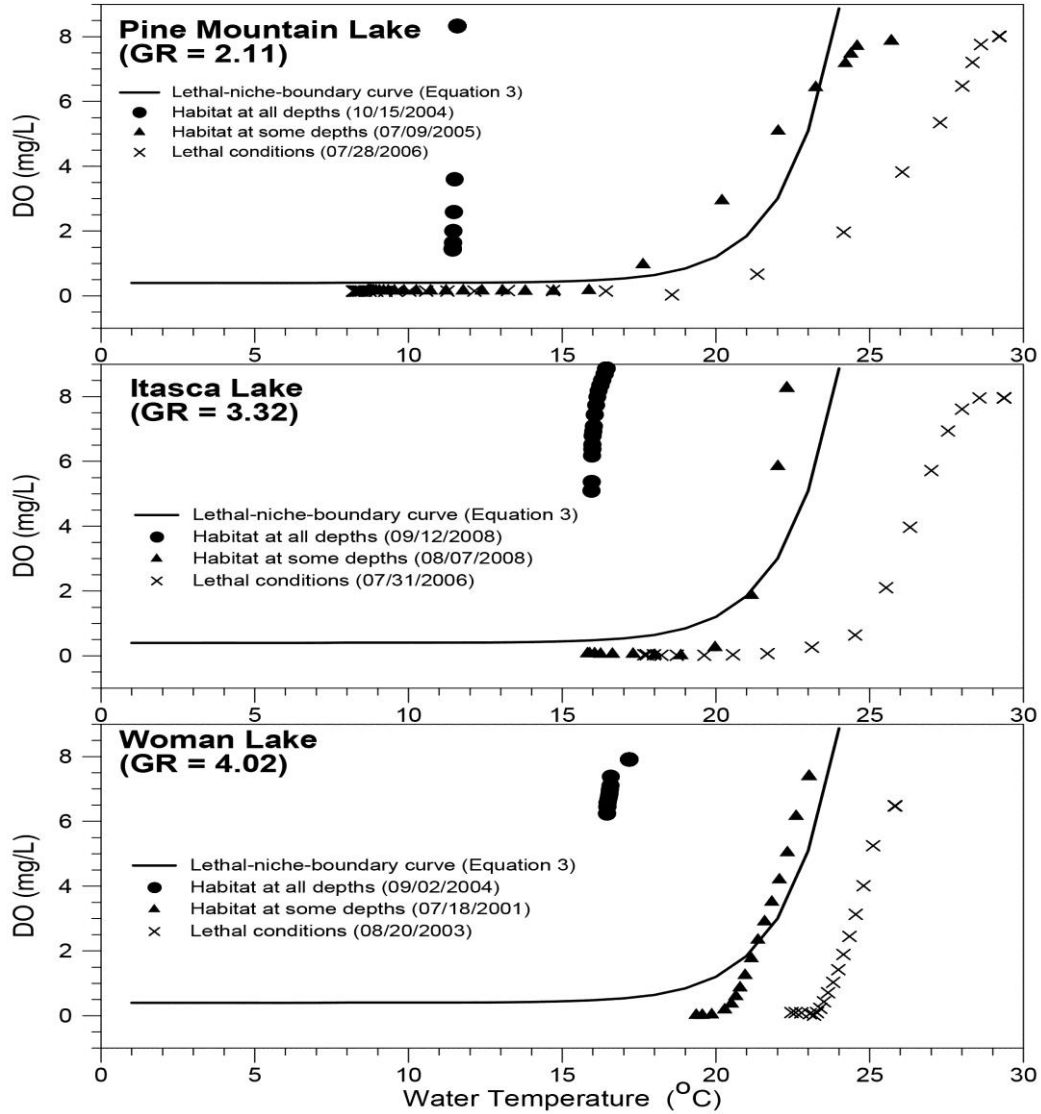


Figure 2.3 Simulated DO versus simulated temperature for three selected days to show three different types of fish habitat in Pine Mountain Lake, Itasca Lake, and Woman Lake (Table 2.1 and the lethal-niche-boundary curve of adult cisco (Equation 2.3). The geometry ratio GR in $m^{-0.5}$ is defined as $A_s^{0.25}/H_{max}$ (surface area A_s is in m^2 and maximum depth H_{max} in m)

Table 2.1 Maximum depth (H_{max}), lake geometry ratio (GR), and fish habitat validation results for 23 Minnesota lakes. Simulated and observed days with lethal conditions for cisco are given as

Julian Days

Lake Name (H_{max} in m, GR)	Lethal conditions			Simulated lethal days in 2006	Observed mortality day in 2006	Model Agreement
	First day	Last day	No. of days			
Little Turtle (8.8, 4.21)	181	222	38	182(4) ¹ , 187(4), 193(30)	200 (7/19) ²	Yes (Yes) ³
Andrusia (18.3, 2.75)	192	234	39	192(37), 233(2)	202 (7/21)	Yes (Yes)
Little Pine (Otter Tail) (19.2, 2.77)	199	216	17	199(1), 201(16)	203 (7/22)	Yes (Yes)
Cotton (8.5, 6.07)	188	225	36	188(1), 190(1), 192(34)	205 (7/24)	Yes (Yes)
Pine Mountain (23.8, 2.11)	192	241	49	192(45), 238(4)	207 (7/26)	Yes (Yes)
Leech (13.0, 10.91)	189	217	22	189(1), 195(6), 203(15)	211 (7/30)	Yes (Yes)
Itasca (13.7, 3.32)	189	222	31	189(1), 193(30)	209 (7/28)	Yes (Yes)
Gull (24.4, 3.26)	209	227	19	209(19)	210 (7/29)	Yes (Yes)
Woman (16.5, 4.02)	183	224	36	183(2), 187(1), 190(1), 193(32)	210 (7/29)	Yes (Yes)
Little Pine (Crow Wing) (11.0, 2.90)	183	240	48	183(5), 190(39), 233(3), 240(1)	214 (8/2)	Yes (Yes)
Eighth Crow Wing (9.1, 4.11)	195	222	28	195(28)	216 (8/4)	Yes (Yes)
Bemidji (23.2, 3.13)	212	217	6	212(6)	208 (7/27)	Yes (No)
Mille Lacs (12.8, 11.89)	216	241	26	216(26)	204 (7/23)	Yes (No)
Star (28.7, 2.26)	212	216	5	212(5)	200 (7/19)	Yes (No)
Seventh Crow Wing (12.8, 2.49)	196	215	20	196(20)	216 (8/4)	Yes (No)
Long (39.6, 1.22)	216	216	1	216(1)	218 (8/6)	Yes (No)
Carlos (49.7, 1.15)			0	No kill	239 (8/27)	No
Straight (19.2, 1.94)			0	No kill	213 (8/1)	No
Reference lakes without cisco kill in 2006						
Big Trout (39.0, 1.24)			0	No kill	No kill	Yes
Kabekona (40.5, 1.38)			0	No kill	No kill	Yes
Scalp (27.4, 1.15)			0	No kill	No kill	Yes
Ten Mile (63.4, 1.06)			0	No kill	No kill	Yes
Rose (41.8, 1.12)			0	No kill	No kill	Yes

Note: ¹ stands for a Julian Day in 2006 and the number of continuous cisco lethal days from the lethal day predicted by the fish habitat model. ² Julian Day followed by month and date in 2006

inside brackets, ³ the first Yes/No gives the agreement of cisco lethal prediction and reported cisco mortality in 2006 and Yes/No inside brackets gives the agreement whether or not cisco lethal days from the model include reported the date with cisco mortality

2.3.4 Past Climate and Future Climate Scenario

Climate conditions control water temperature and DO distribution in a lake. Climate scenarios are model inputs of MINLAKE2012 for producing water temperature and DO concentration scenarios for the study lakes (23 lakes in Table 2.1 and 36 representative lake types in Table 2.2), which are used to assess potential changes in cisco habitats in the lakes. Forty-eight years (1961–2008) of recorded daily weather data, which were obtained from the Solar and Meteorological Surface Observation Network (SAMSON) and Midwestern Regional Climate Center, were used to describe past climate conditions for the study lakes. Weather data used for lake modeling consist of daily air temperature, dew point temperature, wind speed, solar radiation, percent sunshine, and precipitation (both rainfall and snowfall).

Projected changes in climate conditions were obtained from the output of the Model for Interdisciplinary Research on Climate, MIROC 3.2 (Hasumi and Emori 2004), which was developed by University of Tokyo's Center for Climate System Research, the National Institute for Environmental Studies; and the Frontier Research Center for Global Change of the Japan Agency for Marine-Earth Science and Technology. The output from the MIROC 3.2 model with high spatial resolution used in the study has a surface grid whose spatial resolution is roughly 1.12 degrees latitude and longitude, which has 17 grid center points in Minnesota. Some global circulation models (GCMs) used before have only one or two grid points in Minnesota (Stefan et al. 2001). For all GCM grid center points, the differences or ratios known as "change fields" were produced and reported at a monthly interval. The 2070–2099 change field data, 30 year averages

compatible with the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007), were downloaded from the IPCC's website to use in the study. These monthly climate parameter differences or ratios predicted by MIROC 3.2 were then applied to measured daily climate conditions (1961–2008) month by month to produce the projected daily future climate scenario. Monthly differences (or ratios) from the MIROC 3.2 grid center point closest to a weather station were used for the station. The average monthly increases in air temperature range from 3.6 °C to 4.7 °C (3.6–3.8 °C from July–September) in Bemidji, Minnesota.

Table 2.2 Morphometric characteristics and 'names' of the 36 representative lake types simulated with the MINLAKE2012 model

Maximum Depth (m)	Surface Area	Secchi Depth, SD (m)				Geometry
	A_s (km ²)	1.2	2.5	4.5	7.0	Ratio (GR) $A_s^{0.25}/H_{max}$
$H_{max} = 4$	0.2	LakeR01	LakeR02	LakeR03	LakeR28	5.29 m ^{-0.5}
	1.7	LakeR04	LakeR05	LakeR06	LakeR29	9.03 m ^{-0.5}
	10	LakeR07	LakeR08	LakeR09	LakeR30	14.06 m ^{-0.5}
	0.2	LakeR10	LakeR11	LakeR12	LakeR31	1.63 m ^{-0.5}
$H_{max} = 13$	1.7	LakeR13	LakeR14	LakeR15	LakeR32	2.78 m ^{-0.5}
	10	LakeR16	LakeR17	LakeR18	LakeR33	4.33 m ^{-0.5}
	0.2	LakeR19	LakeR20 ¹	LakeR21	LakeR34	0.88 m ^{-0.5}
$H_{max} = 24$	1.7	LakeR22	LakeR23	LakeR24	LakeR35	1.50 m ^{-0.5}
	10	LakeR25	LakeR26	LakeR27	LakeR36	2.34 m ^{-0.5}

Note: ¹ These highlighted lakes are strongly stratified mesotrophic and oligotrophic deep lakes

2.4 Results and Discussion

2.4.1 Simulated Water Temperature and DO under Past and Future Climate

MINLAKE2012 configured for each of the 23 lakes (Table 2.1) was first calibrated using available measured temperature and DO profiles by adjusting calibration parameters to obtain the best match with measured profiles. Model calibration parameters include the wind-sheltering coefficient, the sedimentary oxygen demand coefficient, the multiplier of the diffusion coefficient in metalimnion, and the multiplier for chlorophyll-a concentration below the mixed layer. These parameters were well studied for many other Minnesota lakes with necessary guidance for model calibration (Fang et al. 2012a). Weather data from the closest station were used as model input for calibration. Five weather stations (Bemidji, Brainerd, Grand Rapids, and St. Clouds in Minnesota and Fargo in North Dakota) were used in the study, and weather data at Bemidji were used for 9 of 23 study lakes. Figure 2.4 shows time-series of measured and simulated water temperatures in Woman Lake from 2000 to 2006 and projected temperatures under MIROC 3.2 future climate scenario at three depths (1.0, 7.5, and 15.0 m below the surface). Average standard error (root mean square error) between simulated and measured water temperatures from 18-day profiles (362 data pairs) from 2000 to 2006 was 2.05 °C. Average standard error between simulated and measured DO concentrations was 1.93 mg/L. Simulated water temperatures matched well with measured temperatures at three different depths except one simulated temperature at 15.0 m in 2006 (Figure 2.4). The measured and simulated water temperatures at all three depths responded to the weather variations of each season every year. Surface temperatures ranged from 0.0 to 28.7 °C in 2000–2006 and are projected to range from 0.2 to 31.6 °C under the future climate scenario. Projected increases of surface temperatures during the open-water seasons range from 0.3 to 10.2 °C with a mean increase of 3.6 °C and standard deviation of 1.1 °C for six years. Water

temperatures at all three depths are projected to increase under the future climate scenario (Figure 2.4).

Woman Lake located in Cass County, Minnesota has a maximum depth of 16.5 m and a surface area of 19.2 km². Woman Lake is oligotrophic due to its mean Secchi depth 4.2 m and mean chlorophyll-a concentration 2.6 µg/L and has relatively weak stratification because its geometry ratio 4.02 m^{-0.5} is larger than 3.0 m^{-0.5}. The weak stratification in Woman Lake is indicated by mean temperature difference 2.1 °C (standard deviation 2.3 °C) between surface and bottom layers during the open-water seasons under both past and future climates (Figure 2.4). Attenuation of solar radiation with water depth and vertical mixing are major factors that control the formation of temperature stratifications in a lake during the summer months. Projected increases of bottom temperatures during the open-water seasons are up to 6.8 °C with mean increase 2.2 °C (standard deviation 2.3 °C) in Woman Lake (Figure 2.4).

Simulated DO matched well with measured DO during summer periods at three different depths except one simulated DO at 15.0 m in 2003 (Figure 2.5). Measured and simulated DO near the lake bottom reached anoxic conditions in every late summer in Woman Lake, but anoxic conditions only lasted a short duration (Figure 2.5). DO stratification between surface and bottom layers ranged from 0 to 12.3 mg/L with mean stratification 3.0 mg/L and standard deviation 3.1 mg/L during the open-water seasons in 2000–2006. DO stratification (Figure 2.5) was stronger than temperature stratification (Figure 2.4) in Woman Lake because various chemical and biological oxygen demands and weaker vertical mixing resulted in lower DO in hypolimnion (deep depths). DO during winter ice-cover periods under the future climate scenario is projected to be higher than DO under past climate conditions because of reduction in snow and ice thicknesses and shorter ice-cover period, which were reported before in other northern lakes by Fang and

Stefan (Fang and Stefan 2009a). DO during the open-water seasons is projected to be slightly lower than DO under past climate conditions. Projected differences of surface DO between the future and past climates are up to -1.9 mg/L with mean decrease -0.6 mg/L in Woman Lake during the summer months.

Figure 2.4 and Figure 2.5 are examples to show temperature and DO variations in Woman Lake under past climate conditions and the future climate scenario, and similar variations over seasons and similar changes due to climate warming are projected to occur in other study lakes. These changes in water temperature and DO concentration in lakes are eventually projected to affect cisco habitat, which will be discussed below.

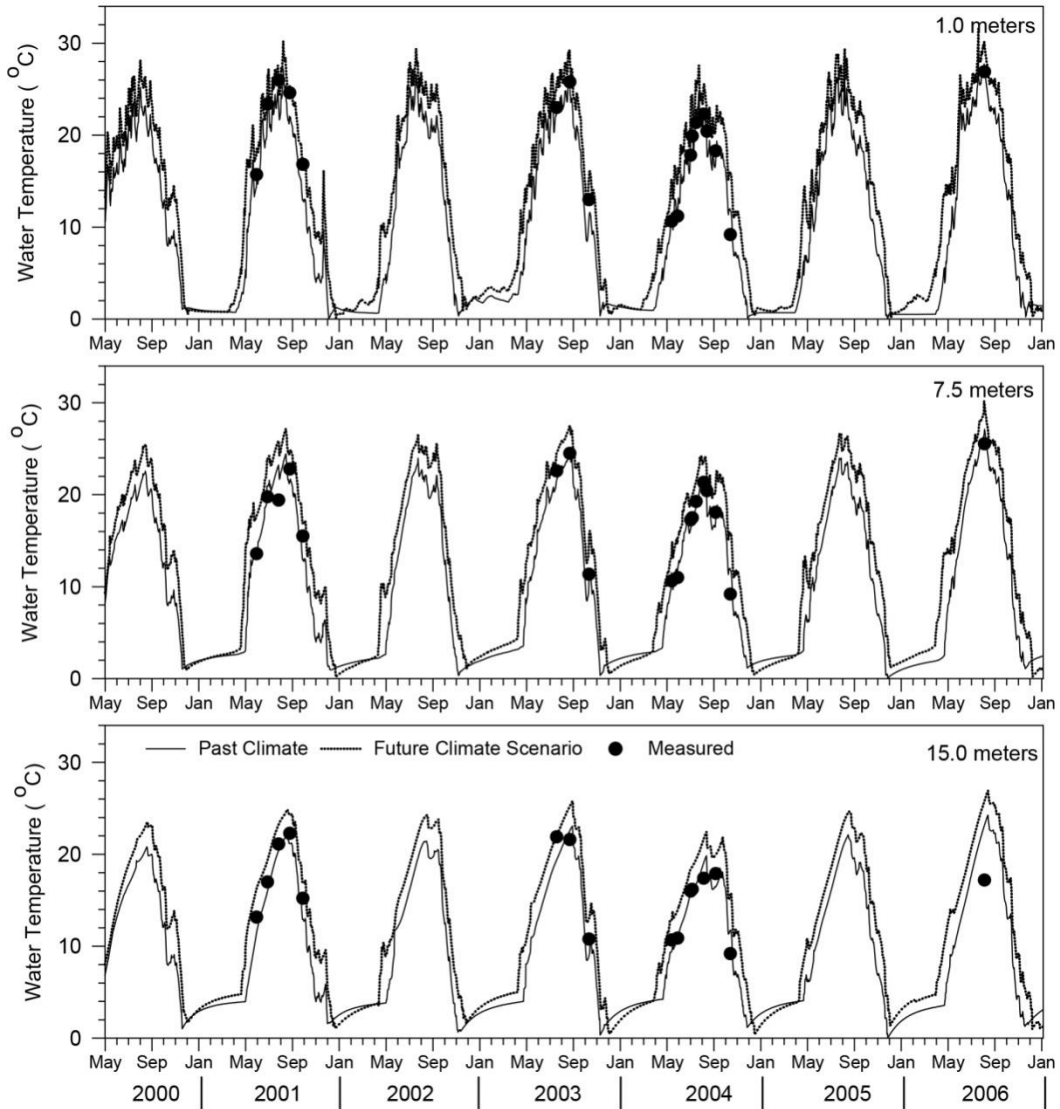


Figure 2.4 Time-series plots (2000–2006) of simulated and measured water temperatures at 1.0, 7.5, and 15.0 m depths for Woman Lake in Minnesota under past climate conditions and the future climate scenario (MIROC 3.2)

Average standard errors between measured and simulated temperatures and DO concentrations were 1.57 °C and 1.72 mg/L, respectively, for all 23 Minnesota lakes (Table 2.1). There were six study lakes with only one profile in 2006 for model calibration. The Nash-Sutcliffe efficiency (NSE) model coefficient (Nash and Sutcliffe 1970) is typically used to assess the predictive power of numerical simulation models. It is defined as:

$$NSE = 1 - \frac{\sum_{n=1}^N (O^n - P^n)^2}{\sum_{n=1}^N (O^n - \bar{O})^2} \quad (2.4)$$

where N is the number of observation and predication data pairs, O^n is the value of the n^{th} observed data, P^n is the n^{th} predicted value from the model, and \bar{O} is the average value of all observed data. The NSE can range from $-\infty$ to 1. An efficiency of 1 ($NSE = 1$) corresponds to a perfect match between modeled values and observed data. An efficiency of 0 ($NSE = 0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas as efficiency less than zero ($NSE < 0$) occurs when the observed mean is a better predictor than the model. The closer the model efficiency is to 1, the more accurate the model is. Average NSE for temperature simulations in the 23 lakes is 0.86 and for DO simulations is 0.66. Therefore, MINLAKE2012 was well calibrated for the 23 lakes.

2.4.2 Validation of Fish Habitat Model

The fish habitat model uses simulated daily temperature and DO profiles in a lake to check day by day whether cisco habitable or lethal conditions occur. Figure 2.3 shows three types of cisco habitat in three different Minnesota lakes. The first case is when cisco habitat exists at all water depths, i.e., simulated DO concentrations are greater than DO_{lethal} values calculated using simulated temperatures and Equation (3), in which all DO-temperature data points (filled circles

in Figure 2.3) are located to the left side of or above the lethal-niche-boundary curve. The three example days 10/15/2004 in Pine Mountain Lake, 9/12/2008 in Itasca Lake, and 9/2/2004 in Woman Lake, are the first cases of survivable cisco habitat at all water depths. The second case is when cisco habitat exists at some depths, i.e., simulated DO concentrations are less than calculated DO_{lethal} values in only some of the water layers. Cisco lethal conditions were not assumed to occur because cisco could swim to other water layers with suitable DO and temperature conditions. For example, Pine Mountain Lake on 7/9/2005 (filled triangles in Figure 2.3) had lower DO at higher temperatures near the surface and near anoxic DO (0.2 mg/L) in the hypolimnion. Therefore, layers near the surface and in the hypolimnion could not support cisco habitat, but some intermediate layers had high enough DO at simulated temperatures to support cisco habitat. Itasca Lake on 8/7/2008 and Woman Lake on 7/18/2001 had suitable cisco habitat in the surface layers and no cisco habitat in the bottom layers (Figure 2.3). Itasca Lake located in Clearwater County, Minnesota has a maximum depth of 13.7 m and a surface area of 4.3 km². Itasca Lake is mesotrophic due to its mean Secchi depth 2.8 m and mean chlorophyll-a concentration 10.4 µg/L and has relatively weak stratifications because of its GR = 3.32 (Gorham and Boyce 1989; Stefan et al. 1996).

When simulated DO concentrations are less than the DO_{lethal} values in all water layers, fish can't live in any depth of the lake, therefore, lethal conditions for cisco occur on that day. Figure 2.6 shows simulated DO versus simulated temperature during two periods (7/11/2006–8/24/2006 and 8/26/2006–8/29/2006) in Pine Mountain Lake when cisco lethal conditions were predicted by the fish habitat model using the cisco lethal-niche-boundary curve. Pine Mountain Lake located in Cass County, Minnesota has a maximum depth of 23.8 m (deep lake) and a surface area of 6.36 km². Pine Mountain Lake is a mesotrophic stratified lake because of its mean Secchi depth 2.4 m,

mean chlorophyll-a concentration 6.5 $\mu\text{g/L}$, and $\text{GR} = 2.11$. Surface water temperatures in Pine Mountain Lake reached 29.4 $^{\circ}\text{C}$ on July 31, 2006. Another study (Jiang and Fang 2016) concluded that lethal temperature for adult cisco is about 22.1 $^{\circ}\text{C}$. In the 49 days in Pine Mountain Lake (Figure 2.6), 43% of water depths had temperatures greater than 22.1 $^{\circ}\text{C}$, and 58% of water depths had $\text{DO} < 3 \text{ mg/L}$. Therefore, cisco mortality in Pine Mountain Lake was reported on July 26, 2006 (Jacobson et al. 2008) when the fish habitat model predicted continuous 16 days of lethal conditions starting from July 11, 2006.

The fish habitat modeling using the cisco lethal-niche boundary curve was validated in the 23 study lakes. Validation results are summarized in Table 2.1 for each lake, which lists the first Julian Day, the last Julian Day, and the total number of days with cisco lethal conditions predicted by the model in 2006 (hindcast or backtesting). It also lists the first Julian Day and the number of continuous days with cisco lethal conditions predicted in 2006. For example, Little Turtle has “182(4)” under “simulated lethal days in 2006” in Table 2.1 that means lethal conditions were simulated on Julian Day 182 (July 1, 2006) and the number of continuous cisco lethal days is four (Julian Days 182–185). The Julian Day and month/day in 2006 inside brackets when cisco mortality was reported in each lake is listed under “Observed mortality day in 2006” in Table 2.1 and used to examine model agreement. In the last column of Table 2.1, the first Yes/No gives the agreement of cisco lethal prediction and reported cisco mortality in 2006, and the second Yes/No inside brackets gives the agreement whether or not cisco lethal days from the model includes reported date with cisco mortality. For example, in Pine Mountain Lake Table 1.1 the fish habitat model predicted a total of 49 days from July 11 (Julian Day 192) to August 29 (Julian Day 241) having cisco lethal conditions, which agree with reported cisco mortality in 2006; and the period of predicted cisco lethal conditions includes the reported day with cisco mortality, i.e., July 26 or

Julian Day 207. Therefore, the model agreement with mortality observation is Yes (Yes) as listed in Table 2.1. The fish habitat model predicted the Yes (Yes) agreement in 11 of the 18 lakes that experienced cisco mortality in 2006.

For five lakes (Bemidji, Mille Lacs, Star, Seventh Crow Wing, and Long), the model predicted cisco lethal conditions, but the predicted lethal periods did not include corresponding reported cisco mortality days in 2006; these lakes have the Yes (No) agreement (Table 2.1). For three lakes (Bemidji, Mille Lacs, and Star), cisco lethal conditions were predicted to occur after the reported cisco mortality days in 2006. In the Seventh Crow Wing Lake, cisco lethal conditions were predicted to occur from Julian Day 196 to 215 (August 3) in 2006, and the cisco mortality was reported on August 4. This case can be considered as Yes (Yes) agreement because cisco mortality might be reported one or a few days after cisco mortality occurred when study lakes were not constantly monitored and observed. Long Lake was predicted with only one day of lethal conditions. Long Lake located in Otter Tail County, Minnesota has a maximum depth of 39.0 m (deep lake) and a surface area of 5.1 km². Long Lake is a mesotrophic strongly stratified lake because of its mean Secchi depth 3.0 m, mean chlorophyll-a concentration 7.2 µg/L, and GR = 1.22. There was only one day in 2006 with observed temperature and DO profiles in Long Lake for model calibration.

There are two lakes (Straight Lake and Lake Carlos) that the model did not predict cisco lethal conditions, but they had cisco mortality in 2006; the model has the No agreement with mortality observation (Table 2.1). Lake Carlos located in Douglas County, Minnesota has a maximum depth of 49.7 m and a surface area of 10.5 km². Lake Carlos is a mesotrophic strongly stratified lake because of its mean Secchi depth 3.0 m, mean chlorophyll-a concentration 5.0 µg/L, and GR = 1.15. The late summer cisco mortality event that occurred on August 27 in Lake Carlos did not fit

the lethal-niche-boundary curve developed from the midsummer events in 16 lakes (Jacobson et al. 2008). Based on the lethal-niche-boundary curve and measured profiles on September 1, 2006 (Jacobson et al. 2008), cisco could exist in some surface layers with low temperatures and high DO, but could not exist in the hypolimnion with anoxic conditions.

Jacobson et al. (Jacobson et al. 2008) also studied the 5 reference lakes that did not experience cisco mortality in 2006. These five reference lakes are all deep strongly stratified lakes (GR < 1.4 in Table 2.1). The fish habitat model using simulated temperature and DO profiles predicted no lethal conditions for cisco in all five reference lakes (Table 2.1). Therefore, the fish habitat model has overall good agreement in the 23 study lakes with and without cisco mortality reported in 2006.

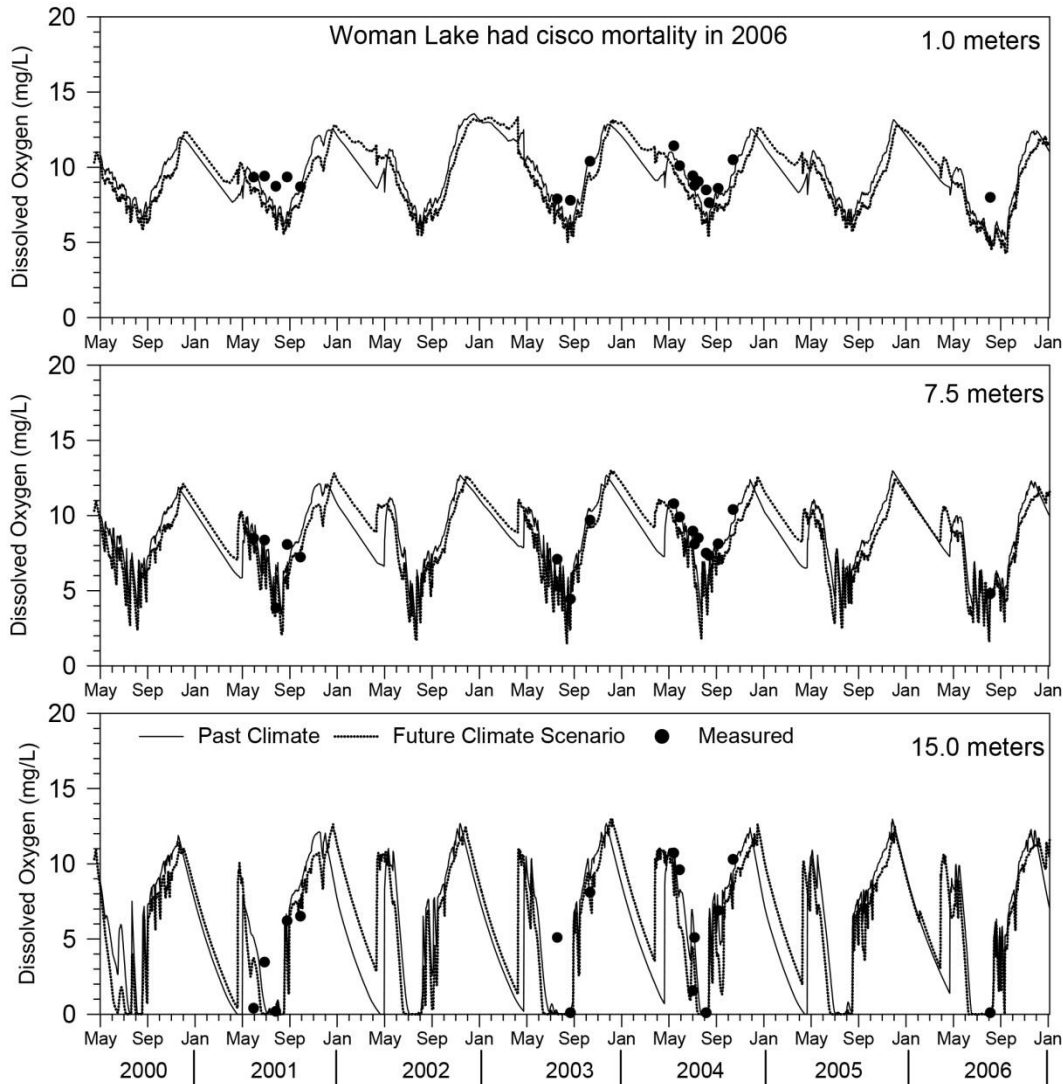


Figure 2.5 Time-series plots (2000–2006) of simulated and measured DO concentrations at 1.0, 7.5, and 15.0 m depths for Woman Lake in Minnesota under past climate conditions and the future climate scenario (MIROC 3.2)

2.4.3 Fish Habitat Simulations in 36 Representative Lake Types

To understand cisco habitat and to determine cisco kill in different lake types, daily water temperature and DO profiles were simulated using MINLAKE2012 under past (1991–2008) climate conditions from Bemidji weather station and the corresponding future climate scenario (MIROC 3.2). Bemidji weather station is close to most of the 23 study lakes (Table 2.1) and has

18 years of weather data. In previous regional fish habitat projections (Stefan et al. 1992), water temperature and DO profiles were averaged over the entire simulation period before the fish habitat model was applied. In this study, the fish habitat model for cisco was applied every day year by year from 1992 to 2008 using simulated daily water temperature and DO profiles. Results for the first simulation year (1991) were not used for cisco modeling in order to remove the possible effect of initial conditions.

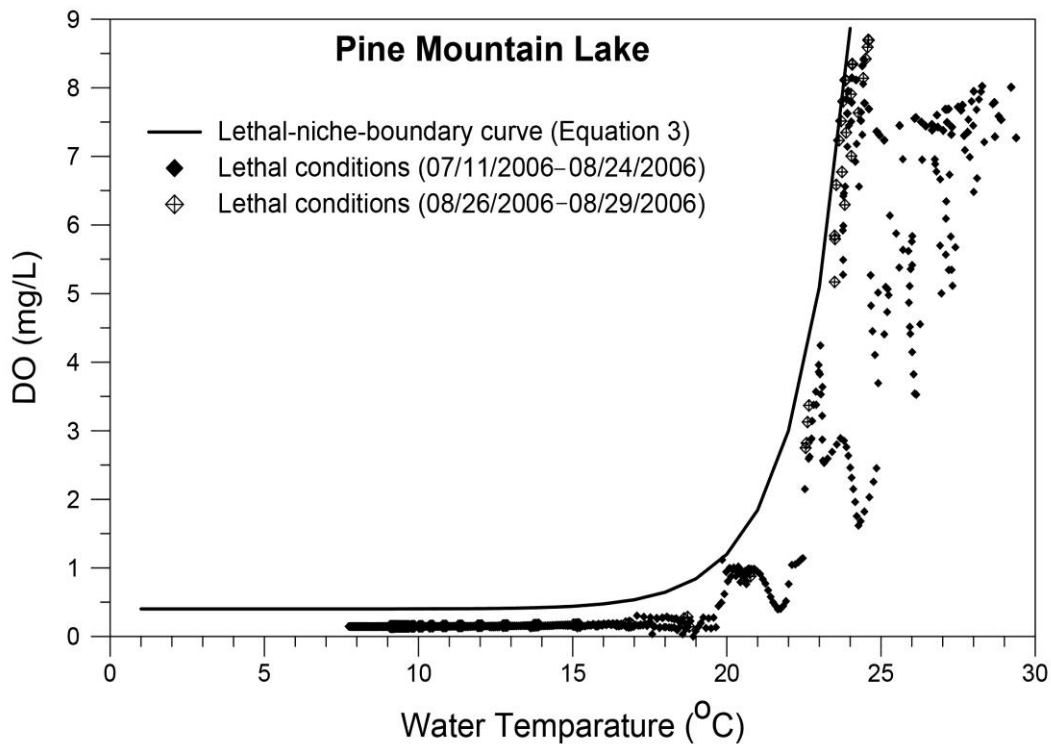


Figure 2.6 Simulated DO versus simulated temperature in 49 cisco lethal days in Pine Mountain Lake and the lethal-niche-boundary curve of cisco

2.4.3.1 Total days of cisco lethal conditions in each year

Total days of lethal conditions for cisco in each year over 17 simulation years were used to create box plots (Figure 2.7) showing the maximum, minimum; and 25%, 50%, and 75% quartile values simulated for each of the 36 representative lake types in Minnesota under past climate

conditions (bottom) and MIROC 3.2 future climate scenario (top). Different scales for y axis were used for results under past climate conditions (maximum 50 days) and the future climate scenario (maximum 100 days) in Figure 2.7. The bottom graph of Figure 2.7 has x axis showing lake name and the top graph has x axis showing corresponding GR ($\text{m}^{-0.5}$) value and SD (m) in brackets. Lethal conditions may be continuous for many days or discontinuous for some days (Table 2.1). For the 12 shallow lakes with $\text{GR} \geq 5.29 \text{ m}^{-0.5}$, median annual days of cisco lethal conditions ranged from 13 to 22 days under past climate conditions and are projected to range from 47 to 55 days under the future climate scenario (Figure 2.7). These results indicate that shallow lakes typically cannot support cisco habitat. In the MNDNR cisco lake database there are total 620 cisco lakes, of which 37 lakes have $\text{GR} \geq 5.29 \text{ m}^{-0.5}$ and maximum depths less than 11.0 m. There are 14 lakes with $H_{\text{max}} < 5.0 \text{ m}$ that are classified as shallow lakes in Minnesota (Stefan et al. 1996), of which 13 lakes have $\text{GR} > 5.29 \text{ m}^{-0.5}$ and one lake has $\text{GR} = 4.4 \text{ m}^{-0.5}$. These lakes had cisco observed in the past but most likely, they cannot sustain cisco habitat.

For the 12 medium-depth lakes with $H_{\text{max}} = 13.0 \text{ m}$ (LakeR10–LakeR18 and LakeR31–LakeR33), GR values are 1.63, 2.78, and $4.33 \text{ m}^{-0.5}$ (Table 2.2). Median annual days of cisco lethal conditions ranged from 0 to 1 day under past climate conditions and are projected to range from 19 to 49 days under the future climate scenario (Figure 2.7). Under past climate conditions, cisco lethal conditions reached a maximum of 30 days for medium-depth lakes during the unusual hot summer in 2006. These lakes are vulnerable to climate warming because lethal conditions are projected up to 80 days.

For the 12 deep lakes with $H_{\text{max}} = 24 \text{ m}$ (LakeR19–LakeR27 and LakeR34–LakeR36), eutrophic deep lakes (LakeR19, R22, and R25) and mesotrophic large deep lake (LakeR26 with

GR = 2.34 m^{-0.5}) are projected to have some cisco lethal days under the future climate scenario (Figure 2.7). Cisco lethal conditions, however, were not simulated to occur under past climate conditions (1992–2008). Large deep lakes with GR = 2.34 m^{-0.5} seem require Secchi depth more than 2.5 m to have non-lethal conditions under the future climate scenario. Other strongly stratified mesotrophic and oligotrophic deep lakes (LakeR20, R21, and R34 with GR = 0.88; LakeR23, R24, and R35 with GR = 1.50, and LakeR27 and R36 with GR = 2.34 in Table 2.2) are possible to support cisco habitat under both past and future climate conditions (Figure 2.7). These deep lakes are good candidates of cisco refuge lakes (Fang et al. 2012b; Jiang et al. 2012).

The results for deep lakes under past climate conditions seem to have certain disagreement with cisco mortality observations (Table 2.1). Minnesota lakes with $H_{max} < 20.0$ m were classified as deep lakes (Stefan et al. 1996), and 7 of the 18 study lakes with cisco mortality in 2006 are deep lakes with GR ranging from 1.15 to 3.26 m^{-0.5}. Generalized model parameters (Fang et al. 2010b) were used for simulations in the 36 representative lake types, but for the 23 lakes (Table 2.1), model parameters were first calibrated against measured profiles before the cisco habitat model was applied. Differences in model parameters is one of the major reasons for disagreement in habitat projections and suggest that other oxythermal habitat parameters, e.g., TDO3 (Jacobson et al. 2010), should be used for studying cisco fish habitat in relatively deep lakes. TDO3 computed in the fixed and variable benchmark periods were successfully used to classify Minnesota cisco lakes into tier 1 to tier 3 refuge lakes (Fang et al. 2012b; Jiang et al. 2012).

Figure 2.7 shows annual cisco lethal days are strongly dependent on lake stratification characteristics (i.e., GR) but vary relatively weakly with trophic status (i.e., SD). The four lakes with the same GR but different Secchi depths were grouped together to compute mean and standard deviation of annual cisco lethal days under past climate conditions and the future climate scenario

(Figure 2.8). There are consistent patterns of average annual lethal days for each group of lakes with the same maximum depth (shallow, medium-depth, and deep). Shallow lakes ($GR > 5.2 \text{ m}^{-0.5}$) have large numbers of cisco lethal days, medium-depth lakes ($GR = 1.63, 2.78, \text{ and } 4.33 \text{ m}^{-0.5}$) have cisco lethal days increasing with geometry ratio (Figure 2.8), and deep lakes ($GR = 0.88, 1.50, \text{ and } 2.34 \text{ m}^{-0.5}$) have little or no cisco lethal days.

The four lakes with $GR = 1.63 \text{ m}^{-0.5}$ (LakeR10–R12 and LakeR31) are small medium-depth lakes ($A_s = 0.2 \text{ km}^2$ and $H_{max} = 13.0 \text{ m}$). Cisco lethal days projected for these four lakes (especially under the future climate scenario) are different from deep lakes with GR less or greater than $1.63 \text{ m}^{-0.5}$ (Figure 2.8). These results may indicate that fish habitat modeling for deep lakes should be separated from the modeling for medium-depth lakes. To further prove the point, four deep lakes (LakeR41–R44) having $GR = 1.63 \text{ m}^{-0.5}$ ($A_s = 2.32 \text{ km}^2$ and $H_{max} = 24.0 \text{ m}$) were created, and daily temperature and DO profiles were simulated using MINLAKE2012 under past climate conditions and the future climate scenario. The simulated number of annual cisco lethal days in these four deep lakes is zero for all years (1992–2008) under past climate conditions and is projected to be zero under the future climate scenario except for LakeR41, an eutrophic deep lake having one year with 4 days of cisco lethal projection. Therefore, simulations of cisco lethal days in these deep lakes (LakeR41–R44) are consistent with other deep lakes but different from medium-depth lakes with the same geometry ratio. Other fish habitat parameters, e.g., good-growth period for cold-water fish in 27 Minnesota lake types, had similar discontinuous patterns in some medium-depth and deep lakes in a previous study (Fang et al. 2004a). In the MNDNR cisco lake database, there are 385 medium-depth lakes with $5 \text{ m} \leq H_{max} < 20 \text{ m}$ and 221 deep lakes with $H_{max} \geq 20 \text{ m}$. Therefore, it is recommended to model cisco habitat and survival separately for medium-depth lakes and deep lakes in the future.

2.4.3.2 Number of years with cisco kill

It is still uncertain how many days that violate the non-survival or lethal-niche limits are necessary to result fish mortality. In previous regional fish habitat projections (Stefan et al. 1996) when daily water temperature and DO concentration profiles used for fish habitat simulations were long-term (30-year) averages, fish kill was assumed to occur when the number of non-survival days (either consecutive or discontinuous) totaled at least seven. In this study, a sensitivity analysis on the number of continuous lethal days for determining cisco kill was performed when daily profiles were not averaged over 17 years (1992–2008), but cisco lethal conditions were checked in each day year by year. A cisco kill was assumed to occur if the number of continuous lethal days was greater than 3, 7, and 14 days for the sensitivity analysis. The 3 days are the half of 7 days used before, and 14 days are double of 7 days. For the 11 study lakes (Table 2.1) in which the simulated lethal days included the reported cisco mortality days in 2006, the number of continuous lethal days to the mortality day was calculated and ranged from 2 (Gull Lake) to 25 (Little Pine Lake in Crow Wing County) days. Median value of the number of continuous lethal days to the mortality day was 14 days (mean value 13 days with a standard deviation 7 days). This result is another reason to use 14 days for the sensitivity analysis.

Using 3, 7, and 14 continuous lethal days for determining cisco kill, Figure 2.9 shows the numbers of years with cisco kill simulated for the 36 representative lake types in Minnesota for 17 simulation years under past (1992–2008) climate conditions (blue triangles) and the future climate scenario (black circles). The x axis gives lake's geometry ratio, and the four lake types with the same geometry ratio (Table 2.2) were grouped together to compute mean and standard deviation of the number of years with cisco kill. Under past climate conditions, the 12 shallow lakes (LakeR01–LakeR09, LakeR28–LakeR30, $GR = 5.29, 9.03, \text{ and } 14.06 \text{ m}^{-0.5}$) were simulated to

have cisco kills on average in 14 to 15 years when 3 continuous lethal days was used to determine whether cisco kill happens or not. Under the future climate scenario (MIROC 3.2), the 12 shallow lakes are projected to have cisco kills in all 17 simulation years. These results provide strong evidence to indicate that shallow lakes cannot support cisco habitat. In the MNDNR cisco lake database, there are only 14 lakes that are classified as shallow lakes with $H_{max} < 5$ m (Stefan et al. 1996). These shallow lakes are weakly stratified or polymictic with relatively high temperatures from surface to bottom during the summer which caused summer cisco kill almost every year from 1992–2008. Although cisco was observed in these 14 lakes in the past, whether cisco still exists in them is unknown. The projection under the future climate scenario shows they are not favorable to support cisco habitat every year.

When 7 continuous lethal days were used to determine whether cisco kill happens, the 12 shallow lakes were simulated to have cisco kills on average in 11 to 12 years (range from 9 to 13 years) under past climate conditions and are projected to have 17 years of cisco kills under the future climate scenario. When 14 continuous lethal days were used to determine whether cisco kill happens, the 12 shallow lakes were simulated to have only 1 year (2006) with cisco kill under past climate conditions and are projected to have 11 to 12 years of cisco kills under the future climate scenario. It projects there are more years with cisco kills in some medium-depth lakes than in the 12 shallow lakes under the future climate scenario (Figure 2.9). This finding may indicate that 14 continuous lethal days for determining cisco kill may be longer than how many lethal days would be needed for cisco mortality to occur because it gives inconsistent results on fish habitat projections. Therefore, the 14 continuous lethal days for determining cisco kill is not recommended for further fish habitat study.

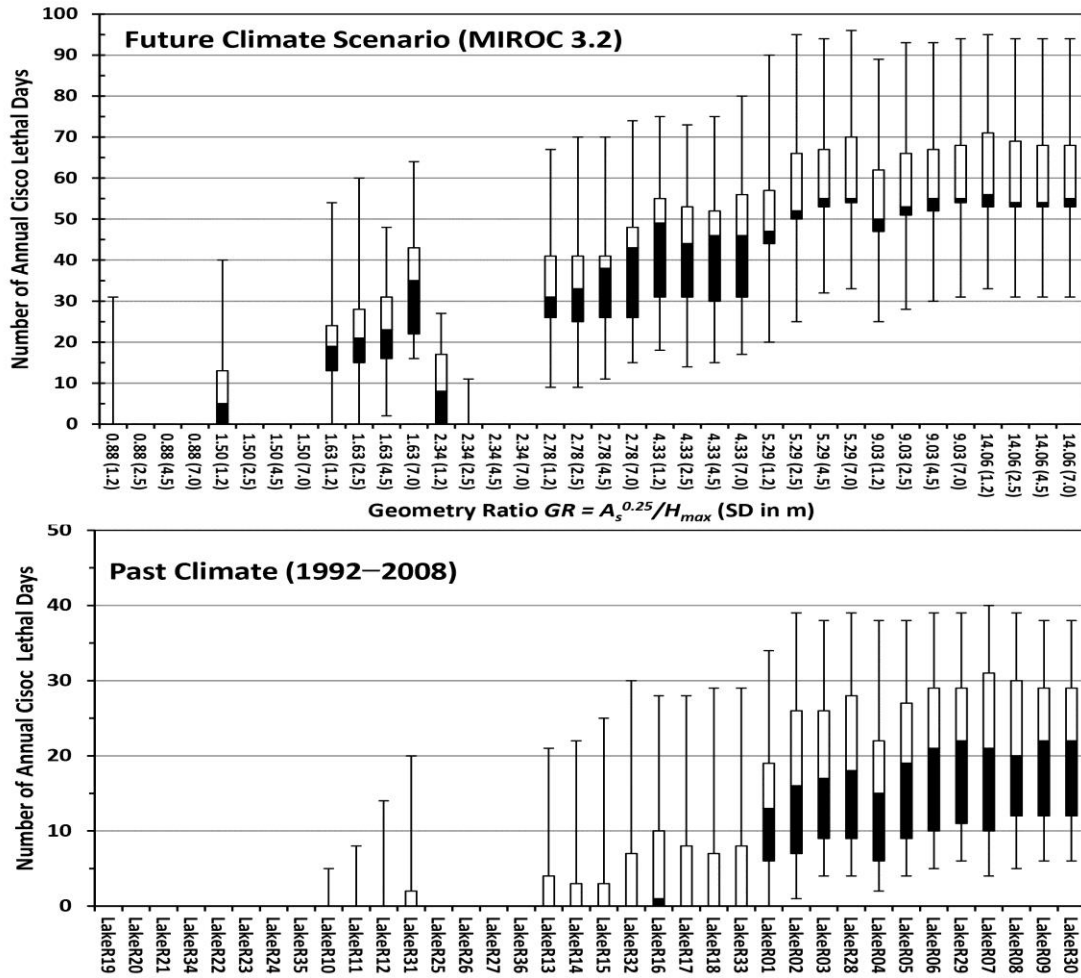


Figure 2.7 Box plots of number of annual cisco lethal days simulated for the 36 representative lake types in Minnesota under past climate conditions (bottom) and the future climate scenario (top).

