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# **Simulations of Cisco Fish Habitat in Minnesota Lakes under Future Climate Scenarios**

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## Abstract

This report makes projections of potential (refuge) habitat for cisco, a coldwater fish, in Minnesota lakes under projected warmer climate scenarios. It is about the identification and selection of potential refuge lakes for cisco under future climate scenarios in Minnesota. This is the third and final project report in a series that describes computer model simulations of cisco (tullibee) lakes for the Minnesota Department of Natural Resources (DNR). The first report gave an overview of the characteristics of cisco lakes in Minnesota, the second gave results of water quality (temperature and dissolved oxygen, DO) model simulations for selected Minnesota cisco lakes, and this third report identifies and quantifies in which Minnesota lakes cisco habitat is most likely to continue to exist under global warming scenarios.

Cisco habitat simulations were first made for continuous, year-round weather time series from 1962 to 2008 (47 years) at the daily time scale. Simulations were then extended to projected future climate scenarios. A year-round water quality model MINLAKE 2010, that had previously been calibrated against 7384 pairs of temperature and DO data points measured in 28 lakes between 1979 and 2008 with overall standard errors of 1.47 °C for water temperature, and 1.50 mg/L for DO, was used in all cisco habitat simulations (Fang et al. 2010).

Adult cisco habitat is limited by critical water temperature and DO conditions in different strata of a cisco lake. The selection was based on the oxythermal parameter TDO3, which relates to the survival stress of adult cisco. The lower the TDO3 is, the lower the stress is to cisco. TDO3 is a water temperature that occurs where DO = 3 mg/L and was used as the oxythermal parameter to select suitable habitat for adult cisco (Jacobson et al. 2010). Twelve TDO3 parameters ranging from single-day values to multi-year averages, and from extreme values to mean values, were defined in Table 3.1 and calculated from simulated daily temperature and DO profiles. The multi-year values AvgATDO3<sub>FB</sub> and AvgATDO3<sub>VB</sub> were ultimately chosen from Table 3.1, lines 6 and 12, for the selection of cisco refuge lakes. Each of these two TDO3 parameters is calculated over the length of a 31-day benchmark period; one uses a fixed benchmark period from DOY 209 to DOY 239 (July 28 to August 27); the other uses a variable (sliding) benchmark period of 31 days.

In this report time-series of the TDO3 parameters and ranges of TDO3 parameter values in selected lakes are analyzed. The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to 2008 were used. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles and associated AvgTDO3<sub>FB</sub> and AvgTDO3<sub>VB</sub> for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes.

One associated weather station had to be selected for the simulation of each lake, but data from only three Class I NWS weather stations were useful and available. Three options (methods) were used to pair each lake with one of the three weather stations: (1) by shortest

distance, (2) by latitude, (3) one single weather station for all lakes simulated. Refuge lakes were determined using each of the three options.

The pool of 620 Minnesota cisco lakes was divided into three tiers. Tier 1 for a TDO3  $\leq 11^{\circ}\text{C}$ , Tier 2 for the range  $11^{\circ}\text{C} < \text{TDO3} \leq 17^{\circ}\text{C}$ , and Tier 3 for  $\text{TDO3} > 17^{\circ}\text{C}$ . Tier 1 and Tier 2 were identified as cisco refuge lakes, Tier 3 as non-refuge lakes for cisco. This decision was based on Jacobson et al. (2010). Tier 1 lakes have the most suitable coldwater fish habitat, Tier 2 lakes have a suitable coldwater fish habitat, and Tier 3 lakes are marginal or unsuitable for cisco. Tier 1 and Tier 2 refuge lakes identified may be called viable cisco lakes where cisco is capable of living, developing, or spawning under favorable conditions. Cisco can still persist in lakes with TDO3 values greater than  $17^{\circ}\text{C}$  but at a reduced probability of occurrence.

Results are presented in tables and in graphical form as isolines of TDO3-values in a diagram of Secchi depth (as an indicator of lake trophic state) vs. lake geometry ratio (as an indicator of lake stratification and mixing dynamics). These contour plots of selected TDO3 parameters were interpolated from data points for 21 cisco study lakes and 30 virtual cisco lakes for both past and two future climate scenarios. Cisco refuge lakes in Minnesota were selected based on limiting values or TDO3-criteria for two future climate scenarios: CGCM 3.1 and MIROC 3.2 (IPCC DDC 2010).

The number of lakes that qualify as cisco refuge lakes depends, of course, on the assumptions and choices made in the method of selection and the climate scenarios. Of the 16 study lakes with adult cisco mortality in 2006, none was identified as a Tier 1 refuge lakes by any of the five methods. All five reference lakes that did not experience adult cisco mortality in 2006, were identified as either Tier 1 or Tier 2 refuge lakes by all of the five methods (Table 5.14). These are remarkable agreements between model predictions of refuge lakes and observed adult cisco mortality events in 2006.

The number of Tier 1 and Tier 2 cisco refuge lakes determined for the future climate scenario MIROC 3.2, varies depending on the selection method used (Tables 5.3 to 5.12). Although the numbers are different, the individual lakes identified by name in Tier 1 or Tier 2 of each of the Tables overlap strongly. Therefore, refuge lakes were listed by name and geographic coordinates in Table 5.16 for Tier 1 and Table E.1 (Appendix E) for Tier 1 plus Tier 2. They are ordered by the number of times that they were found by multiple methods. Lakes that appear most often are on top of the list. These two lists give recommended cisco refuge lakes independent of method used for their determination. The lakes on the list have been plotted on a map of Minnesota in Figures 5.22 and 5.23.

Ultimately 620 cisco lakes in Minnesota were listed by name and location from the most likely refuge lake to the least likely (Tables F.1 and G.1 in Appendixes F and G). Most are located in northeastern Minnesota. A frequency analysis of lake characteristic parameters for the selected refuge lakes was conducted. The results indicate that refuge lakes (Tier 1 plus Tier 2) selected under the future climate scenario MIROC 3.2 have Secchi depths greater than  $\approx 2.5$  m (Fig. 5.18), lake geometry ratio less than  $\approx 2.5 \text{ m}^{-0.5}$  (Fig. 5.19), maximum depths greater than  $\approx 15$  m (Fig. 5.20), and surface area less than  $\approx 30 \text{ km}^2$  (Fig. 5.21).

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## Chapter 1 Introduction

Freshwater fish habitat is constrained by several physical and biological parameters that relate to water quality, food supply, and human interference. Channel geometry and streamflow are important to fish habitat in streams (Rundquist and Baldrige 1990). In lakes, water temperature and dissolved oxygen (DO) concentrations are two of the most significant water quality parameters affecting survival and growth of fishes (Fry 1971; Magnuson et al. 1979; Coutant 1985, 1987; Christie and Regier 1988). Climate warming has the potential to reduce coldwater 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. 2004). Cisco is the most common coldwater stenothermal fish in Minnesota lakes. The Minnesota Department of Natural Resources (MN DNR) has sampled cisco from 648 lakes in netting assessments since 1946 (Minnesota DNR files). The lakes are scattered throughout much of the central and northern portions of the state and cross several ecoregions (boreal forest, hardwood forest, and prairie) and land uses (agricultural, urban, and forested). The wide distribution suggests that cisco are somewhat more eurythermal than other native, lentic coldwater stenotherms such as lake whitefish *Coregonus clupeaformis* (sampled in 155 lakes), lake trout *Salvelinus namaycush* (124 lakes) and burbot *Lota lota* (233 lakes). The combination of a wide distribution and a requirement for cold, oxygenated water, make cisco an excellent “canary in a mineshaft” species that is a sensitive indicator of climate change.

This report is the third in a series of three reports that describe model simulations of cisco (tullibee) lakes for the Minnesota Department of Natural Resources. In anticipation of possible future climate warming, possible cisco refuge lakes in Minnesota are identified in this report.

As discussed in Project Report 2 (Fang et al. 2010) of this study, 15 study lakes were selected in the first phase of this study for model calibration of the MINLAKE 2010 model that was used to simulate daily temperature and dissolved oxygen (DO) profiles and associated cisco habitat in Minnesota lakes. Eight of the 15 selected study lakes were known to have cisco-habitat, and seven were non-cisco lakes.

In the second phase of the study an additional 13 cisco-habitat lakes were chosen for additional model calibration. To identify cisco refuge lakes (Chapters 3 and 4), MINLAKE2010 simulation results for 21 cisco-habitat lakes (8 cisco lakes selected at the first phase and 13 cisco lakes selected at the second phase) were used.

### 1.1 Two approaches to evaluate cisco habitat

In this study, two approaches were explored to determine if cisco habitat existed in a Minnesota lake. The first approach was to determine whether or not cisco can survive in a lake based on separate dissolved oxygen (DO) and water temperature constraints; this approach had previously been used to examine the potential impact of future climate warming on cold-, cool-,

and warm-water fish species (guilds) in small lakes in the contiguous United States (Stefan et al. 2001). If cisco cannot survive under certain environmental conditions, it is assumed that fish kill occurs in a lake. The term “fish kill” is applied to a localized die-off of fish populations which may also be associated with more generalized mortality of aquatic life (Wikipedia 2010). According to Wikipedia fish kill may have a variety of causes including drought, disease, oil or chemical spill, hazardous waste spill, ecological hypoxia caused by sewage or organic matter such as leachate or silage liquor, algae blooms, seaquakes, unusual weather conditions, inappropriate re-stocking of fish, underwater explosions, and other catastrophic events that can perturb a normally stable aquatic population. Figure 1.1 shows a cisco killed in a Minnesota lake in July 2006 when unusual warm weather resulted in unfavorable environment conditions in the lake so that cisco could not survive. In this study thermal DO habitat of cisco was determined in 15 study lakes; this means that observed or projected water temperature and DO were compared separately to requirements for fish survival. This is called “fish kill” approach. The fish kill in this case is only due to unfavorable temperature (thermal) and/or DO conditions but not due to other factors listed above. Background information and results of the fish kill approach are given in Appendix A of the report.



Figure 1.1 A cisco kill event: picture of a dead cisco fish taken from a Minnesota lake during the summer of 2006.

The second approach is to use a single oxythermal habitat variable to define suitable or unsuitable fish habitat. Jacobson et al. (2010) studied coldwater fish oxythermal habitat in Minnesota lakes. They used a generalized oxythermal habitat variable, TDO3, called “temperature at 3.0 mg/L DO” and determined by interpolating the water temperature at a benchmark oxygen concentration (i.e., 3.0 mg/L) from vertical temperature and DO profiles in a

lake. DO = 3 mg/L is an oxygen concentration limit that is probably lethal or nearly so for many coldwater species (Frey 1955; US EPA 1986; Evans 2007). They found that TDO3 has a strong connection with four coldwater taxa (lake trout, cisco, whitefish, and burbot). Cisco were present in lakes with a broad range of maximum TDO3 values, with central borders of 4.0 to 16.9 °C (Jacobson et al. 2010). TDO3 allows to evaluate or quantify which lake has better environmental conditions to support cisco habitat, or to determine which lake is a better refuge lake for cisco under a future climate scenario. This second approach is called “TDO3 approach” in this study.

## 1.2 Twenty-one cisco study lakes and thirty virtual cisco lakes

In previous studies, 27 regional lake classes or types were used to study cold-, cool- and warm-water fish habitat under past and future climate scenarios (Stefan et al., 1996; Stefan et al. 2001, Fang et al. 2004). For the previous lake classification, lake surface areas  $A_s$  chosen were 0.2, 1.7 and 10.0 km<sup>2</sup> for small, medium, and large lakes, respectively; maximum depths  $H_{max}$  chosen were 4.0, 13.0 and 24.0 m for shallow, medium-depth, and deep lakes, respectively (Stefan et al. 1992). Secchi depths (SD) of 1.2, 2.5, and 4.5 m were selected for eutrophic, mesotrophic, and oligotrophic lakes using Carlson’s trophic state index (Carlson 1977), respectively. More important than the individual numbers, is the observation that the likelihood of a strong or weak stratification in a lake can be related to the lake geometry ratio,  $GR = A_s^{0.25}/H_{max}$  (Gorham and Boyce 1989). The above nine (9) types of lakes cover geometry ratios from 0.9 to 14.1. According to Gorham and Boyce (1989) polymictic lakes have the highest numbers, while strongly stratified dimictic lakes occur at the lowest numbers. The transition occurs between 3 and 5. Hence, the full range of stratification behavior is included in the 27 lake types.

In the first of our three project reports (Fang et al 2009), we determined that 620 documented cisco lakes in Minnesota are relative deep mesotrophic or oligotrophic lakes. Twenty-one (21) cisco lakes were selected as study lakes because they had measured water temperature and DO profiles that could be used for model calibration of MINLAKE2010. Table 1.1 lists characteristics of these 21 cisco study lakes. The calibrated MINLAKE2010 model, discussed and summarized in project report 2 (Fang et al. 2010), generated simulated daily water temperature and DO profiles from which the oxythermal parameter TDO3 could be extracted. Figure 1.2 shows the distribution of the 21 study lakes and the 620 cisco lakes in Minnesota on a plot of Secchi Depth, SD, (m) versus Lake Geometry Ratio, GR, (m<sup>-0.5</sup>). It can be seen that the 21 cisco study lakes are not well distributed on the plot, and this may create a problem when contour maps of TDO3 parameters are developed from point values, which will be demonstrated and discussed in Chapter 4.

The highest SD value used in previous studies of regional lakes was 4.5 m. For this cisco lakes study higher SD values and lower GR values are required to fill the gaps in Figure 1.2. Therefore, a new set of virtual cisco lakes with SD values ranging from 1.2 m to 8.5 m and GR values ranging from 0.74 to 3.5 m<sup>-0.5</sup> was introduced and used. The set of virtual cisco lakes includes 30 different types of lake (named LakeC01 to LakeC30; the letter “C” stands for “cisco”

to distinguish the set from the previous lake types named Lake01 to Lake27). The set of 30 virtual cisco lakes 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 km<sup>2</sup>, 0.5 km<sup>2</sup>, 1.5 km<sup>2</sup>, 5.5 km<sup>2</sup>, 13.5 km<sup>2</sup>, and 15.5 km<sup>2</sup>). The maximum depth of all 30 virtual lakes is set at 24 m, because cisco lakes are relatively deep (see Project Report 1; Fang et al. 2009). Combinations of the maximum depth and surface areas give six different geometry ratios for the 30 virtual lakes, i.e. 0.74 m<sup>-0.5</sup>, 1.11 m<sup>-0.5</sup>, 1.36 m<sup>-0.5</sup>, 1.97 m<sup>-0.5</sup>, 2.50 m<sup>-0.5</sup>, and 3.50 m<sup>-0.5</sup>. These and other characteristics of the 30 virtual cisco lakes (or lake classes) used in this study are summarized in Table 1.2.

Table 1.1 Characteristics of the 21 cisco study lakes used for MINLAKE2010 model calibration. These lakes have measured water temperature and DO profiles.

Lake	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry Ratio (m <sup>-0.5</sup> )	Mean Secchi depth (m)	Mean chlorophyll a (mg/L)	Trophic status <sup>1</sup>
Big Trout	5.43	39.01	1.24	4.78	0.00336	O
Blue	0.71	14.63	2.04	6.76	0.00280	O
Burntside	28.90	38.40	1.91	5.80	0.00286	O
Carlos	10.20	50.00	1.13	3.27	0.00500	M
Cedar	0.98	26.80	1.17	3.56	0.00480	M
Elk	1.10	28.00	1.16	2.57	0.00480	M
Fish Hook	6.61	23.16	2.19	3.44	0.00400	M
Greenwood	8.18	34.14	1.57	5.46	0.00255	O
Grindstone	2.13	46.63	0.82	2.88	0.00637	M
Kabekona	9.12	41.00	1.34	4.03	0.00320	M
Little Sand	1.56	24.38	1.45	5.22	0.00231	O
Little Trout	0.97	28.95	1.08	6.33	0.00073	O
Mukooda	3.05	23.77	1.76	5.12	0.00115	O
Siseebakwet	5.29	32.00	1.5	3.89	0.00205	M
Six	0.76	42.67	0.69	3.94	0.00445	M
Snowbank	17.30	45.72	1.41	5.28	0.00271	O
South Twin	4.52	8.80	5.22	2.78	0.00340	M
Ten Mile	18.90	63.00	1.05	5.54	0.00250	O
Trout (Cook)	1.04	23.00	1.39	5.40	0.00140	O
Trout (St. Louis)	30.94	29.87	2.50	4.71	0.00247	O
White Iron	13.88	14.30	4.26	1.44	0.00520	E

<sup>1</sup> E = Eutrophic, M = Mesotrophic, O = Oligotrophic.

Even though the selection of lake bathymetry (surface areas and maximum depth) and Secchi depth for the 30 virtual cisco lakes was subjective, the selected values are representative

of the 620 Minnesota cisco lake database. Figure 1.3 gives the cumulative distributions of lake surface area, geometry ratio and Secchi depth for all 620 cisco lakes in the Minnesota DNR database, as well as for the 30 virtual cisco lakes. Table 1.3 gives cumulative distributions (% less than) and classifications of lake surface area, geometry ration, and Secchi depth for the 30 virtual lakes in comparison to all 620 cisco lakes in the MN DNR database. The 30 virtual cisco lakes are all stratified lakes based on geometry ratio, they cover small to large surface areas and include eutrophic to oligotrophic lakes (Table 1.3). It can be seen that the 30 virtual lakes match the actual 620 lakes well.

Figure 1.2 shows the distribution of the 30 virtual cisco lakes on the plot of SD versus GR as well as the distributions of the 21 cisco study lakes used for model calibration and the 620 cisco lakes in the Minnesota DNR database. The 30 virtual cisco lakes cover the domain of the 620 real cisco lakes more completely than the 21 cisco study lakes in Fig. 1.2. That is the reason why virtual lakes were selected and used in the study. Besides, Secchi depths used to plot the 21 cisco study lakes are the summer average values for the years when temperature and DO profiles were measured, whereas the Secchi depths in the MN DNR database may be different.

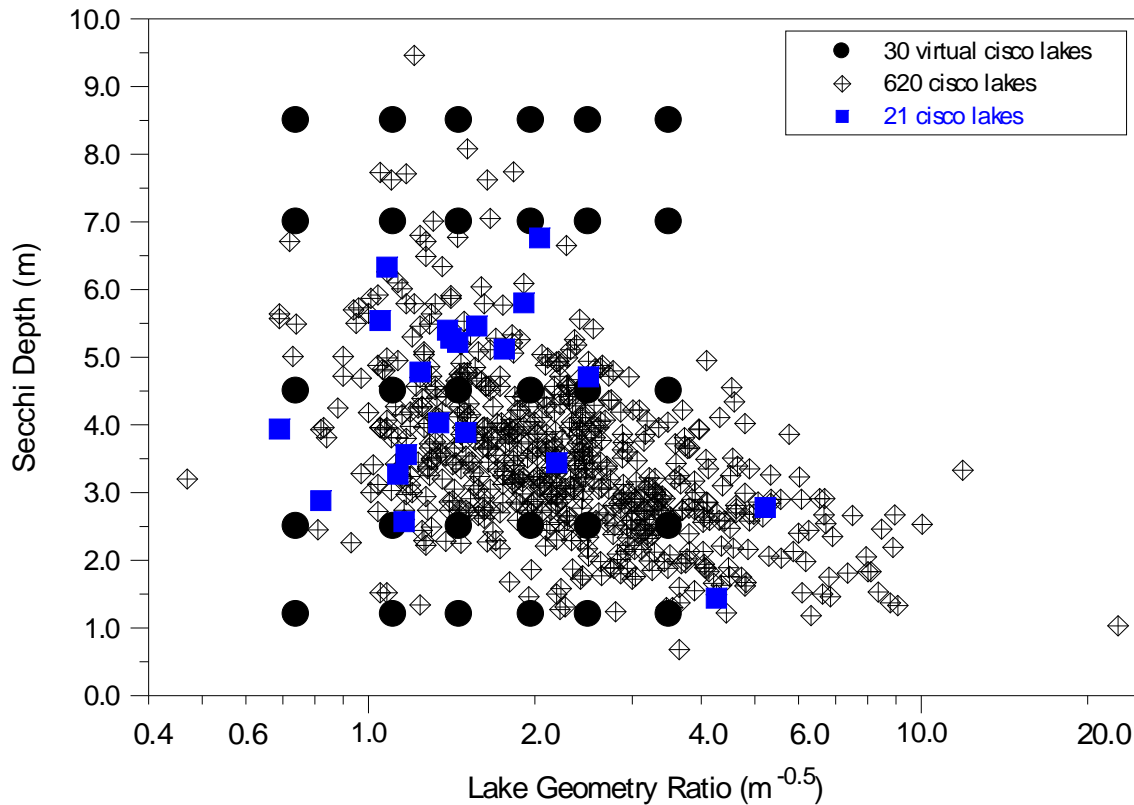


Figure 1.2 Distribution of 30 virtual cisco lakes, 21 cisco study lakes, and 620 cisco lakes in Minnesota on a plot of Secchi depth versus lake geometry ratio ( $GR = A_s^{0.25}/H_{max}$ ).