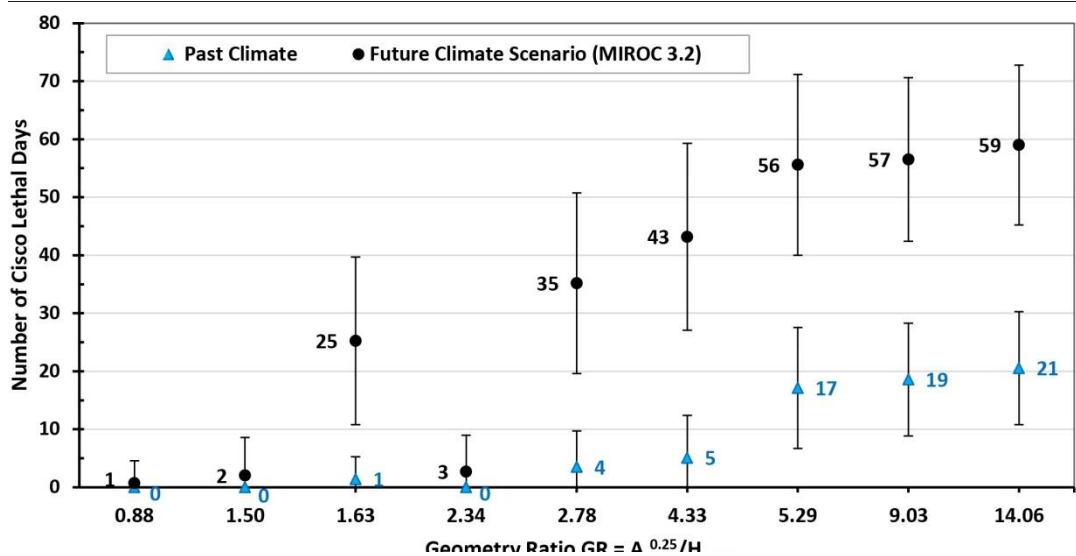


Figure 2.8 Number of annual cisco lethal days (mean \pm standard deviation) simulated for the 36 representative lake types with 9 GR values under past climate conditions and the future climate scenario

Using 3 continuous lethal days for determining cisco kill, the 12 medium-depth lakes were simulated to have cisco kills on average in 2 to 7 years (range from 1 to 8 years) under past climate conditions and are projected to have 16 to 17 years of cisco kills under the future climate scenario. Using 7 continuous days for determining cisco kill, the 12 medium-depth lakes were simulated to have cisco kills on average in 1 to 5 years (range from 0 to 6 years) under past climate conditions and are projected to have 15 to 17 years (range from 13 to 17 years) of cisco kills under the future climate scenario. Figure 2.9 shows medium-depth lakes are most vulnerable to climate warming with average increase of 13 years with cisco kill (range from 9 to 15 years).

The 12 deep lakes were simulated to have no cisco kill under past climate conditions using either 3 or 7 continuous lethal days for determining cisco kill. The 12 deep lakes are projected to have on average 1 to 4 years (range from 0 to 9 years) or 0 to 2 years (range from 0 to 6 years) of cisco kills under the future climate scenario when 3 and 7 continuous lethal days were used for

determining cisco kill, respectively. Only eutrophic deep lakes ($SD = 1.2$ m, LakeR19, LakeR22 and LakeR25) and large mesotrophic deep lake ($A_s = 10$ km², $SD = 2.5$ m, LakeR26) are projected to have a few years with cisco kill under the future climate scenario. Figure 2.9 shows most mesotrophic and oligotrophic deep lakes can support cisco habitat under both past climate conditions and the future climate scenario and are good candidates for cisco refuge lakes, as supported by previous studies (Fang et al. 2012b; Jiang et al. 2012). It seems that 3 or 7 continuous lethal days for determining cisco kill provide quite reasonable results for cisco kill simulations in shallow, medium-depth, and deep lakes in Minnesota.

The box plots of the numbers of annual continuous lethal days greater than or equal to 3 and 7 days simulated for the 36 lake types in Minnesota under past climate conditions (1992–2008) and the future climate scenario (MIROC 3.2) are presented in Figure 2.10. Those lethal days that are not continuous for 3 or 7 days were excluded, therefore, the number of annual continuous lethal days in any lake presented in Figure 2.10 is less than or equal to the number of annual lethal days reported in Figure 2.7 for the corresponding lake. Under past climate conditions, one to a few years with cooler summers did not result in cisco kills in the 12 shallow lakes, but most other years had cisco kills with annual continuous lethal days up to 36 days (Figure 2.10). Under the future climate scenario, projected annual continuous lethal days are up to 94 days and 40 days in shallow lakes and eutrophic deep lakes, respectively. Medium-depth lakes are projected to have relatively large change in annual continuous lethal days (Figure 2.10, different scales on y axis). As explained before, the four medium-depth lakes with $GR = 1.63$ m^{-0.5} seem to behave different from other deep lakes with similar geometry ratio (Figure 2.10), which means they should be studied separately from deep lakes.

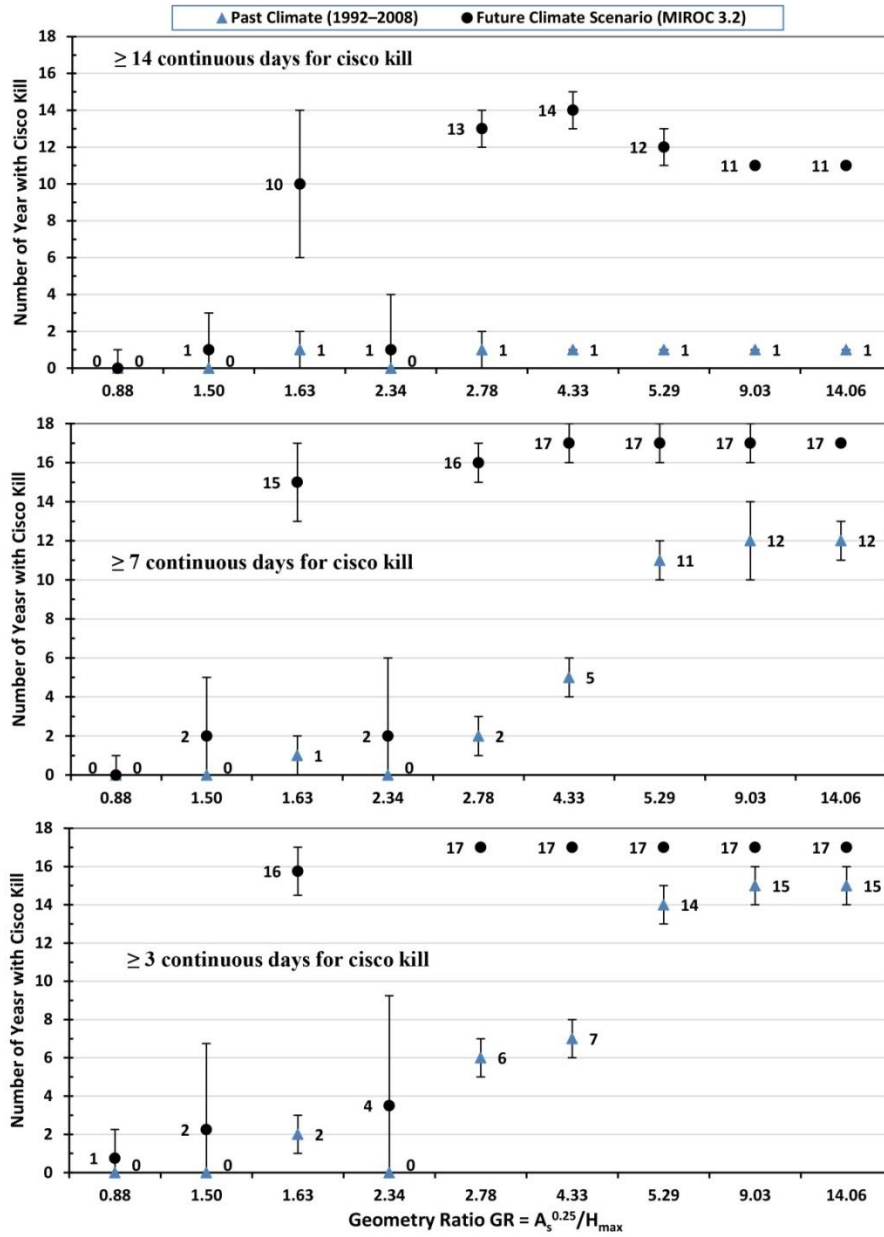


Figure 2.9 Numbers of years with cisco kill simulated for the 36 representative lake types in Minnesota under past climate conditions (triangles) and the future climate scenario (circles) using 3, 7, and 14 continuous lethal days for determining cisco kill

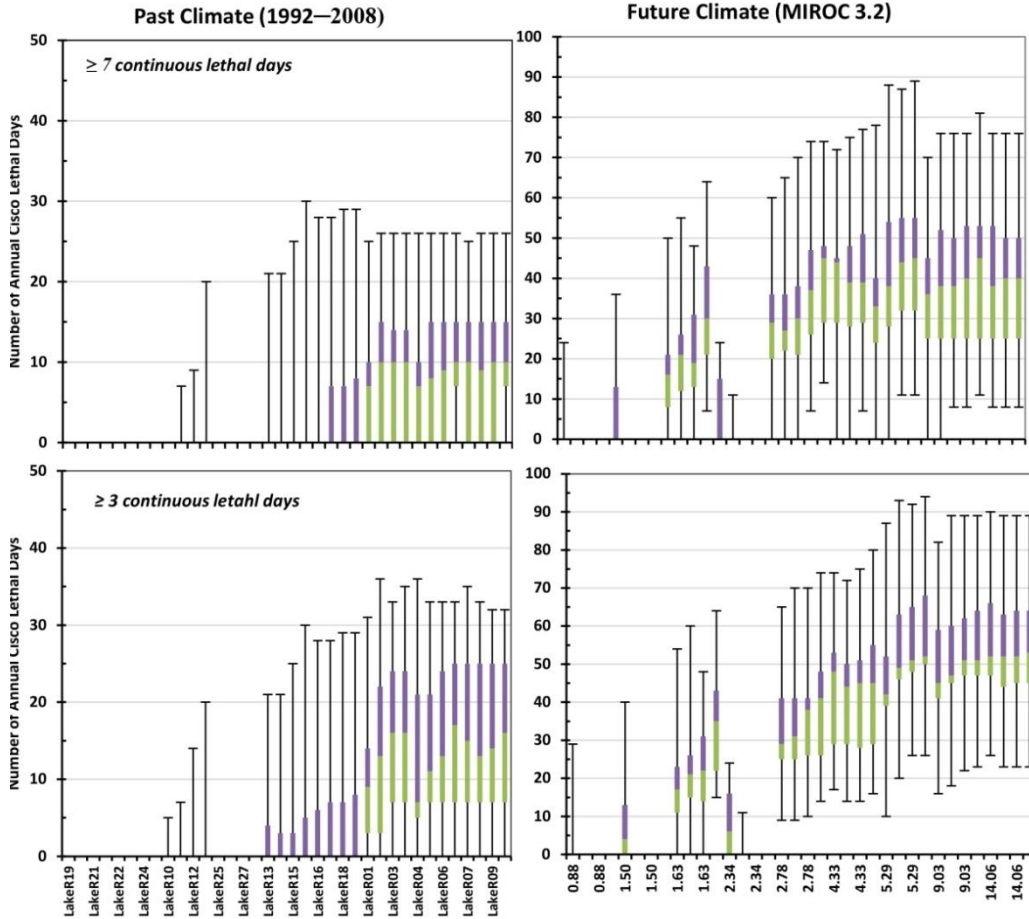


Figure 2.10 Numbers of annual continuous lethal days greater than or equal to 3 and 7 continuous days simulated for the 36 lake types in Minnesota under past climate conditions (1992–2008 Bemidji weather data) and the future climate scenario (MIROC 3.2)

2.5 Limitation

Frey (Frey 1955) postulated that young ciscoes are more tolerant of high temperatures and low DO concentrations than the larger and older ciscoes; they can survive through hot summers in a thin stratum above the thermocline in stratified deep lakes. Therefore, summer mortality events primarily affect adult cisco. Cisco populations can persist in lakes with multiple years of mortality as long as some juveniles remain in the lakes. Recruitment of juveniles is therefore as important

to cisco's survival as the duration of exposure to lethal conditions, but recruitment is not included in current simulations and projections. At the same time, the shallow lakes that are projected to have cisco kill every year with continuous lethal conditions up to 94 days (Figure 2.10) under the future climate scenario are most likely not able to sustain cisco habitat at any life stage.

The increase in the number of annual lethal days in different lake types (Table 2.2) are projected under one future climate scenario (MIROC 3.2) in this study. Many hydrologic studies conducted on the impacts of climate warming or climate change on watersheds and aquatic systems used an assemblage of GCMs. Future studies on cisco habitat projections should include more GCM future climate scenarios, e.g. the Canadian Climate Centre (CCC) GCM 2.0 and CCC Coupled GCM 3.1. Overall, the projection of fish kill and fish growth in lakes is still a challenging and growing research area and needs further model validation with more field observations of fish species in different lakes.

2.6 Chapter Conclusion

Both water temperature and DO in lakes are projected to change due to future climatic warming. The one-dimensional lake water quality model MINLAKE2012 was used to simulate daily water temperatures and DO concentrations under past climate conditions (1992–2008) and MIROC 3.2 future climate scenario in the 36 representative lake types in Minnesota. A fish habitat model using the lethal niche-boundary curve proposed by Jacobson et al. (2008) was developed to evaluate cisco lethal conditions and survival in Minnesota lakes. The fish habitat model uses simulated temperatures to compute required minimum DO concentrations for adult cisco to survive. When simulated DO is less than the minimum required DO based on the lethal-niche-boundary curve at all water depths or layers, lethal conditions for cisco were assumed to occur. Using the fish habitat model, we have obtained the following conclusions:

- (1). MINLAKE2012 was calibrated against measured profiles in 23 Minnesota lakes (Table 2.1) with average standard error of 1.57 °C for temperature and 1.72 mg/L for DO. The fish habitat model using the lethal-niche-boundary curve was applied to the 23 lakes and successfully simulated lethal conditions in 16 of the 18 lakes that experienced adult cisco mortality in 2006 and habitable conditions in five reference lakes that experienced no adult cisco mortality in 2006. Projections from the fish habitat model had an overall good agreement with cisco mortality and survival in 2006.
- (2). The 12 shallow lake types with lake geometry ratio greater than 5.2 m^{-0.5} had 10 to 16 years with many continuous lethal days during 17 simulation years under past climate conditions and are projected to have 16 to 17 years with cisco kill (Figure 2.8) under the future climate scenario. Those shallow lakes projected to have continuous lethal conditions up to 94 days (Figure 2.10) are most likely not able to sustain cisco habitat. This finding supports that there are only 14 shallow lakes out of the 620 cisco lakes (MNDNR database).
- (3). The 12 medium-depth lakes ($H_{max} = 13$ m) were simulated to have lethal conditions under both past climate conditions and the future climate scenario. It is projected that medium-depth lakes have the largest increase in the number of years with cisco kill (average increase 13 years ranging from 9 to 15 years out of 17 simulation years) due to climate warming. Therefore, cisco in the medium-depth lakes are most vulnerable to climate change.
- (3). The four medium-depth lakes with GR = 1.63 m^{-0.5} seem to behave differently in fish habitat projections than deep lakes with similar geometry ratio (Figure 2.7 Figure 2.8 Figure 2.9 Figure 2.10). In the future, fish habitat projections in medium-depth lakes should be studied separately from deep lakes.

(4). Most mesotrophic and oligotrophic deep lakes are good candidates for cisco refuge lakes that can support cisco habitat under both past climate conditions and the future climate scenario. Eutrophic deep lakes and large (surface area) mesotrophic deep lakes are projected to have cisco kills when continuous lethal days are greater than 3 or 7 days. The 3 or 7 continuous lethal days for determining cisco kill give quite reasonable results for cisco kill simulations in all lake types in Minnesota and are recommended for future fish habitat study. Using 14 continuous lethal days for determining cisco kill may be longer than how many lethal days would be needed for cisco mortality to occur and is not recommended for further fish habitat study.

Chapter 3 **Simulation and validation of cisco lethal conditions in Minnesota lakes under past and future climate scenarios using constant survival limits**

3.1 Abstract

Fish habitat in lakes is strongly constrained by water temperature (T) and available dissolved oxygen (DO) that are changed under climate warming. A one dimensional, dynamic water quality model MINLAKE2012 was used for T and DO simulation over 48 years. A fish habitat model FishHabitat2013 using simulated T and DO profiles as input was developed to determine lethal conditions of cisco *Coregonus artedii* in Minnesota lakes. Twenty-three lakes that had observations of cisco mortality or survival in the unusually warm summer of 2006 were used for model validation. The cisco habitat model used a lethal temperature of 22.1 °C and DO survival limit of 3 mg/L determined through model validation and sensitivity analysis. Cisco lethal conditions in 12 shallow, 16 medium-depth, and 30 deep virtual lakes were then simulated. Isopleths of total number of years with cisco kill and average cisco kill days for the years with kills under past (1961–2008) and future climate were generated to understand/extrapolate climate impacts on cisco in 620 Minnesota lakes. Shallow and medium-depth lakes are projected to not be good candidates for cisco refuge lakes, but deep lakes are possible cisco refuge lakes based on lethal condition projection under future warmer climate.

3.2 Introduction

Fish growth and survival in lakes are constrained by several environmental factors such as water temperature (T), available dissolved oxygen (DO), food supply, and human interference. In this study, T and DO, the two most significant water quality parameters affecting survival of fishes in lakes (Fry 1971; Magnuson et al. 1979; Coutant 1985a;

Christie and Regier 1988; Coutant 1990; Jacobson et al. 2008), were simulated using a one-dimensional lake water quality model MINLAKE2012 and were used to simulate/project cold-water fish survival and lethal conditions in 620 cisco lakes in Minnesota under past climate conditions (1961–2008) and one future climate scenario. An increase of atmospheric CO₂ and/or other greenhouse gases is projected to cause climate changes and climate warming (NRC 1983; IPCC 2007), which in turn is projected to warm the water and increase hypolimnetic oxygen depletion during summer stratification in lakes (Blumberg and Di Toro 1990; De Stasio et al. 1996; Fang and Stefan 2009a). Therefore, projected changes of T and DO characteristics due to climate warming have the potential to reduce cold-water fish habitat or result in fish kill in lakes (Stefan et al. 1996; Magnuson et al. 1997; Fang et al. 2004a).

Cisco *Coregonus artedii* is the most common cold-water stenothermal fish in Minnesota lakes, and the Minnesota (MN) Department of Natural Resources (DNR) has sampled cisco from 648 lakes in netting assessments since 1946 (MN DNR files). Cisco also exists in lakes over other northern states, e.g., Wisconsin and Michigan. The combination of a wide geographic distribution in northern Minnesota (Jacobson et al. 2012) and a requirement for cold, oxygenated water (Cahn 1927; Frey 1955; Jacobson et al. 2008) makes cisco a sensitive indicator of ecological stresses caused by climate warming. For example, eighteen lakes (Table 1.1) in north-central Minnesota experienced cisco mortality in the unusually warm summer of 2006 (Jacobson et al. 2008). Ciscoes have been declining in recent years in Minnesota lakes, likely because of climate warming (Jacobson et al. 2012). Sharma, et al. (Sharma et al. 2011) projected that about 30%–70% of the cisco population in about 170 of Wisconsin's deepest and coldest lakes could disappear by 2100. Therefore, the study

Table 3.1 Weather stations and field data used in MINLAKE2012 model calibrations and water temperature and dissolved oxygen calibration results of 23 cisco lakes.

Lake Name (H_{max} (m), GR, (m ^{-0.5})) ¹	Weather Station Used	Field Data Used in Simulation		T		DO	
		Years	Days (Data Pairs) ⁴	RMSE ⁵	NSE ⁶	RMSE	NSE
Little Turtle (8.8, 4.21)	Grand Rapids	06	1 (14)	0.34	0.90	2.27	0.48
Star (28.7, 2.26)	Fargo	73, 00, 06	3 (43)	2.16	0.81	1.15	0.90
Mille Lacs (13.0, 11.89)	Brainerd	81,90–92, 00, 01	70 (699)	1.88	0.86	1.30	0.17
Andrusia (18.3, 2.75)	Bemidji	76–78, 86, 06	11 (95)	2.47	0.81	2.29	0.66
Little Pine (19.2, 2.77) ²	Fargo	80, 85, 86, 06	6(100)	1.97	0.77	2.71	0.50
Cotton (8.5, 6.07)	Bemidji	99, 06	5 (53)	0.92	0.93	1.19	0.82
Pine Mountain (24.4, 2.11)	Brainerd	98, 99, 01, 02, 04–07	27 (519)	1.85	0.82	2.58	0.58
Leech (13.0, 10.91)	Bemidji	06	1 (14)	0.36	0.73	1.86	–0.1
Bemidji (23.2, 3.13)	Bemidji	06	1 (23)	2.08	0.88	0.84	0.95
Itasca (12.2, 3.32)	Bemidji	06, 08	18 (208)	2.89	0.70	2.49	0.56
Gull (24.4, 3.26)	Brainerd	76–78, 89, 91, 92, 04, 06	31 (480)	1.69	0.86	1.24	0.90
Woman (16.5, 4.02)	Grand Rapids	88, 01–04, 06	21 (392)	2.10	0.81	1.99	0.60
Straight (19.2, 1.94)	Bemidji	06, 07	2 (33)	0.88	0.98	1.36	0.93
Little Pine (11.0, 2.90) ³	Brainerd	92–96, 98–02, 06	47 (465)	3.61	0.53	2.46	0.63
7th Crow Wing (12.8, 2.49)	Bemidji	06	1 (12)	0.91	0.88	0.87	0.95
8th Crow Wing (9.1, 4.11)	Fargo	73, 00, 06	3 (43)	1.06	0.91	2.17	0.12
Long (39.0, 1.22)	Fargo	06	1 (18)	0.83	0.97	1.17	0.90
Carlos (49.7, 1.15)	St. Clouds	79, 80, 86, 06, 08	17 (394)	1.62	0.93	1.38	0.86
Total or Average (above 18 lakes with cisco kill in 2006)			266 (3605)	1.65	0.84	1.74	0.64
Reference lakes without cisco kill							
Big Trout (39.0, 1.24)	Brainerd	92–02, 06	47 (938)	1.66	0.92	1.57	0.67
Kabekona (40.5, 1.38)	Bemidji	94, 06	6 (130)	1.31	0.95	0.77	0.93
Scalp (27.4, 1.15)	Fargo	85, 86, 06	4 (75)	1.25	0.97	2.89	0.57
Ten Mile (63.4, 1.06)	Bemidji	01, 02, 06, 08	95 (2771)	1.60	0.91	1.50	0.69
Rose (41.8, 1.12)	Fargo	06	1 (25)	0.68	0.99	1.59	0.80
Total or Average (above 5 lakes without cisco kill in 2006)			153 (3939)	1.30	0.95	1.66	0.73
Total or Average (all 23 lakes)			419 (7544)	1.57	0.86	1.72	0.66

Notes: ¹ H_{max} is the maximum lake depth and GR is the lake geometry ratio (GR) = $A_s^{0.25}/H_{max}$ (A_s is surface area in m²); ² Little Pine Lake at Otter Tail County; ³ Little Pine Lake at Crow Wing County; ⁴ number of pairs of simulated and observed T or DO data (at different days and at different depths) for computing model error parameters; ⁵ Root-mean-square error (RMSE) between simulated and measured (https://en.wikipedia.org/wiki/Root-mean-square_deviation); and ⁶ Nash-Sutcliffe model efficiency (NSE) coefficient (Nash and Sutcliffe 1970).

of survival conditions of cisco in lakes under past and future climate conditions will give natural resource managers information on climate change effects on freshwater organisms and ecosystems.

The goal of the study was to first validate cisco survival and lethal conditions in 23 Minnesota lakes (Table 3.1) under 2006 weather conditions and then simulate daily T and DO profiles in 58 virtual lakes (Table 3.2) (Jiang et al. 2012) to project/extrapolate long-term cisco survival and potential lethal conditions in 620 cisco lakes in Minnesota under a future climate scenario. The physiological response of adult populations of different fish species to T and DO levels has been the subject of numerous laboratory and field studies, e.g., by Coutant (Coutant 1970), McCormick, et al. (McCormick et al. 1972), Hokanson, et al. (Hokanson et al. 1977), Eaton, et al. (Eaton et al. 1995). These studies correlated fish survival, growth, reproduction and other responses to chronic levels of T and DO exposure. The oxythermal habitat approach commonly used in cold-water fish niche modeling (Stefan et al. 2001), defines an upper boundary for T and a lower boundary for DO, which are lethal temperature (LT) and DO survival limit (DO_{Lethal}). These oxythermal habitat models determine the water volume or layer thickness in a stratified lake between the upper temperature and lower DO bounds that represent either optimal thermal habitat (Stefan et al. 2001) or non-lethal/useable habitat (USEPA 1976). The “uninhabitable spaces” or “lethal conditions” for a fish species in a lake are where temperature is above and/or DO is below the survival limits (USEPA 1976). Simulations of oxythermal habitat changes for three fish guilds, i.e., cold-water, cool-water, and warm-water, in response to projected climate warming were conducted in small lakes (up to 10 km² surface area) in Minnesota (Stefan et al. 1996) and in the contiguous USA (USEPA 1976; Fang et al. 2004a). This

study uses the oxythermal habitat approach to simulate and validate the lethal conditions and fish kill in summer for a cold-water fish species—cisco *Coregonus artedii* in 620 Minnesota lakes.

Table 3.2 Morphometric characteristics and “names” of the 12 shallow and 16 medium-depth virtual lakes simulated with the MINLAKE2012 and FishHabitat2013 models.

Maximum Depth (m)	Surface Area	Secchi Depth <i>SD</i> (m)				Geometry Ratio
	A_s (km ²)	1.2	2.5	4.5	7.0	$GR = \frac{A_s^{0.25}}{H_{max}}$
$H_{max} = 4$ (Shallow)	0.2	LakeR01	LakeR02	LakeR03	LakeR28 ²	5.29
	1.7	LakeR04	LakeR05	LakeR06	LakeR29 ²	9.03
	10	LakeR07	LakeR08	LakeR09	LakeR30 ²	14.06
$H_{max} = 13$ (Medium-depth)	0.05	LakeR37 ²	LakeR38 ²	LakeR39 ²	LakeR40 ²	1.15
	0.2	LakeR10	LakeR11	LakeR12	LakeR31 ²	1.63
	1.7	LakeR13	LakeR14	LakeR15	LakeR32 ²	2.78
	10	LakeR16	LakeR17	LakeR18	LakeR33 ²	4.33

Notes: ¹ A_s is the lake surface area in m² when it is used to compute the geometry ratio GR; and ² 10 new virtual lakes added for the study (LakeR19–R27 and LakeR34–R36 are virtual lakes used in other studies).

The processes of pursuing the objective include: (1) validate the FishHabitat2013 model using simulated T and DO profiles given by MINLAKE2012 and cisco mortality or survival data (observations) in 23 Minnesota lakes during an unusually warm summer of 2006; (2) select/develop 58 virtual lakes (12 shallow, 16 medium-depth, and 30 deep), which could represent 620 cisco lakes in Minnesota; (3) perform long-term oxythermal fish habitat modeling in 58 virtual lakes using simulated T and DO profiles, then develop contour plots of total number of years with cisco kill and average cisco lethal days for the years with cisco kill under past climate conditions (1961–2008) and a future climate scenario (MIROC 3.2) for 58 virtual lakes; and (4) qualitatively analyze the cisco mortality

possibility by marking the 620 Minnesota lakes on contour plots generated from oxythermal habitat results in 58 virtual lakes.

3.3 Materials and Methods

3.3.1 Simulation and Validation of Cisco Survival or Lethal Conditions Using Constant Survival Limits

Cisco habitat survival and lethal conditions were determined using LT , DO_{Lethal} , simulated daily T and DO profiles in lakes as model inputs; a method similar to the approach used by Christie and Regier (Christie and Regier 1988) and Fang et al. (Fang et al. 2004a). FishHabitat2013 has two basic and key model parameters: LT and DO_{Lethal} that are kept as constants in all simulation years under past and future climate scenarios; therefore, they are constant survival limits. The fish kill in summer or summerkill is defined as lethal conditions over the entire depth of a lake for 3 continuous days or more during the summer (USEPA 1976).

Depths where simulated daily temperature and DO are equal to LT and DO_{Lethal} are determined day by day in each lake from simulated vertical T and DO profiles. Isopleths of LT and DO_{Lethal} on a depth versus time plot are then developed and used to determine whether, when, and how many days cisco lethal conditions can occur in a particular lake in each simulation year, and an example plot is shown in Figure 3.1 for Lake Andrusia in Minnesota. Simulated T and DO profiles were not averaged during the simulation period as was done in previous studies (Stefan et al. 1996; Fang et al. 2004a). When isopleths of LT and DO_{Lethal} for cisco intersect in a particular day, the entire depth of a stratified lake is under lethal conditions on that day. The lethal conditions occur because water temperature is higher than LT from the water surface to or below the intersecting depth and DO is lower

than DO_{Lethal} from the lake bottom to or above the intersecting depth. When the maximum daily water temperature is lower than the LT, the depth of LT is set to zero (water surface) in Figure 3.1. Therefore, DO_{Lethal} becomes the only lethal criteria during the winter ice-cover period, early spring and later fall, but this study only deals with lethal conditions of cisco during the summer months and Figure 3.1 shows cisco habitat and lethal condition results from 1 April to 31 October (Julian Days 91 to 304).

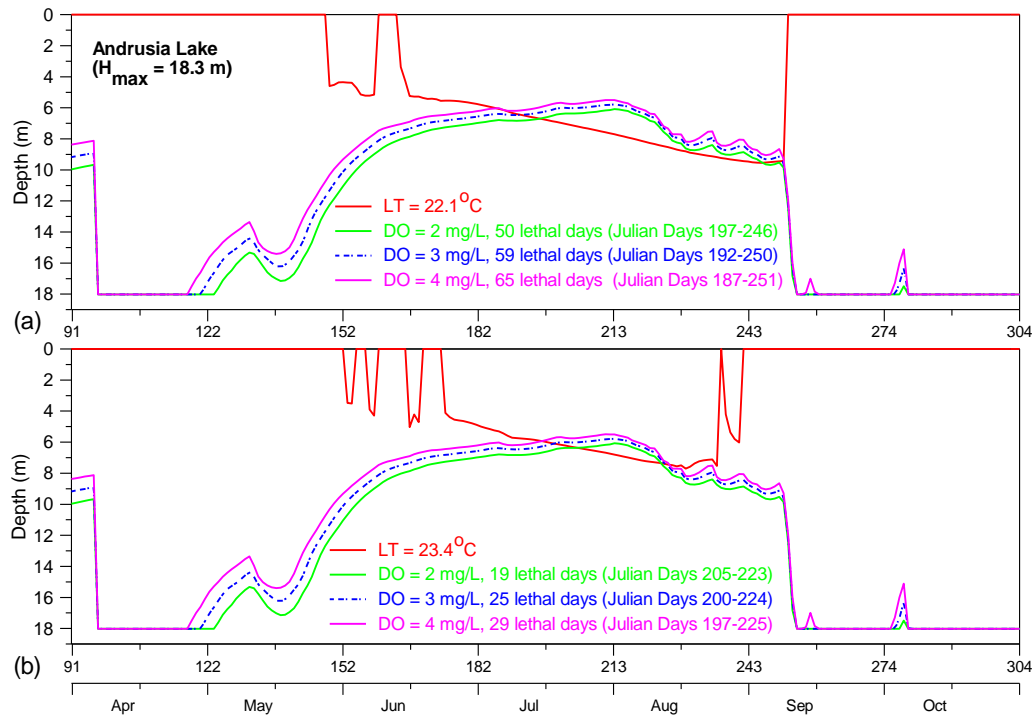


Figure 3.1. Simulated isopleths of lethal temperatures (LT) and DO lethal limits in 2006 for Andrusia Lake. Selected LT are (a) 22.1 °C and (b) 23.4 °C, and selected DO lethal limits are 2, 3, and 4 mg/L for sensitivity analysis (a, b).

In previous studies, LT for each fish species was determined from laboratory, e.g., 22.1 °C for Brook Trout and 26.6 °C for Brown Trout (Eaton et al. 1995; Stefan et al. 1996). Eaton et al. (Eaton et al. 1995) updated the LT values for cold-water fish species that ranged from 19.8 °C (Chum salmon) to 24.1 °C (Brown Trout) with guild mean of 22.9 °C based

on field temperature and fish observations. The LT and DO_{Lethal} for cisco were not well studied in the laboratory by any researcher previously. They were determined through model validation of cisco mortality or survival conditions occurred in the unusually warm summer of 2006 in 23 Minnesota lakes. Adult cisco mortality was reported by Jacobson et al. (Jacobson et al. 2008) in 18 of the 23 cisco lakes in Minnesota (Table 3.1 and Figure 3.2). Cisco mortality happened from mid-July to early August in 2006 (Jacobson et al. 2008). Additional five lakes without cisco mortality in 2006 were also studied by Jacobson et al. (Jacobson et al. 2008); these five lakes were called “reference” lakes by them and in this study. Temperature and DO profiles in 23 lakes were collected shortly after occurrences of adult cisco mortality in 17 lakes (no profile measurement in Mille Lacs Lake) by MN DNR to study LT and DO_{Lethal} . These 23 cisco lakes are located in north central Minnesota (Figure 3.2). The surface areas (A_s) and maximum depths (H_{max}) of the 23 Minnesota lakes ranged from 1.02 to 518.29 km², and 8.53 to 63.4 m (Jacobson et al. 2008), respectively. Based on lake classes developed for Minnesota lakes (Stefan et al. 1996), 12 of the 23 cisco lakes are classified as medium-depth lake as $5 \text{ m} \leq H_{max} < 20 \text{ m}$ (Figure 3a), and remaining 11 lakes are deep lakes as $H_{max} > 20 \text{ m}$ (Figure 3b).

The LT is the water temperature at which fish cannot be acclimated without causing death. The $LT = 23.4 \text{ }^\circ\text{C}$ (Dillon et al. 2003) used for the cold-water fish guild in previous studies (USEPA 1976; Fang et al. 2004a) was the mean value of LT values for ten cold-water fish species (pink salmon, sockeye salmon, chinook salmon, chum salmon, coho salmon, brown trout, rainbow trout, brook trout, lake trout, and mountain whitefish). Jacobson et al. (Jacobson et al. 2008) developed a lethal oxythermal niche boundary curve (equation) for adult cisco. The curve mapped the temperatures and DO concentrations from

the profiles measured in 17 Minnesota lakes (Table 3.1) that experienced cisco mortality in July and August 2006. From the niche boundary curve (Jacobson et al. 2008), the lethal temperature of adult cisco is 22.6 °C at 4.0 mg/L, 22.1 °C at 3.0 mg/L, and 21.2 °C at 2.0 mg/L of DO.

The DO concentration of 3.0 mg/L requirement for the cold-water fish guild, below which mortality is more likely to occur or growth is impaired (Chapman 1986), was developed from an available US EPA database (Chapman 1986). Jacobson et al. (Jacobson et al. 2010) proposed a single oxythermal variable TDO3, and TDO3 is defined as the water temperature at 3 mg/L of DO. The 3 mg/L was selected as a benchmark oxygen concentration that is probably lethal or nearly so for many cold-water species (Frey 1955). Several benchmark DO concentrations (2, 3, 4, and 5 mg/L) were considered by Jacobson et al. (Jacobson et al. 2010) and they were highly correlated as will be demonstrated later.

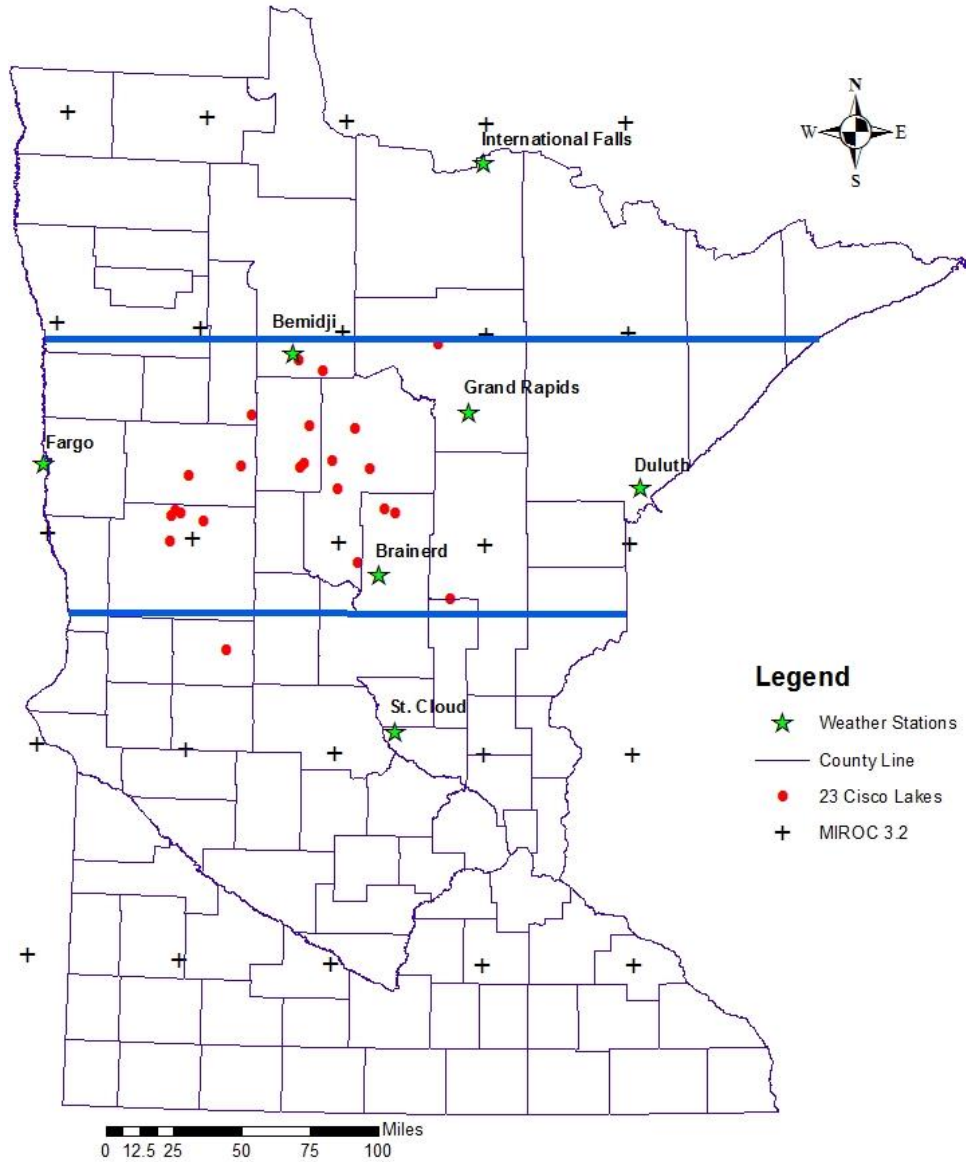


Figure 3.2 Geographic distribution of 23 cisco lakes (red dots) for model calibration and seven weather stations (stars) and grid center point (crosses) of MIROC 3.2 model output on the Minnesota map (with county border lines). Two color horizontal lines are used to separate 620 cisco lakes into northern, mid-latitude, and southern cisco lakes that are associated with three weather stations (International Falls, Duluth, and St. Cloud).

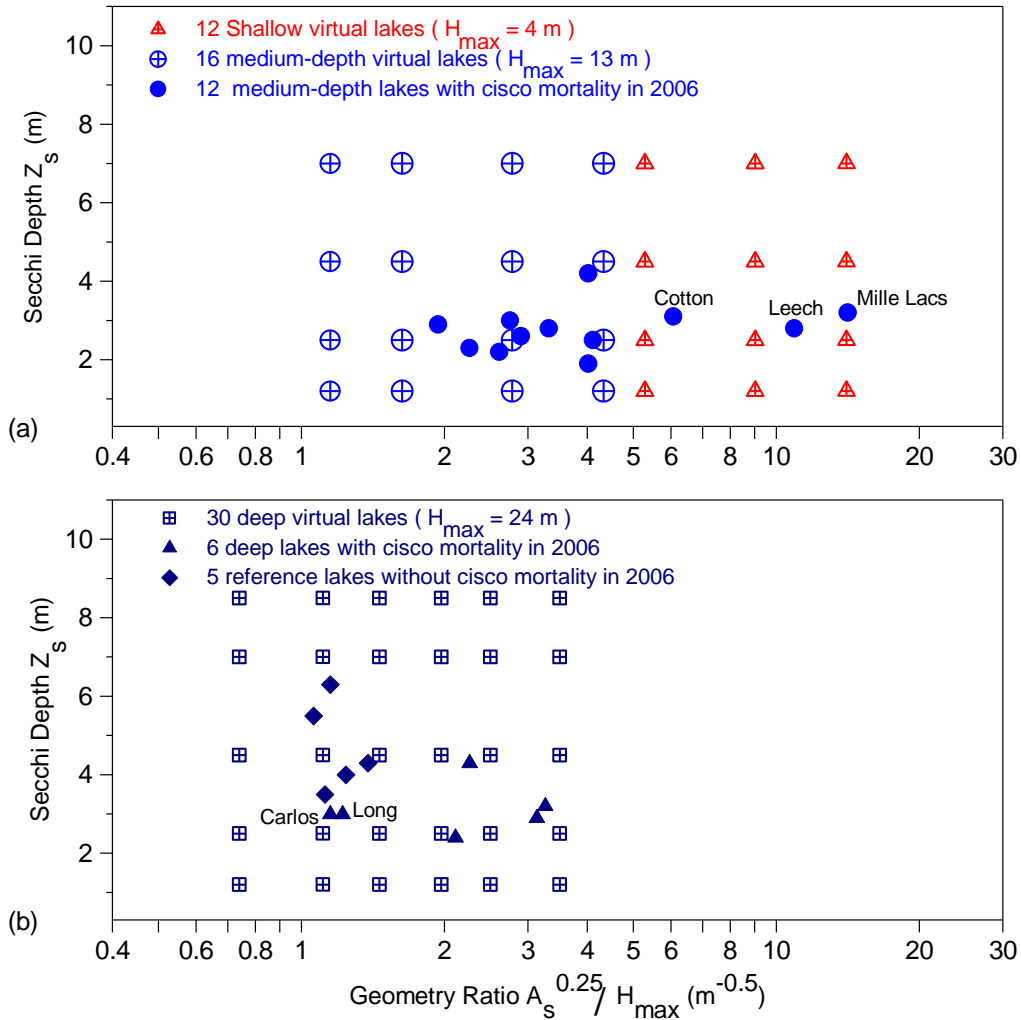


Figure 3.3 Distribution of (a) 12 medium-depth lakes and (b) 11 deep lakes of 23 cisco lakes in Minnesota (Jacobson et al. 2008) including (a) 28 shallow and medium-depth virtual lakes (Table 3.2) and (b) 30 deep virtual lakes (Jiang et al. 2012) plotted using Secchi depth and lake geometry ratio as independent variables.

Before appropriate LT and DO limits for adult cisco were determined in this study, a sensitivity analysis using 22.1 °C and 23.4 °C as LT and 2, 3, and 4 mg/L as DO survival limit was performed. The combinations of two LTs and three DO limits result in six constant LT-DO criteria for the FishHabitat2013 model. The final LT-DO criteria, LT =

22.1 °C and DO = 3 mg/L, was chosen according to fish habitat model validation based on the cisco mortality field data in 2006, discussed and given in the Section 3.4.2.

3.3.2 Selection of 58 Virtual Lakes to Represent 620 Cisco Lakes in Minnesota

An MN DNR lake database contains 620 cisco lakes that were used for this study and previous studies (Coutant 1970). Fang et al. (Fang et al. 2012b) used the fixed benchmark method and Jiang et al. (Jiang et al. 2012) implemented the variable benchmark method to divide these 620 lakes into Tier 1, Tier 2, and Tier 3 refuge cisco lakes using an oxythermal habitat variable TDO3. This study examines the cisco lethal conditions in the same 620 cisco lakes. On average, Minnesota's cisco lakes are deeper, more transparent and less trophic than other lakes in Minnesota (Fang et al. 2009). These 620 lakes are scattered throughout much of the central and northern part of Minnesota (Jiang et al. 2012). Characteristics of 620 lakes are reported previously (Jiang et al. 2012), and they are plotted separately for shallow and medium-depth lakes (Figure 3.4a) and deep lakes (Figure 3.4b) using lake geometry ratio (GR) and Secchi depth (SD) as axes. Mean summer SD is an indicator of lake trophic state (it relates to mean chlorophyll-a levels and summer transparency of a lake), while lake GR is an indicator of summer mixing dynamics of a lake (Gorham and Boyce 1989).