Table 1.2 Morphometric characteristics and names of the 30 virtual cisco lakes used in the MINLAKE2010 model simulations.

Max. Depth	Surface Area	Secchi Depth SD (m)					Geometry Ratio
		$A_s$ (km <sup>2</sup> )	1.2	2.5	4.5	7.0	
H <sub>max</sub> = 24 m  (Deep)	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

Table 1.3 Distributions and classifications of surface area, geometry ratio (GR) and Secchi depth (SD) of the 30 virtual cisco lakes.

Area (km <sup>2</sup> )	% less than <sup>1</sup>	Classification	GR (m <sup>-0.5</sup> )	% less than <sup>1</sup>	Classification	SD (m)	% less than <sup>1</sup>	Trophic status
0.1	1.0%	Small	0.74	1.0%	Stratified	1.2	0.6%	E
0.5	14.6%	Small*	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*	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	-	-	-

\* - These are on the border of the previous 27 regional lake classification, E: Eutrophic lake, M: Mesotrophic lake, and O: Oligotrophic lake. <sup>1</sup> in comparison to all 620 cisco lakes in the MN DNR database.

### 1.3 Cisco refuge lake identification

The goal of this study was to identify potential refuge lakes for cisco survival under future climate scenarios. The TDO3 approach was selected to identify viable cisco habitat in refuge lakes for future climate scenarios. Several different TDO3 parameters were explored for the purpose of refuge lake selection. As discussed in Chapter 3, lake geometry ratio (GR) and Secchi depth (SD) are two important parameters influencing thermal and DO conditions, and hence cisco habitat in a lake. Contours of different TDO3 parameters were drawn on plots with GR and SD as X- and Y-axis for both past climate and future climate conditions in order to identify refuge lakes. It was determined (Figure 1.2) that the 21 cisco study lakes used for model calibration did not cover the entire field of SD and GR values sufficiently well to make reliable contour plots. The 30 virtual cisco lakes discussed above covered the full range of GR

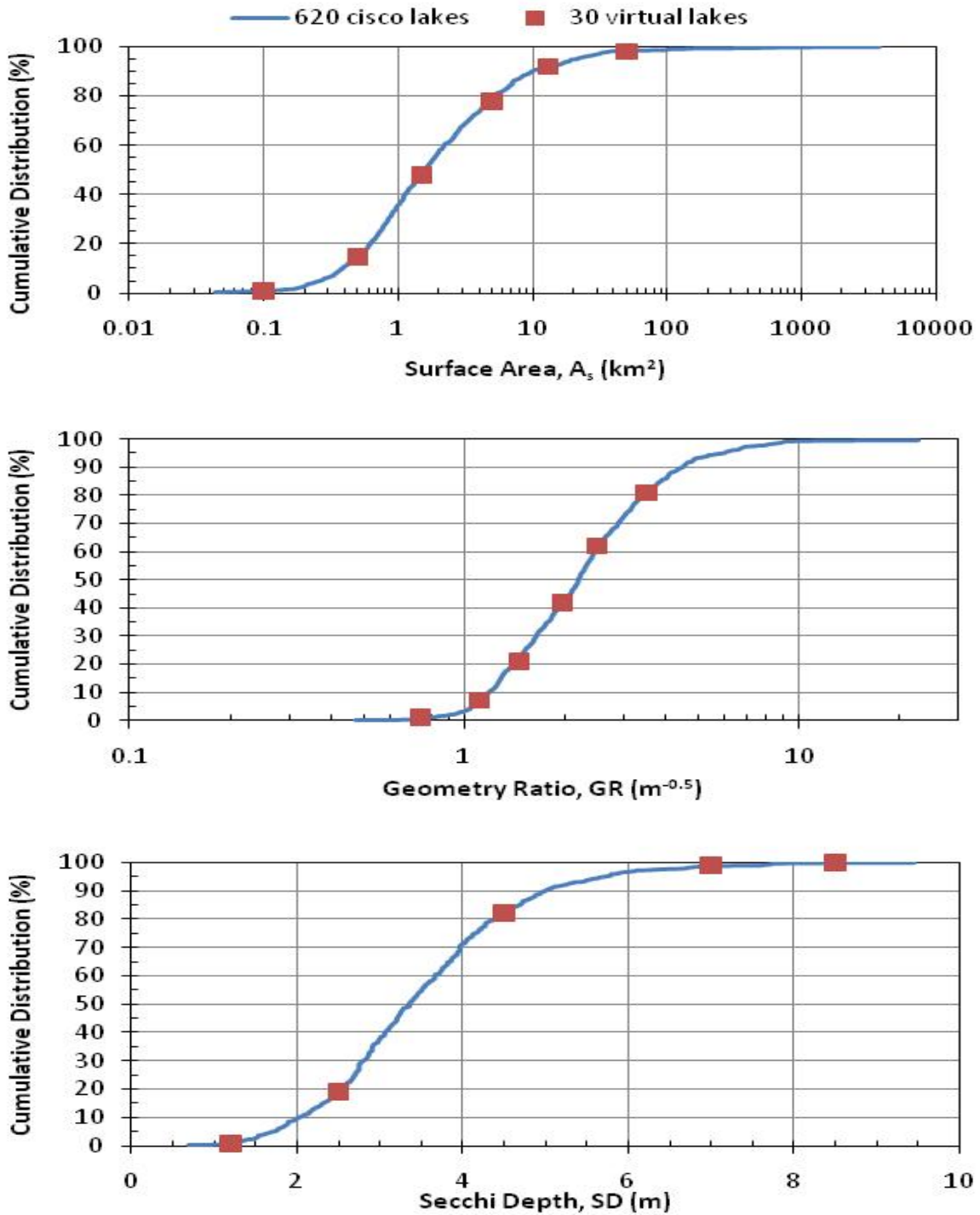


Figure 1.3 Cumulative distributions of lake surface area, geometry ratio, and Secchi depth for all 620 cisco lakes in the Minnesota DNR database and the 30 virtual cisco lakes.

and SD values more completely, and were therefore added. Simulated TDO3 values for the 30 virtual cisco lakes were used to develop the final contour plots of TDO3 to identify refuge lakes.

A lower TDO3 value indicates better living conditions for cisco in a lake. Relative to lethal temperatures for cisco, a lower TDO3 suggests a more suitable thermal and DO environment for cisco to survive and grow. Therefore, lakes with the lowest TDO3 values are potential refuge lakes. Contour plots of TDO3 give valuable information on the limiting values of GR and SD for cisco refuge lakes. Cisco lakes which fall within the limiting values of GR and SD are identified in the MN DNR cisco lake database and proposed as future cisco refuge lakes.

The next five chapters of this third and final project report, provide the following information:

Chapter 2 gives information on future climate scenarios that were used to run the calibrated year-round water quality model in order to make water quality and fish habitat projections.

Chapter 3 defines 12 TDO3 parameters calculated from simulated daily temperature and DO profiles. It presents time-series of TDO3 parameters in selected lakes and ranges of TDO3 parameter values in selected lakes.

Chapter 4 presents contour plots of selected TDO3 parameters that were interpolated from data points simulated for 21 cisco study lakes and 30 virtual cisco lakes.

Chapter 5 presents results for the selection of cisco refuge lakes in Minnesota using different TDO3 parameters and different climate scenarios. It includes a frequency analysis of lake characteristic parameters for selected refuge lakes.

Chapter 6 gives a summary and conclusions of the study and includes recommendations for future investigations.



## Chapter 2 Future Climate Scenarios

In this study we are not only to identify whether a Minnesota lake can support cisco habitat under past (observed historical) climate conditions, but also to project whether a lake can support cisco habitat under future climate scenarios, i.e. after climate warming. To make the projection, we have available the model output from a number of General Circulation Models (GCMs) of the earth's atmosphere. These GCM models simulate time series of climate parameters that can be used to create future climate scenarios. As input to the MINLAKE2010 model, the GCM future climate scenarios facilitate the projection of future lake water quality conditions from which future cisco habitat is derived. In previous fish habitat projections for the contiguous United States (Stefan et al. 2001), GCM 2.0 model output from the Canadian Climate Centre for Climate Modeling and Analysis (CCCma) was used. For the present study, we used the output of two new GCMs (CCCma CGCM 3.1, and MIROC 3.2), and output from the earlier model (CCCma GCM 2.0) used in our previous studies (Stefan et al. 2001). In this chapter these GCM models are described briefly, and the assembly and utilization of the GCM output data are discussed.

### 2.1 General circulation models

A General Circulation Model (GCM) is a mathematical simulation model of the general circulation of a planetary atmosphere or ocean on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat). The fluid dynamic and thermodynamic equations used are the basis for complex computer programs called GCMs and commonly used for simulating the atmosphere or oceans of the Earth. Atmospheric and Oceanic GCMs (AGCMs and OGCMs) are key components of global climate models along with sea-ice and land-surface components. GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change.

In the early stage of GCM research, atmospheric and oceanic GCMs were separate. AGCMs typically contain a land-surface model and impose sea surface temperatures. They may include atmospheric chemistry. AGCMs consist of a dynamical core that integrates the equations of fluid motion, typically for surface pressure, horizontal components of velocity in layers, and temperature and water vapor in layers. There is generally a radiation code, split into solar/short wave and terrestrial/infra-red/long wave. Parameterizations are used to include the effects of various processes. All modern AGCMs include parameterizations for convection, land surface processes, albedo, hydrology, and cloud cover.

OGCMs model the ocean (with fluxes from the atmosphere imposed) and may or may not contain a sea ice model. The standard resolution of HadOM3 (Hadley Oceanic Model 3) is 1.25 degrees in latitude and longitude, with 20 vertical levels, leading to over 2,000,000 variables.

In recent GCM research, atmospheric and oceanic models are combined and called Coupled Atmosphere-Ocean GCMs (AOGCMs) or more simply Coupled GCMs (CGCMs).

These models have removed the need to specify fluxes across the ocean surface, and are the basis for sophisticated model predictions of future climate. CGCMs represent the pinnacle of complexity in climate modeling and incorporate as many processes as possible. They are the only tools that can provide detailed regional predictions of future climate change. However, they are still under development. The simpler models are generally susceptible to simple analysis and their results are generally easy to understand. AOGCMs, by contrast, are often nearly as hard to analyze as the real climate system.

## **2.2 Selection of the GCMs used in the study**

Recent GCM model outputs that can be used to develop future climate scenarios are available on the website (<http://www.ipcc-data.org/>) of the Data Distribution Centre (DDC) of the Intergovernmental Panel on Climate Change (IPCC). The DDC is overseen by the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA). The identification, selection, and application of baseline and scenario data are crucial steps in projections of the potential impact of climate change. The IPCC TGICA defined a set of criteria that were applied to identify a small number of GCM experiments whose results could be deposited at the IPCC DDC website and can be used for climate change impact studies. IPCC selected models that fulfill the following criteria:

- the models should be full 3D coupled ocean-atmospheric GCMs,
- the models should be documented in the peer reviewed literature,
- the models should have performed a multi-century control run (for stability reasons) and
- the models should have participated in CMIP2 (Second Coupled Model Intercomparison Project).

In addition, preferably

- the models have been used to perform a 2 x CO<sub>2</sub> mixed layer run,
- the models have participated in AMIP (Atmospheric Model Intercomparison Project),
- the models have a resolution of at least T40, R30 or 3° latitude x 3° longitude
- the models consider explicit greenhouse gases (e.g. CO<sub>2</sub>, CH<sub>4</sub>, etc.)

For this cisco lake habitat study, we selected two GCMs which meet the standards of IPCC; they are the CGCM 3.1 and MIROC 3.2. We have also used GCM 2.0 that was applied in our previous studies (Stefan et al. 2001). These three GCMs are discussed in the next section.

## 2.3 Description of the GCMs used in the study

Three GCMs were used in this study. Two, i.e. GCM 2.0 and CGCM 3.1 are from the Canadian Climate Centre for Climate Modeling and Analysis (CCC ma). The third is The Model for Interdisciplinary Research on Climate, MIROC 3.2, which was developed at the Center for Climate System Research (CCSR), University of Tokyo and associates. Background information on the future climate scenarios specified by the three selected CGCMs is given below.

### 2.3.1 CCCma Models – GCM 2.0 and CGCM 3.1

The Canadian Centre for Climate Modeling and Analysis has developed a number of climate models. They are used to study climate change and variability, and to understand the various processes that govern the climate system. They are also used to make quantitative projections of future long-term climate change (given various greenhouse gas and aerosol forcing scenarios), and increasingly to make initialized climate predictions on time scales ranging from seasons to decades. The first generation atmospheric general circulation model (AGCM1) was developed in the early 1980s. The first coupled global climate model (CGCM1) was developed in the early 2000s. After the coupled global climate models, called CGCMs, had come on the scene, previous atmospheric general circulation models were first called GCMs, and now AGCMs.

- **GCM 2.0**

The second generation atmospheric GCM 2.0 (Boer et al. 1992; McFarlane et al. 1992), includes higher spatial resolution  $3.75^\circ \times 3.75^\circ$  than previous models and full diurnal and annual cycles. This model provides the increments or ratios for monthly climatic parameter values representative of a doubling of atmospheric  $\text{CO}_2$  ( $2 \times \text{CO}_2$ ). This model was developed in the early 90s. The output of GCM 2.0 was used by the authors in previous studies to examine fish habitat in small lakes in the contiguous United States. Hence, the output of this model was available for the present study. Although GCM 2.0 it is not one of the current models developed by CCCma, the availability of its model output data led us to use the GCM 2.0 for some model runs in the present study. It has one grid center point within Minnesota and eight grid points surrounding Minnesota (Fig. 2.1).

- **CGCM 3.1**

The newest version of the Coupled Global Climate Models (CGCMs) from the Canadian Centre for Climate Modeling and Analysis (CCCma) is CGCM 3.1 (Kim et al. 2002; Kim et al. 2003). This third generation model makes use of the ocean component from the earlier Second Generation Coupled Global Climate Model, but applies a substantially updated atmospheric component - the third Generation Atmospheric General Circulation Model (AGCM). CGCM 3.1 was run at two different resolutions. The T47 version has a surface grid whose spatial resolution is roughly 3.75 degrees latitude and longitude, and 31 levels in the vertical. The T63 version has a surface grid whose spatial resolution is roughly 2.8 degrees latitude and longitude and 31 levels in the vertical. Because not all weather parameters for the T63 version are yet available, the T47 version had to be used for this study. It has one grid center point in Minnesota and eight grid points in surrounding states

and provinces (Fig. 2.2). The distribution of grid center points for CGCM 3.1 looks almost the same as for GCM 2.0 (Fig. 2.1) but the CGCM 3.1 grid center points do have slightly different coordinates.

### 2.3.2 MIROC 3.2 model

The Model for Interdisciplinary Research on Climate, MIROC3.2 (Hasumi and Emori 2004), was developed by the Center for Climate System Research (CCSR), University of Tokyo; the National Institute for Environmental Studies (NIES); and the Frontier Research Center for Global Change (FRCGC) - Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Two sets of output from the MIROC 3.2 model are available: high resolution and medium resolution. For this study, output with high spatial resolution has been used; it has a surface grid whose spatial resolution is roughly 1.12 degrees latitude and longitude. Among the three GCMs selected for this study MIROC 3.2 has the smallest spatial resolution. It has seventeen grid center points in Minnesota and many more grid points in surrounding states and provinces (Fig. 2.3).

## 2.4 Atmospheric CO<sub>2</sub> scenarios for the GCMs

The Intergovernmental Panel on Climate Change (IPCC) published a set of future climate scenarios in 2000 for use in the Third Assessment Report (IPCC 2001) on global climate warming. This publication is known as the **Special Report on Emissions Scenarios (SRES)**. Because the future world may take different routes regarding social, cultural and financial development, the SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. There are four major scenario families (A1, A2, B1, and B2) and a number of sub-scenarios which result in a total of 40 different scenarios. Some of these are reproduced in Figure 2.3. The major scenario families are described as follows:

- **A1 scenario family:** a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies.
- **A2 scenario family:** a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other scenarios.
- **B1 scenario family:** a convergent world with the same global population as in the A1 scenario but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
- **B2 scenario family:** a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

In Table 2.1, atmospheric CO<sub>2</sub> concentrations projected for 2100 under the different emission scenarios are listed. In the future climate scenario A1B the projected atmospheric CO<sub>2</sub>

concentration in 2070 – 2099, would be double of what it was in the base period (1990). The global average CO<sub>2</sub> concentration in 1990 was 375 ppm. Because previous studies related to the present study were also using a doubling of CO<sub>2</sub>, the A1B scenario provides some continuity. Hence, the output of GCMs using the A1B scenario was selected for this study.

Table 2.1 Atmospheric CO<sub>2</sub> concentrations in 2100 for different climate scenarios

Scenarios	CO <sub>2</sub> concentration (ppm)
A1B	705
A2	842
B1	538
B2	618

#### ***2.4.1 Temperature and sea level rise for each SRES scenario family***

There are six families of SRES scenarios in the IPCC's Fourth Assessment Report (Solomon et al. 2007). This Fourth Assessment Report gives projected temperature and sea level rises (excluding future rapid dynamical changes in ice flow) for each scenario family as reproduced in Table 2.2

Table 2.2 Temperature rise and sea level change in different scenarios from IPCC's Fourth Assessment Report (IPCC 2007).

Scenarios	Best estimated temperature rise	Likely range of temperature rise	Sea level rise (cm or inches)	
			cm	inches
B1	3.2 °F (1.8 °C)	2.0 -5.2 °F	18 - 38 cm	7 - 15 inches
A1T	4.3 °F (2.4 °C)	2.5 - 6.8 °F	20 - 45 cm	8 - 18 inches
B2	4.3 °F (2.4 °C)	2.5 - 6.8 °F	20 - 43 cm	8 - 17 inches
A1B	5.0 °F (2.8 °C)	3.1 - 7.9 °F	21 - 48 cm	8 - 19 inches
A2	6.1 °F (3.4 °C)	3.6 - 9.7 °F	23 - 51 cm	9 - 20 inches
A1F1	7.2 °F (4.0 °C)	4.3 - 11.5 °F	26 - 59 cm	10 - 23 inches

Note : Temperature rise is the difference from the period 1980-1999.