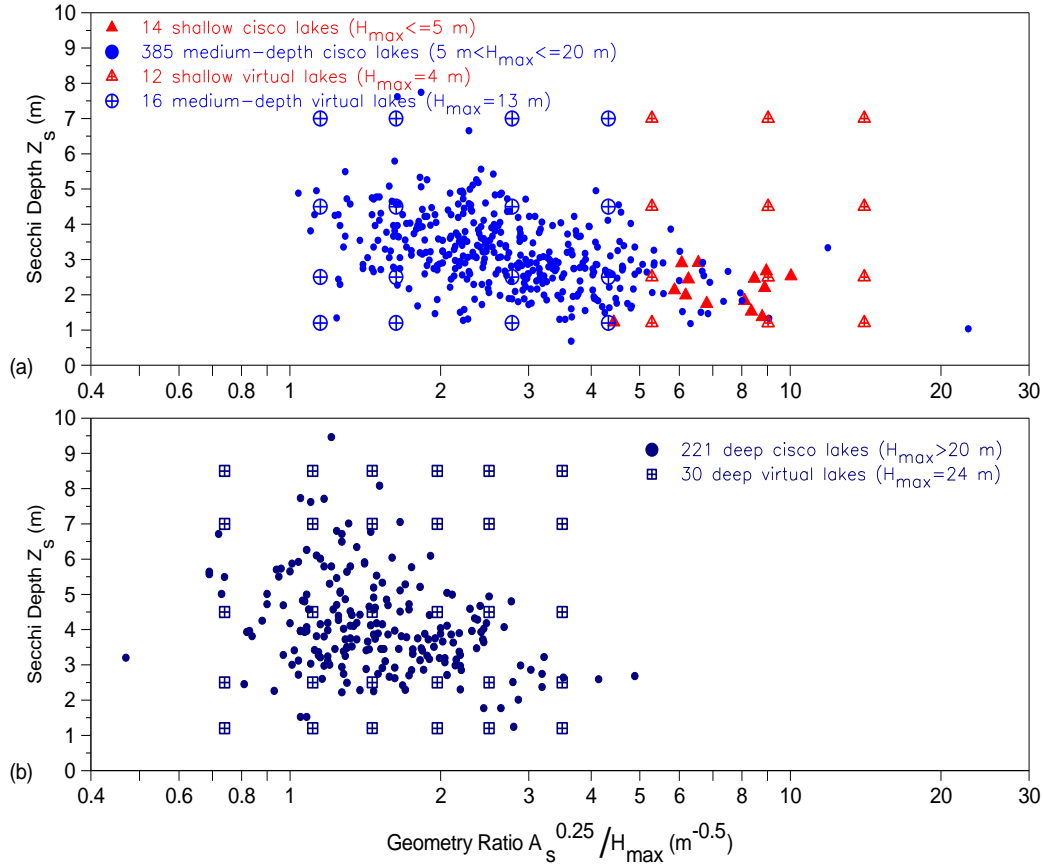


Figure 3.4 Distribution of (a) 14 shallow and 385 medium-depth cisco lakes and (b) 221 deep cisco lakes from 620 cisco study lakes in Minnesota including 58 virtual lakes plotted using Secchi depth and lake geometry ratio as independent variables.

Because it was not feasible to run deterministic lake models for all 620 cisco lakes, we used 58 virtual lakes: 12 shallow, 18 medium-depth (Table 3.2), and 30 deep lakes to represent the entire set of 620 lakes in Minnesota. A similar approach using 27 generic lake types had been used to study climate warming impact on fish habitat in small lakes in Minnesota (Stefan et al. 1996) and in the contiguous USA (Fang et al. 2004a). Each virtual lake is characterized by four attributes: A_s , H_{max} , SD (related to lake trophic status), and location. Location of a lake is categorized into three regions: northern, medium-latitude, and southern Minnesota (Figure 3.2). The geometry ratio GR of a lake is defined as

$A_s^{0.25}/H_{\max}$ in $m^{-0.5}$ when A_s is in m^2 and H_{\max} in m . The strength of the seasonal lake stratification is related to the GR value (Gorham and Boyce 1989). Polymictic lakes (such as large shallow lakes) have the highest GR numbers, while strongly stratified lakes (such as small deep lakes) have the lowest GR; the transition from unstratified to stratified lake occurs for GR between 3 and 5 (Gorham and Boyce 1989).

The 27 generic lake types included 9 shallow lakes (representative $H_{\max} = 4$ m) with $GR > 5.29 m^{-0.5}$, 9 medium-depth lakes ($H_{\max} = 13$ m) with $GR = 1.63, 2.78,$ and $4.33 m^{-0.5}$; and 9 deep lakes ($H_{\max} = 24$ m) with $GR = 0.88, 1.50,$ and $2.34 m^{-0.5}$ (Stefan et al. 1996). Therefore, medium-depth lakes overlap with deep lakes on the plot of SD vs. GR (Figure 3.2 and Figure 3.3). Despite the overlap, simulated water temperature and DO characteristics (Stefan et al. 1996) and snow/ice cover characteristics (Stefan and Fang 1997) in 27 generic lake types have consistent variations with GR and SD. Simulated maximum daily surface and bottom temperatures, days of seasonal stratification, maximum daily percentage of total lake volume with anoxia, and many other T and DO characteristics were successfully presented and analyzed to draw useful information using SD vs. GR plots (Stefan et al. 1993; Stefan and Fang 1994a; Stefan et al. 1996). However, the overlap of GR between medium-depth and deep lakes creates discontinuities to present certain fish habitat parameters on the SD vs. GR plots (Fang et al. 2014), for example, projected good-growth periods are more than 220 days for deep lakes under future climate scenario, but medium-depth lakes with similar GR are projected to have no fish habitat (Fang et al. 2004a). Therefore, we studied cisco survival and lethal conditions separately in shallow and medium-depth lakes using 12 shallow and 16 medium-depth virtual lakes (Table 3.2) and deep lakes using 30 virtual deep lakes (Figure 3.4). For the 620 cisco lakes (Figure 3.4)

in Minnesota, there are 14 shallow lakes ($H_{\max} < 5.0$ m), 385 medium-depth lakes ($5.0 \text{ m} \leq H_{\max} < 20.0$ m), and 221 deep lakes ($H_{\max} > 20.0$ m) (Stefan et al. 1996).

The 12 shallow and 16 medium-depth virtual lakes were extended from the original 9 shallow (LakeR01 R09 in Table 3.2) and 9 medium-depth (LakeR10 R18) virtual lake types used in previous studies (Stefan et al. 1996) by adding 10 new virtual lakes (LakeR28 R33 & LakeR37-R40) for studying cisco habitat. The minimum and maximum GR values for 14 shallow and 385 medium-depth Minnesota cisco lakes are 1.04 and $22.7 \text{ m}^{-0.5}$ (Figure 3.4), respectively, therefore, LakeR37 to LakeR39 were added to represent medium-depth (13 m), small surface area (0.05 km^2) lakes with $\text{GR} = 1.15 \text{ m}^{-0.5}$. The 12 shallow and 16 medium-depth virtual lakes have GR ranging from 1.15 to $14.06 \text{ m}^{-0.5}$ (Table 3.2, Figure 3.3 and Figure 3.4); there are only five Minnesota cisco lakes with GR beyond the range of GR values for these 28 virtual lakes (Figure 3.4a). Mean summer Secchi depths of the 620 cisco lakes ranged from 0.7 to 9.5 m (Coutant 1970), and 10% or 61 cisco lakes had $\text{SD} \geq 5.0$ m; therefore, seven representative cisco lake types (LakeR28 R33 and lake R40 in Table 2) with $\text{SD} = 7.0$ m were added (only two medium-depth cisco lakes with $\text{SD} > 7.0$ m shown in Figure 3.4a). Overall, 28 virtual lakes can well represent the 14 shallow and 385 medium-depth cisco lakes in Minnesota (Figure 3.4a) and 12 medium-depth cisco lakes among the 23 cisco lakes (Figure 3.3a). There are no cisco lakes in Minnesota with $\text{SD} > 4.5$ m and $\text{GR} > 5.3 \text{ m}^{-0.5}$, but those virtual lakes at the right upper corner of Figure 4a are useful to develop smooth contour lines of cisco kill parameters shown later.

The 30 deep virtual lakes proposed for previous studies (Jiang et al. 2012) were used in this study also. Those lakes (LakeC01 to LakeC30) comprise lakes with five different

SD values (1.2, 2.5, 4.5, 7.0, and 8.5 m) and six different surface areas (0.1, 0.5, 1.5, 5.0, 13.0, and 50 km²). The maximum depth of all 30 virtual lakes was set at 24 m (Jiang et al. 2012). The 30 virtual lakes have GR ranging from 0.74 to 3.5 m^{-0.5}, which represent well 221 deep stratified cisco lakes in Minnesota (Figure 3.4b) and 12 deep cisco lakes among the 23 cisco lakes (Figure 3.3b). Twenty of the 30 virtual cisco lake types, LakeC01 to LakeC20, are strongly stratified with GR < 2, and the other ten lake types (LakeC21 to LakeC30) are relatively weakly stratified. The 30 deep virtual lakes are all stratified lakes based on GR, but they cover lakes having small to large surface areas and include eutrophic (SD = 1.2 m), mesotrophic (SD = 2.5 m), and oligotrophic (SD ≥ 4.5 m) lakes (Stefan et al. 1996).

3.3.3 Long-Term Historic and Projected Cisco Lethal Conditions in 58 Virtual Lakes

To understand long-term lethal conditions and cisco kill in 58 virtual lakes (Figure 3.3 and Figure 3.4), daily T and DO profiles were simulated using a deterministic, one-dimensional (vertical) and unsteady year-round water quality simulation model, MINLAKE2012 that was developed from MINLAKE2010 (Fang et al. 2014) and MINLAKE96 model (Fang et al. 2012a) for applications to deeper and more transparent cisco lakes in Minnesota. The most important upgrades of MINLAKE2012 compared to MINLAKE2010 are the conversion to a user-friendly Excel spreadsheet environment and the introduction of variable temporal resolution, allowing to run the model at hourly and daily time step. MINLAKE2012 was used to study temperature dynamics in Lake Kivu, one of the seven African Great Lakes, using hourly time step (Fang and Stefan 1996a) and investigate daily ice/snow characteristics of Harp Lake in Canada (Thiery et al. 2014).

In this study, the year-round model was run in daily time steps over multiple simulation years (1961–2008) including both open-water seasons and ice-cover periods. The one-dimensional heat transfer and DO transport equations were solved numerically for layer thicknesses from 0.02 m (near the water surface or ice-water interface) to 1.0 m (for depths greater than 1.0 m) using an implicit finite difference scheme and a Gaussian elimination method. Descriptions of MINLAKE96 and MINLAKE2010 are presented elsewhere (Nash and Sutcliffe 1970; Blumberg and Di Toro 1990; Fang et al. 2012a). MINLAKE model uses lake bathymetry (A_s , H_{max} , horizontal areas versus depths), lake trophic status (Secchi depth), corresponding model parameters, and daily weather data (depending on lake location) as model input. MINLAKE2010 was calibrated using 21 cisco lakes and 7 non-cisco lakes in Minnesota based on multi-year data availability (7384 data pairs spanning 439 lake-days over 81 lake-years). After calibration, the average standard error of estimates 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) (Fang et al. 2014).

In this study, we further calibrated MINLAKE2012 using measured T and DO profile data collected in 23 cisco lakes under past climate conditions, then simulated T and DO profiles in 2006 were used to calibrate the FishHabitat2013 model using cisco survival or kill observations in these lakes. In order to get better calibration results for MINLAKE2012 and FishHabitat2013 models, the closest weather station to a lake was used for simulations and is listed in Table 3.1 for each of 23 lakes. Four weather stations in Minnesota (Bemidji, Brainerd, Grand Rapids, and St. Clouds) and one station in North Dakota (Fargo) associated with 23 lakes (Table 1) were used and presented in Figure 3.2. Weather stations at St. Clouds, MN and Fargo, ND, are the National Weather Services (NWS) Class I

stations having climate data from 1961 to 2008 for the study, and Brainerd and Bemidji are the NWS Class II stations having climate data from 1973 to 2008 and Grand Rapids from 1984 to 2008.

This study is to project whether 620 Minnesota lakes that had or currently has a cisco population can support cisco habitat under future climate scenarios, i.e., after climate warming. To make the projection, the model outputs from one Coupled General Circulation Models (CGCMs) of the earth's atmosphere and oceans, i.e., MIROC 3.2 (Figure 3.2), were used as input to the MINLAKE2012 model to project future T and DO profiles. Mean monthly increments over 30 years (2070–2099) for climate parameters were obtained from the MIROC 3.2 model outputs, and applied to measured daily climate conditions (1961–2008) to generate projected daily future climate scenario. Monthly increments from the grid center point closest to a weather station were used to specify the future climate.

The MIROC 3.2 (Hasumi and Emori 2004) was developed by the Center for Climate System Research, University of Tokyo; the National Institute for Environmental Studies; and the Frontier Research Center for Global Change—Japan Agency for Marine-Earth Science and Technology. Output of the MIROC 3.2 model with a high spatial surface grid resolution of roughly 1.12 degrees latitude and longitude or approximately 120 km in Minnesota was used. Mean monthly air temperature increments projected by MIROC 3.2 range from 3.53 to 4.70 °C with annual averages of 4.00 to 4.24 °C for the three weather stations.

The long-term lethal conditions and cisco kill were first simulated in 58 virtual lakes under past climate conditions (1961–2008) and MIROC 3.2 future climate scenario (Figure 3.5). Results for 58 virtual lakes from MINLAKE2012 and FishHabitat2013 were

developed using weather data from three class I weather stations (Figure 3.2): International Falls, Duluth, and St. Cloud. Each of these three weather stations has a closest grid center point (Figure 3.2) with mean monthly increments (Coutant 1970; Fang et al. 2012b).

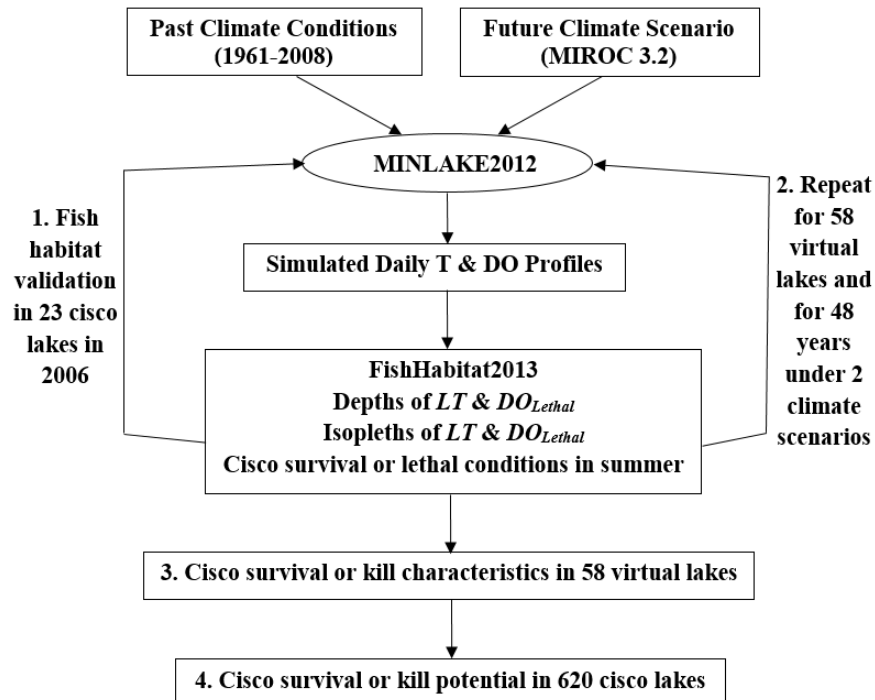


Figure 3.5 Conceptual flowchart of modeling steps implemented in the study.

3.3.4 Understanding/Extrapolating Cisco Lethal Potential in 620 Cisco Lakes

Figure 3.5 shows the flowchart or four modeling steps used for the study to simulate cisco survival and lethal conditions in Minnesota lakes. Past climate conditions (1961 to 2008) and a future climate scenario are model inputs (atmospheric boundary conditions) for the lake water quality model MINLAKE2012 (Fang et al. 2012a). After 2006 model validation of FishHabitat2013, long-term characteristics of cisco lethal conditions such as starting and ending days of cisco kills and non-survival days (NSD) or lethal days are calculated in 58 virtual lakes for projecting or extrapolating cisco lethal conditions for 620 cisco lakes in Minnesota. The simulated characteristics of cisco lethal days in 58 virtual

lakes are plotted and interpolated as isolines on a plot of SD vs. GR. The cisco survival and lethal conditions of the 620 cisco lakes in Minnesota are projected using the mean summer SD and GR of each lake as independent variables on the same plot with results from 58 virtual lakes. In this way, the un-simulated lakes can be connected to simulated virtual lakes (Figure 3.4).

The 620 cisco lakes in Minnesota were divided into three regions based on their geographic locations: northern, medium-latitude and southern cisco lakes in addition to grouping them by the maximum depth; and Figure 3.2 shows the latitude boundary lines to divide lakes by regions, which were the same boundary lines used in previous study (Jiang et al. 2012). Weather data at International Falls were considered to represent for 165 northern cisco lakes, Duluth for 399 mid-latitude cisco lakes, and St. Cloud for 56 southern cisco lakes; which is the same approach used by Jiang et al. (Jiang et al. 2012)

3.4 Results

3.4.1 Temperature and DO Model Calibration and Simulation in 23 Minnesota Lakes

Information and results of model calibration for MINLAKE2012 are summarized in Table 3.1. Observed temperature and DO profiles used for model calibration range from 1 to 95 days, and simulated and measured data pairs from 14 to 2771 (Ten Mile). Six cisco-kill lakes and one reference lake without cisco kill had only one-day profile in 2006 collected by MN DNR for model calibration. The average root-mean-square errors (RMSE in Table 3.1) for T and DO of all 23 lakes are 1.57 °C and 1.72 mg/L, respectively. The average Nash-Sutcliffe model efficiency (NSE in Table 1) for T and DO are 0.86 (11 lakes with NSE > 0.90) and 0.66 (10 lakes with NSE > 0.80). Bennis and Crobeddu (2007) suggested that a good agreement between simulated and measured discharges is achieved

when NSE exceeds 0.7. Model calibration results for 23 lakes are similar to magnitude of error parameters of one-dimensional lake model in previous studies (Fang et al. 2012a). Figure 3.6 shows simulated and measured water temperatures at four depths in Pine Mountain Lake and Big Trout Lake from 1999 to 2007. The first three depths are 1, 6, and 12 m for both lakes and the fourth depth is 23 m for Pine Mountain Lake ($H_{\max} = 23.8$ m) with cisco mortality in 2006 and 38 m for Big Trout Lake ($H_{\max} = 39.0$ m) without cisco mortality in 2006. Figure 3.7 and Figure 3.8 show simulated and measured DO concentrations at four depths in Big Trout Lake and Pine Mountain Lake, respectively. Simulated water temperature and dissolved oxygen match reasonably well with field data based on error parameters in Table 3.1 and graphic comparison (Figure 3.6, Figure 3.7, and Figure 3.8).

Both water temperature and DO concentrations at different depths vary with seasonal weather conditions and also depend on lake geometry ratio and trophic state (Figure 3.6, Figure 3.7, and Figure 3.8). Surface temperatures at 1 and 6 m in some years (Figure 3.6) were above cisco lethal temperature (22.1 °C, discussed in Section 3.4.2) but temperatures at deep depths are cool enough to support cisco habitat. Therefore, DO becomes a controlling factor to determine cisco habitat or survival conditions in these two lakes. Big Trout Lake is a deep mesotrophic/oligotrophic lake (mean SD = 4 m) with DO above 3 mg/L lethal limit (Figure 3.7) and lower water temperature (<12 °C, Figure 3.6) at 12 m that would support cisco habitat for all those years (Figure 3.6 and Figure 3.7). Pine Mountain Lake is deep mesotrophic lake with SD = 2.4 m that results in anoxic conditions at 12 m during the summer (Figure 3.8). DO concentrations at 6 m in Pine Mountain Lake

were below 3 mg/L over number of days, and water temperatures at 6 m were hot enough to possibly result in cisco kill in some years.

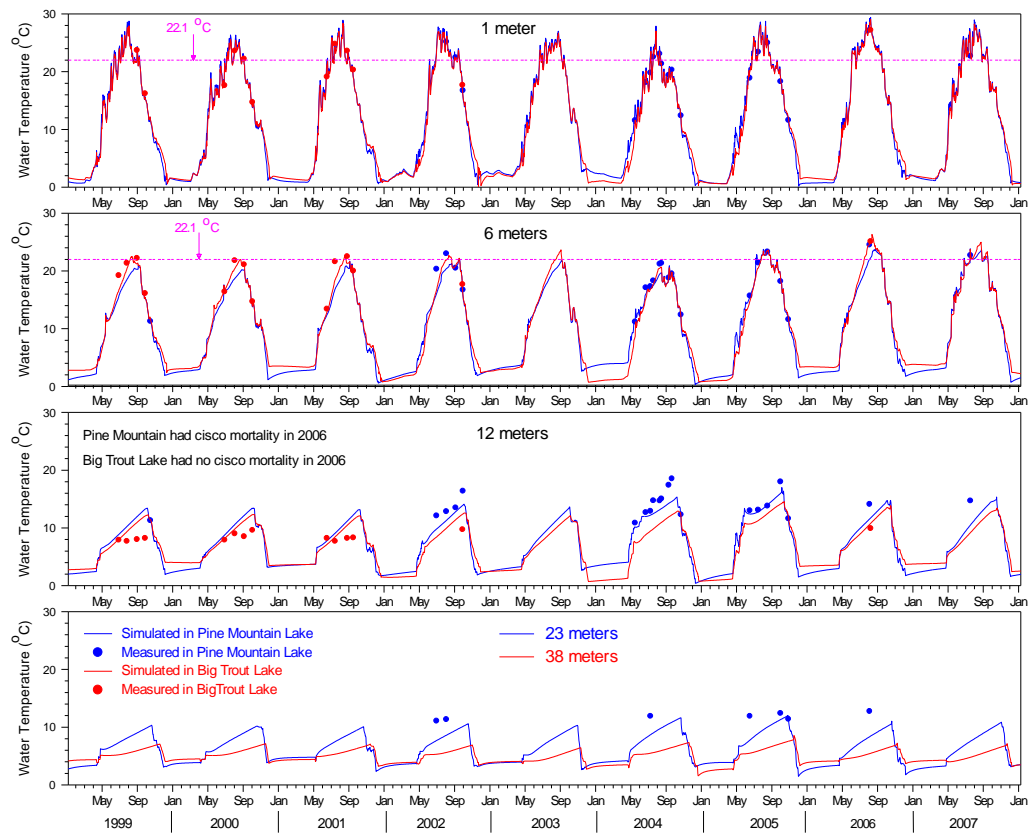


Figure 3.6 Time series of simulated temperature and measured temperature at different depths for Pine Mountain Lake and Big Trout Lake in 1999–2007. Pine Mountain Lake had cisco kill and Big Trout Lake did not have cisco kill in 2006. The lethal temperature of 22.1 °C is presented as horizontal lines.

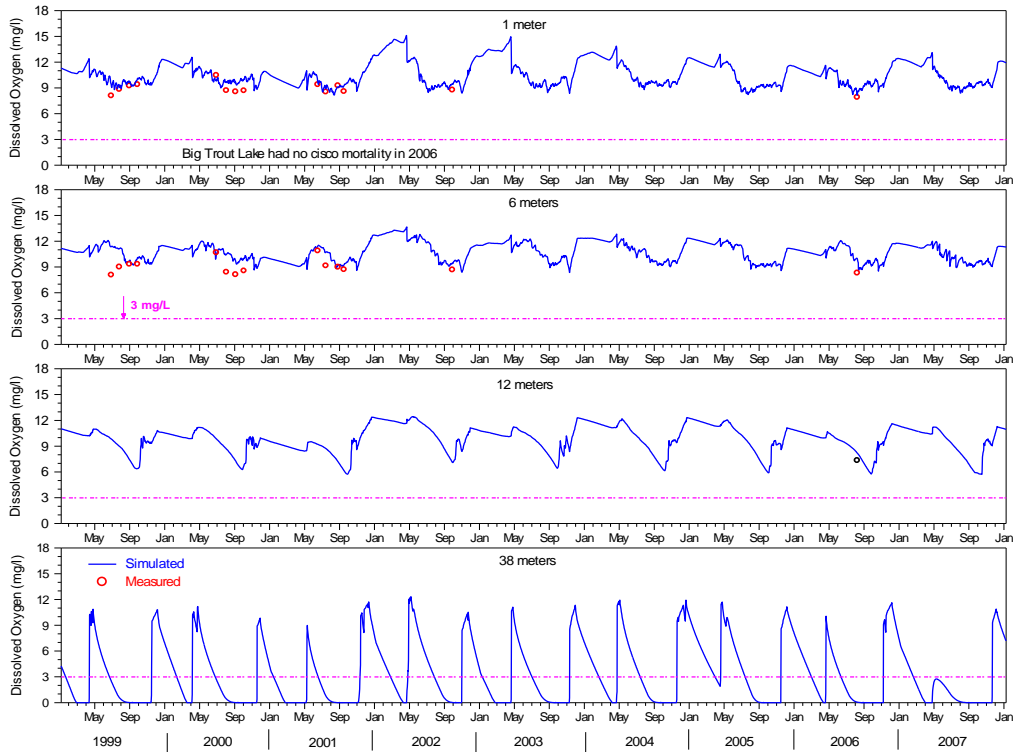


Figure 3.7 Time series of simulated DO and measured DO at different depths in 1999–2007 for Big Trout Lake that had no cisco kill in 2006. DO lethal limit of 3 mg/L is presented as horizontal lines.

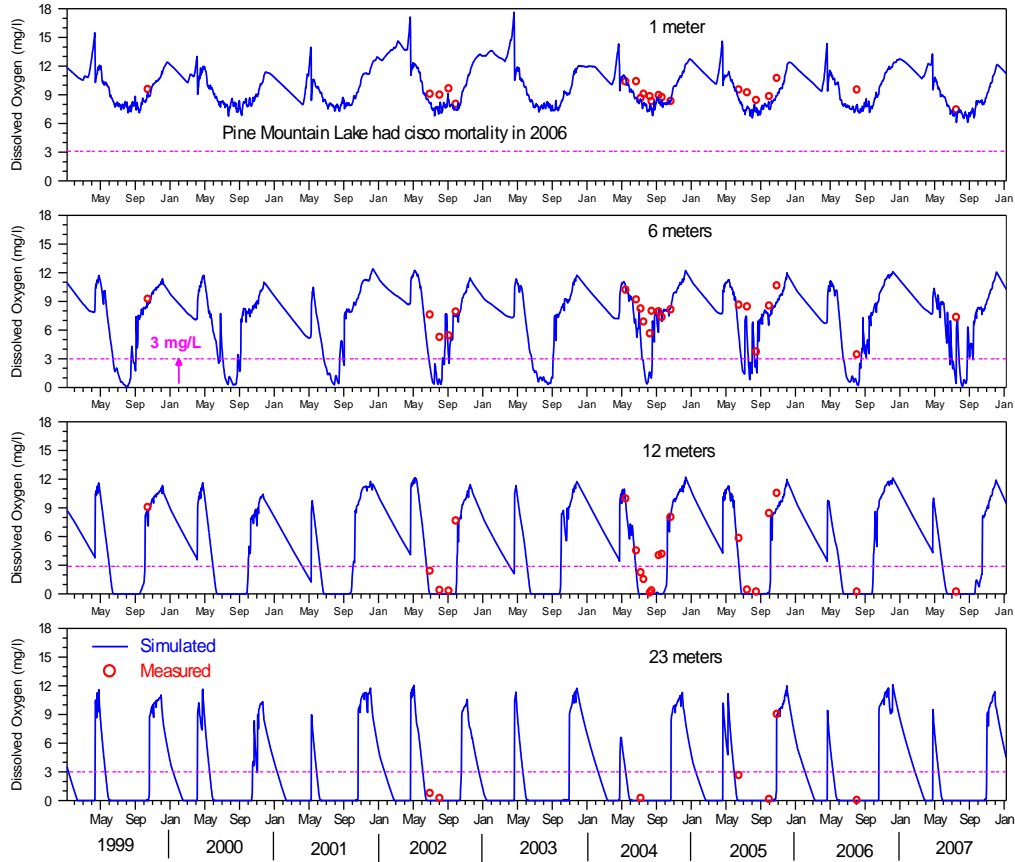


Figure 3.8 Time series of simulated DO and measured DO at different depths in 1999–2007 for Pine Mountain Lake that had cisco kill in 2006. DO lethal limit of 3 mg/L is presented as horizontal lines.

3.4.2 Simulation and validation of FishHabitat2013 for 23 lakes in 2006

Figure 3.1 shows an example of FishHabitat2013 simulation results for determining 2006 cisco lethal conditions in Andrusia Lake using six combinations of constant LT and DO limits. First, constant $LT = 22.1\text{ }^{\circ}\text{C}$ and $DO_{\text{Lethal}} = 3\text{ mg/L}$ were used to simulate cisco lethal conditions in 2006 in 23 Minnesota lakes after water temperatures and DO calibration against measured profiles, and the summary of simulation/validation results of cisco habitat conditions are given in Table 3.3 for each lake. It first lists the information of simulated lethal conditions in 2006 (hindcast or backtesting) including the first Julian Day,

the last Julian Day, and the total number of days with cisco lethal conditions. It also lists the first Julian Day and the number of continuous days with cisco lethal conditions simulated in 2006. For example, Andrusia Lake has “192 (59)” under “simulated lethal days in 2006” (Table 3.3) that means lethal conditions were simulated on Julian Day 192 (11 July 2006) and the number of continuous cisco lethal days is 59 (Julian Days 192–250), which is also given in Figure 3.5. There are four lakes having more than one period of continuous lethal conditions and having some gaps (days) without lethal conditions between periods (Table 3.3).

Table 3.3 2006 lethal conditions of cisco in 23 lakes simulated using the constant value method with lethal temperature of 22.1 °C and DO lethal limit of 3 mg/L and validation results against 2006 cisco mortality or survival conditions.

Lake Name	Lethal Conditions			Simulated Continuous Lethal Days in 2006	Cisco Mortality Day (Julian Day)	Model Agreement
	First Day	Last Day	No. of Days			
Little Turtle	180	241	62	180 (62) ³	7/19 (200)	Yes (Yes) ⁴
Star	204	216	13	204 (13)	7/19 (200)	Yes (No)
Mille Lacs	204	251	48	204 (48)	7/23 (204)	Yes (Yes)
Andrusia	192	250	59	192 (59)	7/21 (202)	Yes (Yes)
Little Pine ¹	202	216	15	202 (15)	7/22 (203)	Yes (Yes)
Cotton	184	241	58	184 (58)	7/24 (205)	Yes (Yes)
Pine Mountain	193	250	53	193 (36); 232 (13); 247 (4)	7/26 (207)	Yes (Yes)
Leech	188	225	35	188 (3); 193 (30); 224 (2)	7/30 (211)	Yes (Yes)
Bemidji	212	217	6	212 (6)	7/27 (208)	Yes (No)
Itasca	189	241	49	189 (2); 192 (34); 227 (10); 239 (3)	7/28 (209)	Yes (Yes)
Gull	206	225	20	206 (20)	7/29 (210)	Yes (Yes)
Woman	183	241	59	183 (59)	7/29 (210)	Yes (Yes)
Straight	211	215	5	211 (5)	8/01 (213)	Yes (Yes)
Little Pine ²	76	250	71	76 (20); 187 (1); 192 (34); 227 (2); 231 (6); 238 (4); 247 (4)	8/02 (214)	Yes (Yes)
7th Crow Wing	197	215	19	197 (19)	8/04 (216)	Yes (No)
8th Crow Wing	188	241	54	188 (54)	8/04 (216)	Yes (Yes)
Long	214	216	3	214 (3)	8/06 (218)	Yes (No)
Carlos	–	–	0	–	8/27 (239)	No (No)
Five reference lakes without cisco kills in 2006						
Big Trout, Kabekona, Scalp, Ten Mile, Rose	–	–	0	No Kill	No Kill	Yes

Notes: ¹ Little Pine Lake at Otter Tail County; ² Little Pine Lake at Crow Wing County; ³ stands for a Julian Day in 2006 and number of continuous cisco lethal days after the day predicted by the fish habitat model; and ⁴ the first Yes/No gives the agreement of cisco lethal prediction and reported cisco mortality in 2006 and Yes/No inside brackets gives the agreement whether or not cisco lethal days from the model include reported date with cisco mortality or not.

The month/day in 2006 (Julian Day inside brackets) when cisco mortality was reported in each of 18 lakes is listed under “Observed mortality day in 2006” in Table 3.3 and used to examine model agreement with the observation. In the last column of Table 3.3, the first Yes/No gives the agreement of cisco lethal simulation and reported cisco mortality in 2006, and the second Yes/No inside brackets gives the agreement whether or not cisco lethal days from the model includes reported date with cisco mortality. For example, in Little Turtle Lake FishHabitat2013 simulated a total of 62 continuous days from 29 June (Julian Day 180) to 29 August (Julian Day 241) having cisco lethal conditions, which agree with reported cisco mortality in 2006; and the period of simulated cisco lethal conditions includes the reported date with cisco mortality, i.e., 19 July or Julian Day 200. Therefore, the model agreement with mortality observation is “Yes (Yes)” as listed in Table 3.3. The fish habitat model had the Yes (Yes) agreement in 13 of the 18 lakes that experienced cisco mortality in 2006.

For four lakes (Star, Bemidji, 7th Crow Wing, and Long), the model simulated cisco lethal conditions, but the simulated lethal periods did not include corresponding reported cisco mortality dates in 2006; these lakes have the Yes (No) agreement (Table 3.3). In the 7th Crow Wing Lake, cisco lethal conditions were simulated for 19 days to occur from Julian Day 197 to 215 (3 August) in 2006, and the cisco mortality was reported on 4 August. This case can be considered as Yes (Yes) agreement because cisco mortality might be reported one or a few days after cisco mortality occurred when study lakes were not constantly monitored and observed. Therefore, the fish habitat model with the constant lethal limits has “Yes (Yes)” agreement in all 12 medium-depth lakes with the maximum depth ranging from 8.5 to 19.2 m (Table 3.1).

For Lake Bemidji and Star, cisco lethal conditions were simulated to occur after the reported cisco mortality days in 2006. Long Lake was simulated with only three days (214–216) having lethal conditions, and the cisco mortality was reported on 6 August (Julian 218). Long Lake located in Otter Tail County, Minnesota has a maximum depth of 39.0 m (deep lake) and a surface area of 5.1 km². Long Lake is a mesotrophic strongly stratified lake because of its mean Secchi depth 3.0 m, mean chlorophyll-a concentration 7.2 µg/L, and GR = 1.22. There was only one day in 2006 with observed temperature and DO profiles in Long Lake for model calibration.

There is only one lake—Lake Carlos—that the model did not simulate cisco lethal conditions, but it had cisco mortality in late August of 2006; the model has the No agreement with mortality observation (Table 3.3). Lake Carlos located in Douglas County, Minnesota has a maximum depth of 49.7 m and a surface area of 10.5 km². Lake Carlos is a mesotrophic strongly stratified lake because its mean Secchi depth is 3.0 m; mean chlorophyll-a concentration is 5.0 µg/L, and GR = 1.15. The phenomenon called metalimnetic oxygen minima (MOM) occurs in late summer or fall in Lake Carlos where DO concentrations in the metalimnion are lower than ones in some depths below (hypolimnion), which may be related to oxidative consumption (respiration) of certain particulates and microcrustaceans accumulated in the metalimnion or low-oxygen water movement (Cole 1994). The MOM was the potential cause of the late summer cisco mortality event that occurred on 27 August in Lake Carlos. Because of MOM, the data of DO and temperature relationship in Lake Carlos did not fit the lethal-niche-boundary curve developed from the midsummer cisco-kill events in other 16 lakes (Table 3.1) (Jacobson et al. 2008). A more advanced one-dimensional (Joehnk and Umlauf 2001) or two-

dimensional (Smith et al. 2014) lake water quality model has to be used to predict MOM in a lake, and MINLAKE2012 is for simulating temperature and DO in virtual lakes (Fang et al. 2012a) and without special modifications would not predict MOM.

Jacobson et al. (Jacobson et al. 2008) also studied the 5 reference lakes that did not experience cisco mortality in 2006. These five reference lakes are all deep strongly stratified lakes ($GR < 1.4$ in Table 3.1). The fish habitat model using simulated temperature and DO profiles predicted no lethal conditions for cisco in all five reference lakes (Table 3.3). Therefore, the fish habitat model has overall good agreement in the 23 cisco lakes with and without cisco mortality reported in 2006 using constant $LT = 22.1$ °C and $DO_{Lethal} = 3$ mg/L. There is only one lake—Lake Carlos that the model did not simulate cisco lethal conditions, but it had cisco mortality in late August of 2006; the model has the No agreement with mortality observation (Table 3.3). Lake Carlos located in Douglas County, Minnesota has a maximum depth of 49.7 m and a surface area of 10.5 km². Lake Carlos is a mesotrophic strongly stratified lake because of its mean Secchi depth 3.0 m, mean chlorophyll-a concentration 5.0 µg/L, and $GR = 1.15$. The late summer cisco mortality event that occurred on August 27 in Lake Carlos did not fit the lethal-niche-boundary curve developed from the midsummer events in 16 lakes (Jacobson et al. 2008). Based on the lethal-niche-boundary curve and measured profiles on September 1, 2006 (Jacobson et al. 2008), cisco could exist in some surface layers at Lake Carlos with low temperatures and high DO, but could not exist in the hypolimnion with anoxic conditions.

A sensitivity analysis of cisco habitat simulations was performed in 23 lakes (Table 3.4) using six different combinations (criteria) of LT and DO_{Lethal} , which include two LT s (22.1 and 23.4 °C) and three DO limits (2, 3, and 4 mg/L). Cisco kill days for Andrusia

Lake in 2006 under six different criteria are given in Figure 3.1. The period of cisco lethal conditions for $LT = 22.1\text{ }^{\circ}\text{C}$ is longer than for $LT = 23.4\text{ }^{\circ}\text{C}$ when DO limit is fixed; when DO survival limits increase from 2 to 4 mg/L, days of lethal conditions increase also while LT is fixed (Figure 3.1 and Table 3.4).

Table 3.4 2006 lethal days simulated in the 23 cisco lakes using the constant value method with six different combinations of lethal temperatures and DO limits.

Lake Name	LT = 23.4 °C			LT = 22.1 °C		
	DO = 2 mg/L	DO = 3 mg/L	DO = 4 mg/L	DO = 2 mg/L	DO = 3 mg/L	DO = 4 mg/L
Little Turtle	27	29	29	55	62	63
Star	0	0	6	0	13	19
Mille Lacs	36	36	36	48	48	48
Andrusia	19	25	29	50	59	65
Little Pine (Otter Tail)	1	3	5	4	15	20
Cotton	37	37	37	57	58	58
Pine Mountain	12	23	35	29	53	69
Leech	24	24	24	35	35	35
Bemidji	0	0	0	0	6	12
Itasca	26	27	28	43	49	54
Gull	0	0	17	2	20	48
Woman	27	28	29	50	59	61
Straight	0	0	5	0	5	18
Little Pine (Crow Wing)	18	50	68	36	71	105
7th Crow Wing	3	10	19	12	19	21
8th Crow Wing	28	29	30	52	54	54
Long	0	0	0	0	3	10
Carlos	0	0	0	0	0	0
Big Trout, Kabekona, Scalp, Ten Mile, Rose	0	0	0	0	0	0

If the first two criteria ($LT = 23.4\text{ }^{\circ}\text{C}$, $DO_{\text{Lethal}} = 2$ or 3 mg/L) were used, fish habitat model predicts zero days of lethal conditions in six of the 18 study lakes with cisco kill in 2006. Comparing all six criteria, the last two criteria ($LT = 22.1\text{ }^{\circ}\text{C}$, $DO_{\text{Lethal}} = 3$ or 4 mg/L) show good agreement with field cisco kill observation in the hot summer of 2006, and both predict 17 lakes had lethal conditions out of 18 lakes. No lethal conditions were predicted by all six criteria for all 5 reference lakes that had no kill in 2006. Considering the study

and recommendation by Jacobson in 2008 (Jacobson et al. 2008), we chose $LT = 22.1\text{ }^{\circ}\text{C}$ and $DO_{\text{Lethal}} = 3\text{ mg/L}$ as the criteria for this study.

3.4.3 Simulated Cisco Lethal Conditions in 58 Virtual Lakes and 620 Cisco Lakes

Fish kill parameters used/analyzed in this study include the total number of years with cisco kill and average cisco kill days for the years with kills. A cisco kill is assumed to occur when the number of continuous days of lethal conditions is 3 or greater (Fang et al. 2014). Results for cisco lethal conditions are presented and discussed separately for shallow and medium-depth lakes and deep lakes (Fang et al. 2014).

3.4.3.1 Results of Shallow and Medium-Depth Lakes

Before cisco habitat results are presented for 58 virtual lakes, sample results for 4 lakes (LakeR10, R11, R12, and R31, Table 3.2) are given in Figure 3.9 and simulated under 2006 Duluth weather conditions. These four lakes are medium-depth small lakes ($H_{\text{max}} = 13\text{ m}$, $A_s = 0.2\text{ km}^2$) and Secchi depth from 1.2 m to 7 m, which are eutrophic, mesotrophic, and oligotrophic lakes. Since their lake geometry ratio is $1.63\text{ m}^{-0.5}$ (Table 3.2), they are relatively strongly stratified lakes. When lakes change from eutrophic to oligotrophic lake, the light or radiation attenuation becomes smaller; therefore, more short-wave solar radiation is available to heat deep water and also provides more solar energy for photosynthesis to produce oxygen at deep depths. Figure 3.9 shows that LT isotherm is at shallower depth for eutrophic LakeR10 and much deeper in oligotrophic LakeR31 ($SD = 7\text{ m}$), meanwhile isopleth of the DO survival limit (3 mg/L) also moves downward when there is more oxygen in deep layers. Resulting lethal conditions for cisco are 2, 5, 0, and 8 days; which are non-linear complex responses to the increase in Secchi depth when lake geometry and weather conditions are the same.

Figure 3.10 and Figure 3.11 show contour plots of simulated total number of years with cisco kill and average cisco kill days for the years with kills, respectively, under past climate conditions (a, c, e) and future MIROC 3.2 climate scenario (b, d, f) in shallow and medium-depth lakes. Corresponding results for deep lakes are presented separately in Figure 3.12. Contours were derived by interpolation from simulated values for either 12 shallow and 16 medium-depth virtual lakes (used 28 data points on Figures 10 and 11) or 30 virtual deep lakes (Figure 12). Results for cisco kill (Figures 10–12) are presented separately for three geographic regions: 165 northern cisco lakes using International Fall weather (a, b), 399 mid-latitude cisco lakes using Duluth weather (c, d), and 56 southern cisco lakes using St. Cloud weather (e, f). All 620 cisco lakes are grouped by maximum depths (shallow, medium-depth, and deep) and climate regions (northern, mid-latitude, and southern) and plotted in Figure 3.10 and Figure 3.11 (b, d, f), and 12 using lake geometry ratio GR and Secchi depth SD as independent variables. Therefore, fish habitat results revealed by contour plots can be referred or extrapolated to each cisco lake group in Minnesota, an approach successfully used in previous studies (Fang et al. 2012b; Jiang et al. 2012).

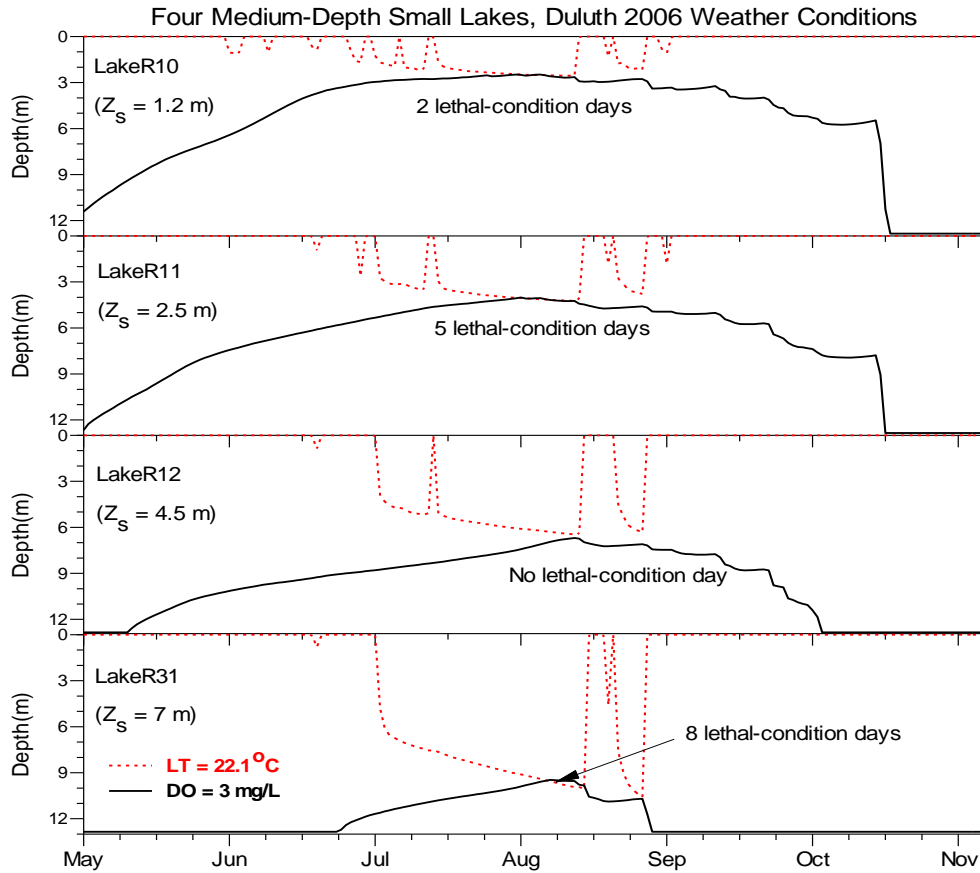


Figure 3.9 Simulated isopleths of LT and DO survival limit in four medium-depth small virtual lakes ($H_{\max} = 13$ m, $A_s = 0.2$ km²) using depth versus time plots showing cisco lethal-condition days. The Secchi depths of four lakes (top to bottom frames) are 1.2, 2.5, 4.5, and 7 m, respectively.