## 2.5 Generation of future climate scenario data for the MINLAKE2010 water quality and fish habitat model simulations

The GCMs generate global weather data (air temperature, dew point temperature, solar radiation, precipitation and wind speed) at all grid points for current and future years, e.g., for 2010-2039, 2040-2069, and 2070-2099. GCM outputs are not generally of a sufficient resolution or reliability to be applied directly to represent the present-day climate. Instead, the **climate change** simulated by GCMs is usually applied to baseline observational weather data, such as time series of historic daily weather data. A scenario of future climate is obtained by adjusting the baseline observations by the difference (or ratio) between period-averaged results from GCM experiments (usually 10 or 30 year periods are used) and the corresponding averages for the GCM control simulation. In recent transient experiments developed for the IPCC's Fourth Assessment Report (IPCC 2007) a simulated baseline period (e.g. 1961-1990) is used in place of the control-run. The differences or ratios known as a "change field" are produced and reported for all grid center points at monthly interval. Table 2.3 lists which types of the change fields are available for the three GCMs selected for the present study. 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 the present study.

**Data available from the Data Distribution Center of IPCC:** As discussed in section 3.2 output data from the GCMs which meet a strict standard are eligible to be stored on the IPCC server. IPCC designed a Data Distribution Center (DDC) (<http://www.ipcc-data.org>) primarily for climate change researchers, but also of interest to educators, governmental and non-governmental organizations, and the general public. For the current study, output of the CGCM 3.1 and the MIROC 3.2 models was retrieved from the website of the DDC. The data files are stored as 'tar' files. Each tar file contains three sets of NetCDF files:

- 20x: Twenty year averages, +20-39, +46-85, +80-99, +180-199 ( used in Chapter 10 of IPCC (2007), Fourth Assessment Report)
- 30a: Thirty year averages, +01-30, +31-60, +61-90 (used by observational climatologists)
- 30b: Thirty year averages, +10-39, +40-69, +70-99 (for compatibility with the IPCC (2001), Third Assessment Report)

For the specific scenarios and models used in the present study, data files for the 20x and 30b options are available to download. We used data files from option 30b, because that was more related to previous studies. For 30b there were 3 files that could be downloaded for each weather parameter. We used only data files for 2070 -2099 (+70-99).

**Location of Grid Points:** The GCM output files do not provide future daily weather data for any specific weather stations, but for grid center points on the globe. Figures 2.1 to 2.3 show the location of the weather stations used and the grid center points in and near Minnesota. When the MINLAKE2010 model is run for a specific weather station, the model identifies the grid center point that is closest to that weather station, based on distance using longitude and latitude as coordinates. Table 2.4 shows the nearest grid center points of the three GCM models for different weather stations used in this study. Tables 2.5 and 2.6 list monthly changes of air

temperature (°C) and solar radiation (Langley/day) projected by CGCM 3.1 and MIROC 3.2 for the three principal weather stations used in this study. They are the Class I weather stations of the NWS in International Falls Duluth and St. Cloud, MN. Projected average annual changes of air temperature ranged from 4.00 to 4.24°C; projected monthly changes of air temperature had relatively larger variations when projected from CGCM 3.1 rather than from MIROC 3.2. For example, the monthly changes of air temperature at International Falls were projected to be from 2.89 to 6.89°C by CGCM 3.1 and from 3.53 to 5.15°C by MIROC 3.2. The highest change of air temperature was projected by CGCM 3.1 to be 8.09°C in February at Duluth.

The monthly ‘change field’ data at the nearest grid point were applied to the daily weather data of the respective weather station for the simulation period (e.g., 1961 to 2008 or 1991 to 2008). The resulting projected daily weather parameter values of the selected climate scenario are used as input to the MIN LAKE2010 model simulation. Figure 2.4 gives plots of the average and the standard deviation for air temperature, dew point temperature, wind speed, and solar radiation at Duluth for past climate (1961-2008) and projected future climate conditions.

Table 2.3 Type of ‘change field’ data provided by the three selected GCM models.

Weather Parameter	GCM 2.0	CGCM 3.1	MIROC 3.2
	Difference or Ratio	Difference or Ratio	Difference or Ratio
Air Temperature	Difference	Difference	Difference
Dew Point Temperature	Difference	Difference	Difference
Wind Speed	Ratio	Difference	Difference
Solar Radiation	Ratio	Difference	Difference
Total Cloud Cover	Ratio	-	-
Precipitation	Ratio	Difference	Difference
Snowfall	Difference	Difference	Difference

Table 2.4 Location (longitude and latitude) of weather stations used in the study and the nearest grid center points of the three GCM models for these stations.

Weather Station			GCM 2.0		CGCM 3.1		MIROC 3.2	
Longitude	Latitude	Location	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
96.800W	46.900N	Fargo, ND	97.50W	46.39	277.5 <sup>1</sup>	46.36	276.75	47.65
92.183W	46.833N	Duluth, MN	93.75W	46.39	273.8	46.36	272.25	47.65
93.383W	48.567N	International Falls, MN	93.75W	50.10	273.8	50.07	273.38	48.78
93.217W	44.883N	Minneapolis, MN	93.75W	46.39	273.8	46.36	273.38	45.41
94.067W	45.550N	Saint Cloud, MN	93.75W	46.39	273.8	46.36	274.5	46.53
94.130W	46.400N	Brainerd, MN	93.75W	46.39	273.8	46.36	274.5	46.53
94.930W	47.005N	Bemidji, MN	93.75W	46.39	273.8	46.36	274.5	47.65
93.510W	47.201N	Grand Rapids, MN	93.75W	46.39	273.8	46.36	273.38	47.65

<sup>1</sup> For CGCM 3.1 and MIROC 3.2 longitudes are expressed in degrees (from 0° to 360°) from the International Date Line clockwise (absolute form), hence  $277.5 = 277.5 - 180 = 97.5^\circ\text{W}$ .



Table 2.5 Monthly changes of air temperature (°C) and solar radiation (Langley/day) projected by CGCM 3.1 for the three principal weather stations used in this study.

Station	International Falls		Duluth		St. Cloud	
Parameters	Air temperature <sup>1</sup>	Solar radiation <sup>2</sup>	Air temperature	Solar radiation	Air temperature	Solar radiation
Jan	6.89	-5.69	4.84	-7.49	4.84	-7.49
Feb	5.07	-9.51	8.09	-38.21	8.09	-38.21
Mar	3.90	1.83	6.25	-55.05	6.25	-55.05
Apr	4.31	-18.77	3.60	-25.99	3.60	-25.99
May	4.12	-29.39	3.47	-19.96	3.47	-19.96
Jun	4.59	9.63	3.28	2.28	3.28	2.28
Jul	3.80	14.43	3.25	14.78	3.25	14.78
Aug	3.30	7.63	3.32	3.66	3.32	3.66
Sep	3.49	10.69	3.34	0.34	3.34	0.34
Oct	3.19	3.94	3.39	-1.18	3.39	-1.18
Nov	2.89	-1.82	3.06	-2.16	3.06	-2.16
Dec	4.14	-4.86	2.91	-1.32	2.91	-1.32
Average	4.14	-1.82	4.07	-10.86	4.07	-10.86

<sup>1</sup> Conversion: 1.0 °C = 1.8 °F ; <sup>2</sup> 1.0 Langley/day = 4.84×10<sup>-5</sup> Watts/cm<sup>2</sup>

Table 2.6 Monthly changes of air temperature (°C) and solar radiation (Langley/day) projected by MIROC 3.2 for the three principal weather stations used in this study.

Station	International Falls		Duluth		St. Cloud	
Parameters	Air temperature	Solar radiation	Air temperature	Solar radiation	Air temperature	Solar radiation
Jan	5.15	-20.34	4.67	-15.92	4.35	-4.60
Feb	4.70	-25.36	4.67	-23.42	4.17	-9.13
Mar	4.64	-24.84	4.53	-15.75	4.08	0.35
Apr	4.52	-3.32	3.89	0.78	3.88	9.80
May	4.37	-4.43	4.21	-15.22	4.33	2.45
Jun	3.62	-3.82	3.59	-3.92	3.67	0.36
Jul	3.53	-5.38	3.68	10.36	3.67	17.08
Aug	3.75	-0.49	3.82	0.52	3.92	3.64
Sep	3.80	16.57	3.81	19.27	3.87	24.14
Oct	4.46	-2.76	4.29	3.03	4.30	9.87
Nov	4.10	-4.22	3.89	3.03	3.87	5.79
Dec	4.18	-12.80	3.99	-9.24	3.92	-3.16
Average	4.24	-7.60	4.09	-3.87	4.00	4.71

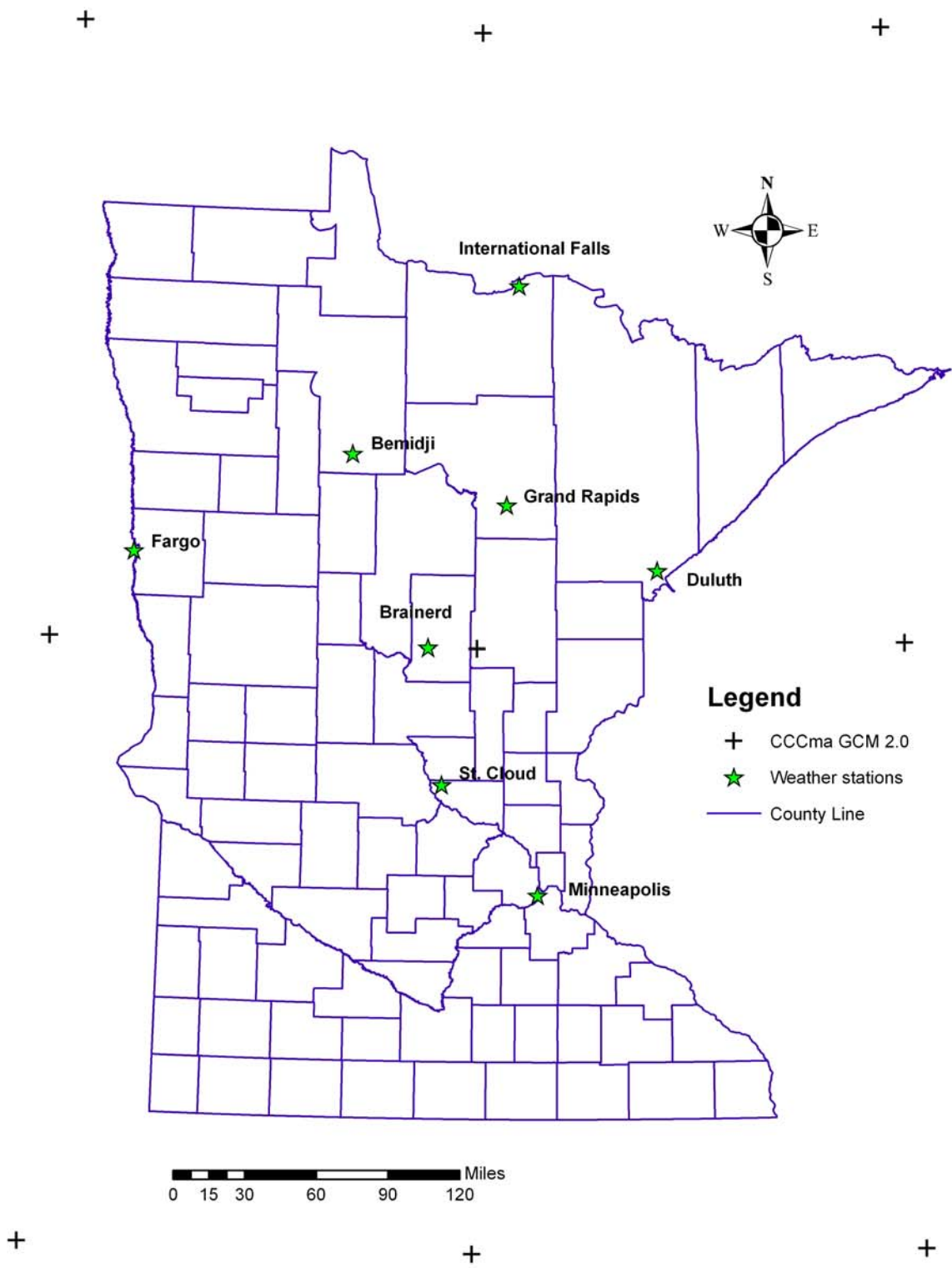


Figure 2.1 Grid center points (+) of CCCma GCM 2.0 and weather stations.

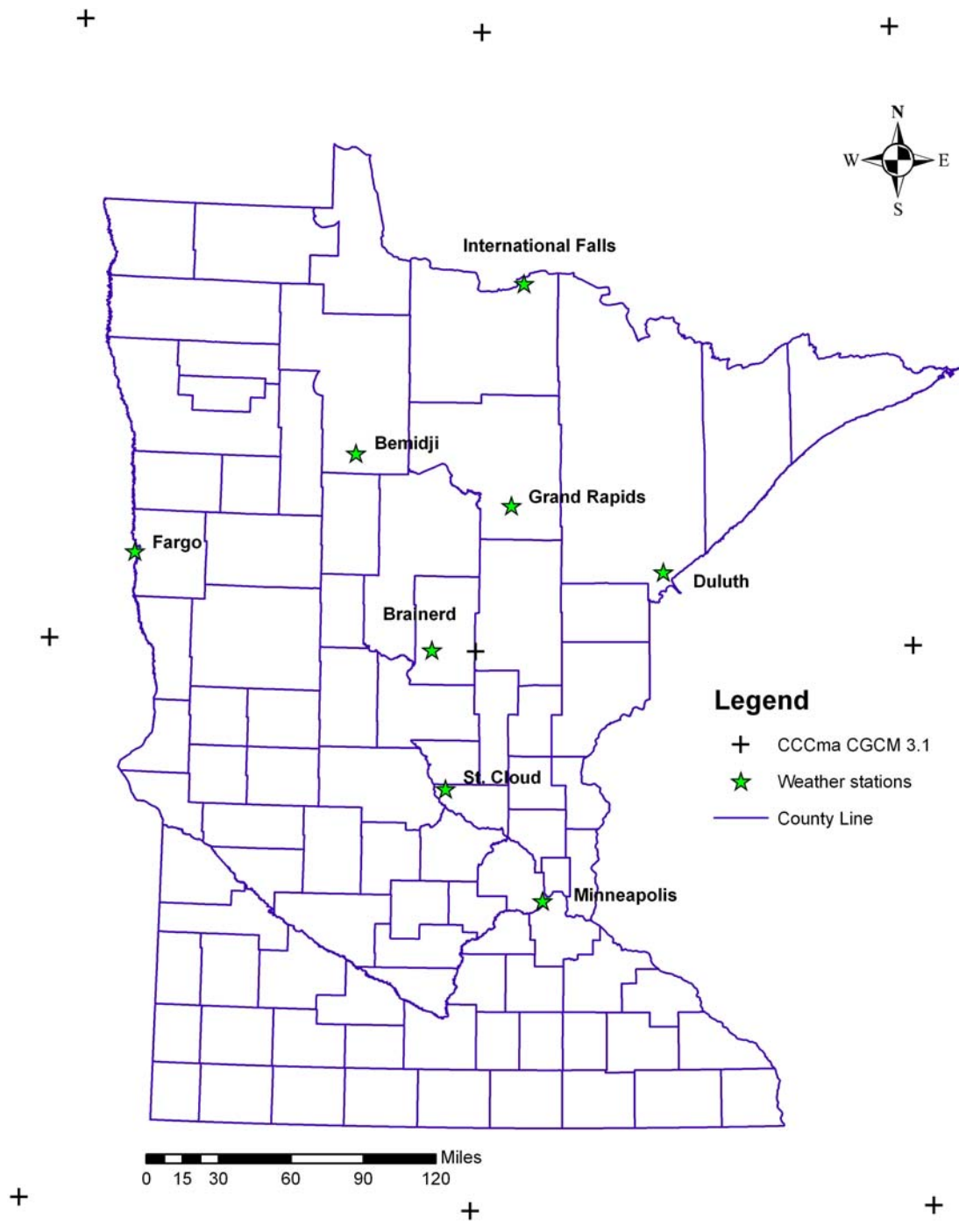


Figure 2.2 Grid center points (+) of CCCma CGCM 3.1 and weather stations

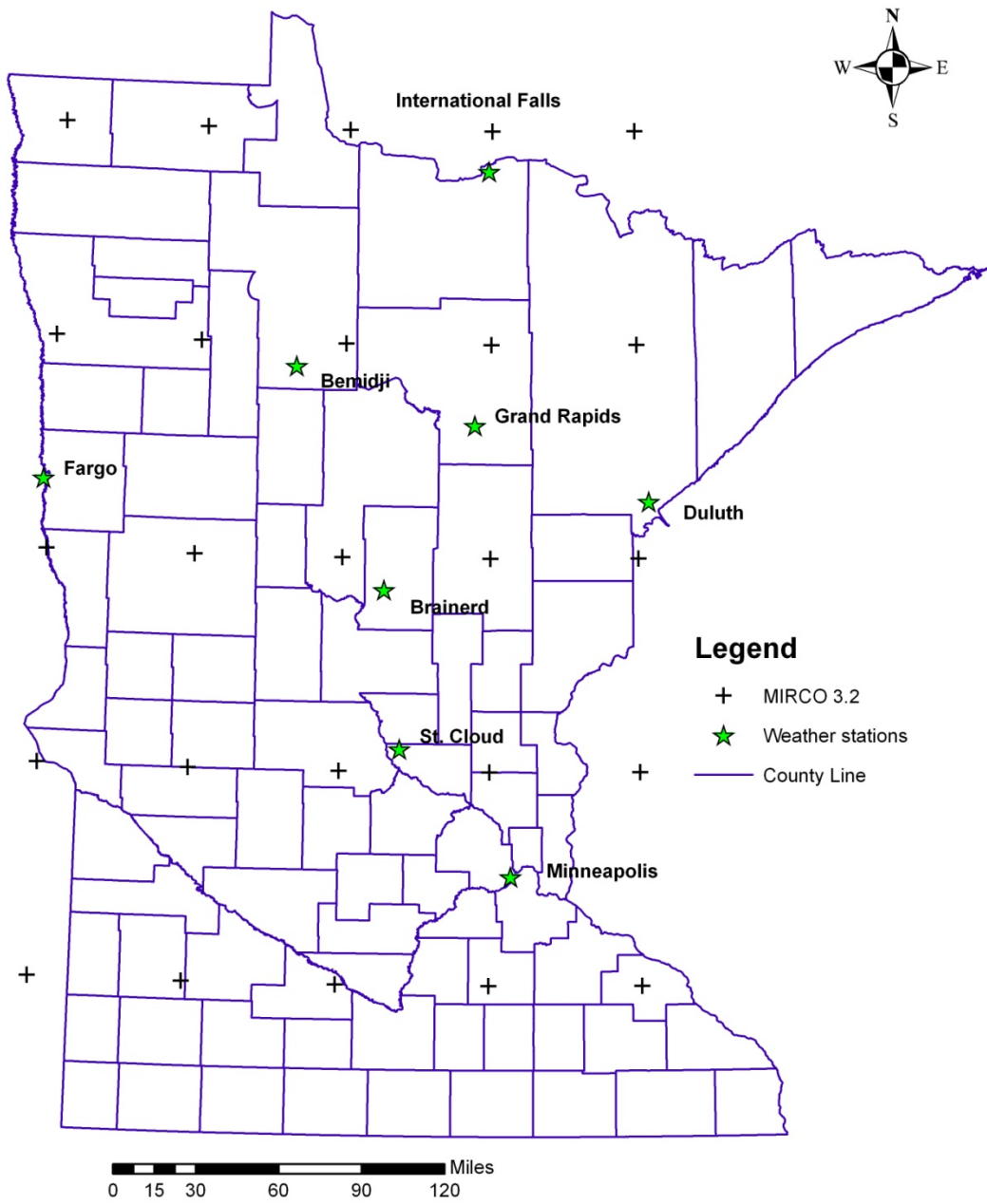


Figure 2.3 Grid center points (+) of MIROC 3.2 and weather stations.

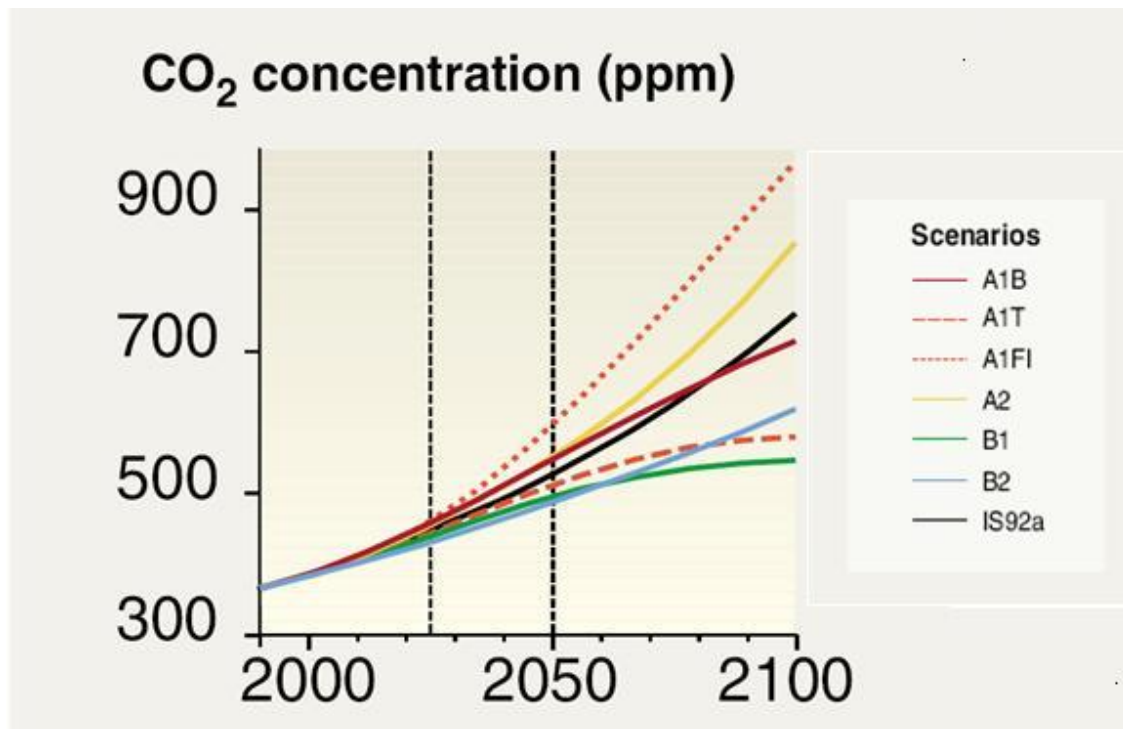


Figure 2.4 Change of atmospheric CO<sub>2</sub> concentration with time for different climate change scenarios (IPCC, Third Assessment Report, 2001).

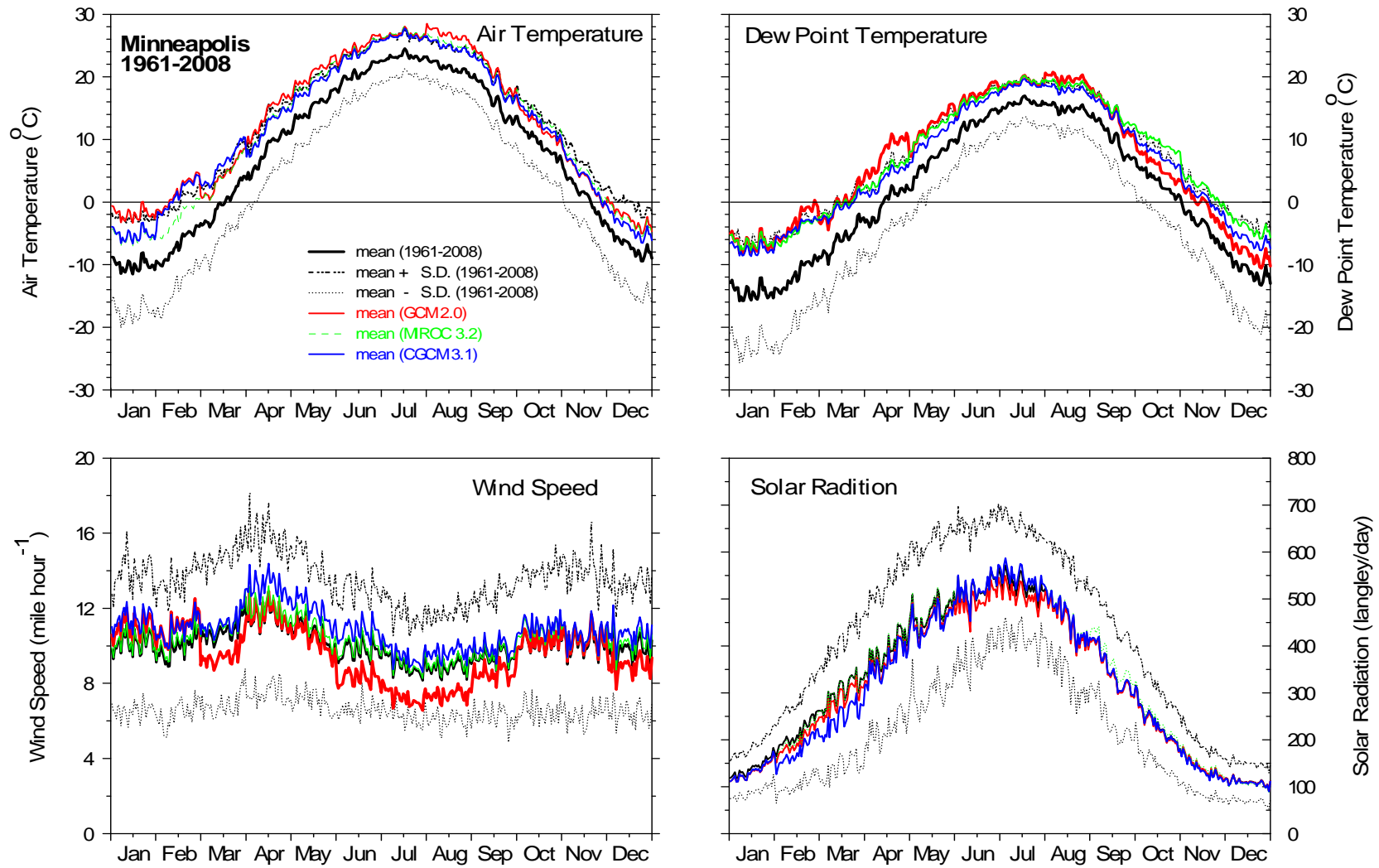


Figure 2.5 Averages and standard deviations (S.D.) for air temperature, dew point temperature, wind speed, and solar radiation at Duluth for past climate conditions and future climate scenarios.

## Chapter 3 Oxythermal Habitat Parameters for Cisco

### 3.1 Oxythermal fish habitat parameter - TDO3

The oxythermal habitat variable, commonly used in coldwater fish niche modeling (Ryan and Marshall 1994; Dillon et al. 2003), defines an upper boundary for temperature and a lower boundary for dissolved oxygen concentration. Previous oxythermal habitat models determine the water volume or layer thickness in a stratified lake between an upper temperature bound and a lower dissolved oxygen bound that represent either optimal thermal habitat (Dillon et al. 2003) or non-lethal/useable habitat (Ryan and Marshall 1994, Stefan et al. 2001). Jacobson et al. (2010) combined the two bounds and proposed a single variable to quantify oxythermal habitat across several coldwater fish species (lake trout, cisco, lake whitefish, and burbot) that have different requirements for cold, oxygenated water. The single generalized oxythermal habitat variable is defined as the water temperature at 3 mg/L of dissolved oxygen (DO), and is called, TDO3. The TDO3 can be determined by interpolating the temperature of water at the DO concentration of 3 mg/L from measured vertical temperature and DO profiles. Non-monotonic profiles generate low oxygen concentrations with more than one TDO3 value, and the coldest TDO3 is used.

As an alternative to the use of measured lake temperature and DO profiles, Jacobson et al. (2010) developed a generalized model to predict TDO3 as a function of lake productivity, climate, and relative depth (lake geometry ratio,  $A_s^{0.25}/H_{\max}$ ). Summer total phosphorus concentration was the variable used to represent lake productivity of each lake (Jacobson et al. 2010).

In this study, total phosphorus concentration was not one of the model parameters to characterize any of the 21 cisco study lakes or 30 virtual lakes; instead Secchi depth (SD), a measure of lake transparency, was used to represent trophic state in addition to radiation attenuation in a Minnesota lake. The trophic state expresses primary productivity and DO production (photosynthesis of plants) in a lake, and ranges from oligotrophy (nutrient-poor, biologically unproductive) to eutrophy (nutrient-rich, productive).

In this study, temperature and DO profiles in lakes are simulated by the MINLAKE2010 model. The model uses climate data as model input, and can therefore simulate future climate conditions for which no measurements exist. 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). Therefore, lake geometry ratio (GR) and Secchi depth (SD) are two representative parameters to characterize each of the 620 cisco lakes in the database, and were used to identify refuge cisco lakes at different geographic locations in Minnesota. That was why contour plots of TDO3 parameters presented in Chapter 4 used lake geometry ratio and Secchi depth as the x- and y-axes.

In summer, DO concentrations and water temperatures in lakes usually decrease monotonically with depth below the thermocline (metalimnetic oxygen maxima are an exception). It is unlikely that suitable oxythermal habitat occurs below a depth at which DO is limiting for coldwater fish. Above that depth, habitat will only exist if water temperatures are suitable for coldwater species. Therefore, the water temperature at the depth where DO starts to become limiting is an indicator of the coldest available, oxythermal habitat. Although identifying one value of DO that is physiologically limiting for all coldwater taxa is impossible, selecting a limiting DO concentration that represents an undesirable level for all species, is useful for a developing a generalized oxythermal habitat variable. 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. However, 3 mg/L is an oxygen concentration that is probably lethal or nearly so for many coldwater species (Frey 1955, USEPA. 1986, Evans 2007) and therefore represents a desirable benchmark for a presence/absence niche model. Low values of TDO3 indicate excellent oxythermal habitat for coldwater fish, i.e., fish have a wide range of temperatures available in the hypolimnion with sufficient oxygen concentrations. High values of TDO3 indicate poor oxythermal habitat for coldwater fish, with little or no cold water with sufficient oxygen. Very high values of TDO3 indicate hypolimnia that are anoxic or are found in unstratified lakes. The oxythermal requirements of different species of coldwater fish can be compared by the maximum tolerated values of the single variable TDO3. Cisco were present in lakes with a broad range of maximum TDO3 values during a summer time benchmark period, with borders of 4.0 and 16.9 °C (Jacobson et al. 2010).

Figure 3.1 illustrates the procedure how TDO3 can be extracted from temperature and DO profiles in two lakes. Rose Lake had good coldwater oxythermal habitat with  $T_{DO3} = 10.6$  °C on August 3, 2006; and Little Pine Lake had very poor coldwater oxythermal habitat with  $T_{DO3} = 23.9$  °C on July 25, 2006. Rose Lake (latitude 46.675° and longitude -95.740°) has surface area of 481 ha, maximum depth of 42 m, and total Phosphorus concentration of 17.0 µg/L (on August 3, 2006). Little Pine Lake (latitude 46.634° and longitude -95.557°) has surface area of 797 ha, maximum depth of 19 m, and total phosphorus concentration of 29.8 µg/L (on 25 July 2006).

In this study, a fish habitat computer program was designed to calculate TDO3, i.e., to search and determine the water depth where  $DO = 3$  mg/L on the simulated daily DO profiles, and then to determine the simulated water temperature at that depth. Examples of time series of daily TDO3 values in four selected lakes are given in Figures 3.2 and 3.3. For each lake, time series plots of daily TDO3 values for two selected simulated years are shown. The two selected years had the highest or lowest annual maximum daily TDO3 in the simulation period. For example,  $TDO3_{AM}$  in South Twin Lake was 20.7 and 26.9°C in 1993 and 2006, respectively (Fig. 3.3).



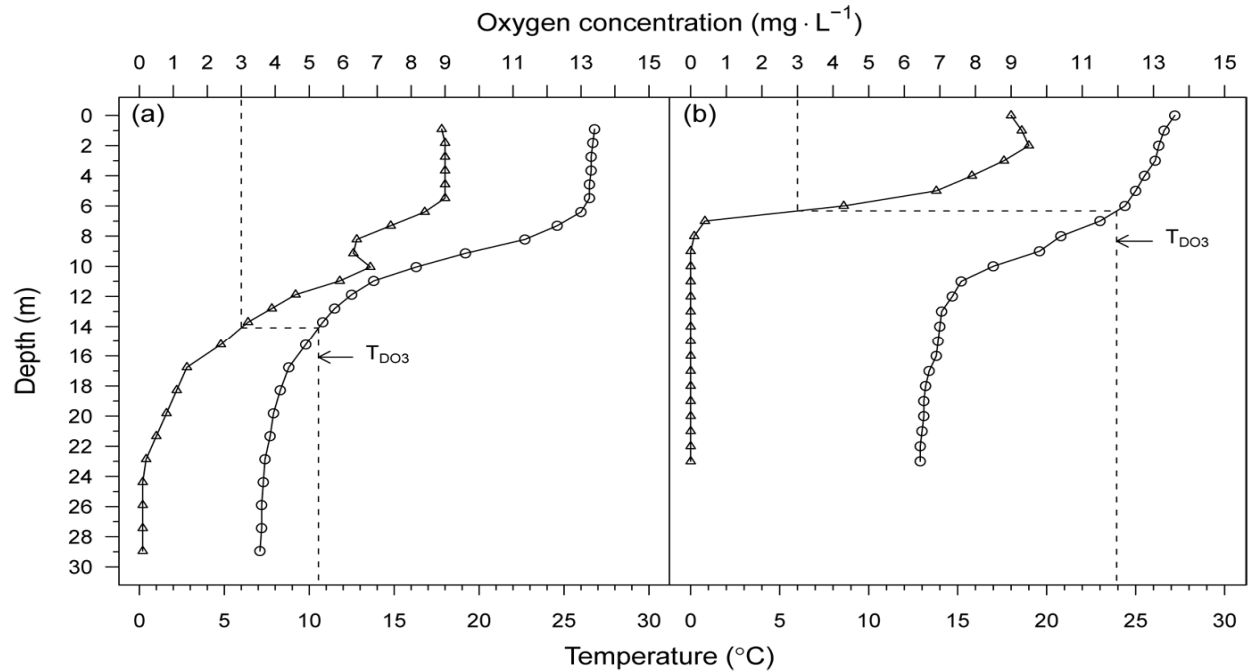


Figure 3.1 Examples of TDO3 (temperature at 3 mg/L DO) determination from temperature (circles) and dissolved oxygen (triangles) profiles in (a) Rose Lake and (b) Little Pine Lake (from Jacobson et al. 2010).

Time series of daily TDO3 values were obtained for each study lake and each simulation year during the simulation period, e.g., 1962 to 2008 or 1992 to 2008, depending on weather station used. The temperature and DO profiles simulated for the first-year (1961 or 1991) were not used to extract TDO3 values in order to avoid possible effects of assumed initial conditions on simulations. When the DO concentration was less than 3.0 mg/L along the entire profile (e.g. in Carrie Lake during winter of 1987, Figure 3.2), TDO3 was set at 0°C (temperature at the ice-water interface) because the program searches for DO = 3.0 mg/L along the DO profile from lake bottom to surface. From the time series of daily TDO3 values for each simulation year and over the total simulation period (1962 to 2008 or 1992 to 2008), different TDO3 values can be extracted as single day values, monthly averages, multi-year averages, etc. Twelve options are defined in Table 3.1, and can be calculated for each lake. These alternatives are further explained and discussed below.

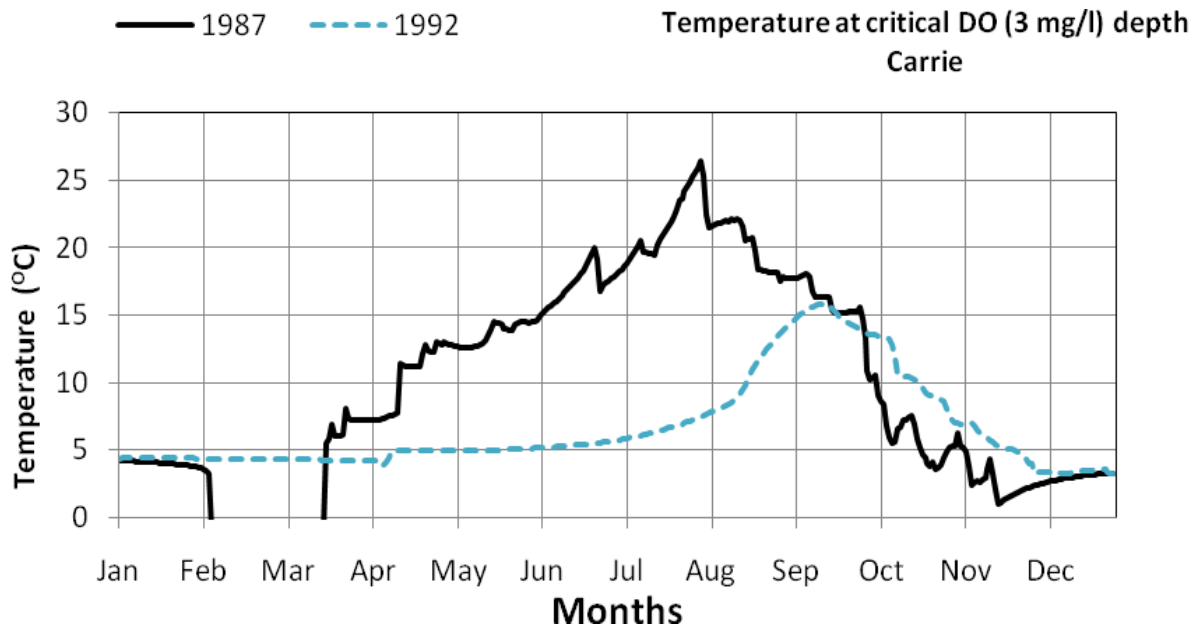
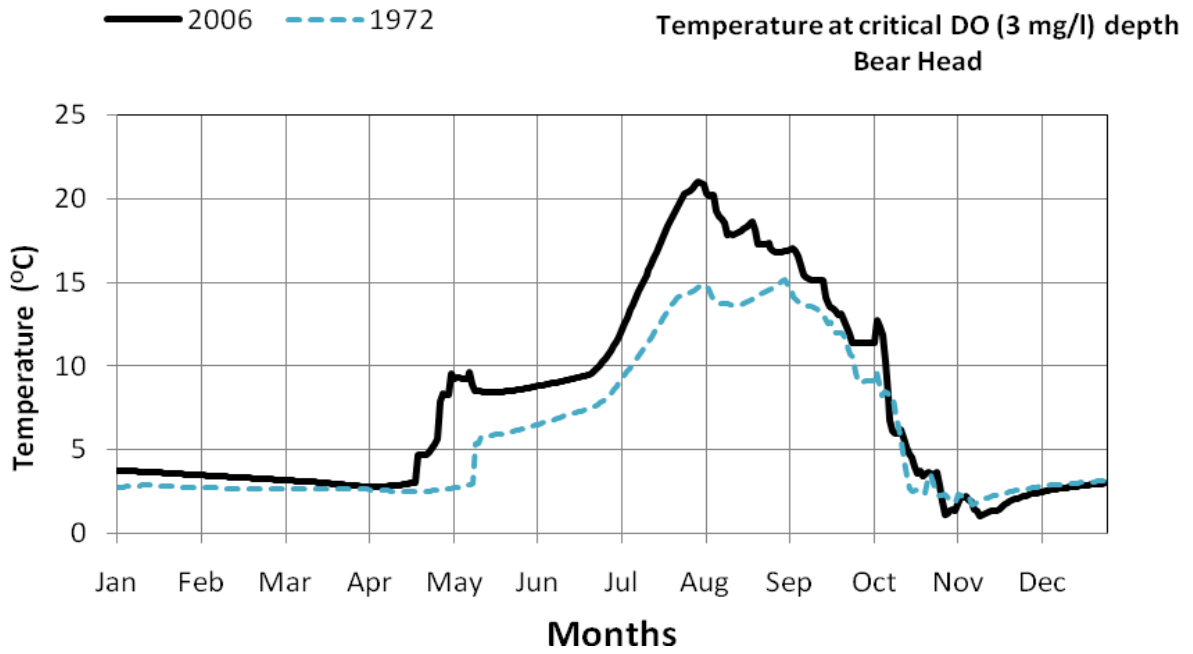


Figure 3.2 Time series of simulated daily TDO3 for Bear Head Lake and Carrie Lake (non-cisco lakes). The two selected years have the highest or lowest annual maximum TDO3 in the simulation period.