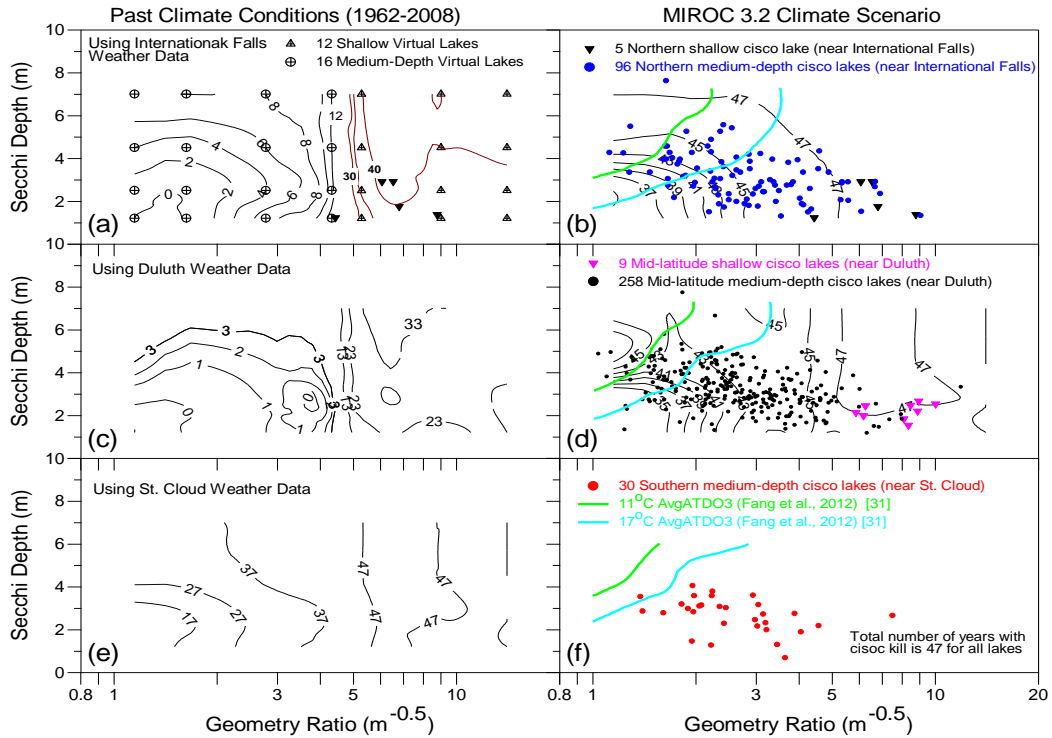


Figure 3.10 Contour plots of total number of years with cisco kills under past climate conditions (a, c, e) and future MIROC 3.2 climate scenario (b, d, f). International Falls (a, b), Duluth (c, d), and St. Cloud (e, f) weather data were used for model simulations. Contours were derived by interpolation from simulated points for 12 shallow and 16 medium-depth virtual lakes. The 11 and 17 °C contours of AvgATDO3 from Fang et al. (Fang et al. 2012b) are included.

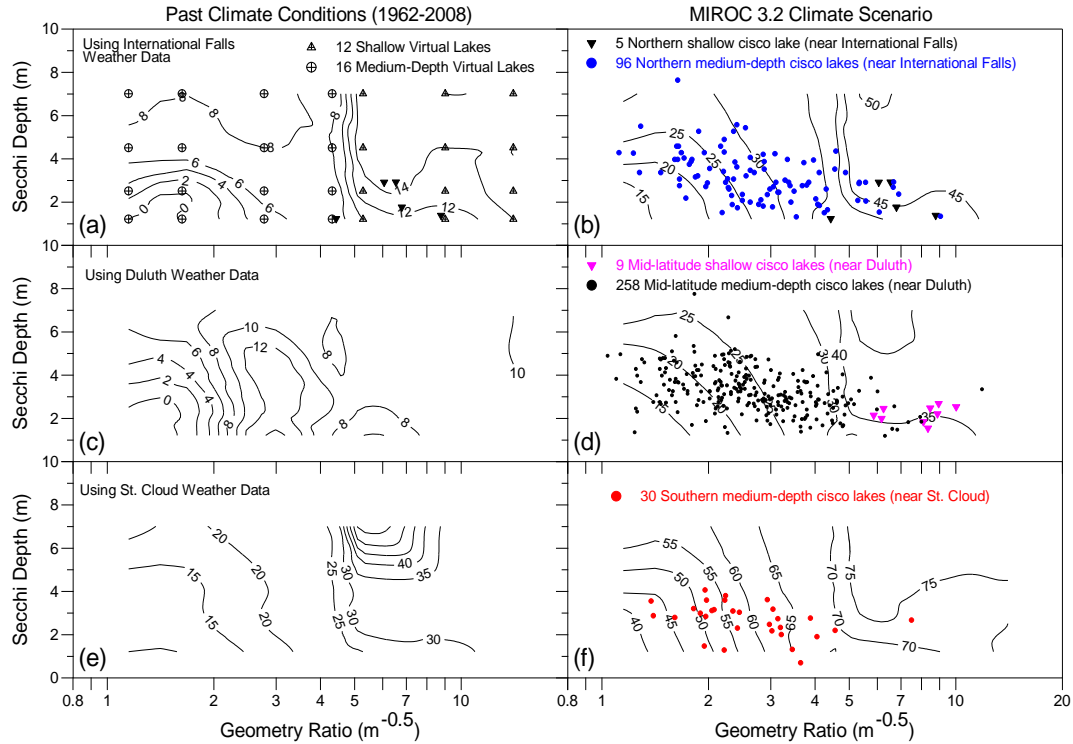


Figure 3.11 Contour plots of average cisco kill days for the years with kills under past climate conditions (a, c, e) and future MIROC 3.2 climate scenario (b, d, f). International Falls (a, b), Duluth (c, d), and St. Cloud (e, f) weather data were used for model simulations. Contours were derived by interpolation from simulated values (points) for 12 shallow and 16 medium-depth virtual lakes.

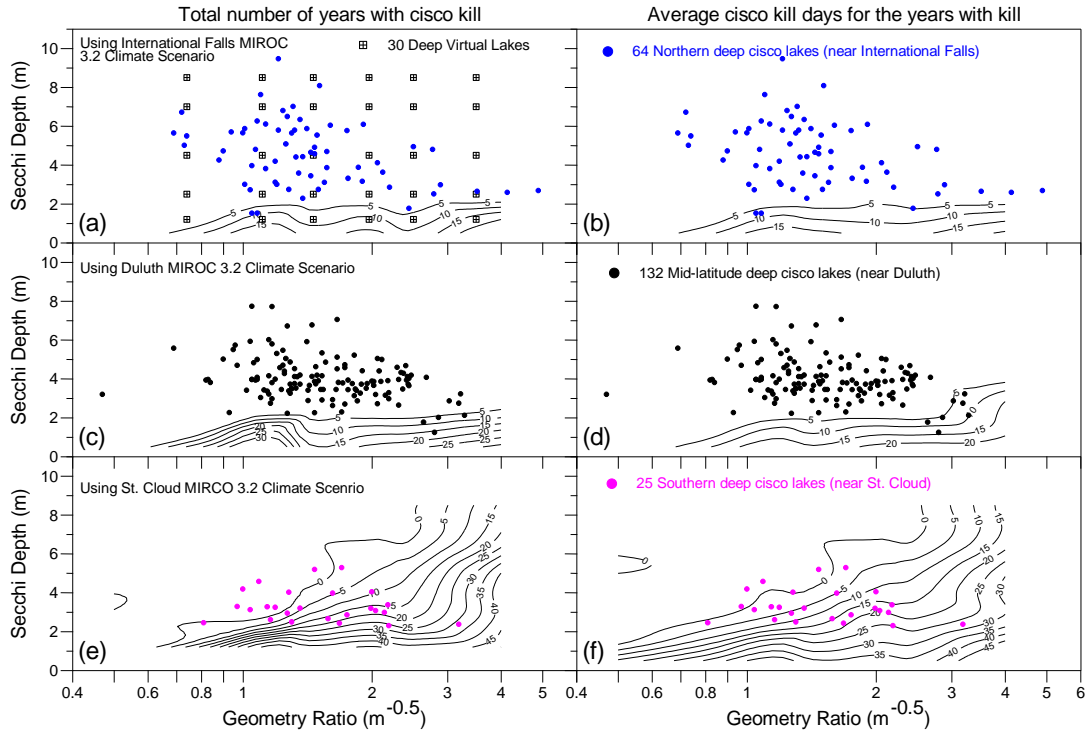


Figure 3.12 Contour plots of total number of years with cisco kills (a, c, e) and average cisco kill days for the years with kills (b, d, f) in deep lakes under future MIRCO 3.2 climate scenario. International Falls (a, b), Duluth (c, d), and St. Cloud (e, f) weather data were used for model simulations. Contours were derived by interpolation from simulated points for 30 virtual deep lakes.

The maximum number of years with cisco kill is 47 since the simulation period was 1961 to 2008 when simulated temperature and DO in 1961 were not used to derive fish habitat results (avoid the effect of initial conditions). The strength of lake stratification strongly affects or controls the total number of years with cisco kill, which is also affected by trophic status (Figure 3.10 and Figure 3.11). Shallow virtual lakes $GR > 5$ (Table 3.2), which are polymictic lakes, and have different results of cisco lethal conditions from ones of medium-depth virtual lake types ($GR < 4.5$). For example, the total number of years with cisco kill are 31–41 in northern shallow cisco lakes but less than 13 in northern

medium-depth cisco lakes under the past climate conditions. Strongly stratified ($GR < 2 \text{ m}^{-0.5}$) mesotrophic and eutrophic medium-depth lakes are simulated to have less years with cisco kill, and very transparent medium-depth lakes ($SD > 4.5 \text{ m}$) can have a few more years with cisco kill in the northern and mid-latitude Minnesota (Figure 3.10), which is also illustrated in Figure 3.9.

Under MIROC 3.2 future climate scenario, the total number of years with cisco kill is 46–47 in northern shallow cisco lakes and 35–47 in northern medium-depth cisco lakes. For southern cisco lakes near St. Cloud, there are 12–47 years and projected 47 years with kills under past and future climate scenarios, respectively (Figure 3.10). Weather conditions at Duluth are affected by Lake Superior and had slightly less cisco kill years simulated using weather data at International Falls. Medium-depth cisco lakes are projected to have most strong impact from climate changes, e.g., average increase of 39, 37, and 16 years in cisco kill for northern, mid-latitude, and southern cisco lakes, respectively.

Average days with cisco kill were calculated for the years with fish kill in each simulated lake. When continuous lethal conditions last only 1 or 2 days, those lethal days were not included in calculating average cisco-kill days (ACKDs). For northern shallow lakes, ACKDs were 10–16 days for those 31–41 years under past climate conditions and are projected to be 38–50 days under MIROC 3.2 climate scenario. Mid-latitude and southern cisco lakes are projected to have 30–40 and 67–76 ACKDs under MIROC 3.2 future climate. This indicates shallow lakes ($H_{\max} < 5 \text{ m}$) are definitely not good candidates for refuge lakes (Fang et al. 2012b; Jiang et al. 2012) that can support cisco under both the past and future warm climate. Fortunately, there are only 14 shallow cisco lakes in total 620 Minnesota cisco lakes (Figure 3.10 and Figure 3.11). Under the MIROC 3.2 climate

scenario, medium-depth southern lakes are projected to have 37–70 ACKDs in all 47 years with cisco kill; northern and mid-latitude lakes have 13–36 and 12–30 ACKDs (Figure 3.11) over 35–47 and 30–45 years (Figure 3.10), respectively. Even though northern and mid-latitude cisco lakes have only 0–9 and 0–14 ACKDs under past climate conditions, these medium-depth lakes are also projected to not be good candidates for refuge lakes to support cisco in the future warm climate.

3.4.3.2 Results of Deep Lakes

Under past climate conditions in Minnesota (1962–2008), none of the 30 virtual lakes ($H_{\max} = 24$ m) was simulated to have cisco kill, and this means that 221 deep lakes out of 620 cisco lakes typically have better cisco habitat conditions compared with shallow and medium-depth lakes. Figure 3.12 shows contour plots of projected total number of years with cisco kill (a, c, e) and average cisco kill days for the years with kills (b, d, f), respectively, under future MIROC 3.2 climate scenario in deep Minnesota lakes. In northern and mid-latitude Minnesota, only relatively eutrophic lakes are projected to have 5 or more years with cisco kill and on average 5 or more days of cisco kill in those years. In southern Minnesota, because of warmer weather conditions, deeper lakes have on average 5–45 days of cisco kill over 5–45 years and show strong dependence on the strength of lake stratification and trophic status, meanwhile, there are a few deep southern lakes that may be able to support cisco in the future as refuge lakes.

3.5 Discussion

In previous studies (Fang et al. 2012b; Jiang et al. 2012), all 620 cisco lakes were not grouped into shallow, medium-depth, and deep lakes by maximum depth, but all lakes regardless of maximum depth were plotted on contour plots of TDO3 using lake geometry

ratio and Secchi depth as independent variables for classify 620 cisco lakes into tier 1, 2, and 3 refuge lakes. The contour plots of TDO3 were generated using simulation results from all 30 virtual deep lakes. Therefore, there was a mismatch between shallow and medium-depth cisco lakes and simulated TDO3 from deep lakes. In this study, cisco lethal conditions were studied separately for shallow, medium-depth, and deep lakes; therefore, this provides more accurate information and consistent extrapolation among lakes with the same maximum depth with respect to cisco survival conditions under past and future climate scenario. The contour plots of total number of years with cisco kill and average cisco kill days for the years with kills simulated for 58 virtual lakes are tools to understand lethal conditions in 620 cisco lakes based on their locations (geometry ratio GR as x axis and Secchi depth SD as y axis) on those plots (Figure 3.10, Figure 3.11, and Figure 3.12).

Fang et al. (Fang et al. 2012b) used the fixed benchmark method and simulated T and DO profiles to determine multiple-year average annual TDO3, called AvgATDO3, to divide 620 Minnesota cisco lakes into Tier 1, Tier 2, and Tier 3 refuge cisco lakes. Lakes with $\text{AvgATDO3} \leq 11 \text{ }^{\circ}\text{C}$ (Tier 1 lakes) were selected to be most suitable for cisco; lakes with $11 \text{ }^{\circ}\text{C} < \text{AvgATDO3} \leq 17 \text{ }^{\circ}\text{C}$ (Tier 2 lakes) had suitable habitat for cisco; and non-refuge lakes with $\text{AvgATDO3} > 17 \text{ }^{\circ}\text{C}$ (Tier 3 lakes) would support cisco only at a reduced probability of occurrence or not at all (Fang et al. 2012b). The 11 and 17 °C contours of AvgATDO3 for each region (northern, mid-latitude, and southern Minnesota) from Fang et al. (Fang et al. 2012b) derived from 30 deep virtual lakes were included with Figure 3.10. All shallow cisco lakes were classified as non-refuge lakes. At the same time, some medium-depth cisco lakes were classified as Tier 1 and Tier 2 refuge lakes using these two contours from deep lakes. Based on lethal conditions projected using constant LT and

DO_{Lethal} , these medium-depth lakes can possibly have many years with cisco kill (Figure 3.10) and have on average two weeks or more days with lethal conditions (Figure 3.11). Therefore, these medium-depth lakes are not good candidates for cisco refuge lakes.

For 221 deep cisco lakes, Figure 12 shows most of them are possibly good candidates for refuge lakes, but it is not feasible to use cisco kill parameters to classify them into tiered cisco refuge lakes. Some other good growth parameters, e.g., good-growth length, area, and volume used in previous studies (Stefan et al. 1996; Fang et al. 2004a), and TDO3 (Fang et al. 2012b), may or can be used to classify them into tiered refuge lakes, which will be studied in the next step.

Comparing Figure 3.12 with Figure 3.10 and Figure 3.11, one can see that cisco kill parameters have a huge decrease from 13 m medium-depth lakes to 24 m deep lakes under future climate scenario, e.g., 37–47 years to zero years ($SD > 2$ m) with cisco kill in northern Minnesota lakes. Because of non-linear complex relationship between lethal condition and lake characteristics (Figure 9), lethal conditions and potential cisco kills in lakes with other maximum depths, e.g., $H_{max} = 18$ m, are currently unknown and should be studied further. We can propose that lakes with $H_{max} = 13$ m represent lakes with H_{max} between 11 to 15 m, lakes with $H_{max} = 18$ m represent lakes with H_{max} between 15 to 21 m, and lakes with $H_{max} = 24$ m represent lakes with $H_{max} > 21$ m for future study.

Simulation of lethal conditions under the past climate conditions and projection under the future climate scenario are affected by various model inputs, model simplification or assumptions, and boundary conditions. Only one future climate scenario (MINLAKE2012's atmospheric boundary condition) was used to project cisco lethal conditions. Future climate projection (mean monthly increments over 30 years) has various

uncertainties from the global circulation model. In a previous study, three future climate scenarios were used for lake fish habitat projections. Many hydrologic studies related to future projections use an assemblage of future climate scenarios, and the same method can be applied for the current study in the next step. Accuracy of T and DO simulation can directly affect the simulation of cisco lethal conditions in lakes and is affected by model calibration using limited data in some lakes (Table 3.1) and model parameter/coefficient generalization for simulations in virtual lakes. Model simplification, for example, MINLAKE2012, does not simulate chlorophyll-a but uses generalized seasonal patterns based on observational data from 56 lakes and reservoirs in Europe and North America (Marshall and Peters 1989), and can create uncertainties in DO simulation. This study does not focus on the uncertainty of model predication; therefore, uncertainties are not specifically quantified here. We believe the study with various uncertainties still provide useful information on future climate impact on cisco lethal conditions in 620 Minnesota lakes, which in turn provides useful information for future fish resource management.

3.6 Summary and Conclusions

Projected future climate warming can affect lake water temperature and dissolved oxygen distribution with depth, which can constrain fish habitat in lakes. In this study, a one dimensional (vertical), dynamic water quality model MINLAKE2012 was further calibrated in 23 Minnesota lakes that had observations of cisco mortality or survival in the unusually warm summer of 2006. The fish habitat simulation model FishHabitat2013 using simulated T and DO profiles, constant lethal temperature LT and DO survival limit as input was used to determine lethal conditions of cisco *Coregonus artedii* in Minnesota lakes. Cisco lethal conditions were simulated in 23 Minnesota lakes for model validation, and in

12 shallow and 16 medium-depth virtual lakes, and 30 virtual deep lakes for model predication/projection. Contour plots of total number of years with cisco kill and average cisco kill days for the years with kills using lake geometry ratio and Secchi depths as x and y axes were used as tools to understand/extrapolate climate impacts on 620 cisco lakes. The following conclusions were drawn.

(1) When the cisco habitat model used constant $LT = 22.1$ °C and $DO_{Lethal} = 3$ mg/L, simulated cisco kill (lethal conditions) and having cisco habitat in 2006 had overall good agreement with observations in 23 lakes (18 lakes with “Yes (Yes)” agreement and 4 lakes with partial or “Yes (no)” agreement) (Table 3.3).

(2) Number of days with lethal conditions strongly depend on the strength of lake stratification (related to lake geometry ratio) and also have a non-linear complex relationship with lake trophic status (represented by Secchi depth) (Figure 3.9). The total number of years with cisco kill are 31–41 in northern shallow cisco lakes but less than 13 in northern medium-depth cisco lakes under the past climate conditions.

(3) Under the future MIROC 3.2 climate scenario, shallow cisco lakes are projected to have cisco kill in almost every year with on average more than 30 kill days; medium-depth lakes are projected to have 25–47 years with cisco kill and on average 12–70 kill days. Therefore, shallow and medium-depth lakes are not good candidates for cisco refuge lakes.

(4) Under the future MIROC 3.2 climate scenario, only relatively eutrophic deep lakes (Secchi depth <2 m) in northern and mid-latitude Minnesota and many southern lakes (Figure 3.12) have 5 or more years with cisco kill, and all other deep lakes are potential good refuge lakes. Cisco kill parameters cannot be used to classify 221 deep lakes into tiered refuge lakes, and other fish growth parameters should be used for future study.

Chapter 4 **Oxythermal habitat parameters and identifying cisco refuge lakes in Minnesota under future climate scenarios using variable benchmark periods**

4.1 Abstract

Fish habitat in lakes is strongly constrained by water temperature (T) and available dissolved oxygen (DO). With climate warming both of these water quality parameters will change. A fish habitat simulation model was developed to calculate an oxythermal habitat variable, TDO3, i.e. water temperature at 3 mg/l of DO, from simulated daily T and DO profiles and used to determine potential refuge lakes for lake herring or cisco (*Coregonus artedii*) in Minnesota. Daily T and DO profiles were simulated using a deterministic, unsteady, one-dimensional (vertical) year-round lake water quality model (MINLAKE2010) that was developed specifically for transparent deep lakes. Profiles for thirty Minnesota cisco lakes were simulated with the MINLAKE 2010 model using recorded (1961-2008) weather data or projected future climate scenarios (CGCM 3.1 and MIROC 3.2) as model input. The average of daily TDO3 values (called ATDO3_{VB}) over a 31-day sliding or variable benchmark period (VB), was first calculated from daily TDO3 values. The annual maximum of ATDO3_{VB} was retained for each simulated lake and year, and the average of 47 ATDO3_{VB} values (called AvgATD3_{VB}) obtained for the 1962-2008 simulation period was compared to oxythermal stress criteria for cisco determined from the analysis of field data. Isopleths of AvgATD3_{VB} were interpolated for the 30 simulated lakes on a plot of Secchi depth vs. lake geometry ratio used as indicators of trophic state and summer mixing conditions, respectively. Marking the 620 Minnesota lakes with identified cisco populations on the plot of AvgATD3_{VB} allowed to partition the 620 lakes into the three tiers depending on where they fell between the isopleths: lakes with AvgATD3_{VB} ≤ 11°C (Tier 1 lakes) were selected to be most suitable for cisco; lakes with 11 °C < AvgATD3_{VB} ≤ 17 °C (Tier 2 lakes) had suitable habitat for

cisco; and non-refuge lakes with $\text{AvgATD3}_{\text{VB}} > 17\text{ }^{\circ}\text{C}$ (Tier 3 lakes) would support cisco only at a reduced probability of occurrence or not at all. About 160 existing cisco lakes were thus projected to be suitable refuge lakes (Tier 1 plus Tier 2) under the two future climate scenarios. The remaining lakes were projected to lose their cisco supporting ability. The methodology to identify the refuge lakes was applied to a cisco kill that occurred in 18 cisco lakes in Minnesota in the hot summer of 2006, and was able to identify the majority of these lakes as non-refuge lakes.

4.2 Introduction

Fish habitat is constrained by water temperature (T), available dissolved oxygen (DO), food supply, human interference, and other environmental factors. In streams channel geometry and flow are important to fish habitat (Rundquist and Baldrige 1990). In lakes, T and DO are the two most significant water quality parameters that affect survival and growth of fishes (Fry 1971; Magnuson et al. 1979; Coutant 1985b; Christie and Regier 1988; Coutant 1990; Jacobson et al. 2010).

An increase of carbon dioxide (CO_2) and/or other greenhouse gases (e.g., methane, nitrous oxide, and ozone) in the atmosphere is projected to cause climate warming (NRC 1983; IPCC 2007), which will alter T and DO characteristics in lakes. Potential effects on the Laurentian Great Lakes have been explored e.g., by (Croley 1990; Magnuson et al. 1997; Kling et al. 2003; Lynch et al. 2010). The impact of climate change on water quality in the many small lakes which cover 60% of the available lake surface area in the U.S. (Markfort et al. 2010) is likely to be equally serious as preliminary studies on lakes with surface areas up to 10 km^2 in the contiguous USA have shown (Fang and Stefan 1999, 2000, 2009b). These changes are in turn expected to have a significant effect on lake fish populations in the contiguous USA (Stefan et al. 2001; Fang et al. 2004c). Climate warming has the potential to reduce cold-water fish habitat in lakes by direct warming of the water, and by 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. 2004b).

Cisco *Coregonus artedi* is the most common cold-water stenothermal fish in Minnesota lakes and a common forage fish for walleye *Sander vitreus* and northern pike *Esox lucius* among other prized sport fishes. The Minnesota (MN) Department of Natural Resources (DNR) has sampled cisco from 648 lakes in netting assessments since 1946 (MN DNR files). These lakes are typically deeper and more transparent than average lakes in Minnesota (Fang et al. 2009). The lakes are scattered throughout much of the central and northern portions of the state (Figure 4.1) and cross several land uses (agricultural, urban, and forested). The wide distribution suggests that cisco are somewhat more eurythermal than other native, lentic cold-water stenotherms such as lake whitefish *Coregonus clupeaformis* (sampled in 155 Minnesota lakes), lake trout *Salvelinus namaycush* (124 Minnesota lakes) and burbot *Lota lota* (233 Minnesota lakes). Cisco physiologically require cold, well-oxygenated water to survive, grow, and reproduce (Cahn 1927; Frey 1955). The combination of a wide distribution (Figure 4.1) and a requirement for cold, oxygenated water, make cisco an excellent “canary in a mineshaft” species that is a sensitive indicator of ecological stresses such as eutrophication and climate warming. For example,

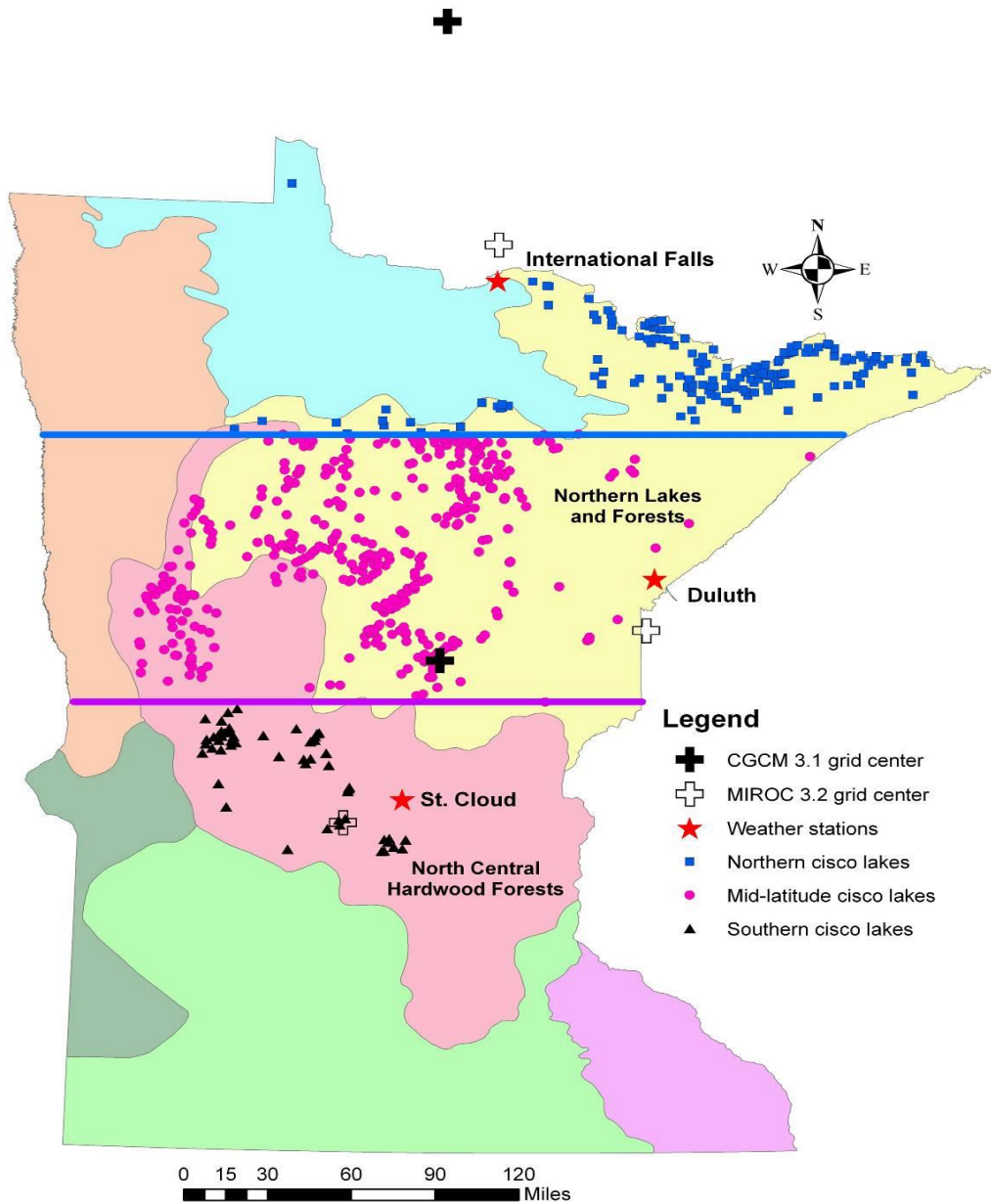


Figure 4.1 Geographic distribution of 620 cisco lakes grouped by latitude, three weather stations (stars) and associated grid center points (crosses) of CGCM 3.1 and MIROC 3.2 used for model simulations. Background shades identify ecoregions of Minnesota. Cisco lakes are essentially in two ecoregions: (1) Northern Lakes and Forests, and (2) North Central Hardwood Forests.

eighteen lakes in north-central Minnesota experienced cisco mortality in the unusually hot summer of 2006 (Jacobson et al. 2008).

The physiological response of adult populations of different fish species to T and DO levels has been the subject of numerous laboratory and field studies. Early studies were described, e.g., by (Coutant 1970), (McCormick et al. 1972), and (Hokanson et al. 1977). A large EPA database was described by (Eaton et al. 1995) and (Eaton and Scheller 1996). Earlier studies attempted to correlate fish survival, growth, reproduction and other responses to chronic levels of T and DO exposure. More recent studies have attempted to include time-variable temperature exposure. (Wehrly et al. 2007) describe such a study and give a review of the pertinent literature.

The oxythermal habitat approach commonly used in cold-water fish niche modeling (Dillon et al. 2003), defines an upper (e.g., lethal) boundary for T and a lower (e.g., lethal) boundary for DO. 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).

In previous fish habitat studies (Stefan et al. 1995; Fang and Stefan. 1998), we validated habitat estimates from T and DO profiles under past climate conditions against actual fish observations in Minnesota lakes. The thermal/DO habitat approach in the above studies utilized separate T and DO criteria to determine not only survival but also good growth habitat parameters and the impact of climate warming on fish survival (Stefan et al. 2001; Fang et al. 2004c).

Jacobson et al. (2010) proposed a single variable to quantify oxythermal habitat that allows for comparison across several cold-water 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, and is called TDO3. Selection of 3 mg/l as the limiting oxygen concentration was somewhat arbitrary because proximate, alternative benchmark concentrations of 2, 4, and 5 mg/l were highly correlated (Jacobson et al.

2010). However, 3 mg/l is an oxygen concentration that is probably lethal or nearly so for many cold-water species (Frey 1955; EPA 1986; Evans 2007) and therefore represents a desirable value for a presence/ absence niche model. The 3 mg/l DO limit was also used previously to examine impacts of climate warming on cold-water fish habitat in small lakes in Minnesota and in the contiguous USA (Stefan et al. 2001; Fang et al. 2004c). A higher TDO3 value represents higher oxythermal stress for the fish.

Of particular interest using TDO3 is to project the effect of climate change on native cold-water fish species. Sharma et al. (2011) reported that 30 to 70% of the cisco population found in about 170 of Wisconsin's deepest and coldest lakes could become a climate change casualty and disappear from most of the Wisconsin lakes it now inhabits by the year 2100.

The goals of the study described herein were to develop a method to project the quality of fish habitat in the about 600 existing cisco lakes in Minnesota, to project how cisco might fare under future climate scenarios, and to identify potential cisco 'refuge lakes' using TDO3. A 'refuge lake' used in this study is a lake that has supported cisco under past (historical) climate conditions and is projected to provide cisco habitat under future climate scenarios. Once refuge lakes are identified, protection efforts can be initiated in lake watersheds to prevent deterioration of water quality and trophic status in these lakes by anthropogenic activities.

To pursue the overall objective of this study we had to concentrate on cold-water fish growth and survival in lakes. We had to develop a fish habitat simulation model based on T and DO that was suitable for cold-water fish in deep lakes of Minnesota. Specifically we had to (1) review how the T and DO habitat constraints on cold-water fishes in lakes can be quantified (oxythermal fish habitat criteria), (2) develop a method to quantify oxythermal fish habitat under past climate, and by how much climate warming will change it in existing cisco lakes, (3) validate that the methods

under (1) and (2) would give results for past climate conditions that would match actual cisco observations in lakes, and (4) apply the method to make projections for a representative number of lakes in the future and (5) extrapolate those results to 620 cisco lakes of Minnesota. Together, these steps would amount to a substantial ecological modeling, analysis and validation effort.

This study was to develop a method to rank the quality of fish habitat for cisco in Minnesota lakes and the identification of potential refuge lakes if and when projected future (warmer) climate scenarios become reality. When a fish species is eliminated by changes in water temperature, it is not only a loss, but also opens the habitat for other, exotic invasive species. For these reasons a method to identify potential refuge lakes is important.

4.3 Methods

4.3.1 Overview of the method developed

Figure 4.2 shows the flowchart of the steps and procedures developed and used for the study to identify cisco refuge lakes in Minnesota. Past climate conditions (1961 to 2008) and future climate scenarios are model inputs (atmospheric boundary conditions) for a deterministic, unsteady and one-dimensional (vertical) lake water quality model (MINLAKE2010) to simulate the year-round daily T and DO profiles in cisco lakes (Figure 4.2). The MINLAKE2010 model used for this purpose was modified from the previous version MINLAKE96 (Fang et al., 2004), for specific application to deeper and clearer cold-water lakes. The algorithm for vertical mixing dynamics in a stratified lake was modified and sedimentary oxygen uptake rates were modified to better capture mass transport across the metalimnion and in the benthic boundary layer so that cisco lakes up to 100 m maximum depth could be simulated (Fang et al. 2012a).

In this study we will apply an oxythermal habitat variable, TDO3, i.e. a water temperature at 3 mg/l of DO (Jacobson et al. 2010), to define suitable cold-water fish habitat in a stratified lake. TDO3 is calculated from simulated daily T and DO profiles for every simulated day except days in 1961 to avoid initial condition effect. To recognize the resilience of fish to water quality fluctuations, the highest average daily TDO3 value in any 31-day sliding (variable) benchmark (VB) period, called ATDO3_{VB}, will be calculated for each simulated lake and year (Figure 4.2).

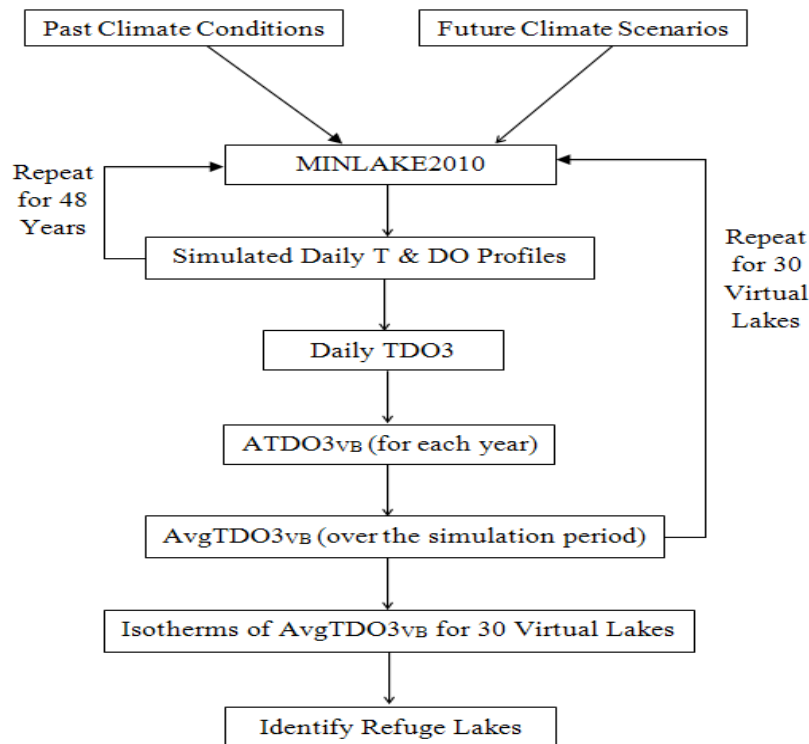


Figure 4.2 Conceptual flowchart of steps proposed for the study to identify cisco refuge lakes.

To assess the quality of cisco habitat in a lake, and to identify refuge lakes, the 47-year average of annual ATDO3_{VB} values in the 1962-2008 simulation period (i.e., AvgATD3_{VB} in Figure 4.2) will be calculated, and compared to TDO3 limits determined by the analysis of field data including fish kills. By dividing lakes into three tiers with different ranges of AvgATD3_{VB} a tool will be created to identify the lakes that are most suitable as refuge lakes (AvgATD3_{VB} ≤ 11°C or Tier 1

lakes) and those that are least suitable or non-refuge lakes ($\text{AvgATD3}_{\text{VB}} > 17^\circ\text{C}$ or Tier 3 lakes). Tier 2 refuge lakes will be in the range $11^\circ\text{C} < \text{AvgATD3}_{\text{VB}} \leq 17^\circ\text{C}$. Criteria for how the TDO3 tier limits were selected are presented in Section 2.6.

Thirty virtual cisco lakes of different bathymetric and trophic conditions, which represent the 620 Minnesota lake database well, will be simulated for 48 years (1961-2008) of past and future climate conditions. The simulated 30 values of $\text{AvgATD3}_{\text{VB}}$ will be plotted and interpolated as isotherms on a plot of Secchi depth (SD) vs. lake geometry (GR). The 11°C and 17°C isotherms will divide lakes into Tier 1 and Tier 2 refuge lakes and Tier 3 non-refuge lakes. Mean summer SD is an indicator of lake trophic state (it relates to mean chlorophyll levels and summer transparency of a lake), while lake GR is an indicator of summer mixing dynamics of a lake (Gorham and Boyce 1989). The 620 existing cisco lakes in Minnesota will be divided into tiers using again the mean summer SD and GR of each lake as independent variables and the 11°C and 17°C isotherms derived for the 30 simulated lakes to draw the boundaries between Tier 1, 2 and 3 lakes. In this way the unsimulated lakes can be connected to simulated lakes.

4.3.2 Past and Future Climate Scenarios

There is a strong climate gradient with latitude in Minnesota, and a weaker one with longitude. There is also a strong climate divide running east-west through about the middle of Minnesota. In earlier studies Minnesota was divided into a northern region and a southern region for this very reason (Hondzo and Stefan 1993a). Therefore, two constant latitudes were proposed as boundary limits to associate cisco lakes with weather stations (Figure 4.1). The latitudes proposed as dividing lines are 46.10°N and 47.65°N . 46.10°N runs through central Minnesota (Figure 4.1). There are currently 55 cisco lakes below 46.10°N that were assigned to the St. Cloud weather station. There are 166 lakes above 47.65°N that were assigned to the International Falls weather

station. There are 399 lakes between latitudes 47.65 °N and 46.10 °N that were assigned to the Duluth weather station (see Figure 4.2). These groups of lakes were named “northern cisco lakes” assigned to International Falls, “mid-latitude cisco lakes” assigned to Duluth, and “southern cisco lakes” assigned to St. Cloud. Figure 4.3 shows 48-year averages for daily air temperature, dew point temperature, wind speed, and solar radiation for past climate (1961-2008) at Duluth as example. Seasonal amplitudes of air temperatures, dew point temperatures and solar radiation are very high. Wind speeds are somewhat lower in summer than in fall, winter and spring.

In this study, we developed first a method that would demonstrate whether a specific Minnesota cisco study lake could support cisco habitat under past (observed historical) climate conditions. We then used this methodology to project whether a lake could support cisco habitat under future climate scenarios, i.e. after climate warming. To make the projection, the model output from two Coupled General Circulation Models (CGCMs) of the earth’s atmosphere and oceans (i.e., CGCM 3.1 and MIROC 3.2) was used. These CGCM models simulate time series of climate parameters that can be used to create future climate scenarios. As input to the MINLAKE2010 model, the CGCM future climate scenarios facilitate the projection of future lake water quality conditions, specifically daily T and DO profiles in lakes from which future cisco habitat is derived.

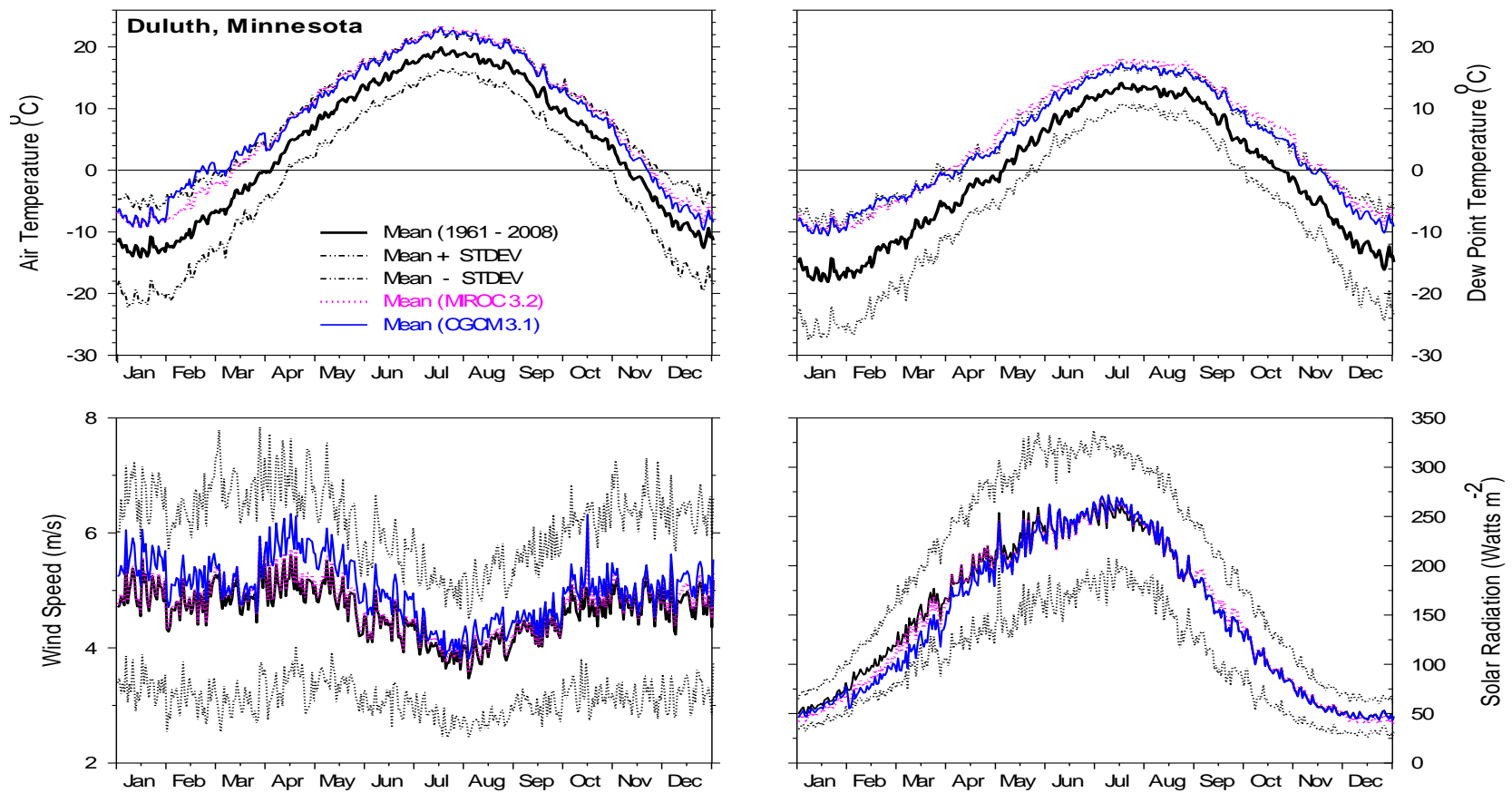


Figure 4.3 Daily averages for air temperature, dew point temperature, wind speed, and solar radiation at Duluth, MN, for past climate conditions (1961-2008) and future climate scenarios (CGCM 3.1 and MIROC 3.2). Daily averages plus and minus one standard deviations (STDEV) are also plotted for past climate conditions.

The CGCM 3.1 (Kim et al. 2002; Kim et al. 2003) is the third generation CGCM from the Canadian Climate Centre for Climate Modeling and Analysis (CCCma). The CCCma's CGCM 3.1 uses the ocean component from the earlier Second Generation CGCM (McFarlane et al. 1992) and applies a substantially updated atmospheric component - the third Generation Atmospheric General Circulation Model. The CGCM 3.1 was run in the T47 version that has a surface grid (spatial) resolution of roughly 3.75 degrees latitude and longitude. It was used for the study because it was available to be downloaded from the IPCC data center.

The MIROC 3.2 simulation model (Hasumi and Emori 2004), was developed by the Center for Climate System Research, University of Tokyo; the National Institute for Environmental Studies; and the Frontier Research Center for Global Change - Japan Agency for Marine-Earth Science and Technology. The output of MIROC 3.2 with high spatial resolution has been used; its surface grid has a spatial resolution of roughly 1.12 degrees latitude and longitude (there are seventeen grid center points within Minnesota).

A scenario of future climate was obtained by adjusting the baseline weather observations by the difference between period-averaged results from CGCM experiments (usually 30 year periods are used) and the corresponding averages for the CGCM control simulation. In recent transient experiments developed for the IPCC's Fourth Assessment Report (IPCC 2007) simulated baseline period (e.g., 1961-1990) was used in place of the control-run. The differences known as a "change field" are produced and reported for all grid center points at monthly interval. The change field data for the period 2070 - 2099, 30 year averages that are compatible with the IPCC's Third Assessment Report (IPCC 2001), were downloaded from the IPCC website for use in this study. Monthly climate parameter increments obtained from the CGCM 3.1 or MIROC 3.2 were applied to measured daily climate conditions (1961 – 2008) to generate the projected daily future climate

scenarios. Monthly increments from the grid center point closest to a weather station were used for that station. Three principal Class I weather stations (International Falls, Duluth, and St. Cloud) shown in Figure 4.1 were used for model simulations. For the MIROC 3.2 future climate scenario, each weather station has its closest grid center from MIROC 3.2 (Figure 4.1); For the CGCM 3.1 future climate scenario, the same grid point center was used for the Duluth and St. Cloud weather stations because CGCM 3.1 has coarser spatial resolution than MIROC 3.2. Monthly air temperature increments at Duluth are projected by the MIROC 3.2 scenario to range from 3.59 °C to 4.67 °C with an annual average of 4.09 °C; the range is from 2.91 °C to 8.09 °C with annual average of 4.07 °C for the CGCM 3.1 scenario. Figure 4.3 also shows 48-year averages for four past climate parameters plus or minus one daily standard deviation (STDEV); 48-year averages of daily air temperature and dew point temperature for projected future climate scenarios are close to 48-year averages for past climate plus one daily standard deviation (Figure 4.3). Daily variations of wind speed and solar radiation over the 48-year period (1961 – 2008) are larger than monthly adjustments for projected future climate scenarios (Figure 4.3).

4.3.3 Daily water temperature and dissolved oxygen profile simulations in lakes

Daily T and DO profiles have to be known from measurements or from simulations to determine if suitable fish habitat exists. To make projections of water quality and fish habitat in lakes under future climate scenarios, numerical simulation models are indispensable. A deterministic, one-dimensional (vertical) and unsteady year-round water quality simulation model, MINLAKE2010 (Fang et al. 2012a), was developed from the MINLAKE96 (Fang et al. 1996; Fang and Stefan 1996a), to simulate daily T and DO profiles under both past and future climate scenarios for the cisco lakes. The MINLAKE96 model had to be modified because cisco lakes are typically deeper and clearer than average lakes in Minnesota. The algorithm for vertical mixing

dynamics in a stratified lake was modified (Fang et al. 2012a) to better capture mass transport across the metalimnion and in the benthic boundary layer so that lakes up to 100 m maximum depth could be simulated. To obtain daily simulated T and DO profiles, 30 Minnesota virtual lake types were simulated with the modified MINLAKE2010 model using recorded (1961-2008) weather data from three Class I weather stations in Minnesota (International Falls, Duluth, and St. Cloud, Figure 4.1) or from two future climate scenarios as model input.

Table 4.1 Characteristics of frequency distributions for maximum depth, surface area and Secchi depth of 620 cisco lakes in Minnesota, and comparison to 3002 typical Minnesota lakes.

Parameter	Cumulative distribution	frequency	Range for 620 cisco lakes	Range for 3002 ¹ Minnesota lakes
Maximum Depth (m)	Lower 30%		3.0 - 12.2	1.0 - 5.0
	Central 60%		12.2 - 32.9	5.0 - 20.0
	Upper 10%		32.9 - 64.9	20.0 - 45.0
Surface Area (km ²)	Lower 30%		0.04 - 0.9	0.06 - 0.4
	Central 60%		0.9 - 10.0	0.4 - 5.0
	Upper 10%		10.0 - 3847.0	5.0 - 40.0
Secchi Depth (m)	Lower 30%		0.7 - 2.8	0.8 - 1.8
	Central 60%		2.8 - 5.0	1.9 - 4.5
	Upper 10%		5.0 - 9.5	4.6 - 7.0

¹ from Schupp's database (Hondzo and Stefan, 1993)

The MINLAKE2010 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 during the winter period (Gu and Stefan 1990; Fang and Stefan 2009a). Each of the horizontal water layers is assumed to be well mixed. 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). A physics-based algorithm was used to predict the date of ice formation in the model (Fang and Stefan 1996a). The vertical DO profile in a lake is computed from a balance between oxygen sources (reaeration and

photosynthesis) and oxygen sinks (sediment oxygen uptake, water column oxygen demand, and plant respiration), with consideration of winter ice cover and low temperature kinetics (Fang and Stefan 1997). The one-dimensional heat transfer and DO transport equations were solved numerically for time steps of one day and layer thicknesses from 0.02 m (near the ice-water interface) to 1.0 m (for depths greater than 1.0 m) using an implicit finite difference scheme and a Gaussian elimination method. More detailed descriptions of MINLAKE96 and MINLAKE2010 are presented elsewhere (Fang and Stefan 1996a; Fang and Stefan 2009a; Fang et al. 2010a; Fang et al. 2012a). Twenty-one cisco lakes and seven non-cisco lakes were selected for model calibration of MINLAKE 2010 based on multi-year data availability; more than half of the 28 lakes had a maximum depth greater than 24.0 m (H_{\max} used for the 30 virtual lakes), and 23 of the 28 lakes were either mesotrophic or oligotrophic lakes (Fang et al. 2012a). Four hundred thirty nine (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 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) (Fang et al. 2012a). The model was run in daily time steps over 48 simulation years from 1961 to 2008 including both open-water seasons and ice-cover periods.

4.3.4 Thirty virtual cisco lakes in Minnesota

A MN DNR lake database contains 620 cisco lakes that were used for analysis. Another Minnesota lake database consisting of 3002 lakes (Schupp 1991) was previously used to project fish habitat in Minnesota lakes (Stefan et al. 1993). Table 4.1 gives information on distributions of maximum depth (H_{\max}), surface area (A_s), and SD of the 620 cisco lakes and the 3002 Minnesota lakes. Maximum lake depths of the 620 cisco lakes range from 3.0 to 64.9 m, surface areas from

0.04 to 3847.0 km², and mean summer Secchi depths from 0.7 to 9.5 m (Table 4.1). The median values of maximum lake depth, lake surface area, and Secchi depth of the 620 cisco lakes are 17.0 m, 1.6 km², and 3.4 m (Fang et al. 2009), respectively. On average, Minnesota’s cisco lakes are deeper, more transparent and less trophic than other lakes in Minnesota (Fang et al. 2009). Figure 4.1 shows the geographic distribution of the 620 cisco lakes grouped by latitude for modeling purposes. Cisco lakes are primarily found in two Level III ecoregions (http://www.epa.gov/wed/pages/ecoregions/na_eco.htm): (1) the northern lakes and forest region and (2) the north central hardwood forests region.

Table 4.2 Morphometric characteristics and “names” of the 30 virtual cisco lakes simulated with the MINLAKE2010 model (Maximum lake depth $H_{\max} = 24$ m).

Surface Area A_s (km ²)	Secchi Depth SD (m)					Geometry Ratio, GR =
	1.2	2.5	4.5	7.0	8.5	$A_s^{0.25}/H_{\max}$
0.1	LakeC01	LakeC02	LakeC03	LakeC04	LakeC05	0.74
0.5	LakeC06	LakeC07	LakeC08	LakeC09	LakeC10	1.11
1.5	LakeC11	LakeC12	LakeC13	LakeC14	LakeC15	1.46
5.0	LakeC16	LakeC17	LakeC18	LakeC19	LakeC20	1.97
13.0	LakeC21	LakeC22	LakeC23	LakeC24	LakeC25	2.50
50.0	LakeC26	LakeC27	LakeC28	LakeC29	LakeC30	3.50

Because it was not feasible to run deterministic models for 620 cisco lakes, we used 30 ‘virtual’ cisco lake types (Table 4.2) that were representative of the entire set of 620 lakes; a similar approach using 27 ‘generic’ lake types had been used to study climate warming impact on fish habitat in small lakes in Minnesota (Stefan et al. 1996) and in the contiguous USA ((Fang et al. 2004c). The set of 30 virtual cisco lakes selected comprises lakes with five different SD values (1.2 m, 2.5 m, 4.5 m, 7.0 m, and 8.5 m) and six different surface areas (0.1 km², 0.5 km², 1.5 km², 5.0 km², 13.0 km², and 50 km²). The maximum depth of all 30 virtual lakes is set at 24 m, because cisco lakes are relatively deep (Fang et al. 2009). Combinations of the maximum depth and surface

areas give six different lake geometry ratios GR for the 30 virtual lakes, i.e. $0.74 \text{ m}^{-0.5}$, $1.11 \text{ m}^{-0.5}$, $1.46 \text{ m}^{-0.5}$, $1.97 \text{ m}^{-0.5}$, $2.50 \text{ m}^{-0.5}$, and $3.50 \text{ m}^{-0.5}$ (Table 4.2). The GR is defined as $A_s^{0.25}/H_{\max}$ in $\text{m}^{-0.5}$ when A_s is in m^2 and H_{\max} is in m. The strength of the seasonal lake stratification is related to the lake geometry ratio (Gorham and Boyce 1989). Polymictic lakes have the highest GR numbers, while strongly stratified dimictic lakes have the lowest; the transition occurs between 3 and 5 (Gorham and Boyce 1989). Twenty of the 30 virtual cisco lake types, LakeC01 to LakeC20 in Table 4.2, are strongly stratified with $\text{GR} < 2$, and the other ten lake types (LakeC21 to LakeC30) are relative weakly stratified. The 30 virtual cisco lakes do not contain any polymictic lakes because (Fang et al. 2012a) studied the oxythermal habitat variable TDO3 in 21 study cisco lakes in Minnesota (a subset of the 620 cisco lakes) and found that two cisco lakes with $\text{GR} > 4.0$ (White Iron Lake and South Twin Lake) had high annual maximum TDO3 values that are not favorable for cisco survival.

Table 4.3 Distributions and classifications of the 30 virtual cisco lakes by surface area, geometry ratio (GR) and Secchi depth (SD).

Area (km ²)	% less than ¹	Classification by area	GR (m ^{-0.5})	% less than ¹	Classification by GR	SD (m)	% less than ¹	Trophic status ³
0.1	1.0%	Small	0.74	1.0%	Stratified	1.2	0.6%	E
0.5	14.6%	Small ²	1.11	7.1%	Stratified	2.5	19.0%	M
1.5	48.0%	Medium	1.46	21.1%	Stratified	4.5	81.5%	O
5.0	77.8%	Medium ²	1.97	41.8%	Stratified	7.0	98.5%	O
13.0	92.0%	Large	2.50	62.0%	Stratified	8.5	99.8%	O
50.0	98.0%	Large	3.50	81.0%	Stratified	-	-	-

¹ The 620 cisco lakes in the MN DNR database represent 100%

² Lakes on the border of the previous 27 regional lake types in the classification by Stefan et al. (1993).

³ E = eutrophic, M = mesotrophic, and O = oligotrophic.

Even though the selection of lake bathymetry (surface areas and maximum depth) and Secchi depths for the 30 virtual cisco lakes was subjective, the selected values are representative of the 620 Minnesota cisco lake database. Table 4.3 gives cumulative distributions (% less than) and classifications of lake surface area, geometry ratio, and Secchi depth for the 30 virtual lakes in comparison to all 620 cisco lakes in the MN DNR database (Fang et al. 2009). The 30 virtual cisco lakes are all stratified lakes based on geometry ratio, they cover lakes having small to large surface areas and include eutrophic to oligotrophic lakes (Table 4.3). It can be seen that the 30 virtual lakes represent the actual 620 lakes well.

4.3.5 Oxythermal habitat parameter TDO3

The water temperature at 3 mg/l of DO, called TDO3, is a single variable proposed by Jacobson et al. (2010) to quantify oxythermal habitat that allows for identification of possible refuge lakes. From the analysis of measured T and DO profiles, (Jacobson et al. 2010) concluded that the highest probability of cisco occurrence was at a late-summer TDO3 of 9.0 °C, and central borders ranged from 4.0 to 16.9 °C. From measured T and DO profiles in 18 Minnesota lakes with cisco kill in 2006, (Jacobson et al. 2008) determined that the lethal temperature for cisco was 22 °C at 3 mg/l of DO. In this study, the oxythermal parameter TDO3 was used to measure stress on adult cisco for identifying cisco refuge lakes: the lower the TDO3, the lower the stress on adult cisco.

The TDO3 can be determined by interpolating the temperature of water at the DO concentration of 3 mg/l from measured or simulated vertical T and DO profiles (Jacobson et al. 2010). In this study, an algorithm was developed to compute the oxythermal habitat parameter TDO3 using simulated daily T and DO profiles in 30 virtual lakes over a 47-year simulation period (1962 to 2008). T and DO profiles simulated for the first-year (1961) were not used to extract TDO3 values in order to avoid possible effects of assumed initial conditions. Figure 4.4 illustrates

the procedure how TDO3 can be extracted from either measured or simulated T and DO profiles. Carlos Lake in Figure 4.4 has a maximum depth of 50 m and mean summer Secchi depth of 3.3 m (mesotrophic lake); it had excellent cold-water oxythermal habitat with TDO3 = 6.6°C on July 24, 1979 (using observed temperature and DO profiles) and is projected to have a TDO3 value of 7.2 °C on July 24 under the future climate scenario MIROC 3.2. South Twin Lake in Figure 4.4 has a maximum depth of 8.8 m and mean summer Secchi depth of 2.8 m (mesotrophic lake); it had a high TDO3 value of 23.0 °C on August 6, 2008 and is projected to have a TDO3 value of 25.2 °C on August 6 under the future climate scenario MIROC 3.2. South Twin Lake is the shallowest of the 21 cisco study lakes used for model calibration of MINLAKE 2010 and has a geometry ratio of 5.3 – it is weakly stratified in temperature and DO profiles (Figure 4.4).

A TDO3 value was determined for each day of the 47-year simulation period for each simulated lake. Examples of time series of daily TDO3 values are given in Figure 4.5 for two selected lakes (Big Trout Lake and White Iron Lake). The annual maximum daily TDO3

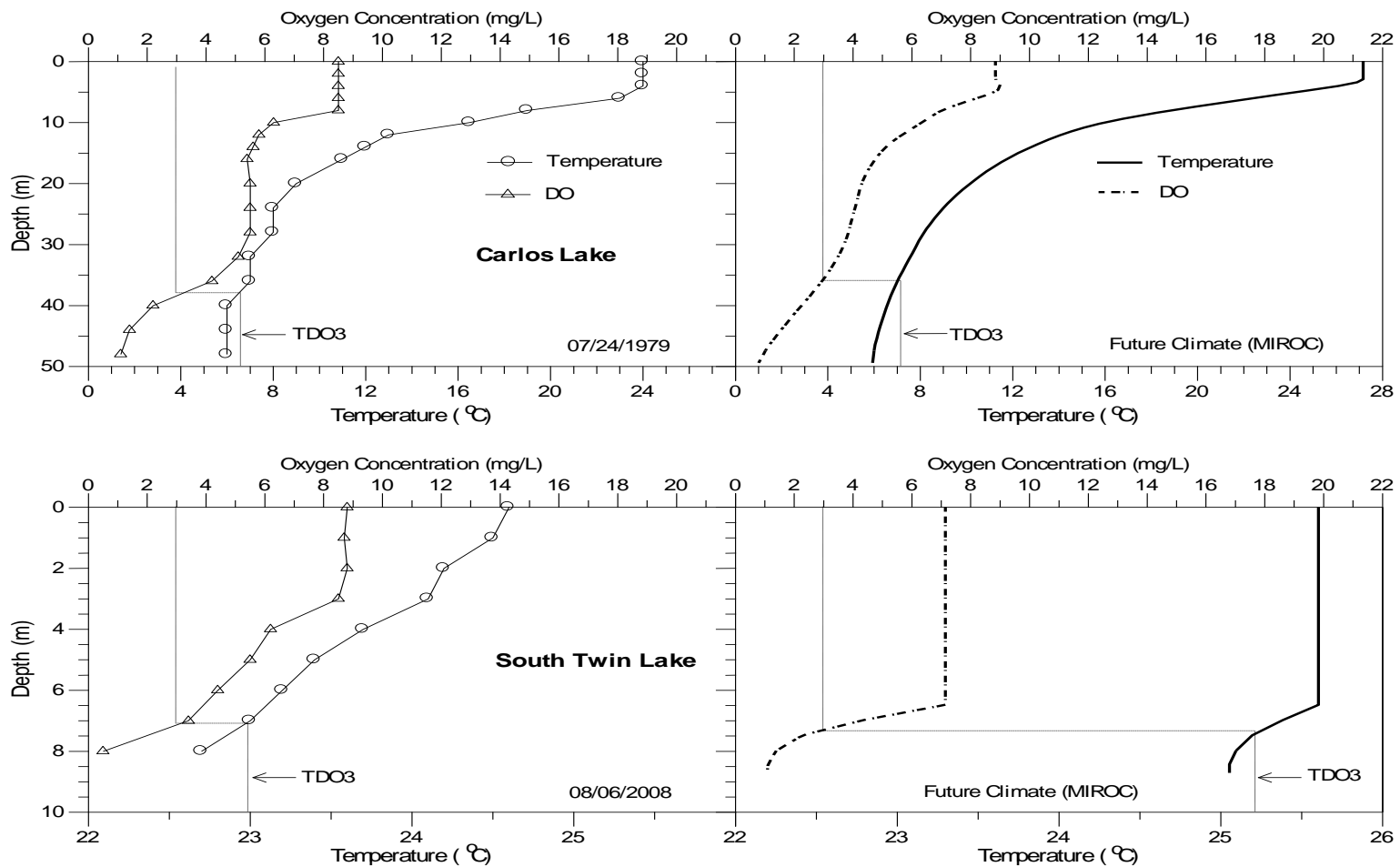


Figure 4.4 Examples of measured (left) and simulated (right) temperature and dissolved oxygen profiles in Carlos Lake (top) and South Twin Lake (bottom) for past (left) and future (right) climate. The determination of TDO3 (temperature at 3 mg/l DO) is also shown.

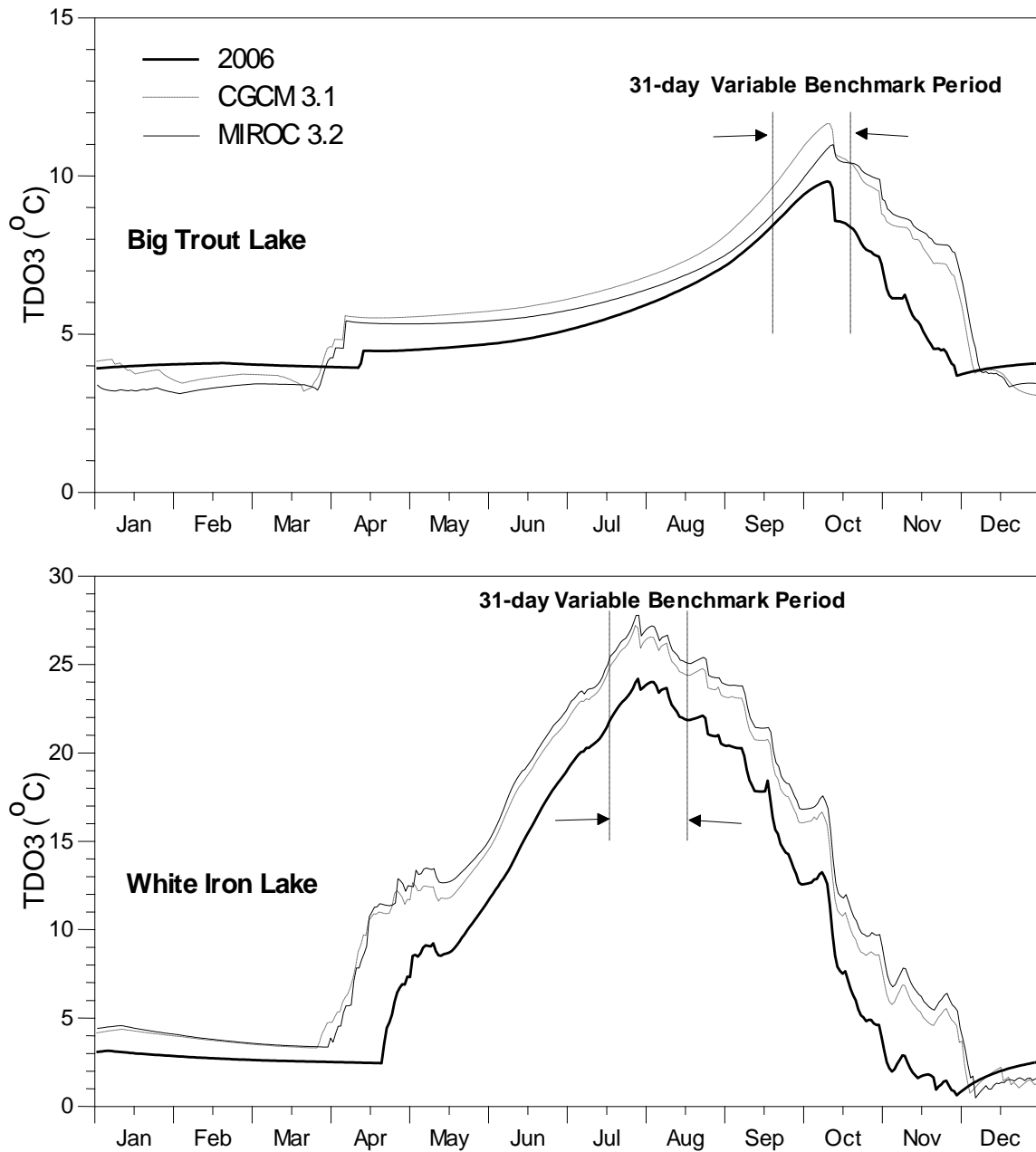


Figure 4.5 Time series of simulated daily TDO3 for Big Trout Lake (top) and White Iron Lake (bottom) in 2006 and for future climate scenarios CGCM 3.1 and MIROC 3.2. The beginning dates of variable benchmark periods of highest mean daily TDO3 in 2006 for Big Trout Lake and White Iron Lake are DOY 262 (September 19) and DOY 199 (July 18), respectively.

(TDO3_{AM}) and the day of its occurrence were retained for each simulated year. The TDO3_{AM} values were 9.8 °C and 24.2 °C in 2006 in Big Trout Lake (top) and White Iron Lake (bottom of Figure 4.5), and occurred on day of year DOY = 283 (October 10) and DOY = 210 (July 29), respectively. The TDO3_{AM} values are projected to increase by 1.2 to 1.8 °C in Big Trout Lake and by 3.0 to 3.6 °C in White Iron Lake under the future climate scenarios CGCM 3.1 and MIROC 3.2 (Figure 4.5). Big Trout Lake, with a maximum depth of 39.0 m and a lake geometry ratio of 1.24, is a seasonally stratified (dimictic) lake and is projected to have a smaller increase in TDO3 under the future climate scenarios than White Iron Lake which has a maximum depth of 14.3 m and a geometry ratio of 4.27 and is a weakly stratified lake (Figure 4.5).

The benchmark period is the period of greatest oxythermal stress for cold-water fish. It is defined as the month (31-day period) with the highest value of TDO3 in late summer (Jacobson et al. 2010). From a total of 9,521 measured temperature and oxygen profiles for the years 1993 through 2005 in 1,623 Minnesota lakes and the computed associated maximum TDO3 values, (Jacobson et al. 2010) determined that the period of greatest oxythermal stress for cold-water fish differed by stratification status of a lake. The stress occurred earlier in unstratified lakes. The 31-day benchmark period of greatest oxythermal stress went from 13 July through 12 August (DOY 194 to DOY 224) for unstratified lakes, and from 28 July through 27 August (DOY 209 to DOY 239) for stratified lakes; these benchmark periods explained 65% of the deviance in TDO3 for the stratified lakes and 68% for the unstratified lakes (Jacobson et al. 2010).

Table 4.4 Categories of refuge lakes and criteria for classification.

Lake Classes	Criteria
Tier 1 refuge lakes	$\text{AvgATDO3}_{\text{VB}} \leq 11.0 \text{ } ^\circ\text{C}$
Tier 2 refuge lakes	$11.0 \text{ } ^\circ\text{C} < \text{AvgATDO3}_{\text{VB}} \leq 17.0 \text{ } ^\circ\text{C}$
Tier 3 or non-refuge lakes	$\text{AvgATDO3}_{\text{VB}} > 17.0 \text{ } ^\circ\text{C}$

The fixed benchmark period (DOY 209 to DOY 239) introduced by (Jacobson et al. 2010) for stratified lakes can be used to compute mean daily TDO3 in later summer (Fang et al. 2010a). However, fixing the benchmark period in time, may introduce a bias for some lakes as will be shown. A variable benchmark (VB) period or sliding window of 31 days was therefore used in this study to find the highest average daily TDO3 (called ATDO3_{VB}) over any 31-day period in each simulated year. The variable (sliding) 31-day benchmark period retained for each simulation year must not only have the highest mean daily ATDO3_{VB} but must also contain the maximum daily TDO3 in that year (i.e., TDO3_{AM}). Using time series of daily TDO3 in each simulated year, the mean daily TDO3 over each sliding benchmark period of 31 days was calculated, and only the highest mean value in any of the sliding benchmark periods of a year (i.e., ATDO3_{VB}) was retained in the fish habitat program.

4.3.6 Criteria used to identify refuge lakes

To determine which lake is an acceptable refuge lake for cisco, especially under future climate scenarios, an upper limit for TDO3 had to be specified. (Jacobson et al. 2010) used species response curves, developed from values of TDO3 measured in the period of greatest oxythermal stress in late summer (maxTDO3), to illustrate oxythermal habitat differences for four cold-water taxa common in Minnesota. Cisco were present in lakes

with a broad range of maxTDO3, with central species response borders (a measure of niche breadth) of maxTDO3 from 4.0 to 16.9 °C (Jacobson et al. 2010). It was decided that cisco refuge lakes should be identified in two categories (Table 4.4): Tier 1 refuge lakes and Tier 2 refuge lakes. Tier 1 refuge lakes have TDO3 less than or equal to 11 °C, and Tier 2 refuge lakes have TDO3 less than or equal to 17 °C but greater than 11 °C. Lakes having TDO3 greater than 17 °C are classified as Tier 3 or non-refuge lakes. The limit of 17 °C corresponds to the upper cisco central response border of TDO3, and the limit of 11 °C closely corresponds to the average of the cisco central response borders of TDO3. Multi-year average of annual maximum oxythermal stress ATDO3_{VB}, i.e., AveATDO3_{VB} (Table 3.4), was used to compare with the TDO3 limits of 11 °C and 17 °C to identify cisco refuge lakes, and AveATDO3_{VB} derived for different lakes will be discussed later.

4.4 Results

4.4.1 Variable benchmark (VB) period

Examples of time series plots of daily TDO3 values are given in Figure 4.5 for Big Trout Lake and White Iron Lake, both cisco lakes in Minnesota. The variable benchmark (VB) periods or time windows that gave the highest mean daily TDO3 or ATDO3_{VB} are also shown. The beginning dates of these periods were DOY 262 (Sept 19) and DOY 200 (July 19) in 2006 in Big Trout Lake and White Iron Lake, respectively (Figure 4.5); they are two months apart, indicating that a fixed benchmark period would have missed the ATDO3_{VB} value considerably.

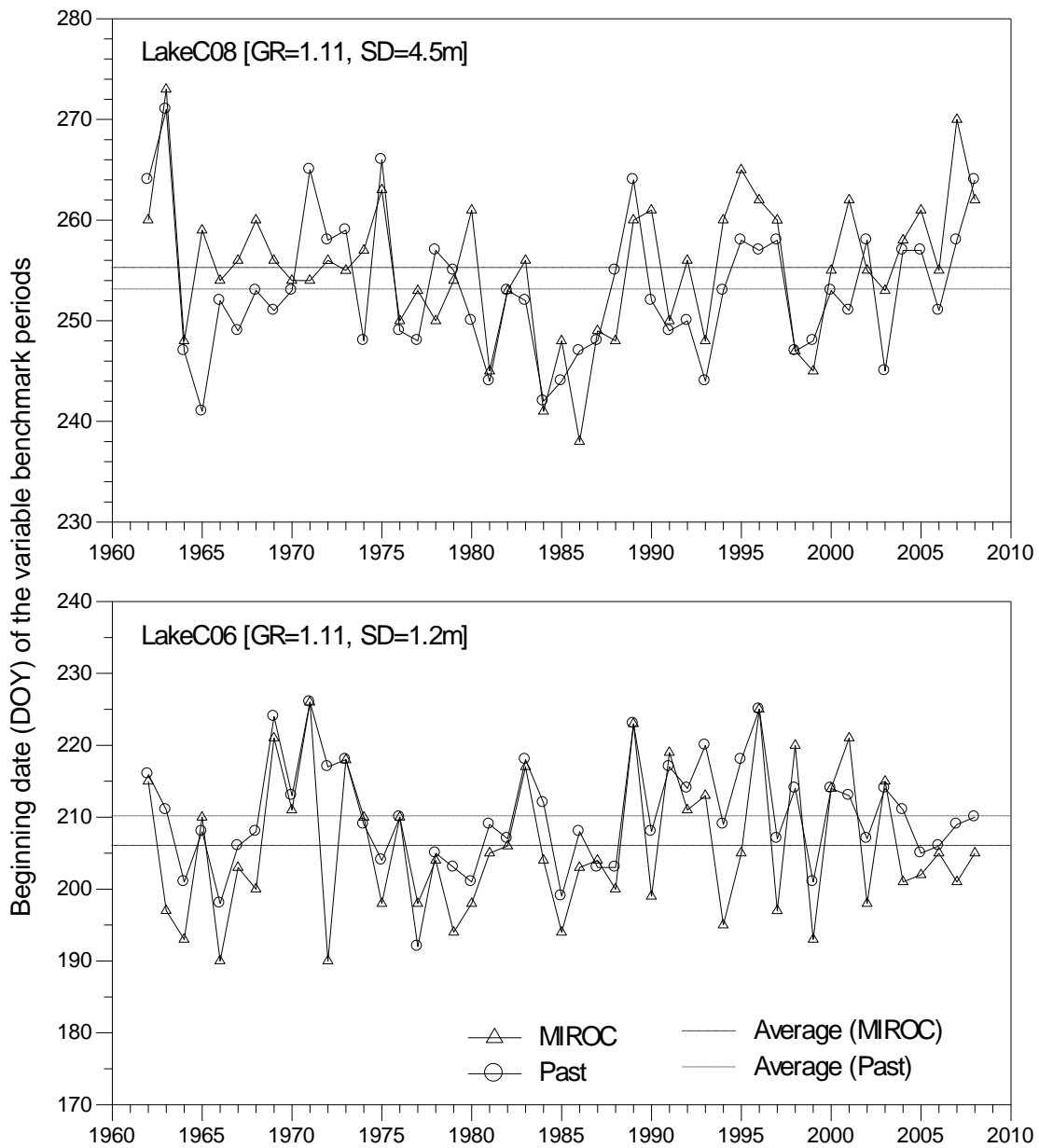


Figure 4.6 Time series of the beginning date (DOY) of the variable benchmark periods for past climate (1962-2008) and the future climate scenario MIROC 3.2 for virtual LakeC08 (top) and LakeC06 (bottom). Corresponding averages of the beginning dates over the simulation period are presented as horizontal lines. Duluth weather data were used for the model simulations.

Under the future climate scenarios MIROC 3.2 and CGCM 3.1, the beginning dates for the ATDO3_{VB} period are projected (simulated) to be DOY 273 and 265 in Big Trout Lake and DOY 199 and 198 in White Iron Lake, respectively; these dates are not much different from the beginning dates of the ATDO3_{VB} for the past climate conditions.

To further illustrate the variability of the VB periods that give the annual ATDO3_{VB} values, the beginning dates of these VB periods for virtual cisco LakeC06 and LakeC08 have been plotted as a time series for past climate (1962 to 2008) and for the future climate scenario MIROC 3.2 in Figure 4.6. Duluth weather data were used as model simulation input. The beginning dates of these VB periods ranged from DOY 192 to 226 for LakeC06 (bottom) and from DOY 241 to 271 for LakeC08 (top) under past climate conditions. Average beginning dates were DOY 210 (July 29) for LakeC06 and DOY 253 (Sept 10) for LakeC08 under past climate conditions (1962 to 2008). These two small virtual lakes have the same lake geometry (Table 4.2) but different Secchi depth; LakeC06 is a eutrophic lake with SD = 1.2 m and LakeC08 is an oligotrophic lake with SD = 4.5 m. Figure 4.6 illustrates, as did Figure 4.5, that the beginning date of greatest oxythermal stress for cold-water fish (cisco) can vary considerably from year to year depending on weather, but it can also vary by lake type, i.e. stratification characteristics and trophic status as further illustrated in Figure 4.7.

Isolines in Figure 4.7 give simulated average beginning dates of the VB periods of greatest oxythermal stress over the 47-year simulation period as a function of Secchi depth (representing trophic status) and lake geometry ratio (representing seasonal mixing characteristics). Plots are given for past climate conditions (1962 to 2008) and for the

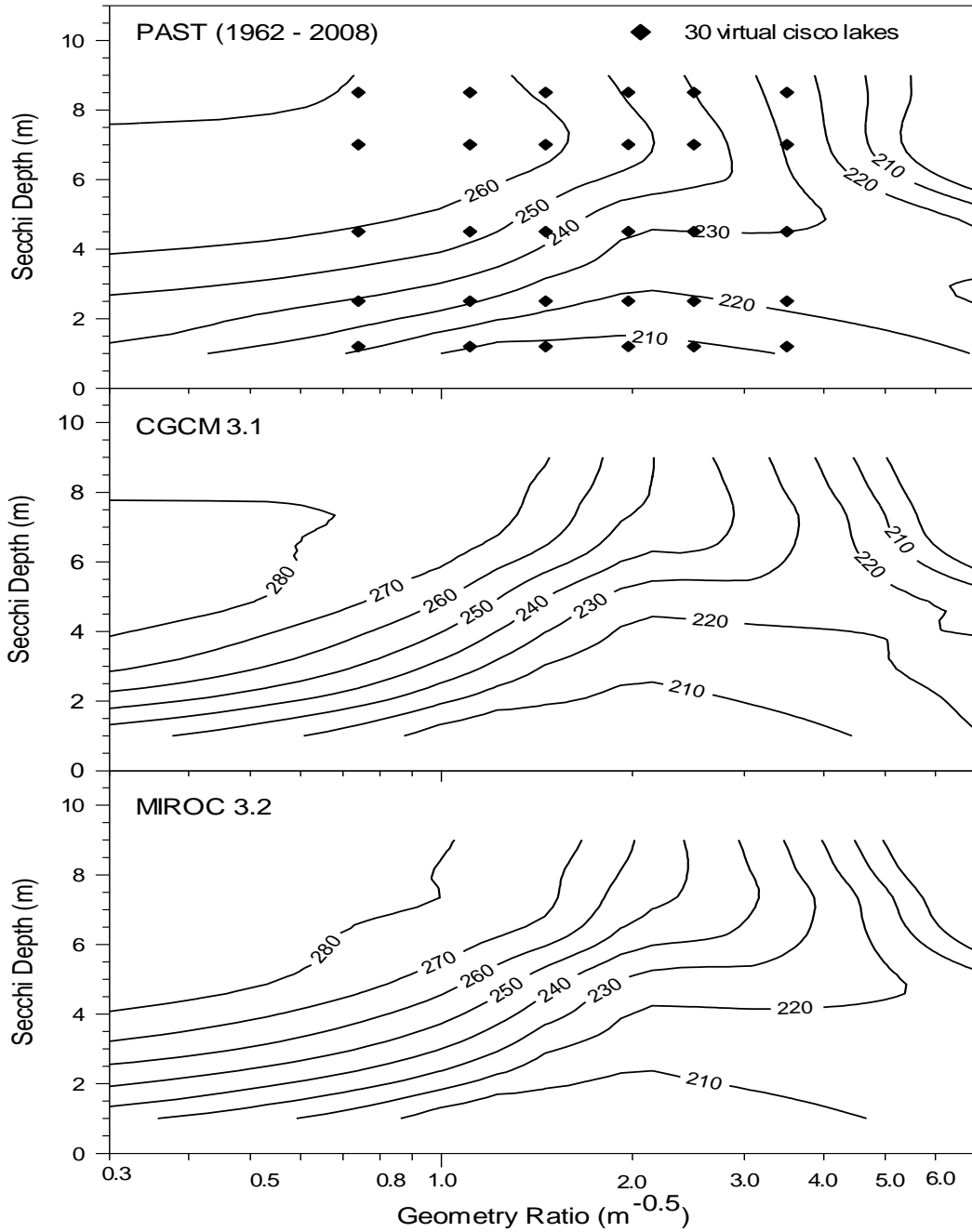


Figure 4.7 Contour plots giving the average beginning dates of the variable (sliding) benchmark periods for past climate (1962-2008), and future climate scenarios CGCM 3.1 and MIROC 3.2. Duluth weather data were used for the model simulations. Contours were derived by interpolation from simulated data points for 30 virtual lakes.

future climate scenarios CGCM 3.1 and MIROC 3.2; Duluth weather data were used as model input, and contours were interpolated from simulated data points for the 30 virtual lakes (diamond symbols in the top frame of Figure 4.7). Averages of the beginning dates of the VB periods for $ATDO3_{VB}$ ranged from DOY 207 (July 26) to DOY 269 (September 26) for the 30 virtual lakes under past climate conditions (1962 to 2008) (see top plot in Figure 4.7).

Statistics of average beginning dates of the VB periods for $ATDO3_{VB}$ for the 30 virtual lakes over the 47-year simulation period are given in Table 3.5. Weather data from three principal weather stations in Minnesota (Figure 4.3) were used as model input for the simulation of past climate, and the future climate scenarios CGCM 3.1, and MIROC 3.2. The average beginning dates of the VB periods for $ATDO3_{VB}$ ranged from DOY 199 (July 18) to DOY 288 (October 15) for the 30 simulated virtual cisco lakes (Table 4.5). Later dates occur in lakes with lower geometry ratio and higher Secchi depth, i.e. stratified oligotrophic lakes produce oxythermal stress for cisco later in the season than other lakes (Figure 4.7). The difference between the latest and earliest average beginning date of the greatest oxythermal stress period for cold-water fish in Minnesota lakes was 59 to 89 days (Table 4.5). Therefore, it seems justified and advisable to calculate the highest mean daily TDO3 values using variable (sliding) benchmark periods ($ATDO3_{VB}$) rather than fixed benchmark periods.

Differences of average beginning dates of the VB periods for highest mean daily TDO3 between future climate scenarios and past climate are given in Table 3.6. Maximum differences were from -11 to 19 days, and mean differences from -1 to 3 days. Under a future climate scenario, the beginning date of the VB period is later if the difference is

Table 4.5 Statistics of the beginning date (DOY = day of year or calendar day. 1 = January 1) of the variable (sliding) benchmark period for highest mean daily TDO3 (ATDO3_{VB}) under past climate conditions (1962-2008) and two future climate scenarios using weather data from three Class A weather stations (International Falls, Duluth and St. Cloud).

Station	International Falls			Duluth			St. Cloud		
	Past	CGCM	MIROC	Past	CGCM	MIROC	Past	CGCM	MIROC
Latest	265	278	284	269	279	282	276	288	288
Earliest	206	200	204	207	204	204	202	199	200
Mean	237	237	240	236	236	238	238	236	238
STDEV ¹	19	25	26	20	25	27	24	28	29

¹ Standard deviation from the mean.

Table 4.6 Statistics of differences in beginning dates of variable (sliding) benchmark periods between future climate scenarios and past climate for the 30 virtual cisco lakes.

Numbers are in days.

Weather station	CGCM 3.1 – Past			MIROC 3.2 – Past		
	International Falls	Duluth	St. Cloud	International Falls	Duluth	St. Cloud
Maximum	13	13	12	19	16	14
Minimum	-11	-9	-10	-8	-8	-8
Mean	0	-1	-1	3	1	1
STDEV ¹	8	7	7	8	8	7

¹ Standard deviation from the mean.

positive. It is noteworthy that the differences in average beginning dates of VB periods with greatest oxythermal stress on cisco are much smaller (nearly negligible) between projected future climate and past climate than the differences between different lake types (Figure 4.6), and the differences from year to year (Figure 4.6).

4.4.2 Annual maximum oxythermal stress ($ATDO3_{VB}$) for variable benchmark periods and multi-year average of maximum oxythermal stress ($AveATDO3_{VB}$)

To evaluate oxythermal stress for cisco in different lake types and under different climate scenarios, annual values of $ATDO3_{VB}$, i.e. the highest mean daily TDO3 over a variable (sliding) benchmark periods in each simulated year, had to be averaged over the simulation period to give $AvgATDO3_{VB}$. The $AvgATDO3_{VB}$ was chosen as the TDO3 parameter to identify and select cisco refuge lakes in this study (Fang et al. 2012a). The $AvgATDO3_{VB}$ is one value for the 47-year simulation period (1962 to 2008) for each lake, whereas $ATDO3_{VB}$ is one value for each simulated year and 47 values in the simulation period.

Examples of the time series of $ATDO3_{VB}$ are plotted in Figure 4.8 for virtual cisco LakeC06 (bottom) and LakeC08 (top). The two lakes have identical geometry, but different trophic state. The plots are for past climate (1962 to 2008) and the future climate scenario MIROC 3.2. Duluth weather data were used for the model simulations. Over the simulation period (1962-2008) values of $ATDO3_{VB}$ ranged from 7.3 to 12.1 °C for LakeC06 (bottom) and from 11.8 to 19.9 °C for LakeC08 (bottom) under past climate conditions. Averages of $ATDO3_{VB}$ over the 47-year simulation period (i.e., $AvgATDO3_{VB}$) were 9.3 °C with standard deviation of 1.0 °C for LakeC06 and 15.6 °C with standard deviation of 1.5 °C for LakeC08 under past climate conditions (1962 to 2008). Values of $AvgATDO3_{VB}$ for the MIROC 3.2 future climate scenario were projected to be 12.6 °C for LakeC06 and 20.7 °C for LakeC08; the projected increases are therefore 3.3 °C and 5.1 °C, respectively.

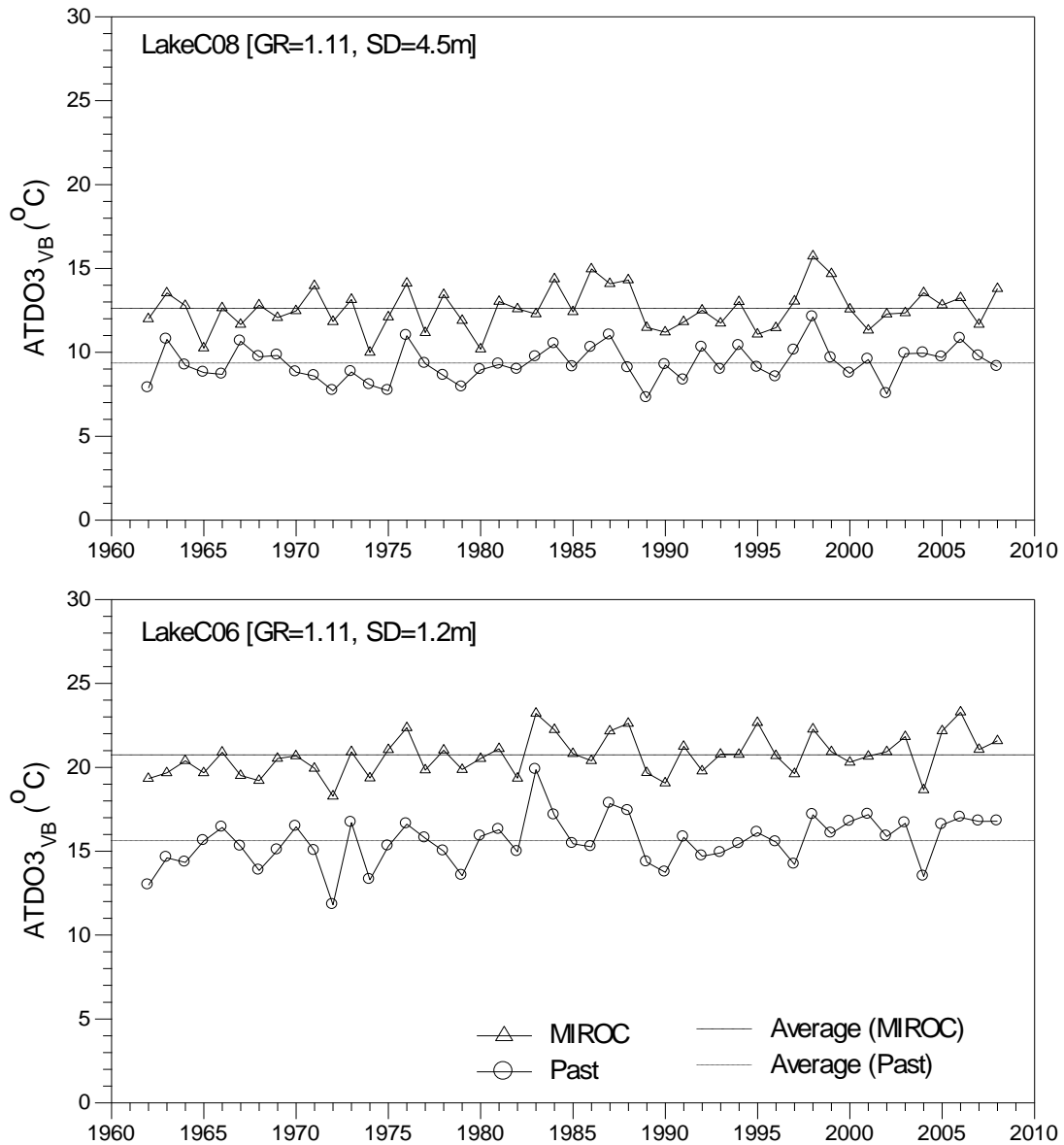


Figure 4.8 Time series of the highest mean daily TDO3 over the variable (sliding) benchmark periods ($ATDO3_{VB}$ in $^{\circ}C$) for past climate (1962-2008) and for the future climate scenario MIROC 3.2 for virtual LakeC08 (top) and LakeC06 (bottom). Averages of the beginning dates of the variable (sliding) benchmark periods over the simulation period are presented as horizontal lines. Duluth weather data were used for the model simulations.

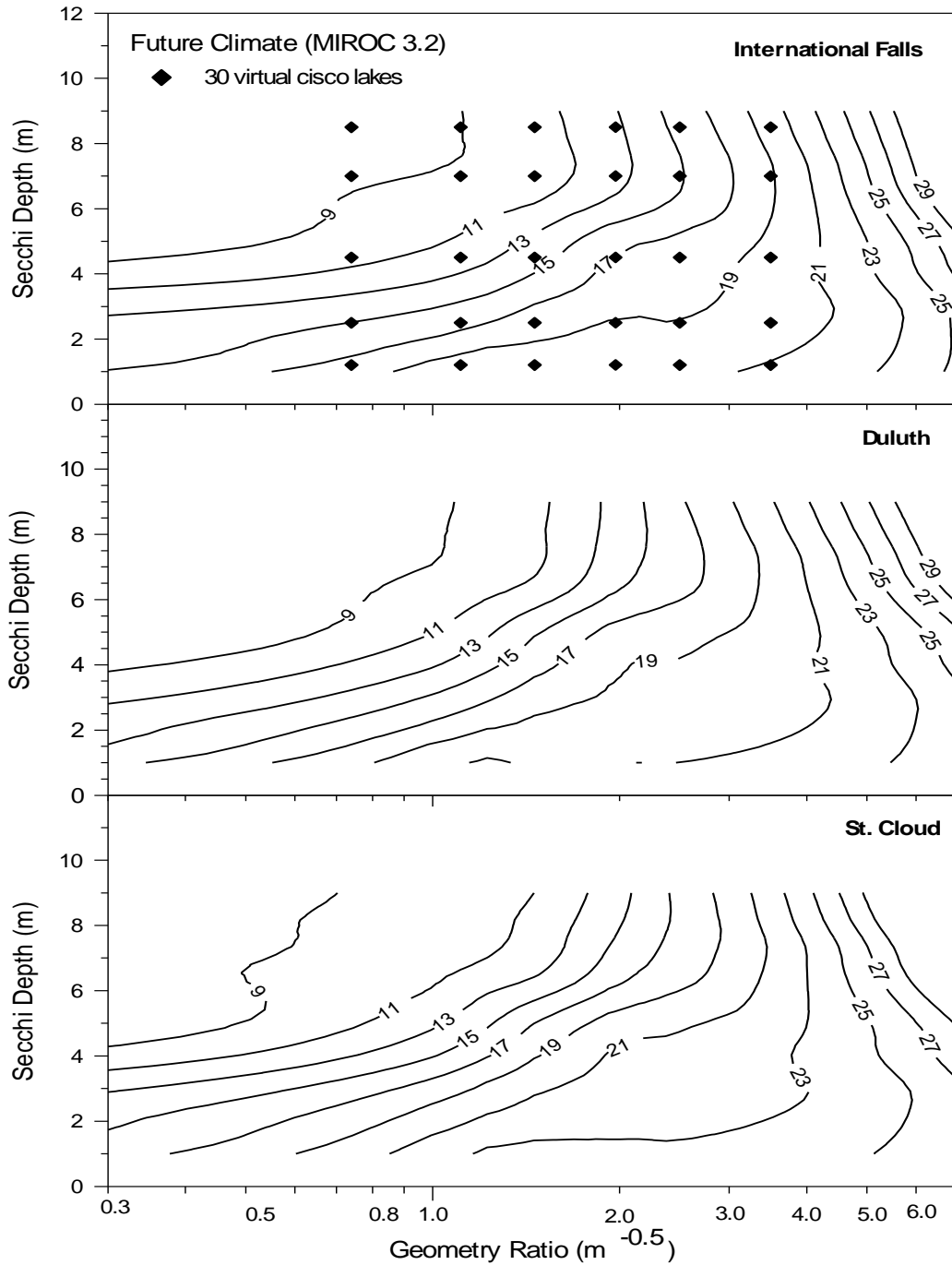


Figure 4.9 Contour plots of the averages of the highest mean daily TDO3 over the variable (sliding) benchmark periods ($AvgATDO3_{VB}$) under the future climate scenario MIROC 3.2. Weather data from International Falls (top), Duluth (middle) and Saint Cloud (bottom) were used for the model simulations. Contours were derived by interpolation from simulated points for 30 virtual lakes.