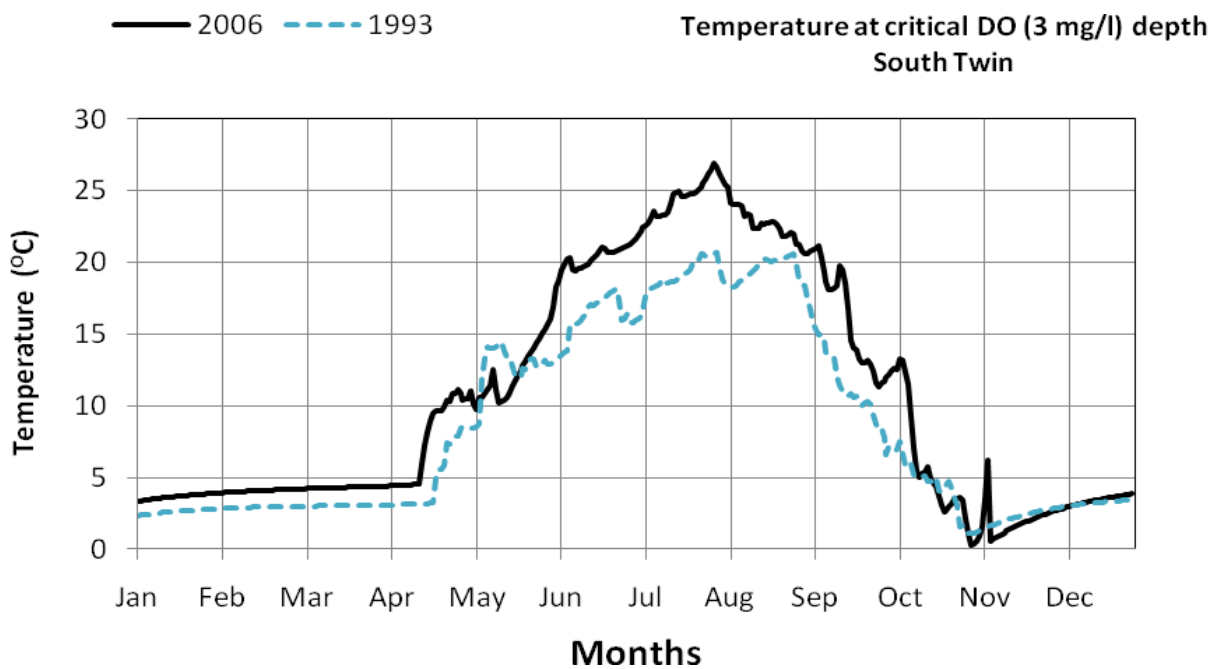
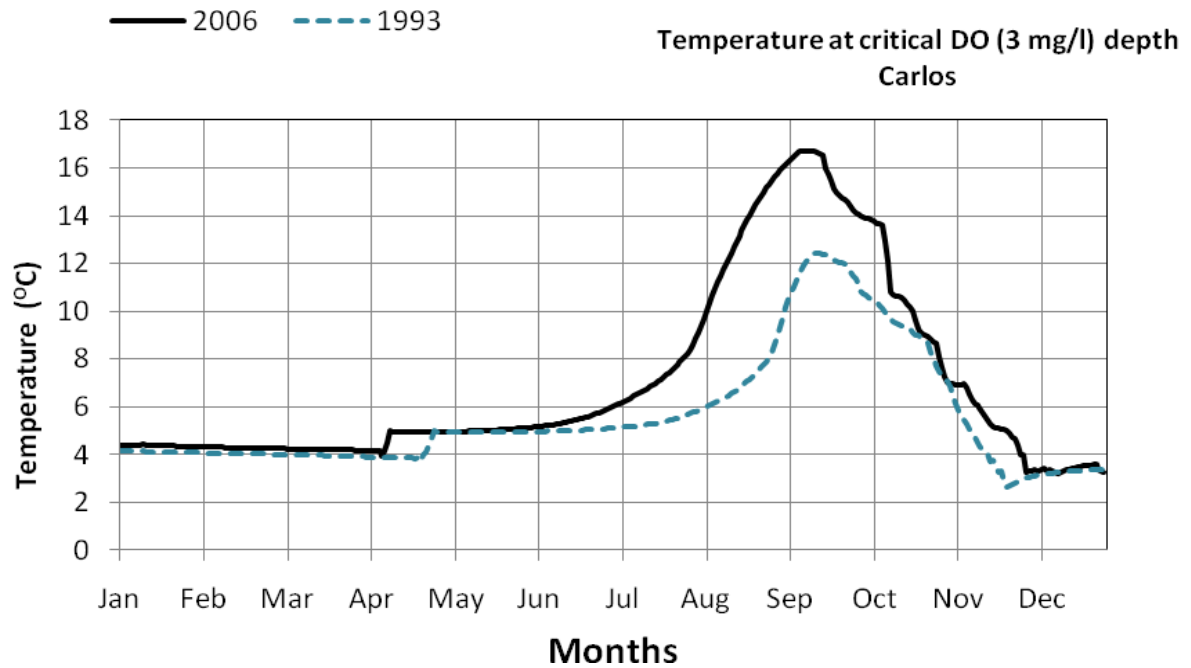


Figure 3.3 Time series of simulated daily TDO3 for Lake Carlos and South Twin Lake (cisco lakes). The two selected years (2006 and 1993) have the highest or lowest annual maximum TDO3 in the simulation period.

Table 3.1 Definitions of twelve different TDO3 parameters that can be extracted from simulated daily temperature and DO profiles.

Parameter		Definition or Description
1. TDO3 <sub>AM</sub>	TDO3 <sub>A</sub>	Maximum daily TDO3 value for each simulated year = annual maximum daily TDO3 (47 values for 1962-2008 simulation period). The subscript “AM” stands for “annual maximum”.
2. MaxTDO3 <sub>AM</sub>	TDO3 <sub>B</sub>	Maximum of annual maximum daily TDO3 values in the simulation period (one value for 1962-2008).
3. AvgTDO3 <sub>AM</sub>	TDO3 <sub>C</sub>	Average of annual maximum daily TDO3 values in the simulation period (one value for 1962-2008).
4. ATDO3 <sub>FB</sub>	TDO3 <sub>D</sub>	Mean daily TDO3 value over the fixed 31-day benchmark period (DOY 209 to DOY 239) for each simulated year (47 values for 1962-2008). The subscript “FB” stands for “fixed benchmark”, and the first letter “A” stands for “average” or mean over the benchmark period.
5. MaxATDO3 <sub>FB</sub>	TDO3 <sub>E</sub>	Maximum of mean daily TDO3 values over the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
6. AvgATDO3 <sub>FB</sub>	TDO3 <sub>F</sub>	Average of mean daily TDO3 values over the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
7. MTDO3 <sub>FB</sub>	TDO3 <sub>G</sub>	Maximum daily TDO3 value within the fixed 31-day benchmark period (DOY 209 to DOY 239) for each simulated year (47 values for 1962-2008). The first letter “M” before TDO3 stands for “maximum daily” within the fixed benchmark period
8. MaxMTDO3 <sub>FB</sub>	TDO3 <sub>H</sub>	Maximum of maximum daily TDO3 values within the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
9. AvgMTDO3 <sub>FB</sub>	TDO3 <sub>I</sub>	Average of maximum daily TDO3 values within the fixed 31-day benchmark period (DOY 209 to DOY 239) in the simulation period (one value for 1962-2008).
10. ATDO3 <sub>VB</sub>	TDO3 <sub>J</sub>	Highest mean daily TDO3 value over variable (sliding) 31-day benchmark periods for each simulated year. The subscript “VB” stands for “variable (sliding) benchmark”. Only the highest mean value in any of the sliding benchmark periods of a year is retained (47 values in 1962-2008).
11. MaxATDO3 <sub>VB</sub>	TDO3 <sub>K</sub>	Maximum of highest mean daily TDO3 values over variable (sliding) 31-day benchmark periods in each simulated year over the simulation period (one value for 1962-2008).
12. AvgATDO3 <sub>VB</sub>	TDO3 <sub>L</sub>	Average of highest mean daily TDO3 values over variable (sliding) 31-day benchmark periods in each simulated year over the simulation period (one value for 1962-2008).

### 3.2 Annual maximum daily TDO3

The maximum daily TDO3 value for each simulated year is labeled  $TDO3_{AM}$ ; the subscript “AM” stands for “annual maximum”. There are 47 values of  $TDO3_{AM}$  if the simulation period is from 1962 to 2008 for a study lake. From these 47 values of  $TDO3_{AM}$ , two more characteristic TDO3 values can be calculated:  $MaxTDO3_{AM}$  and  $AvgTDO3_{AM}$  (Table 3.1).  $MaxTDO3_{AM}$  is the highest of the 47 annual maximum daily TDO3 values in the simulation period, and there is only one value for the entire simulation period 1962-2008.  $AvgTDO3_{AM}$  is the average of the 47 annual maximum daily TDO3 values in the simulation period 1962-2008. The examples of time series of daily TDO3 values in Figures 3.2 and 3.3 are for the years with the highest or lowest annual maximum daily TDO3 in the simulation period. For example,  $TDO3_{AM}$  in South Twin Lake was 26.9 °C and 20.7 in 2006 and 1993, respectively (Fig. 3.3).

Table 3.2 gives the ranges of  $TDO3_{AM}$  values, and the days of occurrence of  $TDO3_{AM}$  in 15 study lakes. For example, water temperature and dissolved oxygen profiles in Lake Carlos were simulated from 1961 to 2008 and  $TDO3_{AM}$  values were found in 47 years (1962 to 2008). Table 3.2 shows that  $TDO3_{AM}$  values in Lake Carlos ranged from 12.43 °C (lowest) to 16.72 °C (highest) and occurred between DOY (day of year or calendar day) 251 (Sep 07) and 275 (Oct 1). Table 3.2 also lists the averages, standard deviations, and ranges (highest and lowest or earliest and latest) annual  $TDO3_{AM}$  values and the day of occurrence of annual  $TDO3_{AM}$  in the 15 study lakes. The highest  $TDO3_{AM}$  values listed in Table 3.2 are the  $MaxTDO3_{AM}$  values in the simulation period. The highest and lowest  $TDO3_{AM}$  values and the earliest and latest days of occurrence in the 15 study lakes are presented graphically in Figures 3.4 and 3.5. Figure 3.6 gives time series plots of annual maximum daily TDO3 in the simulation periods (1961 to 2008 or 1991 to 2008) of the 15 study lakes; cisco lakes are shown by bold lines. The red line for each lake in Figure 3.6 gives  $AvgTDO3_{AM}$ , i.e., the average of annual maximum daily TDO3 values in the simulation period (1961 to 2008 or 1991 to 2008). Values presented in Table 3.2 and Figures 3.2 to 3.6 were calculated from daily temperature and DO profiles simulated using weather stations that are closest to each lake. Table 3.3 lists  $AvgTDO3_{AM}$  values (column 4) for 21 cisco study lakes, which were calculated from daily temperature and DO profiles simulated using International Falls as the same and sole weather station. Two cisco lakes, White Iron and South Twin, have relative large lake geometry ratio ( $GR > 4.0$ ) and their  $AvgTDO3_{AM}$  values are much larger than for the other 19 cisco lakes that have geometry ratios  $GR < 3.0$ . The reason is that  $GR > 4.0$  characterizes polymictic lakes, whereas  $GR < 2.0$  is characteristic of seasonally stratified dimictic lakes.

### 3.3 Average daily TDO3 over a fixed benchmark period

From observed temperature and DO profiles, Jacobson et al. (2010) identified two 31-day summer benchmark periods when the annual maximum daily TDO3 typically occurs in stratified

and unstratified Minnesota lakes. The benchmark period is the period of greatest oxythermal stress for coldwater fish, i.e., it is the period with the highest values of TDO3. For stratified lakes ( $GR < 2.0$ ), the 31-day benchmark period extends from DOY 209 to DOY 239, which is from July 28 to August 27. For unstratified lakes ( $GR > 4$ ), the 31-day benchmark period is from DOY 194 to DOY 224, which is from July 13 to August 12. The difference between stratified and unstratified lakes is about two weeks; unfavorable fish habitat conditions occur earlier in unstratified (polymictic) lakes.

Because most of the cisco lakes in Minnesota are deep stratified lakes, potential refuge lakes will most likely be stratified lakes; a fixed benchmark period from DOY 209 to 239 was therefore used to define the remaining six TDO3 values in Table 3.1.  $ATDO3_{FB}$  is the average or mean daily TDO3 value over the fixed 31-day benchmark period (DOY 209 to 239) for each simulated year. The subscript “FB” stands for “fixed benchmark”, and the first letter “A” stands for “average” or mean over the fixed benchmark period. There are 47 values of  $ATDO3_{FB}$  if the simulation period is from 1962 to 2008 for a study lake. From these 47 values of  $ATDO3_{FB}$ , two more characteristic TDO3 values can be calculated:  $MaxATDO3_{FB}$  and  $AvgATDO3_{FB}$  (Table 3.1).

Figure 3.7 shows time-series plots of average daily TDO3 values over the fixed benchmark period 1962 to 2008 for two cisco lakes: Mukooda Lake (top) with lake geometry ratio  $GR = 1.76$  and mean summer Secchi depth  $SD = 5.12$  m, and Little Trout Lake (bottom) with  $GR = 1.76$  and  $SD = 5.12$  m. TDO3 values were calculated from daily temperature and DO profiles simulated under past climate conditions (1962-2008) at the weather station in International Falls.  $ATDO3_{FB}$  in Mukooda Lake ranged from 5.68 to 9.75°C with standard deviation of 0.78°C over the 47-year period. The maximum value of  $ATDO3_{FB}$  in the simulation period, i.e.,  $MaxATDO3_{FB}$ , occurred in 1965 and 1964, and was 9.75°C and 6.93°C in Mukooda and Little Trout Lake, respectively. Little Trout Lake had better oxythermal habitat conditions for cisco indicated by  $ATDO3_{FB}$  values ranging from 4.53 to 6.93°C with standard deviation of 0.44°C. The average value in the simulation period  $AvgATDO3_{FB}$  was 7.04°C and 5.42°C in Mukooda and Little Trout Lake, respectively.  $AvgATDO3_{FB}$  and  $MaxATDO3_{FB}$  values (lines 5 and 6 in Table 3.1) for the 21 cisco study lakes are summarized in Table 3.3. Lakes in Table 3.3 are arranged by lake geometry ratio, from lowest to highest.

Table 3.2 Statistical summary of TDO<sub>3AM</sub> and calendar day of occurrence of TDO<sub>3AM</sub> in the simulation period (1962-2008 or 1992-2008).

Name of lake	TDO <sub>3AM</sub> in the simulation period (°C)				Day of occurrence of TDO <sub>3AM</sub> in the simulation period				
	Highest TDO <sub>3AM</sub>	Lowest TDO <sub>3AM</sub>	Average TDO <sub>3AM</sub>	Standard Deviation	Earliest Day	Latest Day	Variation <sup>2</sup>	Average day	Standard Deviation
Cisco lakes									
Carlos	16.72	12.43	14.51	0.95	251	275	24	264	6
Cedar	17.77	12.14	15.15	1.39	238	274	36	257	7
Elk <sup>1</sup>	18.45	13.95	16.32	1.24	222	258	36	240	11
Kabekona <sup>1</sup>	14.21	10.94	12.64	1.10	258	277	19	268	5
South Twin <sup>1</sup>	26.89	20.66	23.78	1.64	175	250	75	209	19
Ten Mile <sup>1</sup>	11.52	9.02	10.46	0.74	266	299	33	281	10
Trout	6.81	5.81	6.38	0.26	283	313	30	299	7
White Iron	24.64	19.03	21.51	1.15	201	252	51	222	12
Non-cisco lakes									
Bear Head	20.99	15.13	18.15	1.27	207	253	46	227	11
Carrie	26.36	18.82	22.99	1.59	188	253	65	216	16
Elephant	25.26	19.62	22.56	1.44	179	248	69	213	15
Hill <sup>1</sup>	27.65	10.35	23.26	4.77	202	290	88	230	24
Madison	27.70	20.28	24.16	1.45	176	254	78	210	17
S. Center	25.92	18.44	21.91	1.63	192	251	59	213	15
St Olaf	26.75	19.65	22.99	1.46	177	243	66	211	16

<sup>1</sup> The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008.

<sup>2</sup> “Variation” is the difference between the latest and the earliest day of occurrence of TDO<sub>3AM</sub> in the simulation period.

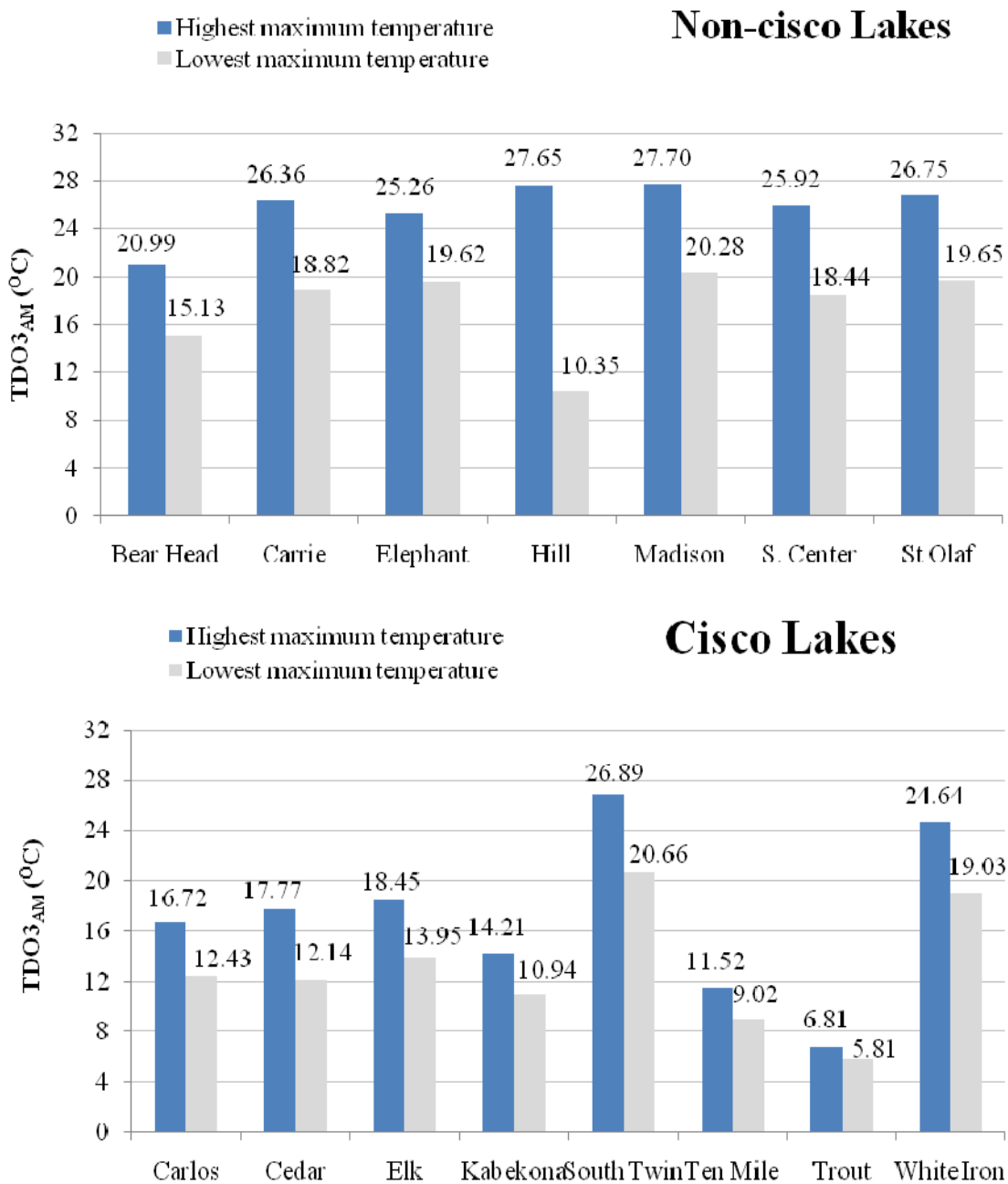


Figure 3.4 Ranges of TDO<sub>3AM</sub> during the simulation period (1962-2008 or 1992-2008) in cisco lakes and non-cisco lakes.