Figure 4.9 shows contour plots of AvgATDO_{3VB} under the MIROC 3.2 future climate scenario. Contours were derived by interpolation from simulated AvgATDO_{3VB} data points for the 30 virtual cisco lakes (dots in top frame of Figure 4.9). Weather data from three principal weather stations in Minnesota (Duluth, International Falls, and St. Cloud, Figure 4.1) were used to obtain the model simulation results plotted in Figure 4.9. Simulated AvgATDO_{3VB} values for the 30 virtual lakes and contour plots were also developed for past climate conditions (1962-2008) and the future climate scenario CGCM 3.1 (Fang et al. 2010a). Statistics of AvgATDO_{3VB} values under past climate and future scenarios for three weather stations (International Falls, Duluth, and St. Cloud) are given in Table 4.7. The AvgATDO_{3VB} values ranged from 7.48 to 19.91 °C under past climate conditions and from 8.02 to 23.28 °C under two future climate scenarios for the 30 virtual cisco lakes (Table 4.7). Statistical differences of AvgATDO_{3VB} values between future climate scenarios and past climate (1962-2008) are given in Table 4.8. The projected increases of AvgATDO_{3VB} values from past climate to future scenarios were from 0.30 to 5.11°C (Table 4.8), and average increases were projected to be from 2.79 to 3.40°C. These increases are crucial, when cisco refuge lakes for future climate scenarios are identified and selected.

Values of AvgATDO_{3VB} vary by lake type depending on stratification characteristics (Figure 4.9) and trophic status (Figure 4.7 and Figure 4.8); stratified oligotrophic lakes produce lower AvgATDO_{3VB} values or lower oxythermal stress for cold-water fish species. AvgATDO_{3VB} values are presented in Figure 4.9 as contours on a plot of Secchi depth, as an indicator of transparency and lake trophic status, vs. lake geometry ratio, as an indicator of seasonal lake stratification.

4.4.3 Cisco refuge lakes in Minnesota

Contour lines of 11 °C and 17 °C in the contour plots of AvgATDO3_{VB} in Figure 4.9 were used to identify cisco refuge lakes in the database of 620 Minnesota cisco lakes. The final selection of cisco refuge lakes was based on TDO3 parameters projected under the CGCM 3.1 and MIROC 3.2 future climate scenario.

Cisco “refuge” lakes were also determined by simulations for past climate conditions (1962 - 2008) because the results would be expected to match actual cisco lakes in Minnesota; they would also be a useful reference to gage the impact of climate warming on cisco lakes in Minnesota. Under past climate conditions (1962 to 2008), 506 lakes or 82% (Table 4.5) were classified as “refuge” lakes (Tier 1 plus Tier 2). In other words, the proposed methodology identified current cisco lakes with an 82% success ratio.

The results of refuge lake selection are summarized in Table 4.9. Figure 4.10 shows the division of the 166 northern, 399 mid-latitude, and 55 southern cisco lakes into Tier 1 and Tier 2 refuge lakes and Tier 3 non-refuge lakes. The selection of refuge lakes shown in Figure 4.10 was based on contour lines of 11 °C and 17 °C for AvgATDO3_{VB} under the future climate scenario MIROC 3.2. Under this scenario, it was projected that 62, 94, and 4 lakes out of 166 northern, 399 mid-latitude, and 55 southern cisco lakes, respectively, would be Tier 1 plus Tier 2 refuge lakes (Table 4.4 and Figure 4.10). A total of 164 and 160 lakes or 26% of 620 cisco lakes were identified as Tier 1 plus Tier 2 refuge lakes under the future climate scenarios MIROC 3.2 and CGCM 3.1, respectively (Table 4.9). Thus, under fairly stringent selection criteria (AvgATDO3_{VB} ≤ 17°C), about one fourth of the 620 lakes that currently have cisco populations, are projected to maintain viable cisco habitat (Tier 1 plus Tier 2) under projected future climate scenarios. In other words, climate

warming under the MIROC 3.2 future climate scenario is projected to potentially decrease the number of Minnesota cisco refuge lakes (Tier 1 plus Tier 2) by 346 (= 506 - 160) from past climate conditions (Table 4.8).

Table 4.7 Statistics of AvgATDO_{3vB} (°C) under past climate conditions (1962- 2008) and the future climate scenarios CGCM and MIROC for the 30 virtual cisco lakes. Simulations and analysis were made with weather data input from weather stations in International Falls, Duluth and St. Cloud.

Statistical parameter	International Falls			Duluth			St. Cloud		
	Past	CGC M	MIRO C	Past	CGC M	MIRO C	Past	CGC M	MIRO C
Maximum	17.23	21.06	21.12	17.66	20.86	21.34	19.91	23.28	23.70
Minimum	7.64	8.33	8.46	7.48	8.02	8.35	8.24	8.54	9.14
Mean	12.59	15.38	15.62	12.96	15.98	16.18	14.63	17.66	18.03
STDEV ¹	3.25	4.34	4.26	3.39	4.25	4.38	3.96	4.90	4.89

¹ Standard deviation from the mean.

Table 4.8 Statistics of differences in AvgATDO_{3vB} (°C) between future climate scenarios CGCM 3.1, MIROC 3.2 and past climate conditions (1962-2008) for the 30 virtual cisco lakes. Simulations and analysis were made with weather data input from weather stations in International Falls, Duluth and St. Cloud.

Statistical parameter	CGCM 3.1 - past			MIROC 3.2 - past		
	International Falls	Duluth	St. Cloud	International Falls	Duluth	St. Cloud
Maximum	4.54	5.11	5.01	4.79	5.11	5.27
Minimum	0.61	0.42	0.30	0.78	0.75	0.90
Mean	2.79	3.02	3.02	3.03	3.22	3.40
STDEV ¹	1.33	1.22	1.33	1.30	1.32	1.31

¹ Standard deviation from the mean.

Table 4.9 Number (%) of lakes selected as Tier 1 and Tier 2 refuge lakes and Tier 3 non-refuge lakes from cisco lakes grouped by latitude. Weather input data from three principal weather stations (International Falls, Duluth and St. Cloud), are each assigned to a different range of latitudes, for use in the simulations. The total number of lakes considered is 620.

Weather station by latitude	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Tier 3 non-refuge lakes	Total number of lakes
Northern (International Falls)	Past	41 (7)	96 (15)	137 (22)	29 (5)	166 (27)
	CGCM 3.1	24 (4)	43 (7)	67 (11)	99 (16)	166 (27)
	MIROC 3.2	19 (3)	43 (7)	62 (10)	104 (17)	166 (27)
Mid-latitude (Duluth)	Past	52 (8)	285 (46)	337 (54)	62 (10)	399 (64)
	CGCM 3.1	10 (2)	83 (13)	93 (15)	306 (49)	399 (64)
	MIROC 3.2	10 (2)	84 (14)	94 (15)	305 (49)	399 (64)
Southern (St. Cloud)	Past	1 (<1)	31 (5)	32 (5)	23 (4)	55 (9)
	CGCM 3.1	0	4 (1)	4 (1)	51 (8)	55 (9)
	MIROC 3.2	0	4 (1)	4 (1)	51 (8)	55 (9)
All three latitudes	Past	94 (15)	412 (66)	506 (82)	114 (18)	620 (100)
	CGCM 3.1	34 (5)	130 (21)	164 (26)	456 (74)	620 (100)
	MIROC 3.2	29 (5)	131 (21)	160 (26)	460 (74)	620 (100)

The projected geographic distribution of refuge lakes and non-refuge lakes in Minnesota based on results in Figure 4.10 is shown in Figure 4.11. A division of the 620 Minnesota cisco lakes into 29 Tier 1 refuge lakes (large circles), 131 Tier 2 refuge lakes (medium-size pentagons), and 460 non-refuge cisco lakes (small dark hexagons) was projected for the MIROC 3.2 future climate scenario when contour lines of AvgATDO3_{VB} were used as boundary limits (Figure 4.10) and refuge lakes were selected separately from

the three groups divided by latitude. Nineteen Tier 1 and 43 Tier 2 refuge lakes (Figure 4.8 and Figure 4.9) are identified among the “northern cisco lakes” of Minnesota where there is little development (land protected by the Superior National Forest); 10 Tier 1 and 84 Tier 2 refuge lakes are found among the “middle-latitude cisco lakes” where more development pressure exists and more protection may be necessary. There are no Tier 1 and only 4 Tier 2 refuge lakes projected among the “southern cisco lakes”; in this region, agricultural land use, urban development and other anthropogenic land uses are the most pronounced.

Table 3.10 summarizes the statistics of four physical lake parameters that appear important for Tier 1, 2 and 3 cisco lakes. For 29 Tier 1 refuge lakes, the mean Secchi depths were from 4.72 to 9.46 m (oligotrophic lakes), lake geometry ratios from 0.69 to 1.64 m^{-0.5} (strongly stratified lakes), maximum depths from 18.0 to 63.4 m and surface areas from 0.19 to 21.27 km². Of the 131 Tier 2 refuge cisco lakes in Table 3.10, 50 percent have a mean summer Secchi depth greater than 4.3 m, a maximum depth greater than 24.7 m, and a geometry ratios less than 1.32 m^{-0.5}. On the other hand, 50 percent of the 460 non-refuge lakes in Table 4.10, have a mean summer Secchi depth less than 3.0 m, a maximum depth less than 14.3 m, and a geometry ratio greater than 2.52 m^{-0.5}.

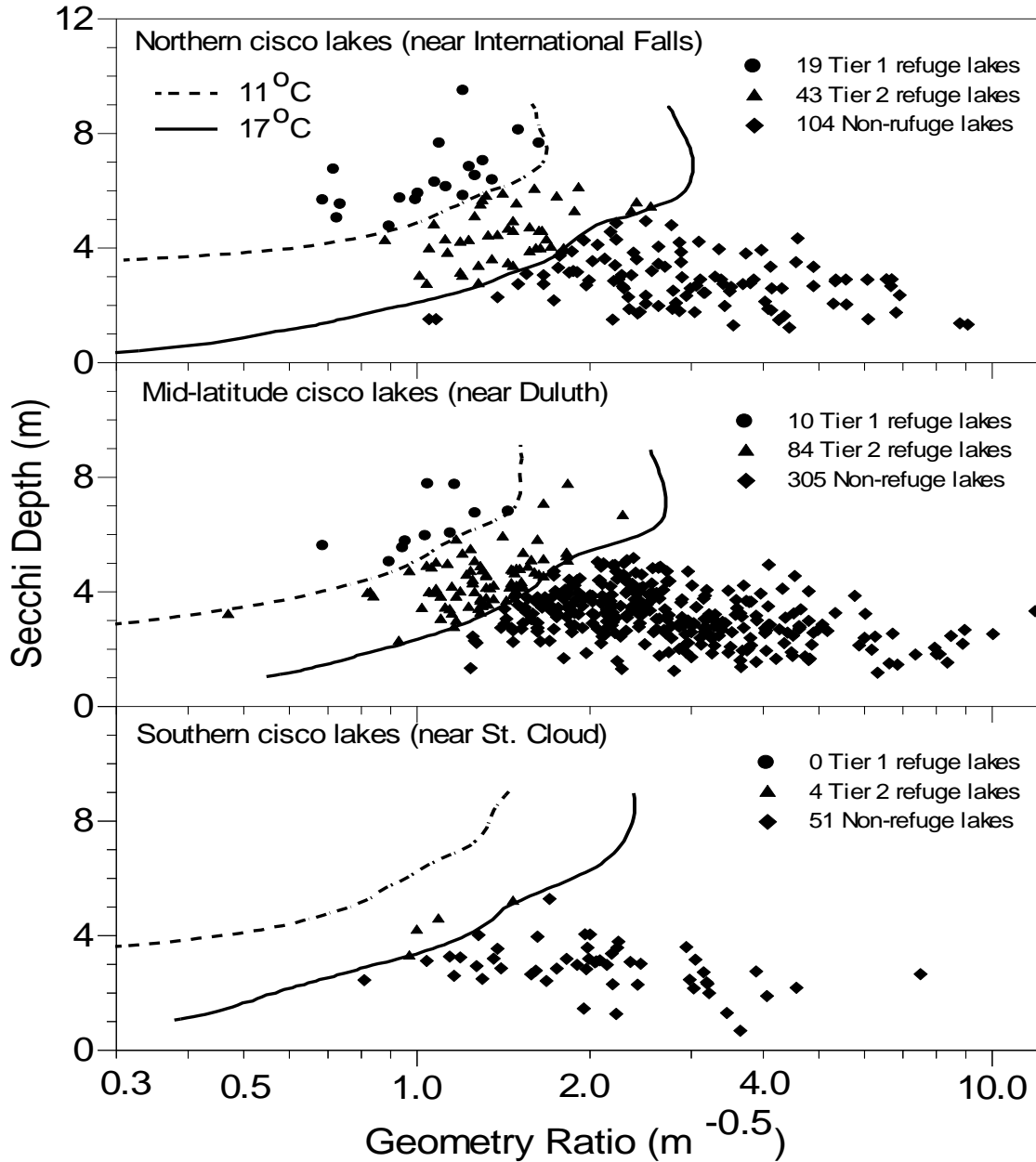


Figure 4.10 Distribution of Tier 1 and Tier 2 refuge lakes, and Tier 3 non-refuge lakes on a plot of Secchi depth vs. lake geometry ratio. The total number of cisco lakes is 620. The boundary contour lines between Tiers 1, 2 and 3 are for $AvgATDO3_{VB} = 11^{\circ}C$ and $17^{\circ}C$, respectively, and were derived for variable benchmark periods simulated for the future climate scenario MIROC 3.2 using weather data from International Falls, Duluth and St. Cloud.

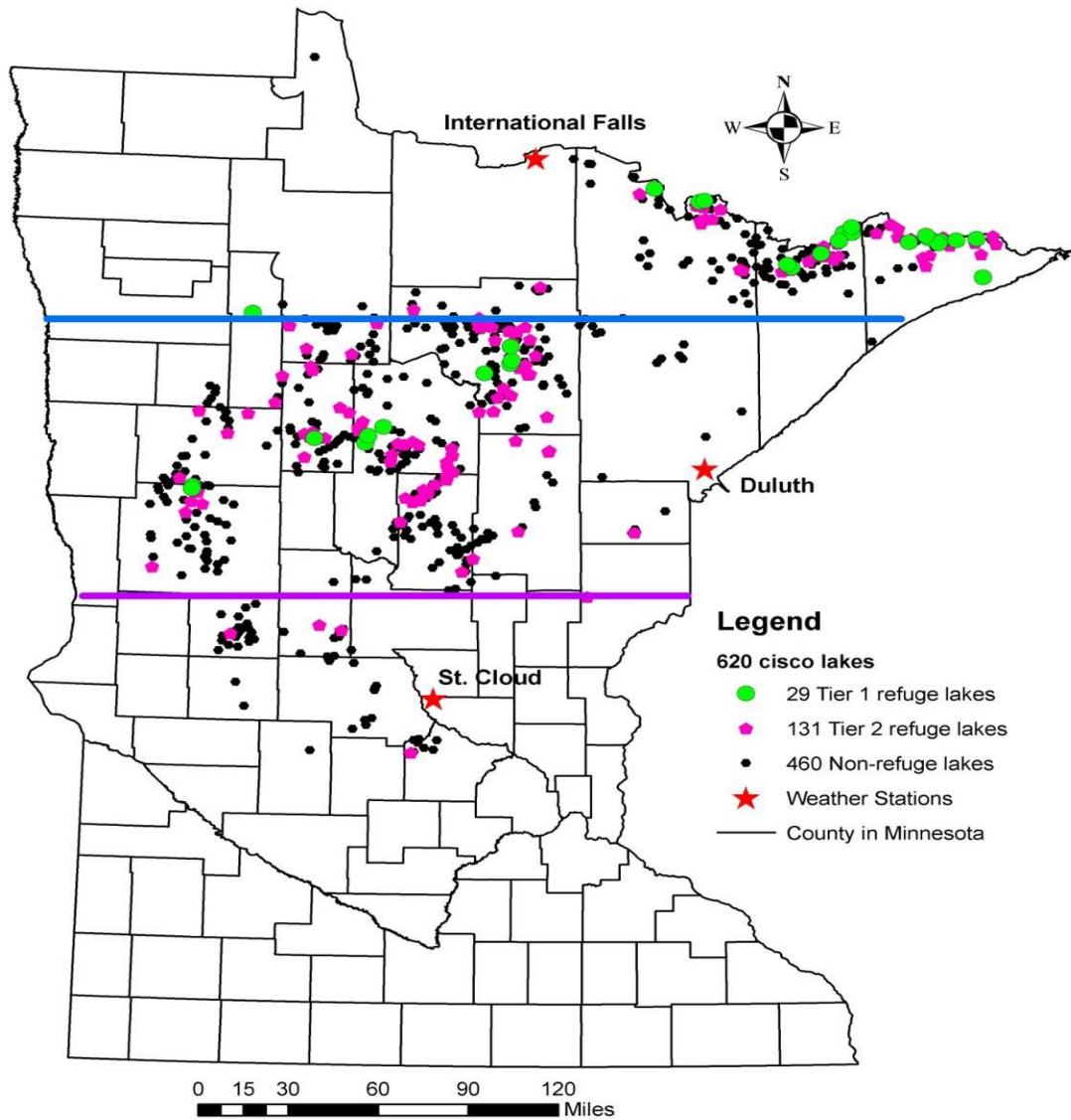


Figure 4.11 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and Tier 3 non-refuge cisco lakes simulated for the future climate scenario MIROC 3.2. Lakes are grouped by latitude into 166 northern, 399 mid-latitude, and 55 southern cisco lakes. The boundary limits for Tier 1 and Tier 2 refuge lakes were contour lines of $AvgATDO3_{VB} = 11^{\circ}C$ and $17^{\circ}C$, respectively. Variable benchmark periods were used, and principal weather stations (International Falls, Duluth, and St. Cloud) were associated by latitude with each lake group.

Table 4.10 Statistics of physical lake parameters for refuge lakes and non-refuge lakes. Lakes are divided into Tier 1, 2, and 3 using AvgATDO3_{VB} obtained by simulations for the MIROC 3.2 future climate scenario. Lakes are grouped by latitude and paired with weather stations at International Falls, Duluth, and St. Cloud.

Statistical Parameter	29 Tier 1 refuge lakes				131 Tier 2 refuge lakes				460 Tier 3 non-refuge lakes			
	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)
Maximum	21.27	63.40	1.64	9.46	28.90	64.92	2.55	7.74	893.93	56.08	11.89	5.28
Minimum	0.19	17.98	0.69	4.72	0.04	13.11	0.47	2.26	0.05	3.05	0.81	0.68
Average	3.28	35.49	1.08	6.38	2.48	26.21	1.36	4.37	9.71	15.91	3.00	3.06
STDEV ¹	5.16	12.00	0.25	1.06	3.93	9.78	0.31	0.91	54.36	8.18	1.54	0.88
3rd Quartile	2.89	41.15	1.24	6.80	2.82	32.00	1.51	4.87	4.92	19.81	3.51	3.66
Median	1.13	35.05	1.08	6.10	0.97	24.69	1.32	4.27	1.86	14.32	2.52	3.01
1st Quartile	0.81	26.21	0.94	5.65	0.51	18.60	1.17	3.81	0.80	10.36	2.02	2.51

¹ Standard deviation from the mean.

Tier 1 plus Tier 2 refuge lakes selected under the MIROC 3.2 climate scenario have a Secchi depth greater than 2.3 m (Table 4.10), a lake geometry ratio less than 2.6 m (Table 4.10), and a maximum depth greater than 13.1 m (Table 4.10). The cumulative distributions of surface areas of projected cisco refuge lakes and the current 620 cisco lakes are not significantly different (Fang et al. 2010a). Refuge lakes selected for the MIROC 3.2 climate scenario have surface area up to 28.9 km². Only 3 percent or 20 out of the 620 cisco lakes in the MN DNR database have a surface area greater than 28.9 km². These 20 large surface area lakes were identified as non-refuge lakes.

4.5 Discussion

Jacobson et al. (2010) developed central species response borders of TDO3 derived from measured T and DO profiles for lake trout, lake whitefish, and burbot. The method developed for a study to rank the quality of fish habitat for cisco in Minnesota lakes was presented as a flowchart in Figure 4.2 and can be applied for other cold-water fish species and at other geographic locations. The next future study could be to use the same methodology to identify refuge lakes for lake trout in Minnesota. Lake trout were present in lakes with the lowest values of maxTDO3 and represented by central species response borders of maxTDO3 from 4.0 to 5.1 °C (Jacobson et al. 2010). It will be interesting and valuable to use the method to identify cisco refuge lakes in Wisconsin, which can be directly compared with results by (Sharma et al. 2011). Requirements for the study include a database of cisco lakes in Wisconsin, observed T and DO profiles in several cisco lakes for further model validation, and historical weather data at representative locations in Wisconsin.

As an alternative to the use of a mechanistic T and DO model, Jacobson et al. (2010) developed an empirical model to predict TDO3 as a function of lake productivity, climate, and relative depth using GR. Summer total phosphorus concentration was the variable selected to represent lake productivity of each lake (Jacobson et al. 2010). In our study, phosphorus was not used to characterize any of the cisco lakes. Instead, Secchi depth, a measure of lake transparency, was used to represent trophic state. The trophic state expresses primary productivity and is directly related to DO production by photosynthesis in the MINLAKE 2010 model. Chlorophyll-a concentration that represents biomass or phytoplankton in the MINLAKE2010 model for each cisco lake was calculated from the relationship between chlorophyll-a and Secchi depth used in the Carlson trophic index (Carlson 1977). Generic seasonal growth patterns derived from extensive field observations in temperate lakes (Marshall and Peters 1989) were imposed in the model (Stefan and Fang 1994b). Therefore SD and GR are representative parameters to characterize each of the 620 cisco lakes in the database. Contour plots using GR and SD as axes were previously and successfully used to present characteristics of water temperature, DO, and fish habitat parameters in lakes (Fang and Stefan 1997; Fang and Stefan 1999; Fang et al. 2004a; Fang and Stefan 2009a).

AvgATDO3_{VB} values derived from 30 virtual lakes are presented as isolines on a coordinate system of lake geometry ratio GR vs. Secchi depth SD (Figure 4.9 and Figure 4.10). GR and SD appear to be sufficient to represent essential features of different lake types, GR characterizes the potential for stratification and mixing dynamics, and SD characterizes transparency, but also trophic state as a surrogate, at least in most Minnesota lakes. Lake turbidity from suspended inorganic sediment is relatively rare in Minnesota,

and total phosphorus or chlorophyll *a* in most Minnesota lakes are well correlated with SD. Monthly variations in these parameters follow well-established generic patterns in Minnesota lakes.

The partitioning of cisco lakes into tiers was useful for distinguishing potential refuge value for cisco and possibly other species after climate warming. The rather stringent Tier 1 TDO3 limit of 11 °C was considerably less than the median value of late summer TDO3 of 18.2 °C for all Minnesota lakes with cisco (Jacobson et al. 2010). The TDO3 limit of 11 °C also corresponded to the upper central niche border for lake whitefish (Jacobson et al. 2010) and suggests that Tier 1 refuge lakes will also be useful for the management of lake whitefish.

Tier 1 and Tier 2 cisco lakes identified for past climate conditions (1961-2008) may be called viable cisco lakes where cisco is capable of living, growing, and reproducing under favorable conditions. Nevertheless 114 of the current 620 lakes (18 percent) with known cisco populations were identified by the simulations as non-refuge lakes under past climate conditions (1962 to 2008) (Table 3.9); this does not mean that these 114 cisco lakes can not support cisco habitat at all. Cisco can still persist in lakes with TDO3 values greater than 17°C but at a reduced probability of occurrence in this marginal habitat (Jacobson et al. 2010).

For the selection of refuge lakes, lakes were divided into three categories (tiers) using only two TDO3 isotherms (11 °C and 17 °C) as contour lines (Figure 4.9). Another approach would be to use more isotherms at finer increments to rank each lake according to where it is located between TDO3 contour lines. To do this, 620 cisco lakes in Minnesota were assembled in narrow (2 °C and 1 °C) bands of TDO3 values (Fang et al.

2012a). Names and locations of lakes in each band were tabulated, and lakes with the lowest TDO3 values were placed on top of the list and were presumed to be the best candidates for cisco refuge lakes, because low TDO3 values are presumed to reflect the least stress on adult cisco.

We cannot validate the projected number of refuge lakes for future climate scenarios, but we did a cross validation on 21 cisco study lakes as described below. Adult cisco mortality was reported in 18 lakes in Minnesota during the summer of 2006 (Jacobson et al. 2008). Water temperature and DO profiles were also measured and analyzed by (Jacobson et al. 2008) in 5 reference cisco lakes without cisco mortality. With the exception of two lakes with cisco mortality (Lake Bemidji and Long Lake), the remaining 21 cisco study lakes used by (Jacobson et al. 2008) are in the MN DNR cisco lake database. Four of the five reference lakes without cisco mortality in 2006, emerged as Tier 1 refuge lakes when simulated for past climate conditions, and only one (Kabekona) as a Tier 2 refuge lake. Six of the sixteen lakes with adult cisco mortality in 2006, emerged as non-refuge lakes when simulated under past climate (1962 to 2008), and ten emerged as Tier 2 refuge lakes. AvgATDO3_{VB} as average of ATDO3_{VB} over a (very long) 47-year simulation period (1962-2008) would be expected to underestimate the oxythermal stress in the unusually hot summer of 2006 and would therefore cause ten lakes to be classified as Tier 2 lakes. For example, AvgATDO3_{VB} simulated using International Fall weather data was 15.0 °C for virtual LakeC01, and ATDO3_{VB} in 2006 was 17.2 °C, that is 2.2 °C higher than the average. When AvgATDO3_{VB} was simulated for the MIROC 3.2 future climate scenario, all the sixteen lakes emerged as non-refuge lakes. Overall, there is remarkable agreement between model predictions and observed adult cisco mortality events in 2006.

Our results, e.g., 74% of cisco lakes projected to be non-refuge lakes, are similar to those of a recent study of about 170 cisco lakes in Wisconsin (Sharma et al. 2011) which was summarized as: "By 2100, 30 to 70 percent of cisco populations could be extirpated in Wisconsin due to climate change, Cisco are much more at risk due to climate change rather than interactions with exotic species."

4.6 Chapter Summary and Conclusions

Cisco is a vulnerable fish species because it depends on cold-water. It is also a good indicator of lake water quality. The selection of cisco refuge lakes under two global warming scenarios (MIROC 3.2 and CGCM 3.1) was based on an oxythermal habitat variable TDO3 (temperature at 3 mg/l of DO) which is a measure of oxythermal stress on adult cisco: the lower the TDO3, the lower the stress. T and DO profiles in lakes had to be simulated for future climate scenarios. A deterministic, unsteady and one-dimensional (vertical) lake water quality model (MINLAKE2010) was developed, calibrated and validated, and then used for the year-round temperature and DO simulations, which were run with past (1961-2008) climate conditions and for two future climate scenarios (CGCM 3.1 and MIROC 3.2) with weather data from three Class I weather stations (Duluth, International Falls and Saint Cloud) in Minnesota as model input.

Simulated time series of daily lake T and DO profiles for the 47-year period were used to first compute daily TDO3 values for each lake and year, then maximum annual $ATDO3_{VB}$ values for each lake and year, and finally multi-year average values $AvgATDO3_{VB}$ over the 47-year simulation period for each of the 30 virtual cisco lake types. To account for fish acclimation and resilience over time, the $ATDO3_{VB}$ value was not the maximum daily value in a year, but the average over a one month (31-day)

benchmark period in summer. The beginning dates of the variable benchmark periods for $ATDO3_{VB}$ varied year by year depending on weather conditions (Figure 4.6) and lake by lake depending on stratification characteristics and trophic status (Figure 4.7). The average beginning dates of the VB periods over the 47-year simulation period varied from July 21 to October 3 for 30 types of lakes under past climate (1962 to 2008) conditions, and were projected to change by up to 19 days under future climate scenarios. Using a VB period instead of a fixed benchmark period is considered very advisable in order to identify the period of greatest oxythermal stress on cisco.

$AvgATDO3_{VB}$ values were presented as a contour plot on a coordinate system of lake geometry ratio GR vs. Secchi depth SD (Figure 4.9). GR and SD appear to be sufficient to represent essential features of different lake types. Six hundred twenty (620) cisco lakes in Minnesota were then divided into three groups (Figure 4.10): Tier 1 refuge lakes having $AvgATD3_{VB} \leq 11\text{ }^{\circ}\text{C}$; Tier 2 refuge lake having $11\text{ }^{\circ}\text{C} < AvgATD3_{VB} \leq 17\text{ }^{\circ}\text{C}$; and Tier 3 or non-refuge lakes having $AvgATD3_{VB} > 17\text{ }^{\circ}\text{C}$.

The model MINLAKE2010 was able to simulate T and DO profiles with RMSEs of $1.47\text{ }^{\circ}\text{C}$ and 1.50 mg/l , respectively, while the cisco habitat model was able to validate cisco kill observations in 18 Minnesota lakes in the hot summer of 2006 remarkably well.

Cisco habitat projections in Minnesota lakes under past climate conditions (1962 to 2008) gave a Tier 1 plus Tier 2 fit for 486 of 620 actual cisco lakes (82% agreement). 114 of the current 620 lakes (18 percent) with known cisco populations were identified by the simulations as non-refuge lakes under past climate conditions. Cisco can still persist in lakes with $TDO3$ values greater than $17\text{ }^{\circ}\text{C}$ but at a reduced probability of occurrence in this marginal habitat (Jacobson et al. 2010).

Under the MIROC 3.2 future climate scenario (Table 4.9), 29, 131, and 460 cisco lakes were selected as Tier 1 refuge lakes, Tier 2 refuge lakes, and Tier 3 non-refuge lakes, respectively. Under fairly stringent selection criteria ($DO > 3 \text{ mg/l}$ and $TDO3 \leq 17^\circ\text{C}$), about one fourth of the lakes that currently have cisco populations, are projected to be able to maintain cisco habitat under projected future climate scenarios, and about three fourths of lakes with current cisco populations are projected to lose the ability to support cisco. Most of the ‘refuge’ lakes are located in northeastern and central Minnesota (Figure 4.11).

Table 4.10 summarizes the statistics of four physical lake parameters that appear important for cisco refuge lakes. Tier 1 plus Tier 2 refuge lakes selected, e.g., under the future climate scenario MIROC 3.2, have Secchi depths greater than 2.3 m, lake geometry ratio less than $2.6 \text{ m}^{-0.5}$, maximum depths greater than 13.1 m, and surface areas less than 28.9 km^2 .

The identification of specific lakes that will be refuges for cisco from effects of climate change will allow resource agencies to target conservation efforts to these systems (Jacobson et al. 2010). Protection of the water quality that allows hypolimnetic oxygen concentrations to remain high throughout the summer is critical for these lakes to function as refuges after climate change. Eutrophication from changing land use has been identified as a serious threat that can reduce hypolimnetic oxygen concentrations even further after climate change (Jacobson et al. 2010). Critical watershed protection efforts will need to be implemented to prevent future degradation of water quality that threatens to reduce the resilience within these systems.

Chapter 5 **Identifying Cisco Refuge Lakes in Minnesota under Future Climate**

Scenarios

5.1 Abstract

Cisco Coregonus artedii is the most common cold-water stenothermal fish in Minnesota lakes. To project its chances of survival under future warmer climate conditions, an oxythermal habitat variable, TDO3, i.e. water temperature at 3 mg/L of dissolved oxygen (DO) in stratified lakes, was calculated from simulated daily temperature and DO profiles in 30 lake types under past (1962-2008) climate conditions and under two future climate scenarios. The mean daily TDO3 values over a 31-day fixed benchmark period were calculated for each of simulated years and then averaged over the simulation period for each lake type. The multi-year average TDO3 was used to identify cisco refuge lakes in Minnesota. 620 known cisco lakes in Minnesota were divided into three groups: Tier 1 refuge lakes having the most suitable habitat for cisco, Tier 2 refuge lakes having suitable habitat for cisco, and Tier 3 or non-refuge lakes supporting cisco only at a reduced probability of occurrence. The multi-year average TDO3 for Tiers 1, 2, 3 lakes were selected to be $\leq 11^{\circ}\text{C}$, between 11°C and 17°C , and $> 17^{\circ}\text{C}$, respectively. Projected increases of the multi-year average TDO3 under the two future climate scenarios and relative to the 47-year simulation period from 1962 to 2008 had averages from 2.6 to 2.9 $^{\circ}\text{C}$. About one third of the 620 lakes that are known to have cisco populations were projected to maintain viable cisco habitat under the two projected future climate scenarios. These selective lakes have a Secchi depth greater than 2.3 m (mesotrophic and oligotrophic lakes) and are seasonally stratified.

5.2 Introduction

An increase of atmospheric carbon dioxide and/or other greenhouse gases is projected to cause climate warming (NRC 1983; IPCC 2007), which in turn is projected to warm the water and increase hypolimnetic oxygen depletion during periods of stratification in lakes (Blumberg and Di Toro 1990; Fang and Stefan 1999, 2000; Fang and Stefan 2009a). Fish habitat is constrained by water temperature (T), available dissolved oxygen (DO), food supply, human interference, and other environmental factors (Frey 1955; Fry 1971). In lakes, water temperature and DO are the two important water quality parameters that affect survival and growth of cold-water fishes (Magnuson et al. 1979; Coutant 1985b; Christie and Regier 1988; Coutant 1990; Jacobson et al. 2010). Therefore, projected changes of water temperature and DO characteristics due to climate warming have the potential to reduce cold-water fish habitat in lakes (Magnuson et al. 1990; Schindler et al. 1996; Stefan et al. 1996; Fang et al. 2004a).

Cisco *Coregonus artedii* is the most common cold-water stenothermal fish in Minnesota lakes. The combination of a wide geographic distribution (Figure 5.1) and a requirement for cold, oxygenated water (Cahn 1927; Frey 1955), makes cisco an excellent “canary in a coal mine” species that is a sensitive indicator of ecological stresses caused by eutrophication and/or climate warming. Ciscoes have been declining in recent years in Minnesota lakes, likely because of climate warming (Jacobson et al. 2012). Recently, Sharma et al. (2011) estimated that 30 to 70% of the cisco population in about 170 of Wisconsin's deepest and coldest lakes could become a climate change casualty and disappear from most of the Wisconsin cisco lakes by the year 2100.

The goal of the study was to simulate daily water temperature and DO profiles in 30 types of cisco lakes to project the quality of cold-water fish habitat in 620 known cisco lakes in Minnesota under future climate scenarios and to identify potential cisco ‘refuge lakes’. A ‘refuge lake’ is a cisco lake that is projected to provide suitable cold-water habitat under future climate scenarios. In this study, cold-water fish habitat was identified by a single oxythermal habitat variable TDO3, temperature at 3 mg/L of DO (Jacobson et al. 2010). Daily TDO3 values were calculated from simulated daily lake water temperature and DO profiles obtained from the process-oriented, one-dimensional year-round water quality model MINLAKE2010 (Fang et al. 2012a). The model was run in daily time steps over a continuous 48-year simulation period for past (1961-2008) climate conditions, and for two projected future climate scenarios (CGCM 3.1 and MIROC 3.2). Monthly (31-day) benchmark periods (Jacobson et al. 2010) were used to identify future cold-water fish habitat in lakes based on simulated projected future temperature and DO profiles.

5.3 Simulation Methods to Identify Cisco Refuge Lakes

5.3.1 Cisco Lakes in Minnesota

Our modeling analysis was conducted for 620 known cisco lakes (Figure 5.1); the MN DNR had netting assessments for these lakes since 1946. On average, Minnesota cisco lakes are deeper, more transparent (larger Secchi depth), and have lower chlorophyll-a concentrations than other lakes in Minnesota (Fang et al. 2009; Fang and Stefan 2009a). The 620 cisco lakes vary in mean Secchi depth (SD) and lake geometry ratio (GR; Figure 5.2). The GR is defined as $A_s^{0.25}/H_{\max}$ in $m^{-0.5}$ when surface area A_s is in m^2 and maximum depth H_{\max} in m. The strength of the seasonal lake stratification is related to the GR (Gorham and Boyce 1989). Polymictic lakes have the highest GR numbers, while strongly

stratified dimictic lakes have the lowest; the transition occurs between 3 and 5 (Gorham and Boyce 1989). Lake geometry ratios of Minnesota cisco lakes range from 0.47 to 22.7 $\text{m}^{-0.5}$ (Figure 5.2), and about 73% of these lakes have GR less than 3.0 $\text{m}^{-0.5}$ (Fang et al. 2009; Fang and Stefan 2009a). Only 6% or 39 of these lakes have GR greater than 5.0 $\text{m}^{-0.5}$ (Figure 5.2); these are very weakly stratified or unstratified lakes during the summer.

Maximum depths of the 620 cisco lakes range from 3.0 to 64.9 m, and 25% of these lakes have maximum depth greater than 24 m (Fang et al. 2009). Surface areas of these lakes range from 0.04 to 3847.0 km^2 (Fang et al. 2009), and mean summer Secchi depths from 0.7 to 9.5 m (Figure 5.2). Nineteen percent and 81% of the 620 cisco lakes (Fang et al. 2009) have mean summer Secchi depth greater than 4.5 m (oligotrophic lakes) and 2.5 m (mesotrophic lakes), respectively, based on regional lake classifications in Minnesota (Stefan et al. 1993).

For modeling purposes the 620 Minnesota cisco lakes were grouped by shortest distance to three Class I National Weather Service (NWS) weather stations in Minnesota (International Falls, Duluth, and St. Cloud; Figure 5.1). Weather data from only these three Class I NWS weather stations were useful and available for lake simulations for the period from 1961 to 2008. Three options (methods) were used to associate each lake with one of the three weather stations: (1) association by shortest distance, (2) association by latitude, (3) association of one single weather station with all lakes simulated. Refuge lakes were determined using each of the three options (Fang et al. 2010b), but results were similar; only results by method (1), association by shortest distance, are presented here. Of the 620 cisco lakes 169, 189, and 262 lakes have the shortest distance to International Falls, Duluth, and St. Cloud, respectively (shown by different symbols, Figure 5.1).

5.3.2 Cisco Habitat Criteria and Selection of Cisco Refuge Lakes

The oxythermal habitat approach commonly used in cold-water fish niche modeling (Dillon et al. 2003) uses an upper boundary for temperature (e.g., lethal temperature) and a lower boundary for DO concentration. These conventional oxythermal habitat models determine the water volume or layer thickness in a stratified lake between the upper temperature and lower DO bounds that represent either non-lethal/useable habitat (Stefan et al. 2001) or optimal thermal habitat (Dillon et al. 2003). In earlier studies of the impact of climate warming on three fish guilds (Stefan et al. 2001; Fang et al. 2004b), thermal/DO habitat was determined using temperature limits (e.g., lethal temperature, lower and upper good-growth temperatures, and optimal temperature) and a lower boundary for DO concentration to extract various habitat parameters.

In this study oxythermal habitat for cisco was determined using a single variable, TDO3, i.e. water temperature at 3 mg/L of DO, proposed by Jacobson et al. (2010). A higher TDO3 value represents higher oxythermal stress for the cold-water fish. For example, if TDO3 is high, then fish must choose between well-oxygenated water that is too warm, or live in hypoxic water that is of a proper temperature. Selection of 3 mg/L as the limiting oxygen concentration was somewhat arbitrary because proximate, alternative benchmark concentrations of 2, 4, and 5 mg/L were highly correlated (Jacobson et al. 2010). However, 3 mg/L is an oxygen concentration that is probably lethal or nearly so for many cold-water species (Frey 1955; EPA 1986; Evans 2007) and therefore

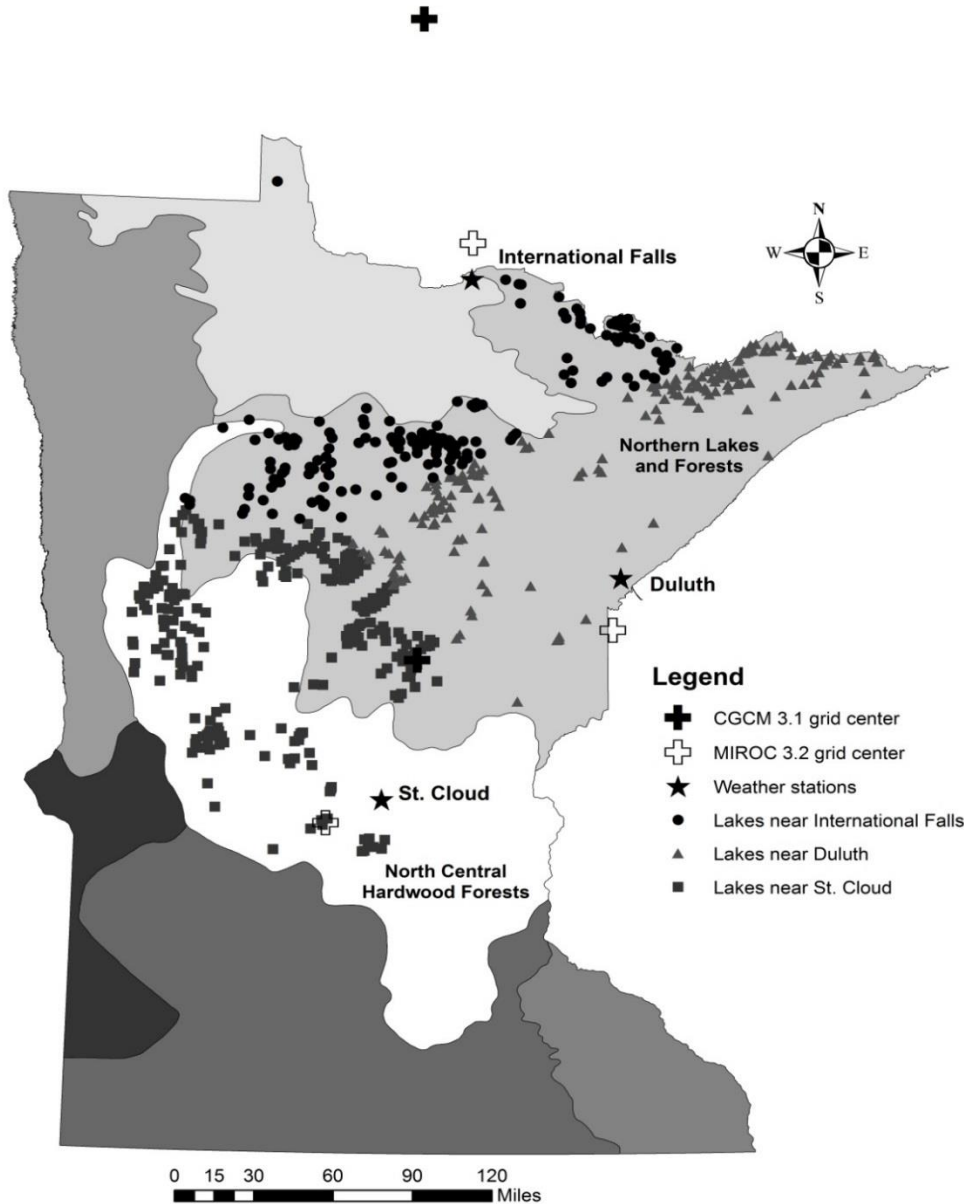


Figure 5.1 Geographic distribution of 620 cisco lakes in Minnesota assigned by shortest distance to one of three Class I NWS weather stations (International Falls, Duluth and St. Cloud). The three weather stations (stars) and the grid center points (crosses) of the CGCM 3.1 and MIROC 3.2 GCM models are also shown. Background shades identify ecoregions of Minnesota. Cisco lakes are found in two ecoregions: (1) Northern Lakes and Forests, and (2) North Central Hardwood Forests.

represents a desirable benchmark for a presence/absence niche model. The 3 mg/L DO limit was also used previously to examine impacts of climate warming on cold-water fish habitat in small lakes in Minnesota and in the contiguous USA (Stefan et al. 2001; Fang et al. 2004b).

Oxythermal habitat niche relationships developed for several cold-water fish (including cisco) by Jacobson et al. (2010) were used to identify potential refuge lakes for cisco under future climate scenarios. Niche breadth measures (central response borders of Heegaard 2002) were used by Jacobson et al. (2010) to identify values of TDO₃ measured in the period of greatest oxythermal stress in late summer (maxT_{DO₃}) useful for describing the quality of cold-water habitat for cisco. Central response borders essentially bracket the core range of a habitat variable required for a species to thrive (Heegaard 2002). The central species response borders for cisco ranged from maxT_{DO₃} of 4.0 to 16.9 °C (Jacobson et al. 2010).

In the present study cisco refuge lakes were selected and identified in two categories: Tier 1 refuge lakes and Tier 2 refuge lakes. Tier 1 refuge lakes have TDO₃ less than or equal to 11 °C, and Tier 2 refuge lakes have TDO₃ less than or equal to 17 °C but greater than 11 °C. Lakes having TDO₃ greater than 17 °C are classified as Tier 3 or non-refuge lakes. The limit of 17 °C corresponds to the upper cisco central response border of TDO₃, and the limit of 11 °C is near the midpoint of the cisco central response borders of TDO₃, as well as the upper central response border of TDO₃ for lake whitefish *Coregonus clupeaformis* (Jacobson et al. 2010). Therefore, Tier 1 refuge lakes identified for cisco in this study are also useful to the management of lake whitefish in Minnesota.