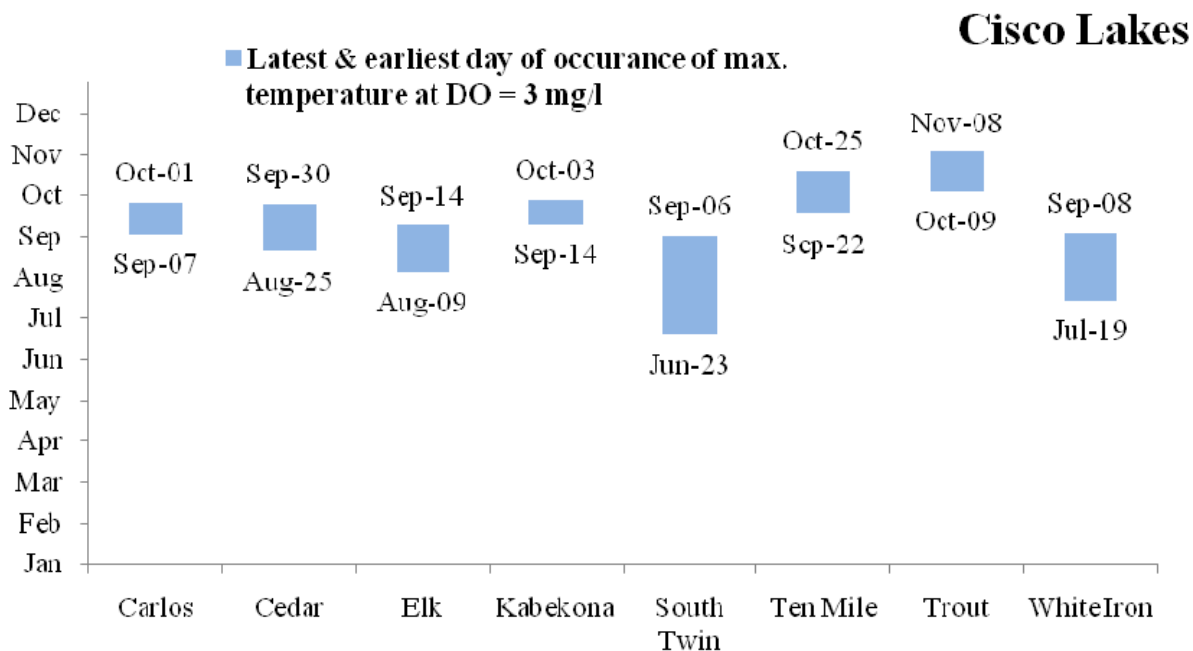
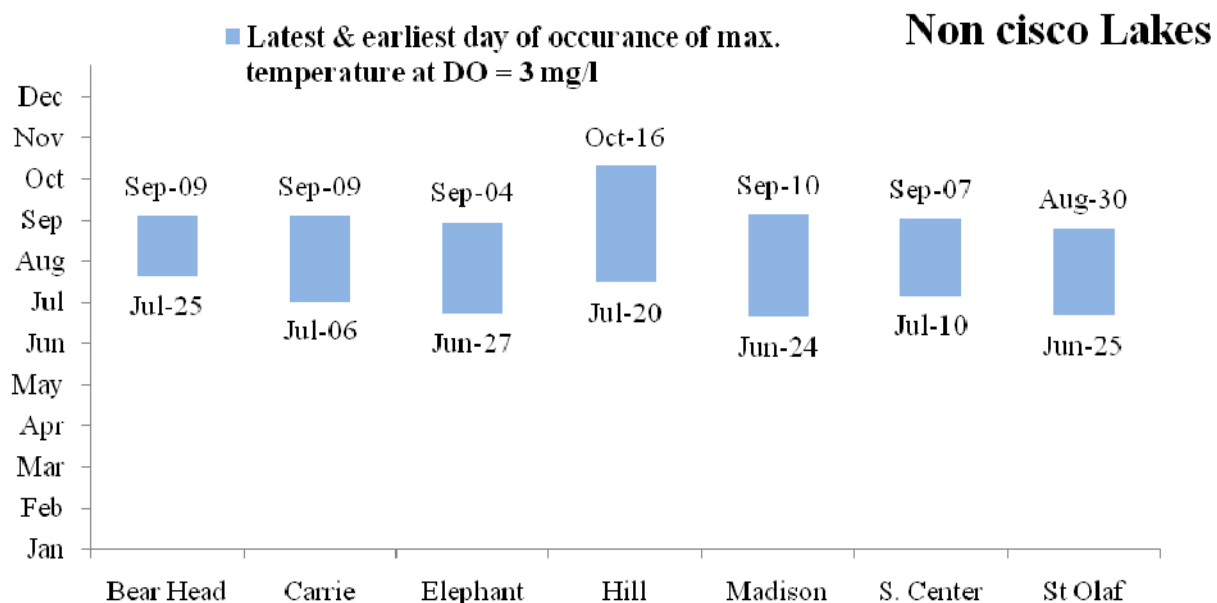


Figure 3.5 Ranges of days of occurrence of TDO<sub>3AM</sub> during the simulation period (1962-2008 or 1992-2008) in cisco lakes and non-cisco lakes.

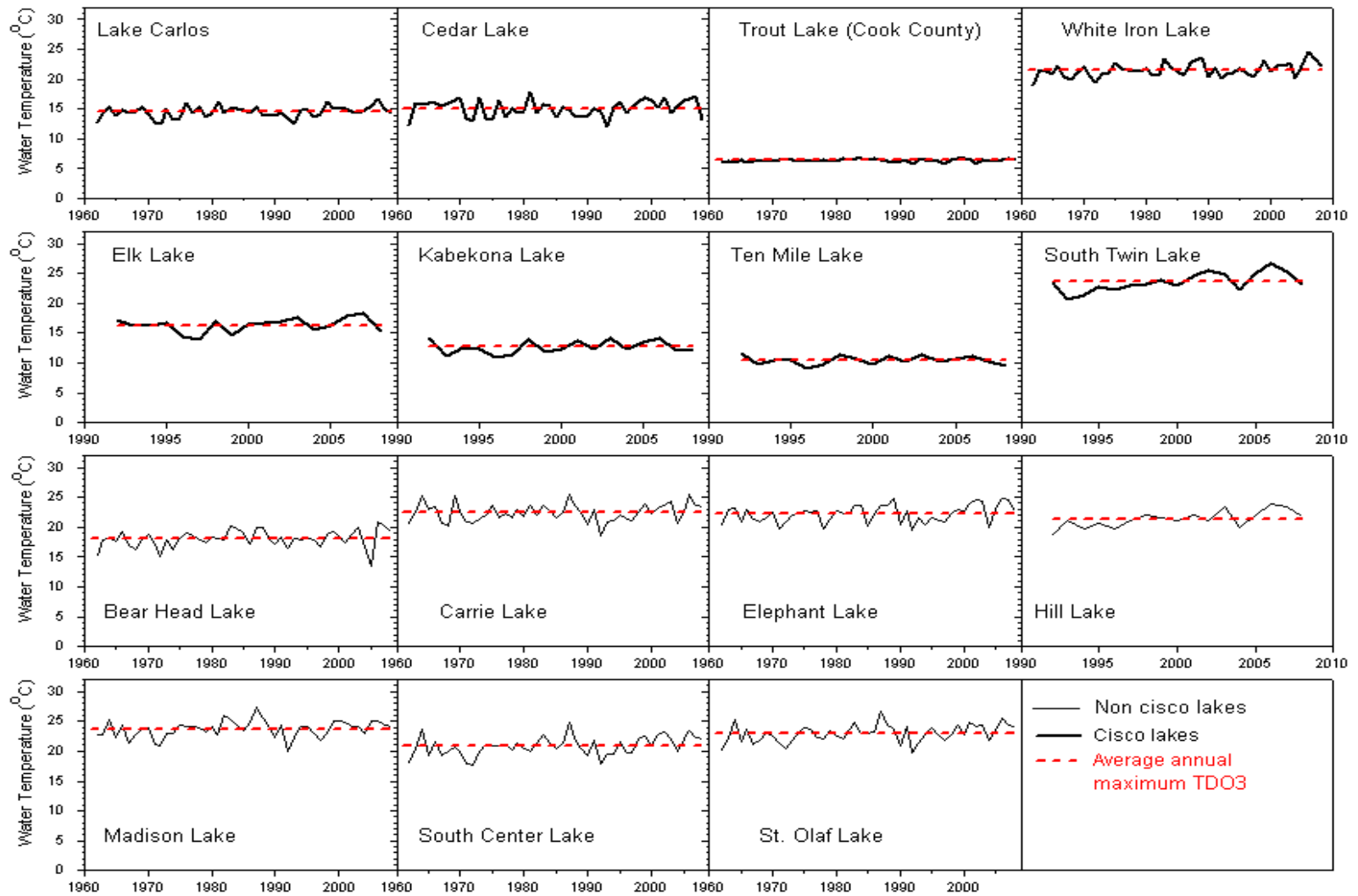


Figure 3.6 Time series of annual maximum TDO3<sub>AM</sub> in 8 cisco and 7 non-cisco lakes under past climate conditions.

Table 3.3 Values of GR, SD, and three TDO3 parameters ( $^{\circ}\text{C}$ ) (**AveTDO3<sub>AM</sub>**, **AveATDO3<sub>FB</sub>**, and **MaxATDO3<sub>FB</sub>**, Table 3.1, lines 4, 5, and 6) for **21 cisco lakes** under past climate conditions from 1962 to 2008. **International Falls weather** data were used for the simulations.

Lake Name	Geometry ratio (GR, $\text{m}^{-0.5}$ )	Secchi depth (SD, m)	Annual maximum AveTDO3 <sub>AM</sub>	Benchmark mean AveATDO3 <sub>FB</sub>	Benchmark maximum MaxATDO3 <sub>FB</sub>
Six	0.69	3.94	9.12	6.62	7.42
Grindstone	0.82	2.88	5.22	4.52	4.55
Ten Mile	1.05	5.92	9.78	8.01	8.54
Little Trout	1.08	6.33	5.72	5.42	5.49
Carlos	1.13	3.40	11.78	6.37	7.47
Elk	1.16	2.50	14.55	12.69	14.11
Cedar	1.17	3.40	12.52	9.24	10.78
Big Trout	1.24	4.78	8.00	5.94	6.30
Kabekona	1.34	3.70	11.55	7.67	9.04
Trout (Cook)	1.39	5.40	10.20	6.51	7.36
Snowbank	1.41	5.28	8.09	6.44	6.74
Little Sand	1.45	5.22	7.65	6.06	6.38
Siseebakwet	1.50	3.89	14.14	10.30	12.30
Greenwood	1.57	5.46	8.09	6.47	6.81
Mukooda	1.76	5.12	9.41	7.04	7.51
Burntside	1.91	5.80	7.41	6.30	6.52
Blue	2.04	6.76	14.93	11.88	13.64
Fish Hook	2.19	3.44	15.06	12.26	14.33
Trout (St. Louis)	2.50	4.71	11.23	8.91	9.51
White Iron	4.26	1.50	21.95	20.47	21.71
South Twin	5.22	2.90	22.95	20.31	22.23

### 3.4 Annual maximum daily TDO3 value within the fixed benchmark period

MTDO3<sub>FB</sub> is the maximum daily TDO3 value within the fixed 31-day benchmark period (DOY 209 to 239) for each simulated year. The letter “M” stands for “maximum daily” within the fixed benchmark period, indicated by subscript FB. There are 47 values of MTDO3<sub>FB</sub> if the simulation period is from 1962 to 2008 for a study lake. From these 47 values of MTDO3<sub>FB</sub>, two more characteristic TDO3 parameters can be calculated: MaxMTDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub> (lines 8 and 9 in Table 3.1). Figure 3.7 shows time-series plots of maximum daily TDO3 values over the fixed benchmark period from 1962 to 2008 (using International Falls weather data) for Mukooda Lake (top) and Little Trout Lake (bottom). MTDO3<sub>FB</sub> in Mukooda Lake ranged from 6.08 to 10.42°C with a standard deviation of 0.87°C. The maximum value of MTDO3<sub>FB</sub> in the simulation period, i.e., MaxMTDO3<sub>FB</sub>, was 10.42°C and 6.95°C in Mukooda and Little Trout Lake, respectively. The average value in the simulation period AvgMTDO3<sub>FB</sub> was 7.51°C and 5.49°C in Mukooda and Little Trout Lake, respectively. The average difference between MTDO3<sub>FB</sub> (maximum daily TDO3) and ATDO3<sub>FB</sub> (average daily TDO3) in Mukooda Lake was 0.46°C (range from 0.28 to 1.06°C from 1962 to 2008); in Little Trout Lake it was only 0.084°C (range from 0.02 to 0.13°C from 1962 to 2008). Figure 3.7 shows that the year by year variations of MTDO3<sub>FB</sub> and ATDO3<sub>FB</sub> due to weather variations within the simulation period are much larger than the differences between the MTDO3<sub>FB</sub> and ATDO3<sub>FB</sub>.

### 3.5 Average daily TDO3 over a sliding benchmark period

The period of greatest oxythermal stress for coldwater fish depends on the type of lake (strongly stratified versus weakly stratified, as related to lake geometry ratio GR). One may ask whether the benchmark period could shift under future climate scenarios. To answer this question, the concept of a sliding benchmark period evolved in discussions among research team members. The sliding benchmark period can still be 31 days long, the same as the fixed benchmark period used before and proposed by Jacobson et al. (2010). In a simulation period from May 1 to October 31 there would be 184 31-day sliding benchmark periods.

Each sliding benchmark period must contain the day when the annual maximum daily TDO3 occurs in that year. Over each sliding benchmark period, the average daily TDO3 can be calculated, and only the highest of these values in any of the sliding benchmark periods of a year is retained. This value is called ATDO3<sub>VB</sub>. The subscript “VB” stands for “variable (sliding) benchmark” period. There are 47 values of ATDO3<sub>VB</sub> for a study lake if the simulation period is from 1962 to 2008. From these 47 values of ATDO3<sub>VB</sub>, two more characteristic TDO3 parameters can be calculated: MaxATDO3<sub>VB</sub> and AvgATDO3<sub>VB</sub> (lines 11 and 12 in Table 3.1).

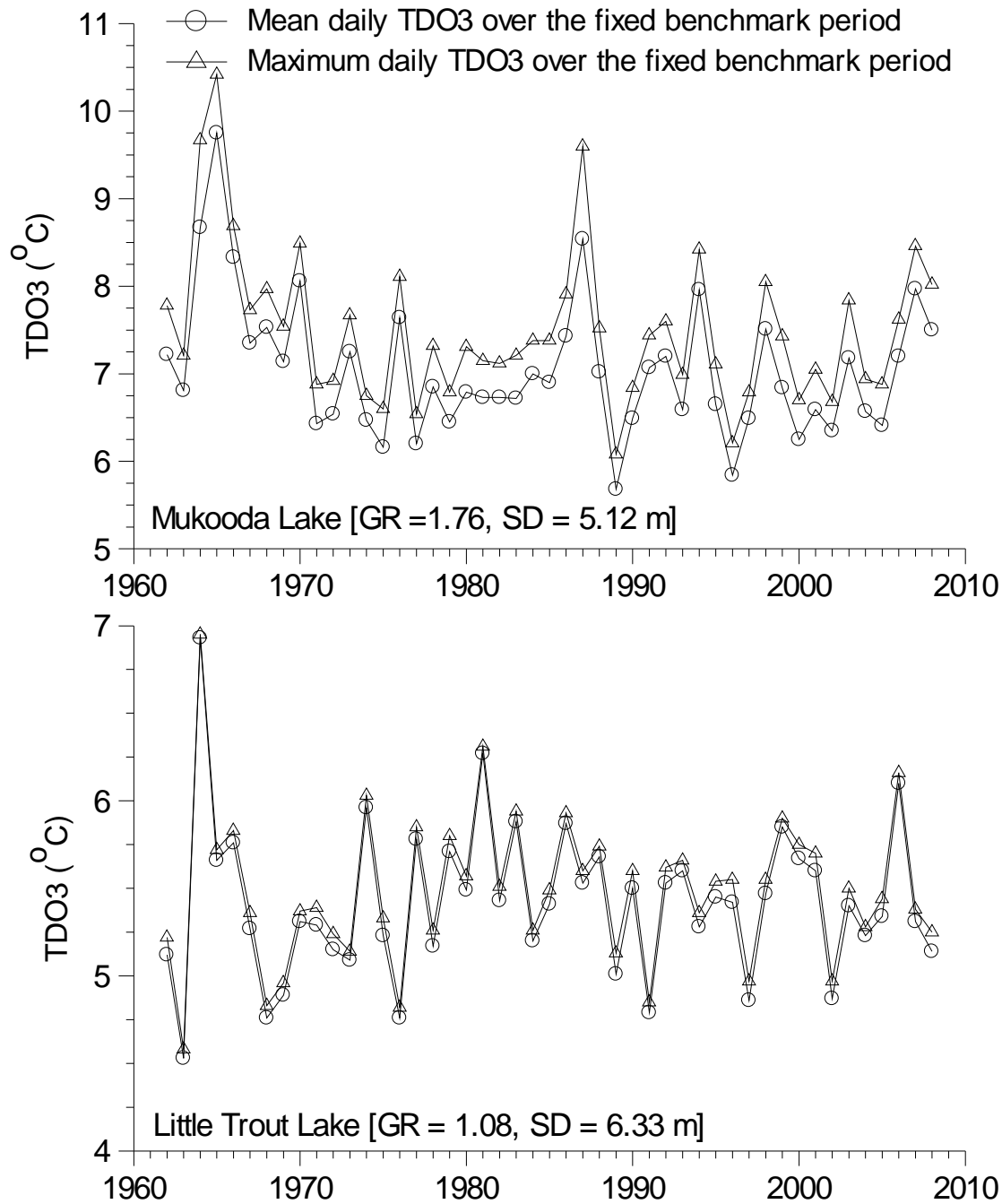


Figure 3.7 Time series plot of average (mean) and maximum daily TDO3 values for the **fixed benchmark period** (DOY 209 to 239) from 1962 to 2008 for Mukooda (top) and Little Trout Lake (bottom). **International Falls weather** data were used for the simulations.

We also determined the beginning dates of the variable (sliding) 31-day benchmark periods that had given the highest  $ATDO3_{VB}$  value, i.e., the average (mean) daily TDO3 value that was the highest of all sliding benchmark periods in each simulated year (line 10 in Table 3.1). The fish habitat computer program was updated for that purpose. Annual time series and average values of the beginning dates over the simulation period (e.g., 47 years from 1962 to 2008) were calculated for each of the 30 virtual lakes. Figure 3.8 shows time series of the benchmark period beginning dates for past climate (1962 to 2008) and the CGCM 3.1 future climate scenario. For these examples, LakeC06 and LakeC08 (Table 1.2), and Duluth weather data were used in the model simulations.

The beginning dates of the variable benchmark periods that had given the highest  $ATDO3_{VB}$  values ranged from DOY 192 to 226 for LakeC06 and from DOY 241 to 271 for LakeC08 under past climate condition. Average beginning dates were DOY 210 for LakeC6 and DOY 253 for LakeC08 under past climate conditions (1962 to 2008). These two virtual lakes have the same lake geometry ( $GR = 1.11$ ) 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 (Table 1.2 and Fig. 3.8). Figure 3.8 illustrates that the beginning date of greatest oxythermal stress for coldwater fish in different types of lakes can be quite different. It is noteworthy that there is not much difference between future and past climate scenarios; the average beginning date of the highest  $ATDO3_{VB}$  benchmark period is projected to be DOY 205 for LakeC06 and DOY 251 for LakeC08 under the CGCM 3.1 future climate scenario, only 5 and 2 days, respectively, different from past climate conditions.

Figures 3.9, 3.10, and 3.11 show the average beginning dates of greatest oxythermal stress under past climate conditions (1962 to 2008), and the CGCM 3.1 and MIROC 3.2 future climate scenarios for Duluth, International Falls, and St. Cloud weather data, respectively. The beginning dates are given as contours on a plot of Secchi depth ( $SD$ ) vs. geometry ratio ( $GR$ ); the contours were derived by interpolation from simulated data points for the 30 virtual lakes (Table 1.2). A listing of average beginning dates of the variable benchmark periods for the 30 virtual lakes is given in Appendix B (Tables B.1 to B.3). Statistical summaries of average beginning dates of variable benchmark periods in the 47-year simulation period are given in Table 3.4 for the three principal weather stations and the three climate scenarios. Average beginning dates of variable benchmark periods for  $ATDO3_{VB}$  ranged from DOY 200 (July 19) to DOY 288 (October 15). 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. The difference between the latest and earliest beginning date of the greatest oxythermal stress period for cisco in Minnesota lakes was 59 to 89 days, i.e. 2 to 3 months. Simulations of 30 virtual lakes with input data from three weather stations gave these results (Table 3.4). Therefore, it seems advisable to calculate mean daily TDO3 values using variable (sliding) benchmark periods in order to identify periods of greatest oxythermal stress. In this study, the

value of AvgATDO3<sub>VB</sub> in Table 3.1, may therefore be the most useful to identify refuge lakes for cisco. A comparison with other options will be given in Chapter 5.

Differences of average beginning dates of variable benchmark periods for highest mean daily TDO3 between future climate scenarios and past climate are given in Table 3.5. Maximum differences ranged from -11 to 19 days (Table 3.5), and mean differences from -1 to 3 days. Under a future climate scenario, the beginning date of the variable benchmark period occurs later if the difference is positive, and earlier if the difference is negative. The differences in beginning dates of oxythermal stress on cisco between future and past climate are much smaller (nearly negligible) compared to the differences among different lake types (Figs. 3.9 to 3.11), and from year to year (Fig. 3.8).

Table 3.4 Statistics of the beginning date (DOY = day of year or calendar date) of the variable (sliding) benchmark period for highest mean daily TDO3 (ATDO3<sub>VB</sub>, line 10 in Table 3.1) under **past climate conditions (1962-2008) and two future climate scenarios** using weather data from **three principal weather stations**.

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

Table 3.5 Statistics of the differences between beginning dates of **variable (sliding) benchmark periods** given in Table 3.4. 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
Standard Deviation	8	7	7	8	8	7

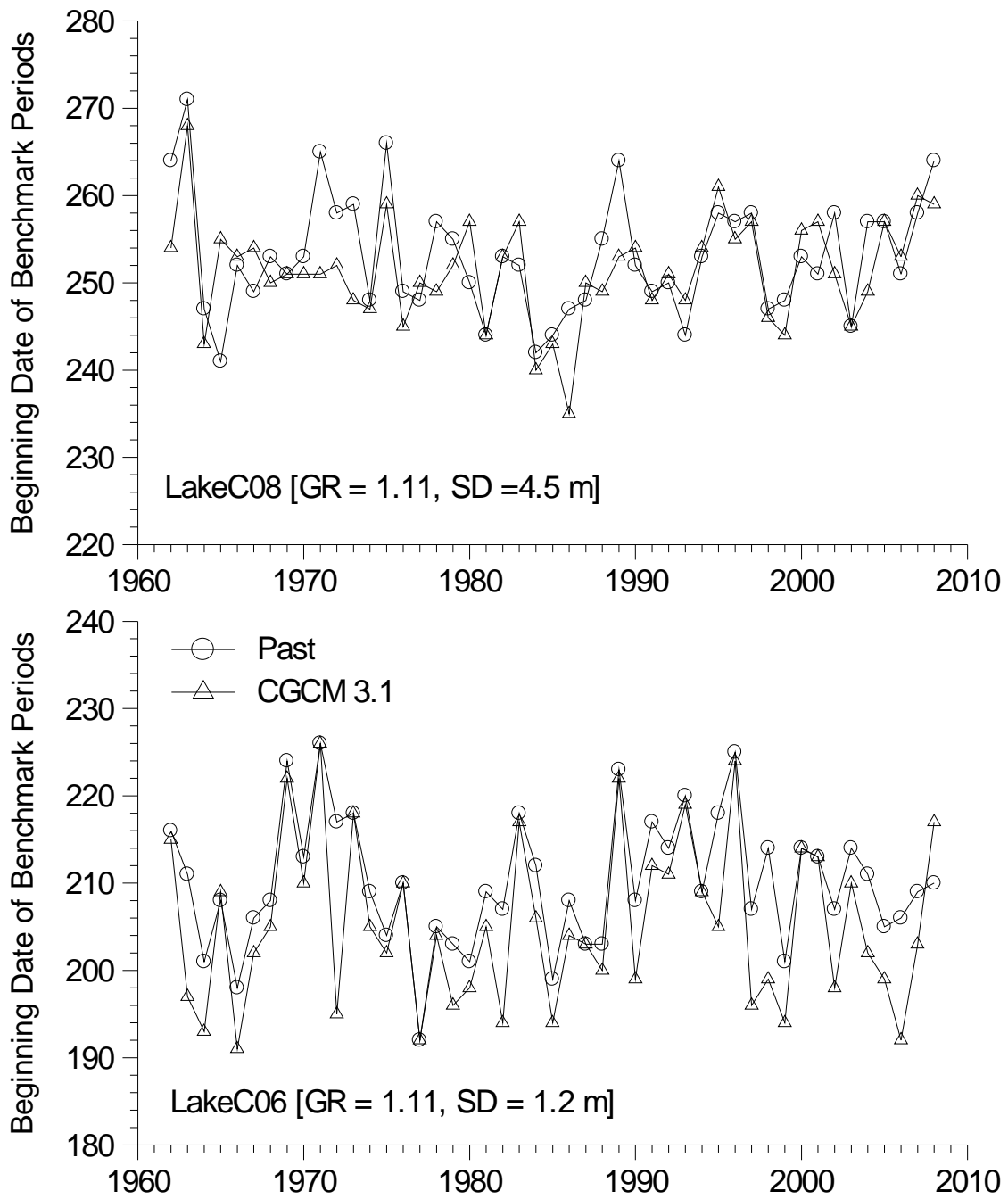


Figure 3.8 Time series plot of the beginning date of the variable benchmark periods for **past climate (1962-2008)** and the **CGCM 3.1 future climate scenario** for virtual LakeC06 and LakeC08. **Duluth weather** data were used for the model simulations.



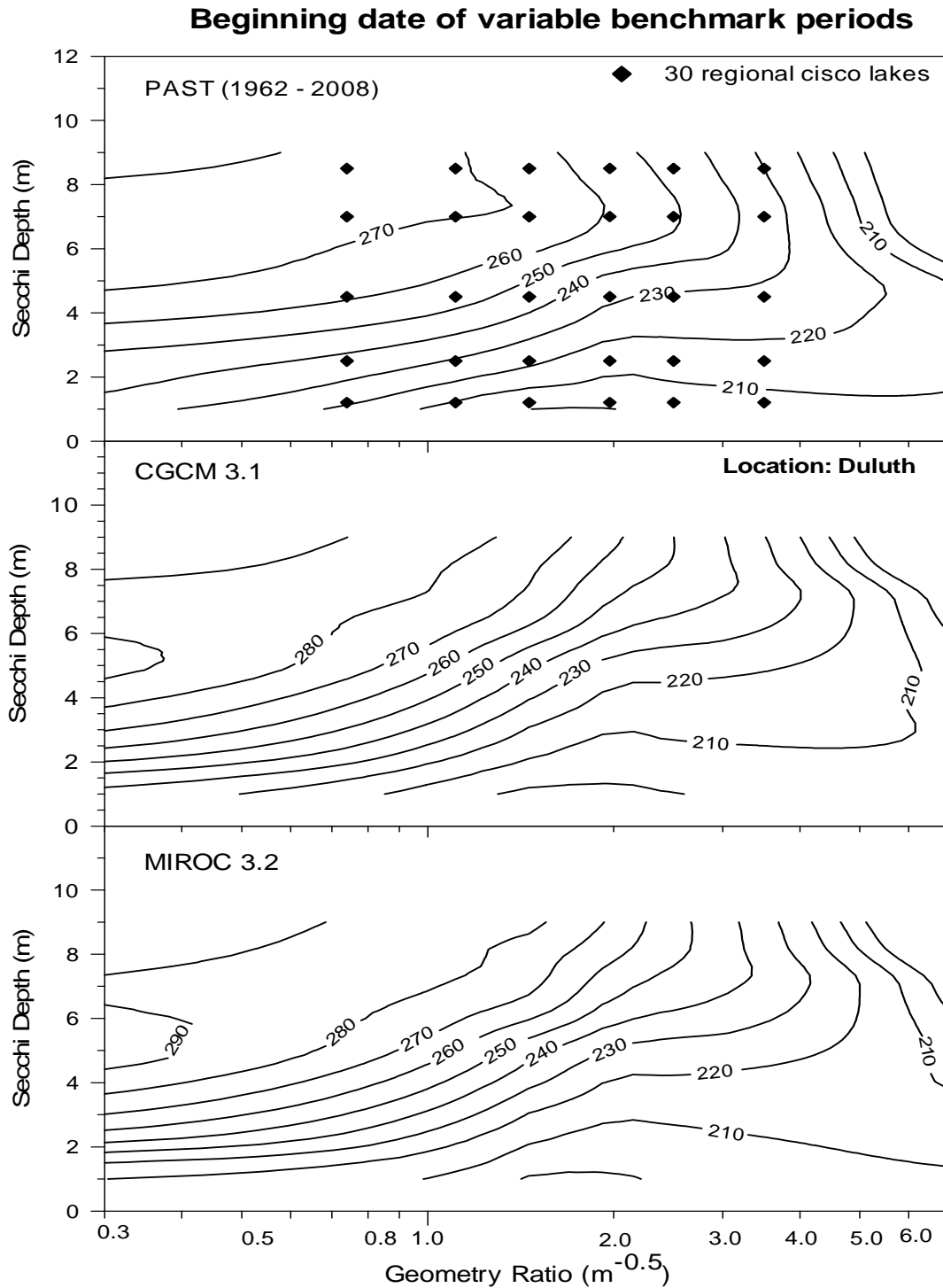


Figure 3.9 Contour plots giving the average beginning date of the variable benchmark periods under **past climate (1962-2008)**, **CGCM 3.1** and **MIROC 3.2** future climate scenarios. **Duluth** weather data were used for the model simulations. Contours were derived by interpolation from simulated data points for **30 virtual lakes**.

### Beginning date of variable benchmark periods

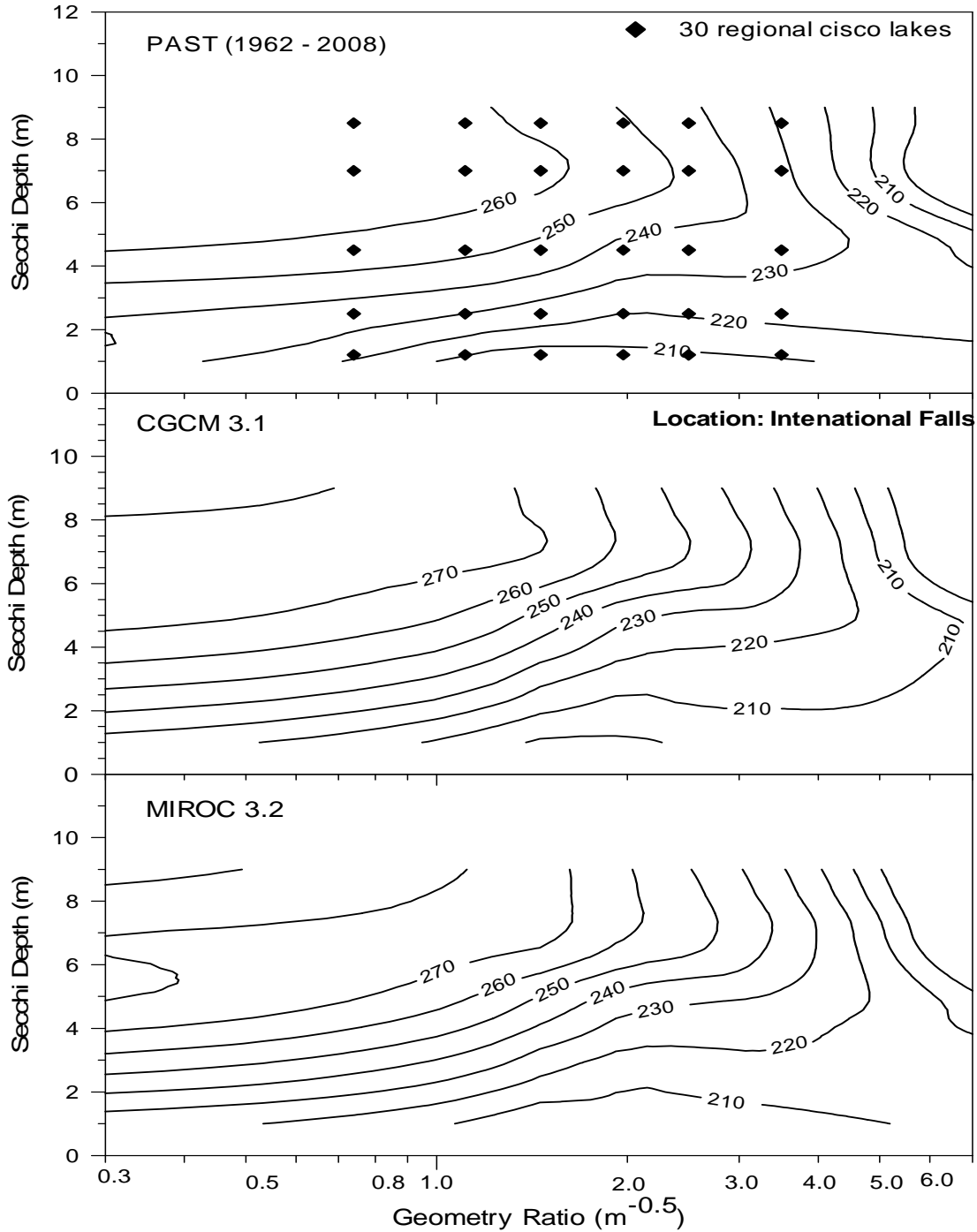


Figure 3.10 Contour plots giving the average beginning date of the variable benchmark periods under **past climate (1962-2008)**, **CGCM 3.1** and **MIROC 3.2 future climate scenarios**. **International Falls weather data** were used for the model simulation. Contours were derived by interpolation from simulated data points for **30 virtual lakes**.

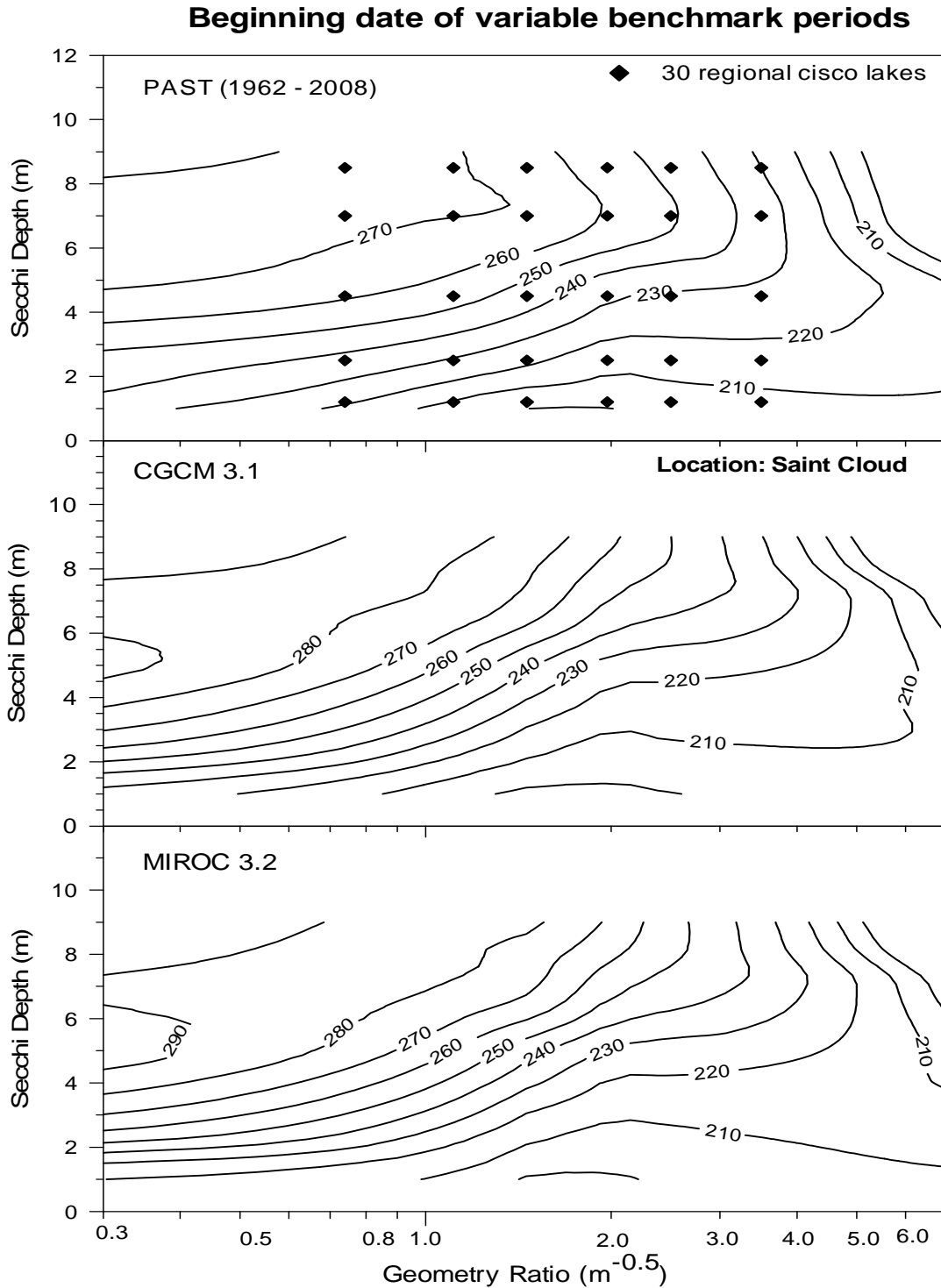


Figure 3.11 Contour plots giving the average beginning date of the variable benchmark periods under **past climate (1962-2008)**, **CGCM 3.1** and **MIROC 3.2** future climate scenarios. **St. Cloud** weather data were used for the model simulation. Contours were derived by interpolation from simulated data points for **30 virtual lakes**.