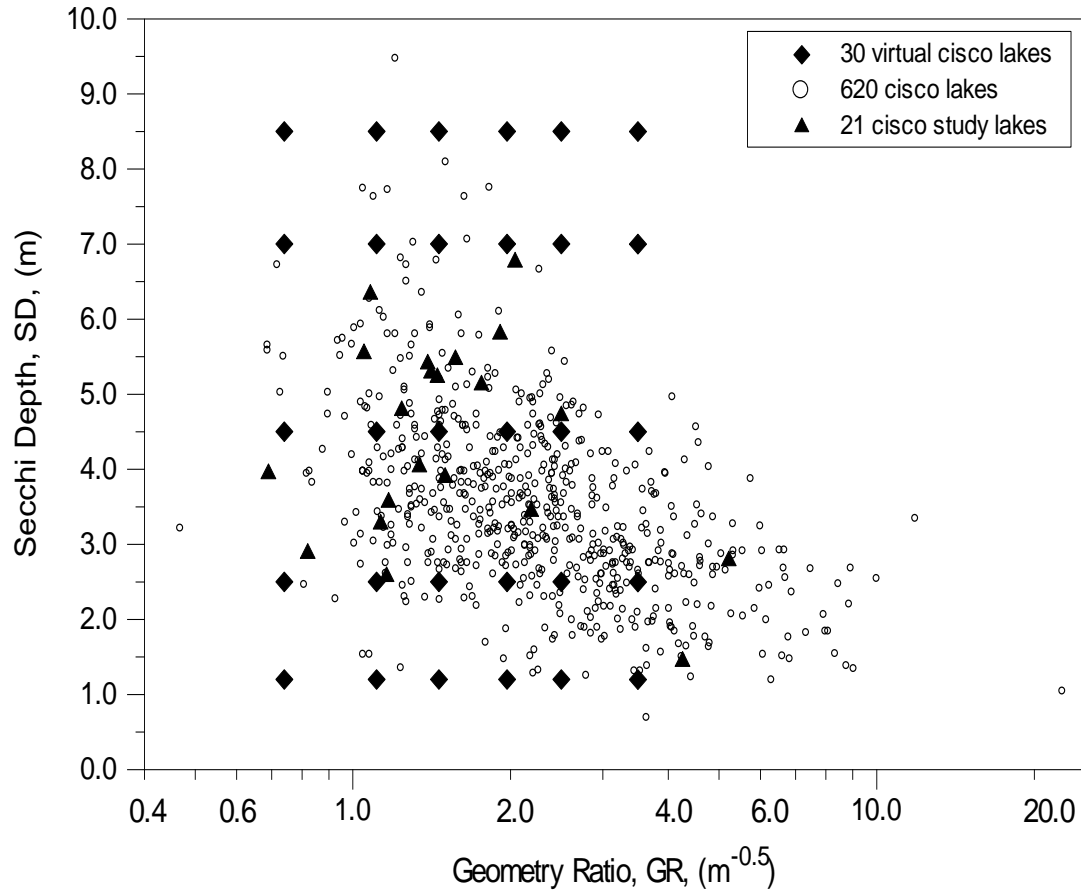


Figure 5.2 Distribution of 30 virtual cisco lakes (diamonds), 21 cisco study lakes (triangles), and 620 cisco lakes (circles) in Minnesota on a plot of Secchi depth SD versus lake geometry ratio GR ($= A_s^{0.25}/H_{\max}$).

The multi-year average TDO3 over a fixed benchmark (FB) period was used to identify cisco refuge lakes in Minnesota. The benchmark period is the period of greatest oxythermal stress for cold-water fish. It is defined as the month (31-day period) with the highest value of TDO3 and typically occurs in late summer (Jacobson et al. 2010). From a total of 9,521 T and DO profiles measured in 1,623 Minnesota lakes in the years 1993 through 2005 and the computed associated maximum TDO3 values, Jacobson et al. (2010) determined that the period of greatest oxythermal stress for cold-water fish differed by stratification status of a lake. The stress occurred earlier in unstratified lakes. In this study, the fixed

benchmark (FB) period from 28 July through 27 August proposed by Jacobson et al. (2010) was chosen to calculate the monthly (31-day) average of daily TDO₃, called ATDO_{3FB}, in each simulated year over the 47-year simulation period because the 30 simulated virtual cisco lakes (Figure 5.2) are strongly stratified lakes.

5.3.3 Overall Modeling Approach

Past climate conditions (1961 to 2008) and future climate scenarios were assembled and used as model inputs (atmospheric boundary conditions) to the deterministic, unsteady, one-dimensional (vertical) lake water quality model MINLAKE2010 which can simulate T and DO profiles in cisco lakes continuously for 48 years.

TDO₃ was calculated from simulated daily T and DO profiles for every simulated day except days in 1961 to avoid effects of initial conditions. To recognize the resilience of fish to water quality fluctuations, the daily TDO₃ values were averaged over the fixed benchmark period (ATDO_{3FB}) for each simulated lake and year.

To assess the quality of cisco habitat in a lake, and to identify refuge lakes, the 47-year average of annual ATDO_{3FB} values in the 1962-2008 simulation period (i.e., AvgATD_{3FB}) was calculated and compared to TDO₃ limits (11°C and 17°C determined by the analysis of field data) to divide cisco lakes into three tiers (Tiers 1 and 2 refuge lakes, and Tier 3 non-refuge lakes).

To implement the above modeling approach, 30 ‘virtual’ cisco lake types (Figure 5.2) were chosen as representative of the entire set of 620 lakes; a similar approach using 27 ‘generic’ lake types had been used to study climate warming impact on fish habitat in small lakes in Minnesota (Stefan et al. 1996) and in the contiguous USA (Stefan et al. 2001; Fang et al. 2004c), because it was not viable to run the deterministic model for all 620 cisco lakes

over 47 years. To apply the TDO3 results to the hundreds of cisco lakes that could not all be simulated, the 30 simulated lakes had to be characterized in a generic way. Following previous practice (Stefan et al. 2001; Fang et al. 2004c) two parameters were chosen for this purpose: a lake geometry ratio GR as an indicator of a lake's potential for strong or weak summer stratification (Gorham and Boyce 1989), and mean summer Secchi depth SD as an indicator of lake trophic state and transparency. Chlorophyll-*a* concentration that represents biomass or phytoplankton in the MINLAKE2010 model was calculated from the relationship between chlorophyll-*a* and Secchi depth used in the Carlson trophic index (Carlson 1977). Lake turbidity from suspended inorganic sediment is relatively rare in Minnesota, and total phosphorus or chlorophyll *a* in most Minnesota lakes are well correlated with SD. Therefore, Secchi depth SD is a representative parameter to characterize trophic state of each of the 620 cisco lakes in the database. Contours (isotherms) on plots with SD vs. GR as axes have been previously used successfully by the authors to give generic, but regional, values, e.g. for maximum surface water temperatures, maximum lake bottom temperatures, minimum DO at the sediment/water interface, and various fish habitat parameters in lakes (Stefan et al. 1996; Fang and Stefan 1997; Fang and Stefan 1999).

5.3.4 Virtual cisco lakes

The set of 30 virtual cisco lakes, shown by diamond symbols in Figure 5.2, comprised lakes with five different SD values (1.2 m, 2.5 m, 4.5 m, 7.0 m and 8.5 m) and six different surface areas (0.1 km², 0.5 km², 1.5 km², 5.0 km², 13.0 km², and 50 km²). The maximum depth of all 30 virtual lakes was set at 24 m (Fang et al. 2009). Combinations of the maximum depth and surface areas gave six different geometry ratios for the 30 virtual

lakes, *i.e.*, $0.74 \text{ m}^{-0.5}$, $1.11 \text{ m}^{-0.5}$, $1.46 \text{ m}^{-0.5}$, $1.97 \text{ m}^{-0.5}$, $2.50 \text{ m}^{-0.5}$, and $3.50 \text{ m}^{-0.5}$ (Figure 5.2). Twenty of the 30 virtual cisco lake types were strongly stratified with $\text{GR} < 2$; the other ten lake types were weakly stratified (Figure 5.2). The 30 virtual cisco lakes did not include any polymictic lakes (Figure 5.2) because they likely will not provide suitable cold-water habitat in Minnesota after climate warming. For example, Fang et al. (2012) studied the oxythermal habitat variable TDO3 in 21 study cisco lakes in Minnesota (shown as filled triangles in Figure 5.2) and found that two cisco lakes with $\text{GR} > 4.0$ (White Iron Lake and South Twin Lake) had high annual maximum TDO3 values indicating unfavorable conditions for cisco survival and growth. Values of TDO3 extracted from observed temperature and DO profiles were lowest in lakes with small geometry ratios ($\text{GR} < 2 \text{ m}^{-0.5}$); a geometry ratio of $4 \text{ m}^{-0.5}$ effectively marked the transition between stratified and unstratified lakes (Jacobson et al. 2010).

Even though the lake bathymetry (surface area and maximum depth) and Secchi depth of the 30 virtual cisco lakes were subjective, the selected values were representative of the 620 Minnesota cisco lake database (Fang and Stefan 2009a). The 30 virtual cisco lakes were all stratified lakes based on geometry ratio, and included eutrophic to oligotrophic lakes (Figure 5.2). The 30 virtual cisco lakes were more or less uniformly distributed on the plot of SD vs GR (Figure 5.2). The $\text{AvgATDO3}_{\text{FB}}$ obtained for each of the 30 lakes was plotted on a coordinate system of GR vs. SD and contour lines (isotherms) of $\text{AvgATDO3}_{\text{FB}}$ ranging from 7°C to 29°C were interpolated. This contour plot was then used for the selection of refuge lakes from 620 cisco lakes in Minnesota (Figure 5.1). Using the mean summer Secchi depth and the lake geometry ratio of each lake as independent variables, and the 11°C and 17°C isotherms drawn for the 30 simulated lakes as boundaries

between Tier 1, 2, and 3 lakes, all 620 cisco lakes in Minnesota were divided into tiers. In this way, the cisco fish habitat in un-simulated lakes could be estimated from simulated lakes.

A cross-validation on the refuge lake selection method was performed against the cisco kills that occurred in 18 Minnesota lakes during the hot summer of 2006; it is presented at the end of the discussion section. To compare with netting assessment data, a cisco abundance analysis in tiered refuge lakes was performed and is presented in the results section.

5.3.5 Water Quality Simulation Model

To simulate daily temperature and DO profiles the deterministic, one-dimensional (vertical) and unsteady year-round water quality simulation model, MINLAKE2010 (Fang et al. 2012a) was developed from the MINLAKE96 model (Fang and Stefan 1996a) for applications to deeper and more transparent cold-water lakes. The year-round model is run in daily time steps over multiple simulation years including both open-water seasons and ice-cover periods. The one-dimensional heat transfer and DO transport equations were solved numerically for layer thicknesses from 0.02 m (near the water surface or ice-water interface) to 1.0 m (for depths greater than 1.0 m) using an implicit finite difference scheme and a Gaussian elimination method. Descriptions of MINLAKE96 and MINLAKE2010 are presented elsewhere (Fang and Stefan 1996a; Fang and Stefan 2009a; Fang et al. 2012a).

Table 5.1 Monthly changes of air temperature (°C) and solar radiation (Langley/day) projected by MIROC 3.2 and CGCM 3.1 for the three principal Minnesota weather stations used in this study.

Station	International Falls		Duluth		St. Cloud	
Parameters	Air temperature ¹	Solar radiation ²	Air temperature	Solar radiation	Air temperature	Solar radiation
Jan	5.15/6.89 ³	-20.34/-5.69	4.67/4.84	-15.92/-7.49	4.35/4.84	-4.60/-7.49
Feb	4.70/5.07	-25.36/-9.51	4.67/8.09	-23.42/-38.21	4.17/8.09	-9.13/-38.21
Mar	4.64/3.90	-24.84/1.83	4.53/6.25	-15.75/-55.05	4.08/6.25	0.35/-55.05
Apr	4.52/4.31	-3.32/-18.77	3.89/3.60	0.78/-25.99	3.88/3.60	9.80/-25.99
May	4.37/4.12	-4.43/-29.39	4.21/3.47	-15.22/-19.96	4.33/3.47	2.45/-19.96
Jun	3.62/4.59	-3.82/9.63	3.59/3.28	-3.92/2.28	3.67/3.28	0.36/2.28
Jul	3.53/3.80	-5.38/14.43	3.68/3.25	10.36/14.78	3.67/3.25	17.08/14.78
Aug	3.75/3.30	-0.49/7.63	3.82/3.32	0.52/3.66	3.92/3.32	3.64/3.66
Sep	3.80/3.49	16.57/10.69	3.81/3.34	19.27/0.34	3.87/3.34	24.14/0.34
Oct	4.46/3.19	-2.76/3.94	4.29/3.39	3.03/-1.18	4.30/3.39	9.87/-1.18
Nov	4.10/2.89	-4.22/-1.82	3.89/3.06	3.03/-2.16	3.87/3.06	5.79/-2.16
Dec	4.18/4.14	-12.80/-4.86	3.99/2.91	-9.24/-1.32	3.92/2.91	-3.16/-1.32
Average	4.24/4.14	-7.60/-1.82	4.09/4.07	-3.87/-10.86	4.00/4.07	4.71/-10.86

¹ Conversions: 1.0 °C = 1.8 °F

² 1.0 Langley/day = 0.484 Watts/m²

³ The first value is for MIROC 3.2 and the second value is for CGCM 3.1

Twenty-one cisco lakes (filled triangles in Figure 5.2) and seven non-cisco lakes were selected for model calibration of MINLAKE2010 based on multi-year data availability; more than half of these 28 lakes had maximum depths greater than 24.0 m (H_{\max} used for the 30 virtual lakes), and 23 of the 28 lakes were either mesotrophic or oligotrophic lakes (Fang et al. 2012a). Measured water temperature and DO profiles (7,384 data pairs) spanning four hundred thirty nine (439) lake-days over 81 lake-years were used for model calibration. After calibration the average standard error of estimates 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) (Fang et al. 2012a). There were 99 measured T and DO profiles that had adequate data to extract TDO3 values for the 21 cisco lakes. The standard error of TDO3 determined from simulated profiles against TDO3 from 99 measured profiles was 2.19°C with correlation coefficient $R = 0.88$.

5.3.6 Future Climate Scenarios

In this study, we projected whether a lake that currently has a cisco population can support cisco habitat under future climate scenarios, i.e. after climate warming. To make the projection, the model outputs from two Coupled General Circulation Models (CGCMs) of the earth's atmosphere and oceans (*i.e.*, CGCM 3.1 and MIROC 3.2) were used as input to the MINLAKE2010 model to calculate a range of future water quality conditions.

The CGCM 3.1 (Kim et al. 2002; Kim et al. 2003) is the third generation of CGCMs from the Canadian Centre for Climate Modeling and Analysis (CCCma). The CCCma CGCM 3.1 uses the ocean component from the earlier Second Generation CGCM (McFarlane et al. 1992) and applies a substantially updated atmospheric component - the third Generation Atmospheric General Circulation Model. Output of the CGCM 3.1 model

with a coarse global surface grid resolution of roughly 3.75 degrees latitude and longitude or approximately 410 km in Minnesota was used for this study because it is available to be downloaded from the IPCC data center. There is one grid center point within Minnesota (Figure 5.1).

The MIROC 3.2 (Hasumi and Emori 2004), was developed by the Center for Climate System Research, University of Tokyo; the National Institute for Environmental Studies; and the Frontier Research Center for Global Change - Japan Agency for Marine-Earth Science and Technology. Output of the MIROC 3.2 model with a high spatial surface grid resolution of roughly 1.12 degrees latitude and longitude or approximately 120 km in Minnesota was used.

Mean monthly increments for climate parameters were obtained from the CGCM 3.1 or MIROC 3.2 model outputs, and applied to measured daily climate conditions (1961 – 2008) to generate projected daily future climate scenarios. Monthly increments from the grid center point closest to a weather station were used to specify the future climate. For the MIROC 3.2 future climate scenario, each of the three Class I NWS weather stations used (International Falls, Duluth and St. Cloud) had a close grid center point (Figure 5.1); for the CGCM 3.1 future climate scenario, Duluth and St. Cloud used the grid center point in Minnesota (Figure 5.1), and International Falls used a point in Canada (Figure 5.1). Monthly air temperature and solar radiation increments from CGCM 3.1 and MIROC 3.2 for all three weather stations are listed in Table 5.1. Monthly air temperature increases projected by MIROC 3.2 range from 3.53 °C to 4.70 °C with annual averages of 4.00 to 4.24 °C for the three weather stations; CGCM 3.1 projected a range from 2.89 °C to 8.09 °C with annual averages of 4.07 to 4.14 °C for the three weather stations (Table 5.1).

5.3.7 Computing TDO3 Parameters

The TDO3 is the water temperature at the DO concentration of 3 mg/L; it can be determined by interpolation from measured or simulated (vertical) temperature and DO profiles in a stratified lake. 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, an algorithm was developed to compute the oxythermal habitat parameter TDO3 using simulated daily water temperature and DO profiles in 30 cisco lakes over a 47-year simulation period (1962 to 2008). Temperature and DO profiles simulated for the first-year (1961) were not used in order to avoid possible effects of assumed initial conditions. Figure 5.3 illustrates the procedure how TDO3 can be extracted from either measured or simulated temperature and DO profiles. Elk Lake (Figure 5.3) has a maximum depth of 27 m and mean summer Secchi depth of 3.6 m (mesotrophic lake). Elk Lake has a lake geometry ratio of 1.16 and is a strongly stratified (dimictic) lake; it has excellent cold-water oxythermal habitat with TDO3 = 5.8 °C on June 24, 2008 (using observed temperature and DO profiles) and is projected to have a TDO3 value of 6.3 °C on June 24 under the future climate scenario MIROC 3.2.

5.4 Results

5.4.1 Mean Daily TDO3 in the Fixed Benchmark Periods

From the time series of daily TDO3 for each year in the 47-year (1962 to 2008) simulation period, different TDO3 statistics can be extracted, e.g., the annual maximum of daily TDO3 (TDO3_{AM}), or monthly (31-day) averages over fixed benchmark periods (ATDO3_{FB}), or multi-year averages of the above, etc. Twelve options of TDO3 characteristic values or statistics were calculated and explored (Fang et al. 2010a).

Examples of daily TDO3 time series for Elk Lake are given in Figure 5.3. The TDO3_{AM} value was 15.5 °C in 2004 for Elk Lake (bottom of Figure 5.3); the day of occurrence of TDO3_{AM} was DOY = 222 (August 10). The TDO3_{AM} values are projected to increase by 3.8 or 4.3 °C in Elk Lake under the future climate scenarios CGCM 3.1 and MIROC 3.2, respectively (Figure 5.3).

Three of the 21 cisco study lakes, White Iron Lake, Mukooda Lake, and Little Trout Lake, were selected to illustrate examples of time series of mean daily TDO3 in the 31-day FB periods, ATDO3_{FB}, for past climate (1962 to 2008) and for the future climate scenario MIROC 3.2 (Figure 5.4). Lake geometry ratios for White Iron Lake, Mukooda Lake, and Little Trout Lake are 4.27, 1.76, and 1.08 m^{-0.5}, respectively. White Iron Lake is a weakly stratified lake or a relatively shallow, large and eutrophic lake (maximum depth H_{max} = 14.3 m, surface area A_s = 13.9 km², Secchi depth SD = 1.4 m). Mukooda Lake (H_{max} = 23.8 m and SD = 5.1 m) and Little Trout Lake (H_{max} = 29.0 m and SD = 6.3 m) are strongly stratified and oligotrophic lakes. Values of ATDO3_{FB} ranged from 17.2 to 22.9 °C for White Iron Lake (using fixed benchmark period for unstratified lakes), 5.7 to 9.8 °C for Mukooda Lake, and from 4.5 to 6.9 °C for Little Trout Lake under past climate conditions. ATDO3_{FB} values in weakly stratified eutrophic White Iron Lake are much larger than ones in strongly stratified oligotrophic Mukooda Lake and Little Trout Lake.

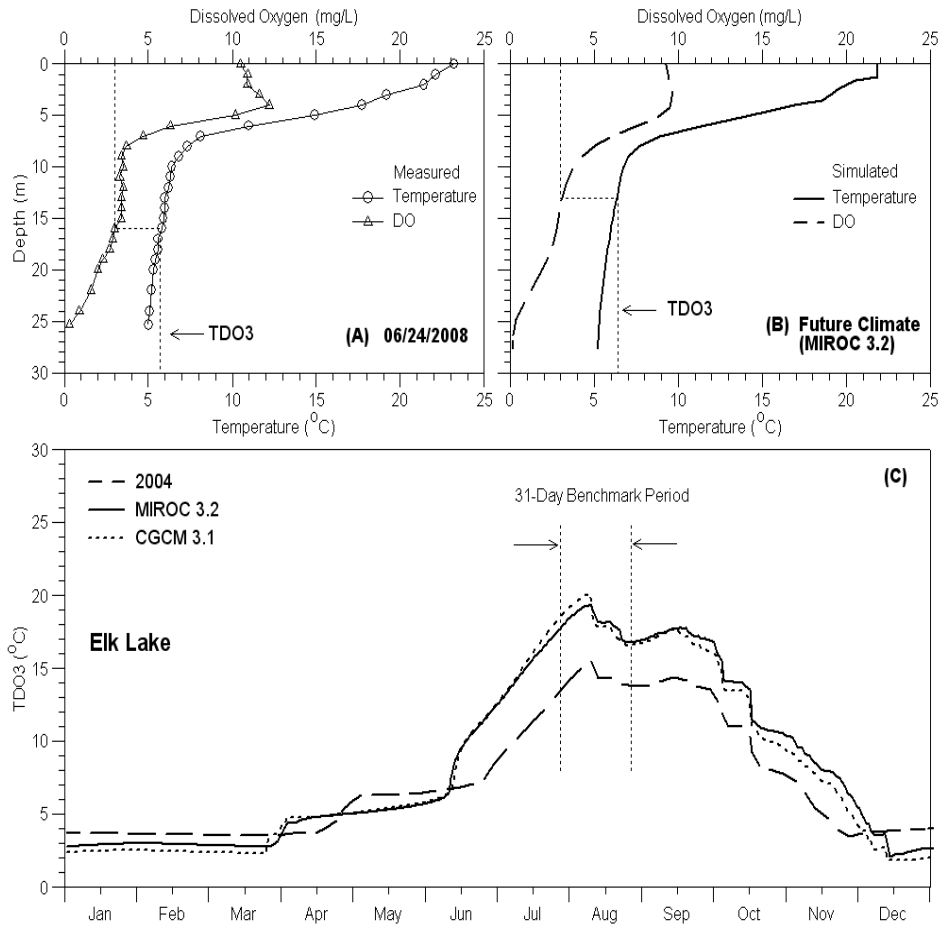


Figure 5.3 Examples of measured (A) and simulated (B) temperature and dissolved oxygen profiles in Elk Lake for past (A) and a future (B) climate to show the determination of TDO3 (temperature at 3 mg/L DO), and (C) time series of simulated daily TDO3 values for Elk Lake in 2004 and for future climate scenarios CGCM 3.1 and MIROC 3.2. The fixed benchmark periods for stratified lakes are between the vertical dashed lines.

Under the future climate scenario MIROC 3.2, values of ATDO3_{FB} are projected to range from 20.9 to 26.2 $^{\circ}\text{C}$ for White Iron Lake, from 6.4 to 12.2 $^{\circ}\text{C}$ for Mukooda Lake, and from 4.6 to 7.1 $^{\circ}\text{C}$ for Little Trout Lake (Figure 5.4). Projected changes are from 3.0

to 4.0 °C for White Iron Lake, from -1.4 to 3.5 °C for Mukooda Lake, and from -1.2 to 1.9 °C for Little Trout Lake.

5.4.2 Multi-year Average of Oxythermal Stress ($AvgATDO3_{FB}$)

Mean daily TDO3 values over the fixed benchmark ($ATDO3_{FB}$) period for each simulated year were averaged over the simulation period to obtain the parameter value $AvgATDO3_{FB}$, which had been chosen as the TDO3 characteristic parameter for the selection of cisco refuge lakes (Fang et al. 2010a). The $AvgATDO3_{FB}$ value is one value for the 47-year simulation period (1962 to 2008) for each lake and each climate scenario; whereas $ATDO3_{FB}$ has one value for each simulated year and 47 values in the simulation period.

Examples of $AvgATDO3_{FB}$ calculated from the time series of $ATDO3_{FB}$ are plotted as horizontal (dashed) lines in Figure 5.4 for past (1962-2008) climate and for the future climate scenario. The $AvgATDO3_{FB}$ values were 20.0 °C (standard deviation $STD = 1.19$ °C) for White Iron Lake, 7.0 °C ($STD = 0.77$ °C) for Mukooda Lake, and 5.4 °C ($STD = 0.44$ °C) for Little Trout Lake under past climate conditions (1962 to 2008). $AvgATDO3_{FB}$ is typically higher for weakly stratified lakes (e.g., White Iron Lake) than for stratified lakes (e.g., Mukooda and Little Trout lakes; Figure 5.4). Values of $AvgATDO3_{FB}$ for the future climate scenario MIROC 3.2 were projected to be 23.5 °C for White Iron Lake, 8.2 °C for Mukooda Lake, and 5.7 °C for Little Trout Lake; the projected increases of $AvgATDO3_{FB}$ are therefore 3.5 °C, 1.2 °C, and 0.2 °C for the three lakes, respectively.

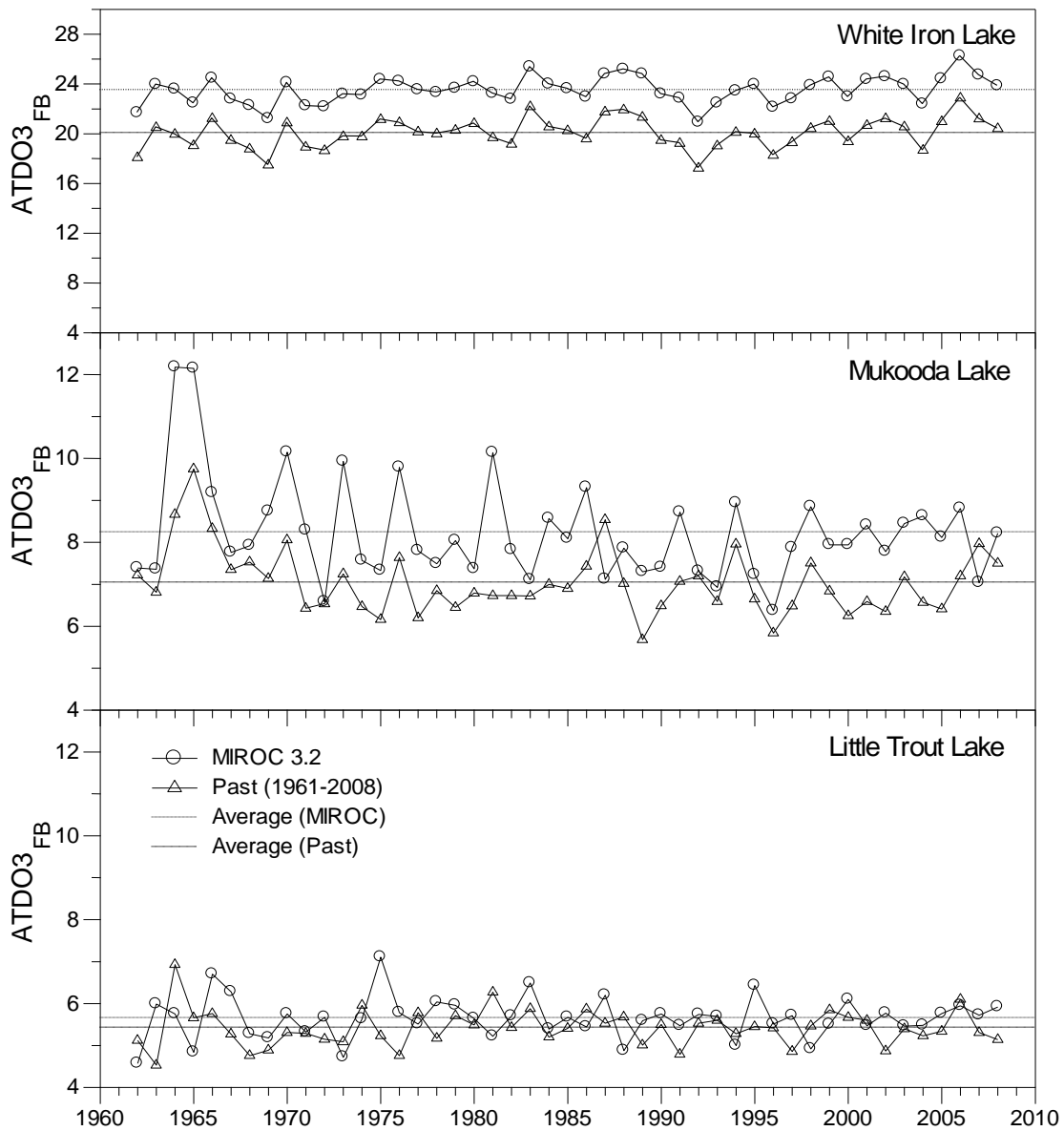


Figure 5.4 Examples of annual time series of mean daily TDO3 values for the fixed benchmark periods for past climate (1962-2008) and for the future climate scenario MIROC 3.2. Averages (AvgATDO3_{FB}) over the 47-year simulation period are presented as dashed horizontal lines. Weather data from the closest Class I NWS weather station were used for the model simulations (Duluth for White Iron Lake and International Falls for Mukooda and Little Trout Lake).

Simulated AvgATDO3_{FB} values are affected by lake bathymetry (lake geometry ratio, a combined parameter using surface area and maximum depth) and trophic state (Secchi depth was used, Figure 5.5). From the shape of the contours (isotherms) in Figure 5.5 one can conclude that AvgATDO3_{FB} values are less dependent on Secchi depth (trophic status) when a lake is weakly stratified, e.g., GR > 4, but that they depend on both lake geometry ratio and trophic state for stratified lakes. This is very similar to the findings by Jacobson et al. (2010) that lake productivity did not significantly affect TDO3 in the unstratified lakes. Simulated AvgATDO3_{FB} values are lower in northern Minnesota (International Falls) than in central Minnesota (St. Cloud), but that they have similar relationships (patterns) as function of GR and SD at all three locations (Figure 5.5). Simulated AvgATDO3_{FB} values for the 30 virtual lakes and contour plots similar to Figure 5.5 were also developed for past climate conditions (1962-2008) and the future climate scenario CGCM 3.1 (Fang et al. 2010a).

The AvgATDO3_{FB} values ranged from 6.1 to 19.6 °C under past climate conditions and from 6.3 to 23.3 °C under two future climate scenarios at three weather stations for the 30 virtual cisco lakes (Table 5.2). Statistics of differences in AvgATDO3_{FB} values (°C) between future climate scenarios and past climate (1962-2008) are given in Table 5.3. The projected increases of AvgATDO3_{FB} values from past climate to future scenarios were from 0.0 to 6.5 °C in the 30 virtual lakes (Table 5.3), and average increases were projected to be from 2.6 to 2.9 °C, which is about 1.0 to 1.5 °C less than projected annual air temperature increases under the climate scenarios MIROC 3.2 and CGCM 3.1 (Table 5.1). These increases are crucial, when cisco refuge lakes in Minnesota for future climate scenarios are identified and selected.

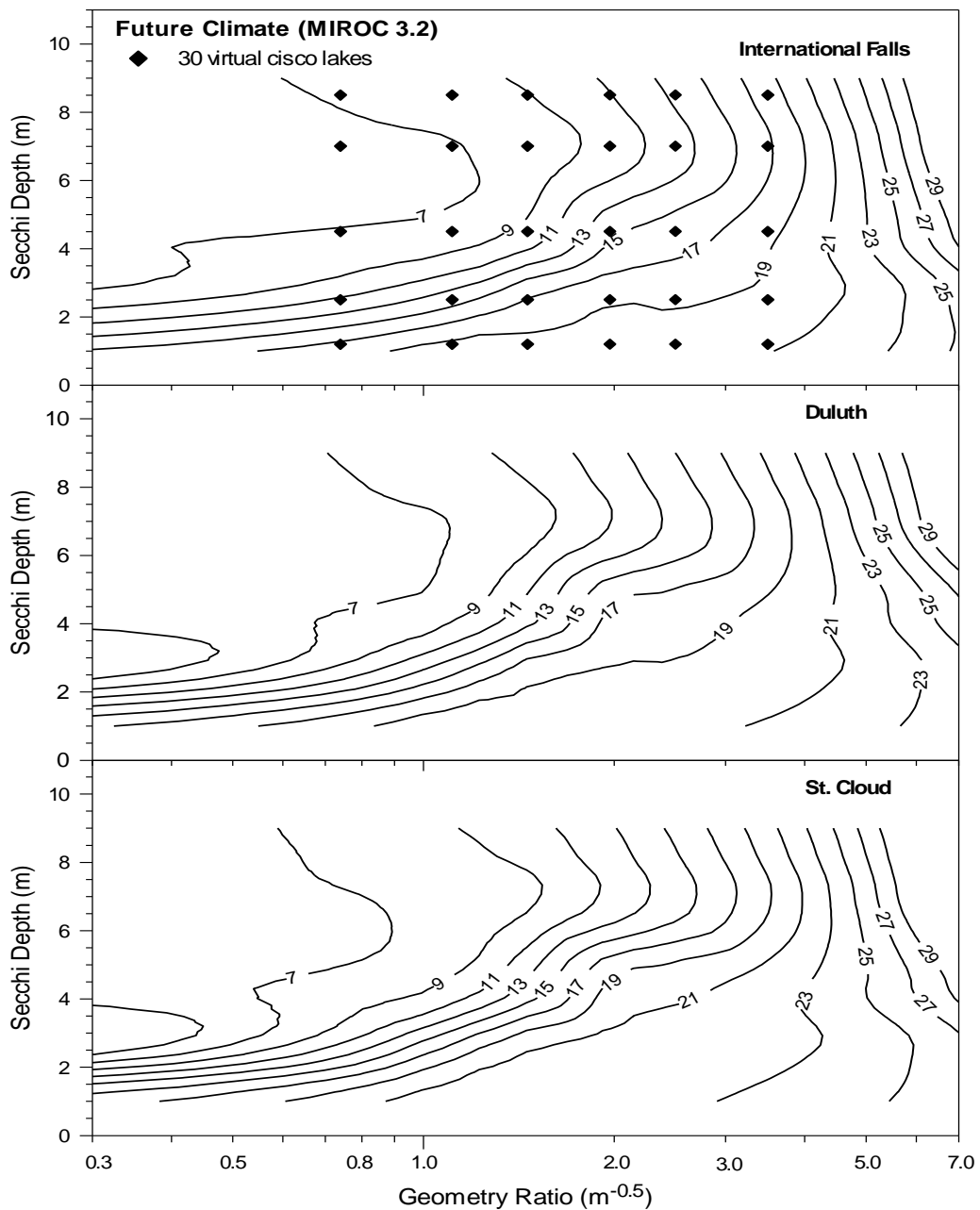


Figure 5.5 Contour plots of AvgATDO3_{FB} values (= 47-year averages of mean daily TDO3 over the fixed benchmark period DOY 209 to 239) under the future climate scenario MIROC 3.2. Model simulation results with weather data from International Falls (top), Duluth (middle) and St. Cloud (bottom) are plotted separately. Contours were derived by interpolation from simulated data points for 30 virtual cisco lakes.

Table 5.2 Statistics of AvgATDO3_{FB} (°C) under past climate conditions (1962- 2008) and future climate scenarios CGCM 3.1 and MIROC 3.2 for the 30 virtual cisco lakes. Simulations and analysis were made with weather data input from weather stations in International Falls, Duluth and St. Cloud, Minnesota.

Statistic (°C)	International Falls			Duluth			St. Cloud		
	Past	CGCM	MIROC	Past	CGCM	MIROC	Past	CGCM	MIROC
Maximum	16.96	20.65	20.75	17.18	20.57	21.03	19.60	22.84	23.29
Minimum	6.29	6.58	6.57	6.14	6.28	6.43	6.56	6.56	6.90
Mean	11.25	13.83	13.87	11.70	14.52	14.52	13.10	15.85	16.03
STD ¹	3.61	4.96	4.97	3.79	4.99	5.17	4.52	5.80	5.91

¹ Standard deviation from the mean.

5.4.3 Identified Cisco Refuge Lakes in Minnesota

The selection of cisco refuge lakes was based on TDO3 parameters projected under the CGCM 3.1 and MIROC 3.2 future climate scenarios using the temperature boundaries derived from 30 simulated lakes (Figure 5.5). Cisco refuge lakes were also determined by simulations for past climate conditions (1962 - 2008) because the results would be expected to match actual cisco lakes in Minnesota and would be a useful reference to gauge both the reliability of the selection procedure, and the impact of climate warming on cisco lakes in Minnesota.

The lakes are divided into Tier 1 and Tier 2 refuge lakes and Tier 3 non-refuge lakes (Table 5.4) by the 11°C and 17°C isotherms for cisco lakes assigned to International Falls (169 lakes), to Duluth (189 lakes), and to St. Cloud (262 lakes, Figure 5.6). The selection of refuge lakes shown in Figure 5.6 was based on contour lines of AvgATDO3_{FB} for the fixed benchmark period simulated under the future climate scenario MIROC 3.2. Under this scenario, it was projected that 66, 89, and 56 lakes associated with International Falls, Duluth, and St. Cloud, respectively, would be Tier 1 plus Tier 2 refuge lakes (Table 5.4 and Figure 5.6). A total of 211 or 205 lakes of 620 cisco lakes were identified as refuge lakes (Tier 1 plus Tier 2) under the future climate scenarios MIROC 3.2 and CGCM 3.1, respectively (Table 5.4). In other words, about one third of the 620 lakes that currently have cisco populations are projected to maintain cisco habitat under future projected warmer climate scenarios.

Table 5.3 Statistics of AvgATDO3_{FB} (°C) differences between future climate scenarios CGCM 3.1, MIROC 3.2 and past climate conditions (1962-2008) for the 30 virtual cisco lakes. Simulations and analysis were made with weather data input from weather stations in International Falls, Duluth and St. Cloud, Minnesota.

Statistic (°C)	CGCM 3.1 – Past			MIROC 3.2 – Past		
	International Falls	Duluth	St. Cloud	International Falls	Duluth	St. Cloud
Maximum	5.21	5.58	6.51	5.10	5.53	6.40
Minimum	0.29	0.13	0.00	0.28	0.28	0.34
Mean	2.58	2.82	2.75	2.62	2.82	2.93
STD ¹	1.70	1.63	1.79	1.70	1.75	1.81

¹ Standard deviation from the mean.

Table 5.4 Number (%) of lakes selected as Tier 1 and Tier 2 refuge lakes and Tier 3 non-refuge lakes from cisco lakes partitioned by shortest distance to weather stations in International Falls, Duluth and St. Cloud, Minnesota. The total number of lakes considered is 620.

Closest weather station	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
International Falls	Past	49 (8)	88 (14)	137 (22)	31 (5)	169 (27.2)
	CGCM 3.1	23 (4)	39 (6)	62 (10)	106 (17)	169 (27.2)
	MIROC 3.2	23 (4)	43 (7)	66 (11)	103 (17)	169 (27.2)
Duluth	Past	78 (13)	91 (15)	169 (27)	20 (3)	189 (30.5)
	CGCM 3.1	36 (6)	51 (8)	87 (14)	102 (16)	189 (30.5)
	MIROC 3.2	39 (6)	50 (8)	89 (14)	100 (16)	189 (30.5)
St. Cloud	Past	49 (8)	128 (21)	177 (29)	85 (14)	262 (42.3)
	CGCM 3.1	19 (3)	37 (6)	56 (9)	206 (33)	262 (42.3)
	MIROC 3.2	22 (4)	34 (5)	56 (9)	206 (33)	262 (42.3)
All three stations	Past	176 (28)	307 (50)	483 (78)	137 (22)	620 (100)
	CGCM 3.1	78 (13)	127 (20)	205 (33)	415 (67)	620 (100)
	MIROC 3.2	84 (14)	127 (20)	211 (34)	409 (66)	620 (100)

Under past climate conditions (1962 to 2008), 483 lakes or 78% of the 620 lakes with documented cisco populations (Table 5.4) were classified as refuge lakes (Tier 1 plus Tier 2). Mean values of gillnet catch per unit effort (CPUE – number of cisco gillnet) were determined from standard MN DNR netting assessments of cisco in 474 lakes. The CPUE is used as a measure of relative abundance. Mean CPUE values were 5.1, 4.1, and 3.6 for 49 Tier 1, 97 Tier 2, and 328 Tier 3 refuge lakes, respectively. The netting assessment data shows that there is a correlation between the tier and relative abundance, i.e., cisco abundance diminishes from Tier 1 to Tier 3 lakes.

The geographic distribution or a division of the 620 Minnesota cisco lakes into 84 Tier 1 refuge lakes (large circles), 127 Tier 2 refuge lakes (medium-size pentagons), and 409 non-refuge cisco lakes (small hexagons) was projected for the future climate scenario MIROC 3.2 (Figure 5.7). Twenty three (23) Tier 1 and 43 Tier 2 cisco refuge lakes (Table 5.4) are associated with International Falls where there is little urban or agricultural development (protected by the Superior National Forest); 39 Tier 1 and 50 Tier 2 refuge lakes (Table 5.4) are near Duluth where more development pressure exists and more protection may be necessary; and there are 22 Tier 1 and 34 Tier 2 refuge lakes (Table 5.4) associated with the St. Cloud area and its moderate development pressure.

We found that 84 Tier 1 refuge lakes (Table 5.5) have mean summer Secchi depths from 3.20 to 9.46 m (oligotrophic lakes), lake geometry ratios from 0.47 to 1.83 m^{-0.5} (strongly stratified lakes), maximum depths from 13.7 to 64.9 m and surface areas from 0.08 to 21.27 km². We have also learned that the upper 50% of the 127 Tier 2 refuge cisco lakes (Table 5.5) have a mean summer Secchi depth greater than 3.89 m, a geometry ratio from 1.13 to 2.66 m^{-0.5}, and a maximum depth greater than 21.3 m. On the other hand, the

lower 50% of the 409 Tier 3 non-refuge lakes in Table 5.5 have a mean summer Secchi depth less than 2.9 m, a geometry ratio from 1.16 to 2.72 m^{-0.5}, and a maximum depth less than 13.4 m.

Tier 1 plus Tier 2 refuge lakes selected under the MIROC 3.2 climate scenario have a Secchi depth greater than 2.3 m (Table 5.5), a lake geometry ratio less than 2.7 m (Table 5.5), and a maximum depth greater than 11.6 m (Table 5.5). The cumulative distributions of surface areas of projected cisco refuge lakes and the current 620 cisco lakes are not significantly different (Fang et al. 2010). Refuge lakes selected for the MIROC 3.2 climate scenario have surface area up to 137.9 km², and only 4 of the 620 cisco lakes in the MN DNR database have a surface area greater than 137.9 km². These four lakes are projected to become non-refuge lakes in the future.

The geographic distribution of the projected cisco refuge lakes in Minnesota was surprisingly uniform (Figure 5.7). Refuge lakes are not exclusively found in the northern and colder region; in fact, many non-refuge lakes are in the north, and a few refuge lakes are near St. Cloud in the south. This is because stratification characteristics related to lake geometry ratio and trophic status play an important role in determining cold-water habitat for cisco in addition to climate conditions.

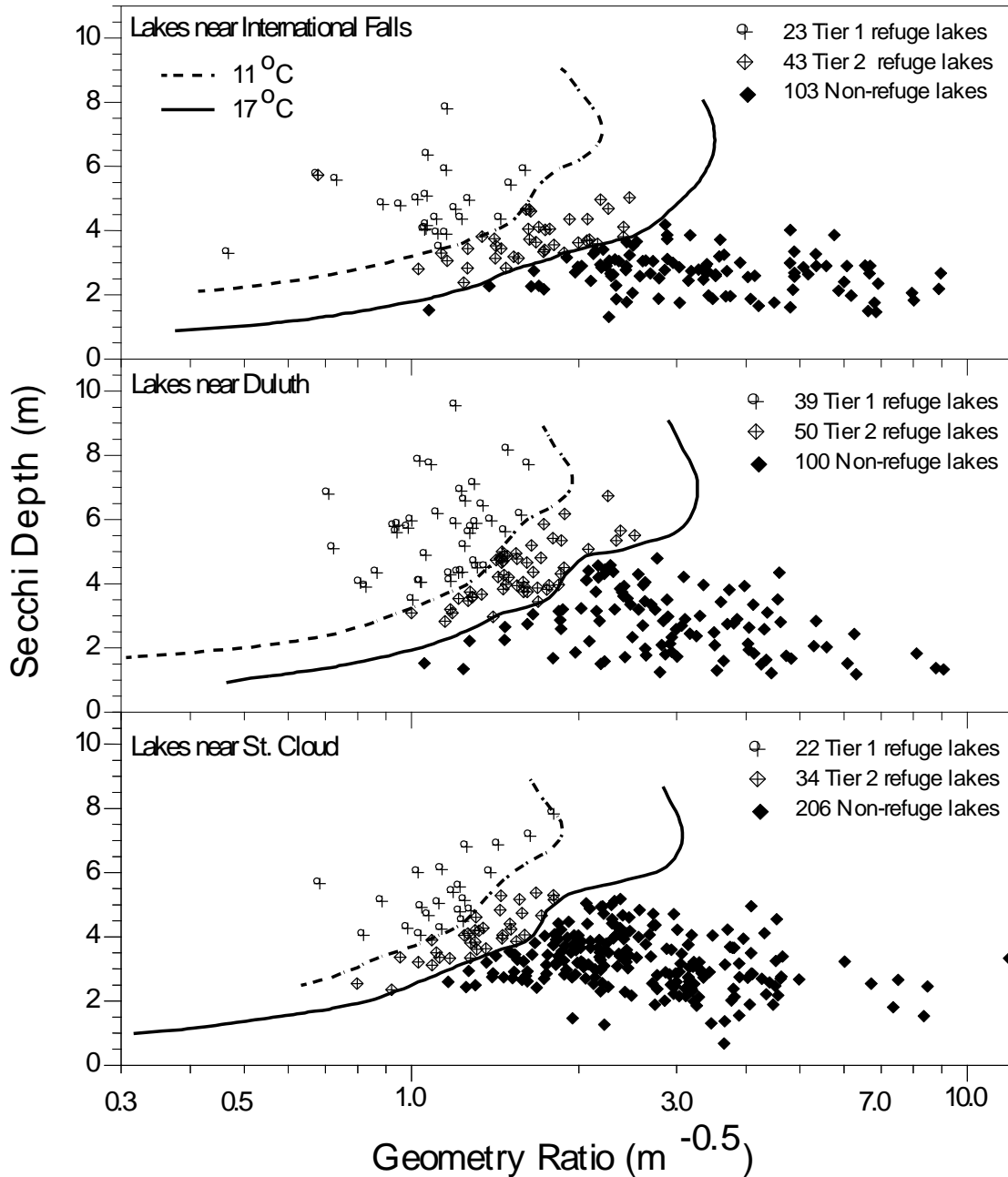


Figure 5.6 Distribution of Tier 1 and Tier 2 refuge lakes, and Tier 3 non-refuge lakes on a plot of Secchi depth SD vs. lake geometry ratio GR. The total number of cisco lakes is 620. The boundary contour lines between Tiers 1, 2 and 3 are for $AvgATDO_{3FB} = 11^{\circ}C$ and $17^{\circ}C$, respectively, and were determined by the fixed benchmark method for the future climate scenario MIROC 3.2 using weather data from International Falls, Duluth and St. Cloud, Minnesota, as simulation model input.

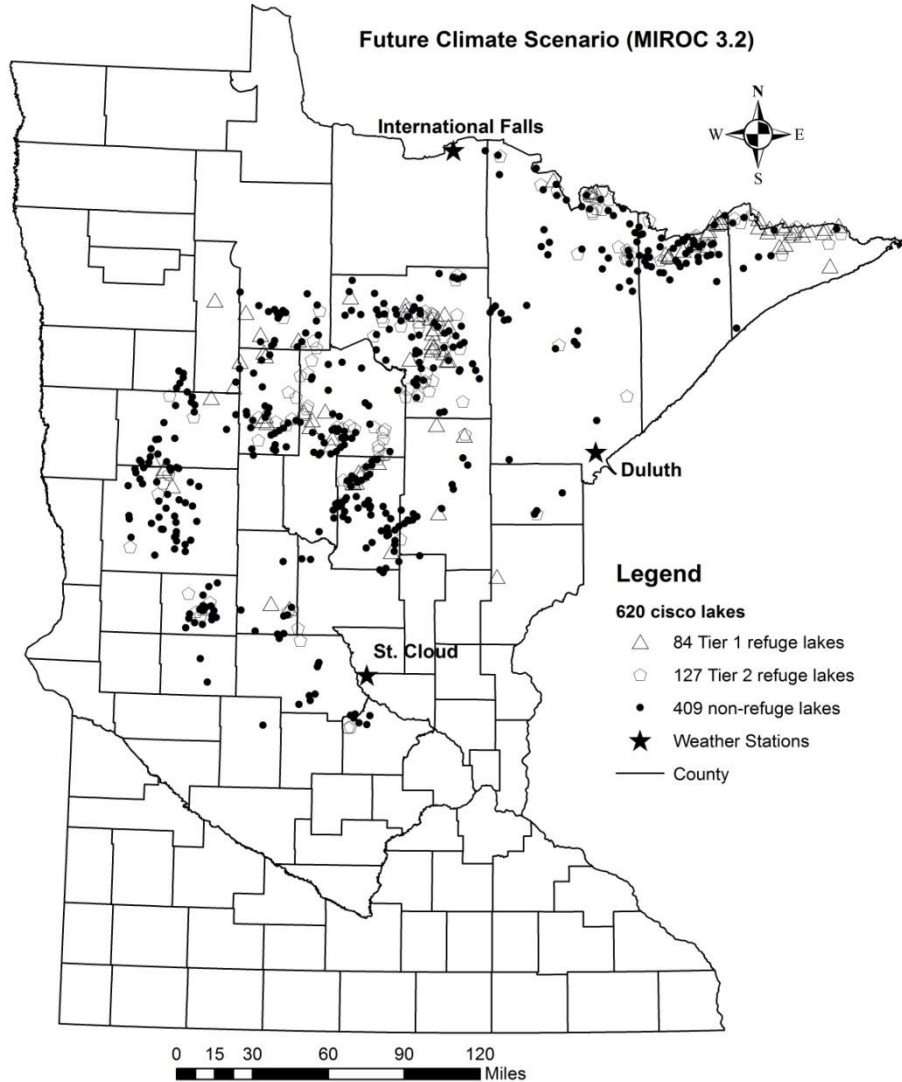


Figure 5.7 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and Tier 3 non-refuge cisco lakes obtained from simulations for the future climate scenario MIROC 3.2. The boundary limits for Tier 1 and Tier 2 refuge lakes were contour lines of $AvgATDO3_{FB} = 11\text{ }^{\circ}\text{C}$ and $17\text{ }^{\circ}\text{C}$, respectively. The fixed benchmark method and weather data from principal weather stations in International Falls, Duluth, and St. Cloud, Minnesota, were used.

5.5 Discussion

The MINLAKE2010 model simulated cisco oxythermal habitat similar to Jacobson et al. (2010), who developed an empirical model to predict TDO3 as a function of lake productivity, climate, and lake geometry ratio. Summer total phosphorus concentration was selected by Jacobson et al. (2010) to represent primary productivity of each lake. In our study, trophic state, as measured by Secchi depth, was used to express primary productivity and is directly related to DO production by photosynthesis in the MINLAKE2010 model.

The effects of dissolved organic carbon (DOC), e.g. in the form of humic acids, were not modeled explicitly in this study, although DOC can contribute to water color and light attenuation in Minnesota lakes; this effect is captured by Secchi depth, but it also weakens the relationship between SD and primary productivity, chlorophyll-*a* concentrations and DO production by photosynthesis. Variations in these parameters follow well-established seasonal patterns in Minnesota lakes, and these patterns were imposed in the simulation model for DO. MINLAKE2010 did not include nutrient input from the surrounding watershed into a lake, or groundwater inflow. Simulation results obtained with MINLAKE 2010 are, nevertheless, representative of the nutrient input from the watershed which is reflected in the trophic state, and therefore the Secchi depth SD of the lake; but groundwater inflow and its effect on stratification is not accounted for in SD or GR.

Based on measured temperature and DO profiles in Minnesota lakes (Jacobson et al. 2010), the 31-day FB period from 28 July to 27 August is considered to be well-chosen for the study. In an ongoing model study of 18 Minnesota lakes that had cisco kills in the summer of 2006, TDO3 is being computed over periods of 3 days, 7 days, 14 days, and 31

days. Results will be used to identify which multi-day average TDO3 has the best correlation with cisco kill in summer.

Projected changes in the multi-year average TDO3 (i.e. AvgATDO3_{FB}) between future and past climate conditions have mean values from 2.58 °C to 2.93 °C (Table 5.3). The potential impact of climate change on fish habitat is inevitable. Our results predict that 67% of the current cisco lakes will become non-refuge lakes, which is similar to those of a recent study of about 170 cisco lakes in Wisconsin (Sharma et al. 2011) using a different methodology.

Table 5.5 Statistics of physical lake parameters for cisco refuge lakes and non-refuge lakes. Lakes are divided into Tier 1 and Tier 2 refuge lakes, and Tier 3 non-refuge lakes using AvgATDO_{3FB} obtained by simulations for the MIROC 3.2 future climate scenario. Lakes are assigned by shortest distance to weather stations in International Falls, Duluth, and St. Cloud, Minnesota. 620 cisco lakes are analyzed.

Statistic	84 Tier 1 refuge lakes				127 Tier 2 refuge lakes				409 Tier 3 or non-refuge lakes			
	A _s (km ²)	H _{max} (m)	GR (m ^{-0.5})	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ⁻)	SD (m)	A _s (km ²)	H _{max} (m)	GR (m ⁻)	SD (m)
Maximum	21.27	64.92	1.83	9.46	137.94	51.20	2.66	6.65	893.93	56.08	11.89	5.18
Minimum	0.08	13.72	0.47	3.20	0.04	11.58	0.69	2.26	0.05	3.05	1.06	0.68
Average	2.60	30.94	1.16	5.28	4.80	23.83	1.61	4.01	9.94	15.04	3.13	2.98
Standard deviation	4.21	11.73	0.24	1.24	14.28	9.17	0.40	0.81	57.29	7.40	1.52	0.86
3rd Percentile	2.63	36.57	1.29	5.88	3.08	29.11	1.78	4.58	5.03	18.75	3.69	3.54
Median	0.98	27.43	1.16	5.03	1.13	21.33	1.56	3.89	1.92	13.41	2.72	2.90
1st Percentile	0.52	23.16	1.04	4.27	0.59	16.76	1.32	3.46	0.84	9.75	2.16	2.44

The fish habitat simulation program developed in this study also can extract the highest mean daily TDO3 over a sliding or variable 31-day benchmark (VB) period. This is significant because the fixed benchmark (FB) period is a very good average for many lakes, but may not fit some individual lakes. For example, the annual maximum daily TDO3 in Big Trout Lake for simulations from 1992 to 2008 occurred between October 6 and October 26, i.e. significantly outside the FB period. Average beginning dates of the 31-day VB periods that gave the highest mean TDO3 (ATDO3) ranged from July 21 to October 3 for the 30 virtual lakes under past climate conditions (1962 to 2008) (Jiang et al. 2012). In a given year ATDO3 in the FB period can be different from the highest ATDO3 over the VB periods. There were moderate differences in the number of refuge lakes obtained using FB and VB periods with identical TDO3 isotherms (11 °C and 17 °C) as boundary lines. When VB periods were used 34 (past), 64 (CGCM 3.1), and 74 (MIROC 3.2) fewer refuge lakes were identified than with a FB period (Table 5.4). Details in refuge lake selection using variable benchmark periods were explored elsewhere (Fang et al. 2010a; Jiang et al. 2012).

The partitioning of the cisco lakes into Tiers 1, 2, and 3 was guided by TDO3 temperatures of 11 °C and 17 °C. These boundary lines are considered fairly stringent because the upper ultimate lethal temperature of young ciscoes was determined in a laboratory study by Edsall and Colby (1970) to be 26 °C and mortality of adults begins at 22 °C at 3 mg/l of oxygen based on the analysis of observed temperature and DO profiles in 23 Minnesota lakes (Jacobson et al. 2008). Median values of maxTDO3 were 18.2 °C for lakes with cisco populations (Jacobson et al. 2010).

Tier 1 and Tier 2 cisco lakes identified for past climate conditions (1961-2008) may be called ‘viable cisco lakes’, i.e. lakes where cisco is capable of surviving, growing, and reproducing under favorable conditions. Nevertheless, 137 of 620 lakes (Table 5.4) with known cisco populations were identified as non-refuge lakes under past climate conditions (1962 to 2008); this does not mean that these 137 lakes cannot support cisco habitat at all. Cisco can still persist in lakes with TDO3 values greater than 17 °C but at a reduced probability of occurrence (Jacobson et al. 2010).

We cannot validate the projected number of refuge lakes for future climate scenarios, but we did a cross-validation of refuge lake selection as follows. Adult cisco mortality was reported in 18 lakes in Minnesota during the summer of 2006 (Jacobson et al. 2008). Water temperature and DO profiles were measured in five reference lakes without cisco mortality, and analyzed by (Jacobson et al. 2008). With the exception of two lakes with cisco mortality (Lake Bemidji and Long Lake), the 21 cisco study lakes used by Jacobson et al. (2008) are in the MN DNR cisco lake database. All five reference lakes without cisco mortality in 2006 emerged as Tier 1 refuge lakes when simulated for past climate conditions using the fixed benchmark period. Nine of the 16 lakes with adult cisco mortality in 2006, emerged as non-refuge lakes when simulated under past climate (1962 to 2008), and six emerged as Tier 2 refuge lakes. The average of ATDO3_{FB} over the 47-year simulation period 1962-2008, would be expected to underestimate the oxythermal stress in the unusually hot summer of 2006, which would explain why six lakes that experienced cisco mortality might be classified as Tier 2 lakes. When AvgATDO3_{FB} was simulated under the MIROC 3.2 future climate scenario, 15 of the 16 lakes with cisco mortality emerged as non-refuge lakes. Only Lake Carlos had cisco mortality in 2006, but

was classified as a Tier 1 refuge lake under both past and MIROC 3.2 climate scenarios. We cannot explain this disagreement, but Jacobson et al. (2008) note that “Cisco mortality occurred at lower temperatures in Lake Carlos than in the lakes with midsummer mortality events”. Overall, there is remarkable agreement between model predictions and observed adult cisco mortality events in 2006 in consideration of uncertainties (e.g., model errors of simulated T and DO profiles with off-lake weather data). The cross-validation on adult cisco mortality events and the relative abundance analysis using CPUE indicate that results for refuge lakes derived using modeled T and DO profiles are reasonably accurate and should be useful to managers.

5.6 Chapter Summary and Conclusions

A procedure (model simulation and analysis method) was developed and applied to estimate if cisco is likely to survive in some Minnesota lakes under future warmer climate, and what the bathymetry and trophic status of these ‘refuge lakes’ are. An oxythermal habitat variable $AvgATD_{3FB}$ was calculated over a 31-day fixed benchmark period in the 47-year simulation period for each of 30 virtual cisco lakes and used for identifying cisco refuge lakes in Minnesota. Six hundred twenty cisco lakes in Minnesota were partitioned into Tier 1 refuge lakes ($AvgATD_{3FB} \leq 11$ °C); Tier 2 refuge lakes (11 °C < $AvgATD_{3FB} \leq 17$ °C); and Tier 3 or non-refuge lakes ($AvgATD_{3FB} > 17$ °C). Under the above selection criteria, about one third of the 620 lakes that currently have cisco populations are projected to be able to maintain cisco habitat under projected future climate scenarios. Tier 1 plus Tier 2 refuge lakes selected under the future climate scenario MIROC 3.2 have Secchi depths greater than 2.3 m (mesotrophic or oligotrophic), lake geometry ratios less than $2.7 m^{-0.5}$, and maximum depths greater than 11.6 m. Once refuge lakes are identified,

protection efforts on lake watersheds can be initiated to prevent deterioration of water quality in these lakes by anthropogenic activities. These watershed efforts will need to be sufficiently robust to protect against projected increases in heavy storm events that have the potential to deliver increased sediment and nutrient loads. Only by protecting the water quality in these lakes, will they truly be able to function as refuges from climate warming for cold-water fish such as cisco.

Chapter 6 **Summary and Conclusions**

6.1 Summary

The objective of this study is to identify refuge lakes for cisco (a cold-water fish species) from 620 lakes in Minnesota. These refuge lakes should not only support cisco habitat under the past climate conditions but also should support cisco habitat under future climate warming scenarios. Daily water temperature (T) and dissolved oxygen (DO) were simulated using a one-dimensional water quality model MINLAKE2010/2012 for both past and future climate conditions. Input data for MINLAKE2010/2012 water quality model include weather data associated with lake location, lake bathymetry, model parameters and coefficients (e.g., kinetics coefficients, light extinction coefficient, temperature correction coefficients, etc.), initial T and DO profiles for model simulation, and lake biochemical conditions (e.g., biochemical oxygen demand, sediment oxygen demand, and chlorophyll-a). Forty-eight year (1961-2008) past climate conditions and two future climate scenarios (CGCM 3.1 and MIROC 3.2) were used by the model as the meteorological boundary conditions. Simulated daily temperature and dissolved oxygen profiles were then used as inputs for the fish habitat model FishHabitat2013 that has four different modules (presenting in Chapters 2, 3, 4, and 5) related to four different methods or options that help us to understand cisco habitat or lethal conditions in different lake types and eventually identify cisco refuge lakes in Minnesota.

The method one of FishHabitat2013 model was presented in Chapter 2 that used a lethal-niche-boundary curve, which gives variable lethal T and DO limits, to determine fish habitat condition along depth in each day in the 44 virtual lakes (shallow, medium-depth, and deep lakes). The method one predicted that deep lakes are typically good candidates

of refuge lake, shallow lakes will not support cisco in the future climate warming scenarios, medium-depth lakes are vulnerable to climate changing and need further study. To implement the method two of FishHabitat2013 model (Chapter 3) we presented simulation results separately for deep lakes from shallow and medium-depth lakes as suggested by one of the important findings from the method one. Instead of using a single curve that couples temperature survival limit with DO survival limit in the method one, the method two used separate temperature and DO survival limits for cisco. The key finding of the method two is that through model validation of cisco kill and habitat in 23 Minnesota lakes, we suggested the survival limits for cisco are lethal temperature (LT) equal to 22.1 °C and DO survival limit (DO_{lethal}) equal to 3 mg/L, which haven't proposed by other studies. The fish habitat model that implemented the method one and two was first calibrated/validated using 2006 cisco kill or habitat observations in 23 Minnesota lakes, then the method one of FishHabitat2013 model was applied to 36 virtual lakes that include 27 lake types (LakeR01-LakeR27) used in previous study (Fang and Stefan 1996b) and 9 new lake types (LakeR28-LakeR36) created for deep oligotrophic cisco lakes. The method two of FishHabitat2013 model was applied to 58 virtual lakes (12 shallow, 16 medium-depth, and 30 deep lake types) (Table 1.2 and Table 3.2). Number of annual cisco lethal days were analyzed by the method one; under the past climate conditions, both 12 medium-depth and 12 deep lakes have average 1–5 annual cisco lethal days whereas 12 shallow lakes have average 17–21 annual cisco lethal days (Figure 2.8). The 12 shallow lakes are projected to have average 57–59 annual cisco lethal days, which proves that shallow lakes will not be good candidate as cisco refuge lakes in the future. Under the future climate scenario MIROC3.2, 12 deep lakes are projected to have average 1–3 annual cisco lethal days which

proves deep lakes are still good candidates to support cisco habitat under climate warming scenario. The 12 medium-depth lakes had average 1–5 annual cisco lethal days in the past but are projected to have average 25–43 annual lethal days in the future. Cisco annual lethal days are projected to change/increase dramatically for medium-depth lakes which proves that medium-depth lakes cannot be considered as refuge lakes. By applying the method two to 58 virtual lakes (Table 1.2 and Table 3.2) we further confirmed that deep lakes are good candidates as refuge lakes but shallow and medium-depth lakes cannot be refuge lakes under future climate warming scenario. Overall, the method two had slightly better calibration results against cisco kill or habitat observations but the main findings for refuge lakes are almost the same for the methods one and two.

The fish habitat parameters determined by the methods one and two were cisco lethal parameters which can give good prediction of which types of lakes are good candidates as refuge lakes but the limitation of these two methods are that they cannot be used to classify 620 cisco lakes in Minnesota into different categories or levels of refuge lakes. In order to further classify 620 cisco lakes we used a single oxythermal parameter TDO3 in the method three (Chapter 4) and four (Chapter 5), and TDO3 is the temperature when DO is equal to 3 mg/L. TDO3 is an oxythermal stress parameter for cisco. The smaller TDO3 is the less stress the cisco feels, i.e., has better habitat condition for cisco. The fish habitat modules that implemented the methods three and four find the ‘most stressful period’ for cisco using TDO3 in two different ways. The method three uses variable bench mark periods over the simulation years to determine long-term average TDO3 for classifying refuge lakes when the module searches for and identifies the most stressful 31 days for cisco in each year. The method four uses a 31-day fixed bench mark period (July 28th to August 27th for stratified

lakes) recommended by fish biologists after their data analysis. TDO3 values were calculated day by day and then averaged during the variable bench (VB) mark period and the fixed bench (FB) mark period to get annual 31-day average TDO3 values: $ATDO3_{VB}$ and $ATDO3_{FB}$, respectively, then multi-year average (48 years, from 1961 to 2008) of $ATDO3_{VB}$ and $ATDO3_{FB}$ were calculated for 30 deep virtual lakes to create contour lines used to classify 620 lakes. The contour lines 11°C and 17°C which were recommended by fish biologists were used both in the method three and method four to divide 620 cisco lakes into three groups: Tier 1 refuge lakes, Tier 2 refuge lakes and Tier 3 non refuge lakes. Overall, from the methods three and four, there are around one quarter to one third of the 620 cisco lakes that can be considered as refuge lakes under future climate warming scenarios.

6.2 Conclusions

Based on the results of this study presented in Chapters Two to Five, the following conclusions have been developed:

1. MINLAKE2010/2012 was calibrated against measured profiles in 23 Minnesota lakes with average standard error of 1.57 °C for temperature and 1.72 mg/L for DO.
2. The fish habitat method one using the lethal-niche-boundary curve was applied to the 23 Minnesota lakes and successfully simulated lethal conditions in 16 (11 lakes with perfect agreement and 5 lakes with partial agreement) of the 18 lakes that experienced adult cisco mortality in 2006 and habitable conditions in five references lakes that experienced no adult cisco mortality in 2006 (Table 2.1). Projections from the fish habitat method one had an overall good agreement with cisco mortality and survival observations in 2006.

3. When the cisco habitat method two (Chapter 3) used constant lethal temperature $LT = 22.1$ °C and DO survival limit $DO_{Lethal} = 3$ mg/L, simulated cisco kill (lethal conditions) and having cisco habitat in 2006 had a better overall good agreement with observations in 23 lakes (18 lakes with perfect agreement and 4 lakes with partial agreement, Table 3.1).
4. When calibrated fish habitat model for the method one was applied, the 12 shallow virtual lakes with lake geometry ratio greater than $5.2 \text{ m}^{-0.5}$ had 10 to 16 years with many continuous lethal days during 17 simulation years (1992-2008) under past climate conditions (Bemidji, Minnesota) and are projected to have 16 to 17 years with cisco kill (Figure 2.8) under the MIRCO3.2 future climate scenario. Those shallow lakes projected to have continuous lethal conditions up to 94 days (Figure 2.10) are most likely not able to sustain cisco habitat. This finding supports that there are only 14 shallow lakes out of the 620 cisco lakes (MNDNR database) that cisco was presented or sampled.
5. Number of days with lethal conditions strongly depend on the strength of lake stratification (related to lake geometry ratio) and also have non-linear complex relationship with lake trophic status (represented by Secchi depth). When calibrated fish model for the method two (constant survival limits) was applied, the total number of years with cisco kill are 31–41 in northern shallow cisco lakes under the 48 year (1961-2008) past climate conditions. Under future MIROC 3.2 climate scenario, shallow cisco lakes are projected to have cisco kill in almost every year with an average of more than 30 kill days. Therefore, both the method one and two concluded that shallow lakes are not good candidates as cisco refuge lakes.

6. The 12 medium-depth lakes ($H_{max} = 13$ m) were simulated by the method one to have lethal conditions under both past climate conditions and the future climate scenario. It is projected that medium-depth lakes have the largest increase in the number of years with cisco kill (average increase 13 years ranging from 9 to 15 years out of 17 simulation years) due to climate warming. Therefore, cisco in the medium-depth lakes are most vulnerable to climate change. The method two (constant temperature and DO limits) also indicated that the total number of years with cisco kill are less than 13 in northern medium-depth cisco lakes under the past climate conditions and projected to have 25–47 years with cisco kill out of 48 simulation years (1662-2008) and on average 12–70 kill days.
7. Using the method one of FishHabitat2013, it was concluded that the four medium-depth lakes with $GR = 1.63 \text{ m}^{-0.5}$ behave differently in fish habitat projections than deep lakes with the same geometry ratio. Therefore, fish habitat projections in medium-depth lakes should be studied separately from deep lakes. This conclusion was successfully implemented for model applications of the method two of FishHabitat2013.
8. Most mesotrophic and oligotrophic deep lakes are possible good candidates for cisco refuge lakes that can support cisco habitat under both past climate conditions and the future climate scenario. Eutrophic deep lakes and large (surface area) mesotrophic deep lakes are projected to have cisco kills when continuous lethal days greater than 3 or 7 days are used to determine the occurrence of cisco kill. The 3 or 7 continuous lethal days for determining cisco kill give quite reasonable results for cisco kill simulations in all virtual lake types in Minnesota and are

- recommended for future fish habitat study. Using 14 continuous lethal days for determining cisco kill may be longer than how many lethal days would be needed for cisco mortality to occur and is not recommended for further fish habitat study.
9. Under future MIROC 3.2 climate scenario, only relatively eutrophic deep lakes (Secchi depth < 2 m) in northern and mid-latitude Minnesota and many southern lakes (Figure 12) have 5 or more years with cisco kill, and all other deep lakes are potential refuge lakes. Cisco kill parameters determined using the constant limit method cannot be used to classify 221 deep lakes into tiered refuge lakes.
 10. The 31-day bench mark period used in the methods three and four (Chapter 4 and Chapter 5) is the period of the year which cisco supposed to have the largest oxythermal stress. The average beginning dates of the variable benchmark periods during the simulation period (1961-2008) varied from July 21 to October 3 for 30 virtual deep cisco lakes, and were projected to change by up to 19 days under future climate scenarios. Compared with fixed bench mark period (July 28th to August 27th), variable bench mark periods work better to find the period of greatest oxythermal stress on cisco.
 11. The multi-year averages of annual 31-day TDO3s under variable benchmark periods, i.e., $AvgATDO3_{VB}$, ranged from 7.48 to 19.91 °C under past climate conditions and from 8.02 to 23.28 °C under two future climate scenarios for 30 virtual lakes (Table 4.7). The projected increases of $AvgATDO3_{VB}$ values from past climate to future scenarios were from 0.3 to 5.11 °C, and average increases were projected to be from 2.79 to 3.40 °C for two climate scenarios at three weather

stations (Table 4.8). Similar findings of AvgATDO3_{FB} were given in Table 5.2 and Table 5.3 for using the fixed bench mark period.

12. There are about one fourth to one third of all 620 cisco lakes that are classified as tier 1 (AvgATDO3 less than 11°C) and tier 2 refuge lakes under future climate scenarios (CGCM 3.1 and MIROC 3.2) by using variable and fixed bench mark period methods (Table 4.9 and Table 5.4).
13. Compared the simulation results with netting assessment or observations in 23 Minnesota lakes (18 with and 5 without cisco mortality in the unusually warm summer of 2006) both fixed and variable bench mark period methods showed good agreement with observations.
14. Under future MIROC3.2 climate scenario, the lake parameters for classified refuge lakes (tier 1 and tier 2) for both fixed and variable bench mark periods are listed as followings: Secchi depths are greater than 2.3 m; lake geometry ratios are less than $2.7 \text{ m}^{-0.5}$; and maximum depths are greater than 13.1 m (Table 4.10 and Table 5.5).

6.3 Future Directions

The total number of years with cisco lethal days and average cisco kill days for the years with lethal conditions under MIROC3.2 plotted against lake geometry ratio and Secchi depth (Figures 3.10, 3.11 and 3.12) were not used to divide 385 medium-depth and 221 deep cisco lakes into Tier 1 to Tier 3 refuge lakes as it was done using TDO3 (Fang et al. 2012b; Jiang et al. 2012). Several good-growth parameters, e.g., the good-growth period, good-growth habitat area (GGHA) and volume fraction (GGHVF), were derived when the fish model was run for these lakes but have not been analyzed. These good-growth habitat parameters used in previous studies (Stefan et al. 1996; Stefan et al. 2001;

Fang et al. 2004a) may be used to classify cisco lakes into tiered refuge lakes in a future study.

Jacobson et al. (2010) developed central species response borders of TDO3 derived from measured T and DO profiles for lake trout, lake whitefish, and burbot. The method developed to rank the quality of fish habitat for cisco in Minnesota lakes was presented as a flowchart in

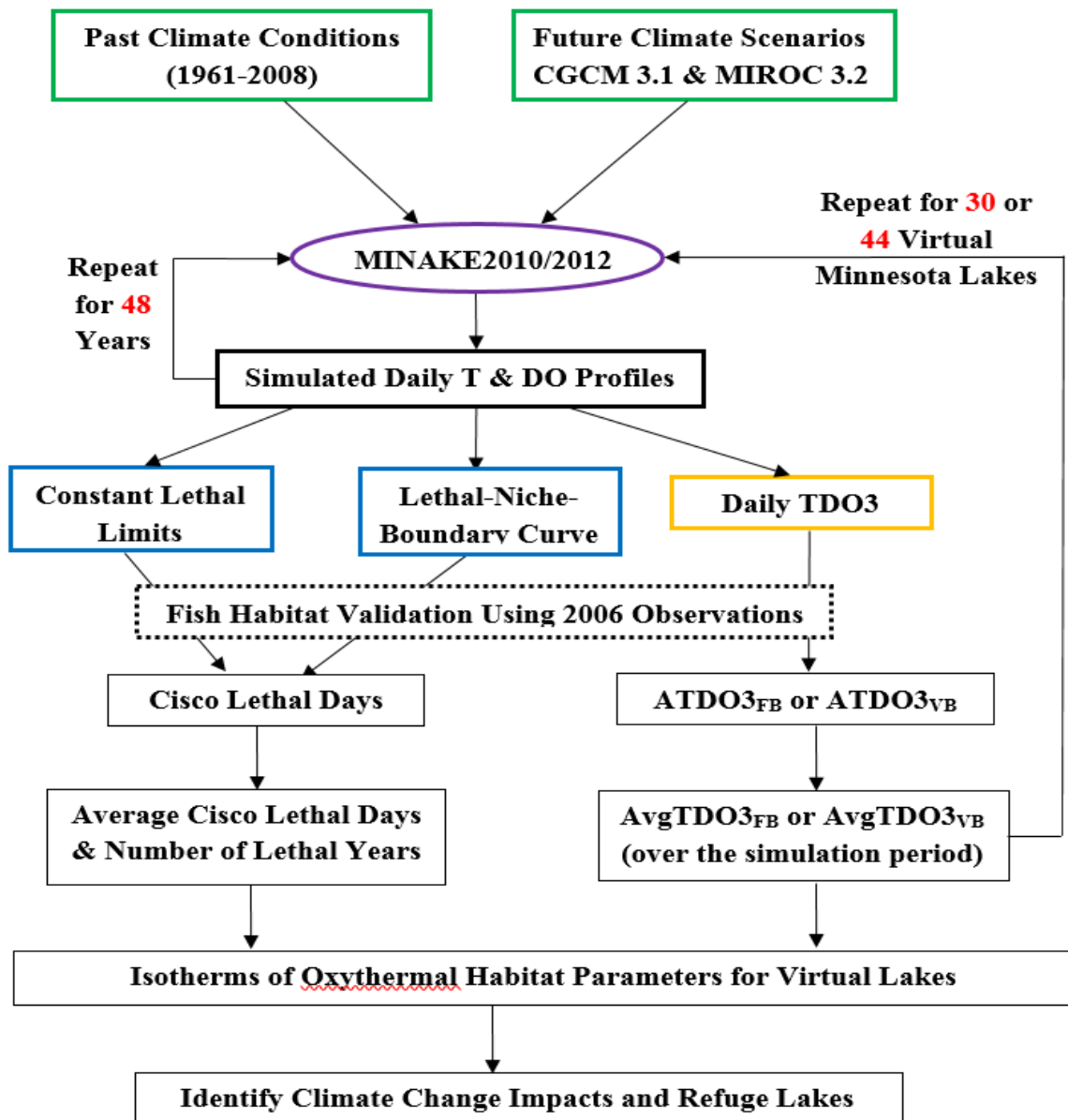


Figure 1.3 and can be applied for other cold-water fish species and at other geographic locations. The next future study could be to use the same methodology developed in this study to identify refuge lakes for lake trout in Minnesota. Lake trout were present in lakes with the lowest values of maxTDO3 and represented by central species response borders of maxTDO3 from 4.0 to 5.1 °C (Jacobson et al. 2010). It will be interesting and valuable to use the method to identify cisco refuge lakes in Wisconsin, which can be directly compared with results from Sharma et al. (2011). Requirements for the study include a database of cisco lakes in Wisconsin, observed T and DO profiles in several cisco lakes for further model validation, and historical weather data at representative locations in Wisconsin.

Although variable benchmark periods can more accurately quantify the maximum oxythermal stress to a fish species, using the fixed benchmark period to determine average TDO3 is useful and valuable because the cold-water fish niche model developed by Jacobson et al. (2010) defines boundaries (i.e., 11 °C and 17 °C tier thresholds) for identifying refuge lakes, and these boundaries were based on the fixed benchmark period. To fully use a variable benchmark model, it is necessary to redo the niche model with variable benchmark periods in the future research.

Comparing Figure 3.12 with Figure 3.10 and Figure 3.11, one can see that cisco kill parameters have a huge decrease from 13 m medium-depth lakes to 24 m deep lakes under future climate scenario, e.g., 37–47 years to zero years ($Z_s > 2$ m) with cisco kill in northern Minnesota lakes. Because of non-linear complex relationship between lethal condition and lake characteristics (Figure 3.9), lethal conditions and potential cisco kills in lakes with other maximum depths, e.g., $H_{max} = 18$ m, are currently unknown and should be studied

further in the future. We can propose that lakes with $H_{max} = 13$ m represent lakes with H_{max} between 11 to 15 m, lakes with $H_{max} = 18$ m represent lakes with H_{max} between 15 to 21 m (Table 6.1), and lakes with $H_{max} = 24$ m represent deep lakes with $H_{max} > 21$ m for future study.

Table 6.1 Morphometric characteristics and “names” of the 30 virtual medium-deep cisco lakes (maximum lake depth $H_{max} = 18$ m).

Surface Area A_s (km ²)	Secchi Depth SD (m)					Geometry Ratio, GR = $A_s^{0.25}/H_{max}$
	1.2	2.5	4.5	7.0	8.5	
0.1	LakeM01	LakeM02	LakeM03	LakeM04	LakeM05	0.99
0.5	LakeM06	LakeM07	LakeM08	LakeM09	LakeM10	1.48
1.5	LakeM11	LakeM12	LakeM13	LakeM14	LakeM15	1.94
5.0	LakeM16	LakeM17	LakeM18	LakeM19	LakeM20	2.63
13.0	LakeM21	LakeM22	LakeM23	LakeM24	LakeM25	3.34
50.0	LakeM26	LakeM27	LakeM28	LakeM29	LakeM30	4.67

Appendix A **Review of Lake Water Quality Models**

Lake water quality can be affected by so many factors, such as temperature, DO, nutrients, contaminant, and so on. The following is a brief overview of some of the existing lake water quality models which were developed for different purposes. Some of the models are used for water temperature simulation. Others may focus on specific problems, like water pollution.

Computer models can be classified based on different criteria: stochastic or deterministic; steady-state or dynamic; continuous or discrete; time step, and dimensionality. The water quality models described here are grouped by their dimensionality.

A.1 One-Dimensional Models

All one-dimensional models assume a lake can be represented by a vertical series of well-mixed horizontal layers. The one-dimensional approximation is valid when the forces acting to destabilize a water body (wind stress, surface cooling or plunging inflows) do not act over prolonged periods of time. The limitations associated with this assumption are: longitudinal and lateral variations in water quality constituents cannot be predicted; all inflow quantities and constituents are instantaneously dispersed throughout the horizontal layers.

A.1.1 MINLAKE2010

MINLAKE2010 (Fang et al. 2004c) is a one-dimensional, process-oriented, unsteady, lake water quality model which simulates daily water temperature and DO profiles as well as ice/snow covers on lakes in a continuous mode for multiple years. The one-dimensional heat transfer and DO transport equations were solved numerically for time steps of one-day and layer thickness of one-meter using an implicit finite difference scheme and a Gaussian elimination method.

A.1.2 Flake

Flake (Mironov 2008) can be used to simulate vertical lake water temperature on time scales from several hours to many years. It divided lake into two layers, the upper layer is well-mixed. Self-similarity method is used to describe the temperature-depth curve. The effect of both lake bottom sediment and ice/snow cover are considered in this model. Water temperature, mixed layer depth, ice thickness, water-sediment heat flux, surface fluxes can be reported.

A.1.3 CE-QUAL-R1

CE-QUAL-R1 (USACE 1995) is a dynamic, one-dimensional model for vertical water quality simulation in lakes and reservoirs. Reservoirs or lakes are divided into several horizontal layers, each layer is assumed well mixed. Inflows and outflows are added directly to or removed directly from the appropriate layers. Layer thicknesses are variable based on the inflowing and outflowing waters. The model deals with physical, chemical, and biological processes. Water quality addressed includes thermal stratification, anoxic conditions, algal bloom, and so on. The model does not contain ice and snow cover algorithm.

A.1.4 DYRESM

DYRESM (DYnamic REservoir Simulation Model) is a one-dimensional hydrodynamic model for predicting the vertical distribution of temperature, density, salinity in lakes and reservoirs (Imberger and Patterson 1981). It can be run for purely hydrodynamic studies or coupled to CAEDYM (Computational Aquatic Ecosystem Dynamics Model) to investigate the biological and/or chemical processes (Trolle et al. 2008). DYRESM has been used for simulation periods extending from weeks to decades.

A.1.5 Hostetler

Hostetler model simulates the vertical temperature profiles by dividing lake into different horizontal layers including snow/ice, but the model assumes zero heat flux at the lake bottom (Hostetler 1991). Heat and radiation fluxes are calculated between atmosphere and water surface.

A.1.6 SimStrat

SimStrat simulates vertical temperature profiles in water body. The sources of turbulent kinetic energy (TKE) are wind and buoyancy (Goudsmit et al. 2002). The TKE induced by seiche motion is included in SimStrat model.

A.2 Two-Dimensional Models

A two-dimensional model for a deep lake or reservoir assumes laterally well mixed and focus on the concentration gradients of vertical and longitudinal directions. For large shallow water bodies, two-dimensional models assume well mixed along depth.

A.2.1 CE-QUAL-W2

CE-QUAL-W2 (Cole and Buchak 1995) is a two-dimensional, laterally averaged, hydrodynamic and water quality model for rivers, estuaries, lakes, reservoirs and river basin systems. W2 was developed by the United States Army Corps of Engineers Waterways Experiment Station (USACE-WES). It is suitable for relatively long and narrow water bodies (Cole and Buchak 1995). The model can be used to predict water surface elevations, velocities, temperatures, dissolved oxygen (DO), nutrients, phytoplankton, ice cover (onset, growth, and breakthrough), and so on. Inflow and outflow are considered in this model, whereas regional MINLAKE model doesn't consider. One limitation of CE-QUAL-W2 is the lack of consideration of heat transfer at the sediment-water interface. W2 employs a finite difference solution of a set of six equations for hydrodynamics and constituent transport. The unknown parameters for the six

equations are the free water surface elevation, pressure, horizontal velocity, vertical velocity, constituent concentrations, and density (Cole and Wells 2002).

A.2.2 RMA-2

RMA-2 is a two-dimensional, depth averaged, FEM (finite element method) based, hydrodynamic model which can simulate water surface elevation and horizontal velocity for free surface flow (King 1994).

A.2.3 WASP

WASP (Water Quality Analysis Simulation Program) can predict the water quality in response to natural phenomena and manmade pollution. 1-D, 2-D, and 3-D system can be accessed by users. Pollutant types considered in this model are nitrogen, phosphorus, dissolved oxygen, BOD, sediment oxygen demand, algae, organic chemicals, metals, mercury, and temperature (Ambrose et al. 1993)

A.3 Three-Dimensional Models

Three-dimensional models are used to simulate the most complicated water quality manage issues.

A.3.1 EFDC

EFDC (Environmental Fluid Dynamics Code) model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid (Craig 2012). The model uses a stretched or sigma vertical coordinate and Cartesian or curvilinear, orthogonal horizontal coordinates. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The equations of motion are solved using second order accurate spatial finite difference on a staggered or C grid. EFDC can be linked with WASP (water quality analysis simulation program).

A.3.2 Mike 3

Mike 3 (http://smig.usgs.gov/cgi-bin/SMIC/model_home_pages/model_home?selection=mike3) is a three-dimensional model simulating flows, cohesive sediments, water quality and ecology in rivers, lakes, estuaries, bays, coasts and seas. Its applications include hydrographic conditions assessment for design, coastal sediment dynamics, Lake Hydrodynamics and ecology, coastal restoration and so on (Cesana and Siwek 2001).

A.3.3 Delft3D

Delft3D is a three-dimensional model which can be used to simulate flows, sediment transports, waves, water quality, morphological developments and ecology for coastal, river, lake and estuarine areas (Hydraulics 1999).

A.3.4 UnTRIM

In UnTRIM, three-dimensional Reynolds-averaged Navier-Stokes equations are solved on an unstructured grid in the horizontal plane (MacWilliams et al. 2007). The boundaries between vertical layers are at fixed elevations, and cell heights can be varied vertically to provide increased resolution near the surface or other vertical locations. Volume conservation is satisfied by a volume integration of the incompressible continuity equation, and the free-surface is calculated by integrating the continuity equation over the depth and using a kinematic condition at the free-surface. The governing equations are discretized using a finite difference – finite volume algorithm. The numerical method allows full wetting and drying of cells in the vertical and horizontal directions.

A.4 Other Models

Lake Orta model deals with copper contamination. Baikal Model includes the impacts by toxic chemical. Lake Ecosystem assesses the tradeoff between increasing model complexity and

collecting data of quality or quantity. Lake model Lavsoe focus on the seasonal description of the algal growth, water transparency and the cycling of phosphorus and nitrogen (Halling-Sørensen and Nielsen 1996).

A.5 Summary

All models described above have different simplifications, applications and limitations. Model selection is greatly affected by the specific research questions, such as water body (lake, reservoir, and ocean), water body morphology (depth, fetch, surface area), climate conditions (wind, temperature, ice/snow), inflow and outflow factors, and so on.

A.6 Reasons of choosing MINLAKE2010/2012

My study deals with fish habitat prediction in more than 600 lakes in Minnesota under future climate warming conditions; the model was supposed to run for a long period of time, i.e., several decades. I chose MINLAKE2010/2012 among many existing lake water quality models for several reasons.

1) MINLAKE2010/2012 was specifically developed to study climate impacts on water quality and fish habitat in small lakes in the temperate region of North America. The model (from MINLAKE96 to MINLAKE2010) had been extensively tested using observed water temperature and DO profiles in summer and winter, and snow and ice thickness during the winter ice-cover period.

2). MINLAKE2010/2012 is regional lake water quality model that requires very limited amount of input data but still reasonably and accurately predict lake stratification and temperature and DO dynamics over the season year by year in order to predict fish habitat. Most of other models reviewed above require much more input data for regional lake studies. For example, two and

three-dimensional models require bottom elevation changes of the study lake, but for many of cisco study lakes we only know the surface area and maximum depth.

2) Cisco lakes in Minnesota are mostly mesotrophic and oligotrophic lakes and relative deep lakes. MINLAKE2010/2012 was developed and enhanced from MINLAKE96 for simulating temperature and DO profiles in deep mesotrophic and oligotrophic lake after including additional model calibration parameters.

3) Many small lakes in Minnesota are more or less isolated without much inflows and outflows or typical water surface elevations do not vary much over years. Simplified regional temperature and DO model without inflow and outflow, i.e., MINLAKE2010/2012, is suitable for study.

4) All study lakes are freshwater lakes, salinity doesn't need to be considered and simulated.

5) Snow and ice covers are simulated in MINLAKE2010/2012, so that the year-round which makes it can predict both temperature and DO for continuous study years.

6) MINLAKE is the lake model deals with the impacts of future climate warming on lake water quality that uses/reads three future climate scenario datasets.

7) The heat exchange between water and sediment is important for not only shallow lakes but also the shallow depth region of a deep lake. MINLAKE96 and MINLAKE2010 include sediment heat exchange for all water layers, but none of other 1-D lake models does include heat exchange through all the layers.

9) Both temperature and DO can be simulated at the same time in MINLAKE with minimum requirement of input data, but other models either cannot simulate temperature and DO at the same time or require much more input data that are unavailable for 600 cisco lakes.

10) We chose one-dimensional model for this study because of the large number of study lakes and long study period (48 years), even though two-dimensional and three-dimensional models are more accuracy than one-dimensional models but the computing time is much longer.

Appendix B **Review of Fish Habitat Model**

There are so many factors which can influence the aquatic ecosystems, such as water depth, velocity, bathymetry, substrate, water temperature, dissolved oxygen, pH, turbidity, light penetration, pollutant transport, sediment transport, vegetation, food resources, and so on. Human activities, such as urbanization, power generation, waste water treatment, agriculture, industrialization, and so on, which make it necessary to develop management tools to analyze and predict the aquatic habitat quality. Fish habitat model is mostly based on analyzing the hydraulic, hydrological, chemical, morphological, and biochemical variables which affect the distribution of species in aquatic ecosystems. A few fish habitat models are reviewed and summarized below.

A.7 PHABSIM (1-D)

PHABSIM (Physical Habitat Simulation System), software distributed by the US. Geological Survey Fort Collins Science Center, can predict the fish habitat through analyzing the flow rate and depth in rivers (Waddle 2012). Parallel streamlines assumption is used in this model. PHABSIM can give quantitative prediction of suitable fish habitat under different flow scenarios (Milhous et al. 1989). The limitation is that it only addresses the effect of flow and neglects other factors such as water temperature.

A.8 CCHE2D

CCHE2D, a two- dimensional, FVM (finite volume method) based model, can be used to predict the flow, sediment transport, heat transport, pollutant transport, water quality, and ecology

in aquatic systems (Wu et al. 2005). PHABSIM concept is used in its habitat module. CCHE2D has been used to analyze fish habitat in several rivers (Wu et al. 2006).

A.9 River2D

River2D (available at <http://www.river2d.ualberta.ca/>), developed by the University of Alberta, is a two dimensional, depth averaged, GUI (Graphical user interfaces), hydrodynamic model which can be used for fish habitat evaluation studies. The model contains four parts: R2D_Bed, R2D_Ice, R2D_Mesh and River2D. Bed topography, ice topography, and computational meshes, used as input of River2D, are developed by R2D_Bed, R2D_Ice, R2D_Mesh, respectively. River2D is then used to simulate water depths and velocities. The results can be used to perform PHABSIM (Physical Habitat Simulation System) fish habitat analyses.

A.10 Fish Bioenergetics 3.0

Fish Bioenergetics 3.0, also known as the Wisconsin Model, is a bioenergetics model. Physiology of species is used to determine the effect of environmental changes on fish populations (Hartman and Kitchell 2008).

A.11 CASIMIR

CASIMIR (Computer Aided Simulation Model for Instream Flow Requirements) is used mainly in Europe (Mouton et al. 2007). It can be linked to HYDRO_AS-2D or GIS to get the fish maps and habitat distribution.

A.12 Other models

GIS (geographical information system), as a useful tool, can be used in fish habitat analysis through analyzing land-cover variables (trees, pasture) and stream condition variables (flow, stream size, slope, bed condition) in the study areas (Wall et al. 2004). There are models focus only on the trophic status of lakes/ rivers, such as NPZD (Fennel 1999).

A.13 Reasons to choose MINLAKE2010 FishHabitat model

The reasons of choosing MINLAKE2010 FishHabitat model are list as follows:

- 1) MINLAKE2010 FishHabitat model was designed to analyze the temperature and DO simulation results given by MINLAKE2010.
- 2) LGGT (lower good-growth temperature limit), UGGT (upper good-growth temperature limit), LT (lethal temperature) and TDO3 (water temperature at 3mg/L of DO), the most important oxythermal habitat variables related to different study methods of analyzing fish habitat in our study, can be determined from daily temperature and DO profiles by MINLAKE2010 FishHabitat model.
- 3) Most existing fish habitat models were developed to predict the suitable habitat either in certain locations along the river/channel or in different vertical locations in rivers/lakes/channels. MINLAKE2010 FishHabitat model were designed to predict the most suitable lakes among more than 600 study lakes in Minnesota under global climate warming, which cannot pursued by the other models.
- 4) Most of the time, fish habitat models need to be linked to specific hydraulic models to predict the suitable habitat. MINLAKE2010 FishHabitat was designed specifically to link to MINLAKE2010.

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