### 3.6 TDO3 values under future climate scenarios

MINLAKE2010 was run to simulate water temperature and DO profiles under two future climate scenarios: CGCM 3.1 and MIROC 3.2. Annual maximum daily TDO3 ( $TDO3_{AM}$ ) values for the first set of 15 study lakes were calculated using projected temperature and DO profiles in lakes under the future climate scenario CGCM 3.1. Results are plotted in Figure 3.12. A comparison between Figure 3.4 and Figure 3.12 shows that all 15 study lakes have higher  $TDO3_{AM}$  values under a future warmer climate scenario.

The three cisco lakes with the lowest projected  $TDO3_{AM}$  values under the future CGCM 3.1 climate scenario were Kabekona, Ten Mile and Trout Lake. These three lakes have a low geometry ratio ( $GR = 1.34, 1.05$  and  $1.39 \text{ m}^{-0.5}$ , respectively), and a high Secchi depth ( $SD = 5.92 \text{ m}$  for Ten Mile and  $SD = 5.4 \text{ m}$  for Trout Lake). These are strongly stratified and very transparent lakes in summer. On the other hand, two cisco lakes (South Twin and White Iron Lake) have relatively high  $TDO3_{AM}$  values for both past (Fig. 3.4) and future climate (Fig. 3.12) conditions. Both lakes are weakly stratified (or polymictic) lakes ( $GR = 5.22$  and  $4.26 \text{ m}^{-0.5}$ , respectively). These observations show that TDO3 values are closely related to GR and SD values of individual lakes. This will be illustrated and analyzed further in Chapter 4.

Table 3.6 gives sample results of average TDO3 values for a 47-year simulation period for the 21 cisco study lakes in the expanded sample set. The future climate scenario CGCM 3.1, and International Falls weather data were used for the model simulations. Lakes in Table 3.6 are sorted by lake geometry ratio from lowest to highest. The values given in Table 3.6 are for  $AveTDO3_{AM}$ ,  $AveATDO3_{FB}$ , and  $MaxATDO3_{FB}$  as defined in Table 3.1. Values of these same TDO3 parameters for simulated past climate conditions (1962 to 2008) were given in Table 3.3 and can be compared with those in Table 3.6.

Table 3.6 Values of GR, SD and three TDO3 parameters (°C) (**AveTDO3<sub>AM</sub>**, **AveATDO3<sub>FB</sub>**, and **MaxATDO3<sub>FB</sub>**, Table 3.1, lines 4, 5, and 6) in the simulation period for **21 cisco study lakes** under the **CGCM 3.1 future climate scenario**. **International Falls weather data** were used.

Lake Name	Geometry ratio (GR, m <sup>-0.5</sup> )	Secchi depth (SD, m)	Annual maximum AveTDO3 <sub>AM</sub>	Benchmark mean AveATDO3 <sub>FB</sub>	Benchmark maximum MaxATDO3 <sub>FB</sub>
Six	0.69	3.94	10.89	7.45	8.39
Grindstone	0.82	2.88	5.63	4.79	4.85
Ten Mile	1.05	5.92	11.59	8.80	9.34
Little Trout	1.08	6.33	6.30	5.73	5.82
Carlos	1.13	3.40	15.31	8.11	10.57
Elk	1.16	2.50	18.46	16.91	18.2
Cedar	1.17	3.40	16.43	12.44	14.52
Big Trout	1.24	4.78	10.23	6.98	7.54
Kabekona	1.34	3.70	14.61	9.94	12.02
Trout (Cook)	1.39	5.40	12.95	7.50	8.83
Snowbank	1.41	5.28	10.05	7.31	7.74
Little Sand	1.45	5.22	10.07	6.85	7.55
Siseebakwet	1.50	3.89	17.64	13.85	16.38
Greenwood	1.57	5.46	11.33	7.48	8.47
Mukooda	1.76	5.12	12.01	8.43	9.33
Burntside	1.91	5.80	8.29	6.89	7.08
Blue	2.04	6.76	18.66	14.79	17.38
Fish Hook	2.19	3.44	18.54	16.35	18.11
Trout (St. Louis)	2.50	4.71	14.95	10.77	13.17
White Iron	4.26	1.50	25.32	23.46	24.93
South Twin	5.22	2.9	26.15	23.2	25.31

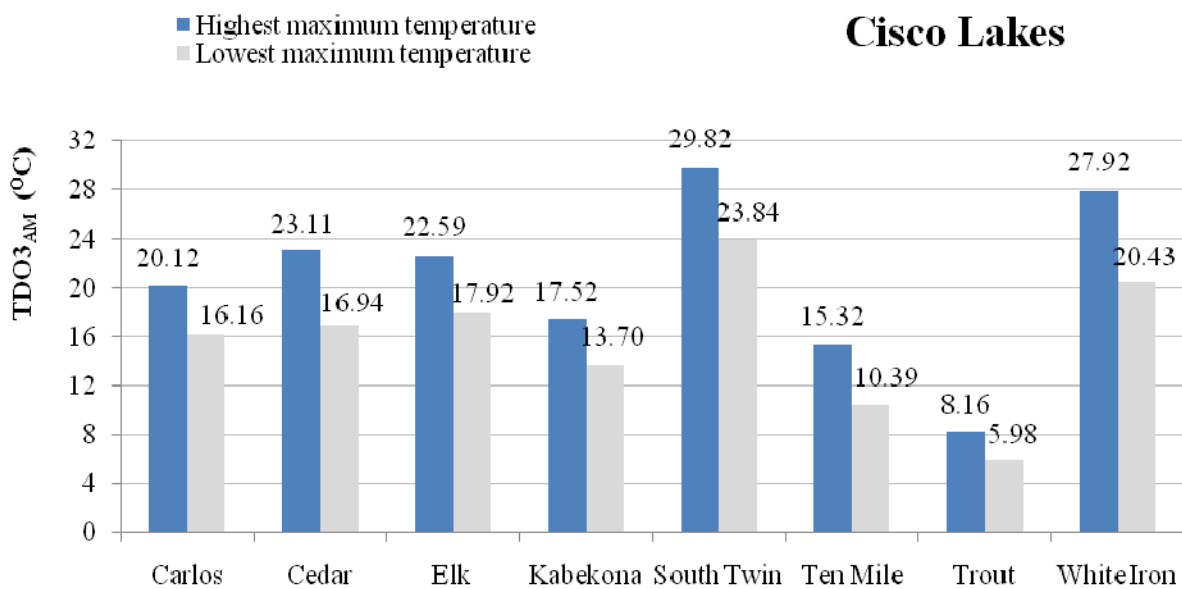
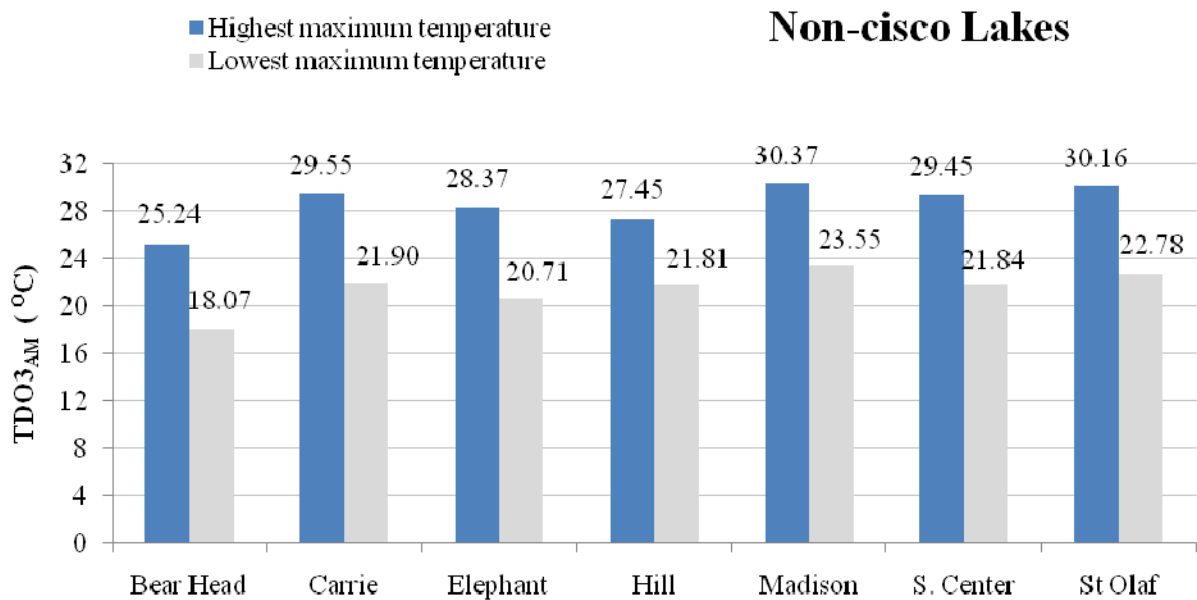


Figure 3.12 Ranges of TDO<sub>3AM</sub> (annual maximum temperature where DO is 3.0 mg/L) under the CCC GCM 3.1 future climate scenario (A1B scenario) in cisco and non-cisco lakes.

## **Chapter 4 Simulation Results for TDO3 Parameter Values in Minnesota Cisco Lakes under Past and Future Climate Scenarios**

Oxythermal habitat parameters TDO3 defined in Table 3.1 were calculated from simulated daily temperature and DO profiles for the 21 cisco study lakes (Table 1.1) and 30 virtual cisco lakes (Table 1.2) under past and future climate conditions. Daily water temperature and DO profiles were simulated using the MINLAKE2010 model. In this chapter the simulated and computed results for selected TDO3 parameters are presented as tabulated results and in contour plots as a function of two principal lake characteristic parameters, i.e., lake geometry ratio (GR) (Gorham and Boyce 1989) as a measure of the strength of stratification, and Secchi depth (SD) as a measure of transparency and lake trophic status. The choice of these two parameters will be justified in the next paragraphs. The results given in this chapter provide the basis for the selection of cisco refuge lakes presented in Chapter 5.

As an alternative to the use of measured lake temperature and DO profiles, Jacobson et al. (2010) developed a generalized model to predict TDO3 as a function of lake productivity, climate, and relative depth (lake geometry ratio,  $GR = A_s^{0.25}/H_{max}$ ). Summer total phosphorus concentration was the variable to represent lake productivity of each lake (Jacobson et al. 2010).

In this study, total phosphorus concentration was not a model parameter, and is not used to characterize any of the 21 cisco study lakes or 30 virtual lakes. Instead, Secchi depth (SD), a measure of lake transparency, was used to represent trophic state as well as radiation attenuation in a Minnesota lake. The trophic state expresses primary productivity and is directly related to DO production by photosynthesis in a lake. Trophic state ranges from oligotrophy (nutrient-poor, biologically unproductive) to eutrophy (nutrient-rich, productive).

In this study, daily water temperature and DO profiles in lakes were simulated by the MINLAKE2010 model under past climate conditions and two future climate scenarios. The model uses climate data as model input, and can therefore simulate future climate scenarios for which no measurements exist. 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). Typical (generic) seasonal growth patterns derived from extensive field observations in temperate lakes (Marshall and Peters 1989) were imposed in the model. Secchi depth (SD) and lake geometry ratio (GR) are representative parameters to characterize each of the 620 cisco lakes in the database. Contour plots of TDO3 parameters presented in this chapter used lake geometry ratio and Secchi depth as x- and y- axes.

#### 4.1. Contour plots of TDO3 characteristic parameters in 21 cisco study lakes

During a research project meeting in February 2010, three TDO3 characteristic parameters,  $AvgTDO3_{AM}$ ,  $AvgATDO3_{FB}$ , and  $AvgMTDO3_{FB}$  (Table 3.1, line 3, line 6 and line 9, respectively), were identified as useful TDO3 parameters to identify and select refuge lakes that have the potential to sustain cisco habitat after climate warming in Minnesota. Because summer water temperature and DO stratification in a lake are very much related to geometry ratio (GR) and Secchi depth (SD) of a lake (Stefan et al. 1996), contour plots of  $AvgTDO3_{AM}$ ,  $AvgATDO3_{FB}$ , and  $AvgMTDO3_{FB}$  were created for the 21 cisco study lakes using GR and SD as independent variables.

Calibrations of the MINLAKE2010 model for each of the 21 cisco study lakes had been conducted with climate data from a weather station closest to each lake as model input as described in Project Report 2 of this study (Fang et al. 2010). Although Class I weather stations in Minnesota had continuous daily weather data from 1961 to 2008, daily data for Class II weather stations were limited to the period from 1991 to 2008. A common simulation period from 1991 to 2008 was therefore used to calculate numerical values of the above three TDO3 characteristic parameters for use in the contour plots.

Table 4.1 gives geometry ratio, mean summer Secchi depth, and  $AvgTDO3_{AM}$  for the 21 cisco study lakes, determined by using the weather station closest to each lake and the same simulation period (1991 to 2008). Figure 4.1 shows contour plots of  $AvgTDO3_{AM}$ ,  $AvgATDO3_{FB}$ , and  $AvgMTDO3_{FB}$  that were obtained by interpolating computed values at the data points shown as filled circles in Fig. 4.1. TDO3 parameter values reported in Figure 4.1 were calculated using simulated daily temperature and DO profiles using weather data from the weather station closest to each individual lake.

To facilitate the comparison of TDO3 parameter values, contour plots should be developed by using weather data over the same simulation period and from the same weather station for all study lakes. Figure 4.2 presents contour plots of  $AvgTDO3_{AM}$ ,  $AvgATDO3_{FB}$ , and  $AvgMTDO3_{FB}$  using the same weather data (from Duluth) for all 21 cisco study lakes for the same simulation period from 1962 to 2008.

The distribution of the 21 cisco study lakes (dots) on the plot of lake geometry ratio (GR) vs. Secchi depth (SD) is shown in the top frame of Figs. 4.1 and 4.2. One can see that the 21 cisco study lakes are not distributed uniformly on the contour plot as previously discussed in Chapter 1. In areas of the plot where simulated TDO3 parameter values are missing extrapolations can result in misleading contour patterns. This is the case in Figs. 4.1 and 4.2 where Secchi depth becomes larger, and most of the contour lines bend towards smaller geometry ratios (to the left), although no data points exist to support this behavior. TDO3 parameter values for lakes with higher Secchi depths (more oligotrophic lakes) are missing from



the plot. The extrapolated higher TDO3 parameter values in the more oligotrophic lakes erroneously indicate unfavorable habitat conditions for cisco. This is incorrect, because it contradicts field observations: we have already documented that cisco prefer to live in deep oligotrophic lakes. Additional data points are needed for areas not covered by actual study lakes on the plot. These data points can be provided by simulations of virtual cisco lakes that fill in the gaps on the contour plots of TDO3 parameters using geometry ratio (GR) and Secchi depth (SD) as x- and y-axes.

Thirty virtual cisco lakes were introduced as discussed in Section 1.2. They are more or less uniformly distributed on the plot of lake geometry ratio versus Secchi depth (Figure 1.2). Even though the selection of lake geometry (surface areas and maximum depths) and SD for the 30 virtual cisco lakes was arbitrary, the selected values are in general representative of the 620 cisco lake database as indicated in Table 1.3 and Figure 1.3. Therefore, daily water temperature and DO profiles were simulated using MINLAKE2010 under past climate conditions and two future climate scenarios not only in the 21 cisco study lakes but also in the 30 virtual cisco lakes. Characteristic TDO3 parameters defined in Table 3.1 were calculated from these profiles and plotted as point values in a coordinate system of SD versus GR. By interpolation of simulated data points of characteristic TDO3 parameter values from the 21 study cisco lakes and the 30 virtual cisco lakes combined, or only using the 30 virtual cisco lakes, contour plots for selected TDO3 parameters were developed for past and future climate conditions.

In the model simulations of the 21 cisco study lakes, calibrated model parameters were used to enhance the performance of the MINLAKE2010 model. Six model parameters were used for model calibration as described in Project Report 2 (Fang et al. 2010). An analysis of each calibration parameter was performed, and generalized model parameters were proposed and tested. For example, the proposed BOD values are 1.50, 0.75, and 0.50 mg/L for eutrophic, mesotrophic, and oligotrophic lakes, respectively. EMCOE(2) is the multiplier for sedimentary oxygen demand (SOD) below the mixed layer and was found to depend on both maximum depth and trophic status (Fang et al. 2010). Proposed SOD values below the mixed layer after applying EMCOE(2) were 1.50, 1.25, and 1.00 g O<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup> for deep ( $H_{\max} \geq 24$  m) eutrophic, mesotrophic, and oligotrophic lakes, respectively. Although there is no lake with a Secchi depth greater than 7.0 m in the 21 cisco study lakes we have some knowledge of model parameter values for virtual cisco lakes having large Secchi depths. For these highly oligotrophic lakes with large SD values, photosynthesis is not limited by light but by low phytoplankton populations expressed by low chlorophyll-concentrations in the model. In these lakes photosynthesis occurs at a low rate throughout the euphotic zone, and there is little production of organic matter in the epilimnion that settles into the hypolimnion and to the lake bottom (Cole 1983). Therefore, sediment oxygen demand below the mixed layer is low, and the multiplier for SOD below the mixed layer needs to be reduced. For virtual cisco lakes with SD = 7.0 m and 8.5, the proposed SOD values below the mixed layer after applying EMCOE(2) were 0.40, and

0.20 g O<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup>, respectively. These generalized model parameters were used in the model simulations of the virtual cisco lakes for past and future climate scenarios.

Table 4.1 Values for GR, SD, and the average of annual maximum daily TDO3 (**AvgTDO3<sub>AM</sub>**, Table 3.1, line 3) for the **simulation period (1962 to 2008)** determined with **weather data input from a station closest to each of the 21 cisco study lakes**.

<b>Lake Name</b>	<b>Geometry Ratio (m<sup>-0.5</sup>)</b>	<b>Secchi depth (m)</b>	<b>AvgTDO3<sub>AM</sub> (°C)</b>
Big Trout	1.24	4.78	8.75
Blue	2.04	6.76	15.49
Burntside	1.91	5.80	7.92
Cedar	1.17	3.40	13.70
Carlos	1.13	3.40	11.64
Elk	1.16	2.50	15.43
Fishhook	2.19	3.44	15.20
Greenwood	1.57	5.46	8.91
Grindstone	0.82	2.88	5.44
Kabekona	1.34	3.70	11.95
Little Sand	1.45	5.22	8.67
Little Trout	1.08	6.33	6.08
Mukooda	1.76	5.12	10.26
Siseebakwet	1.50	3.89	13.62
Six	0.69	3.94	9.00
Snowbank	1.41	5.28	8.49
South Twin	5.22	2.90	22.26
Ten Mile	1.05	5.92	10.12
Trout (Cook )	1.39	5.40	9.87
Trout (St. Louis)	2.50	4.71	11.49
White Iron	4.26	1.50	21.51

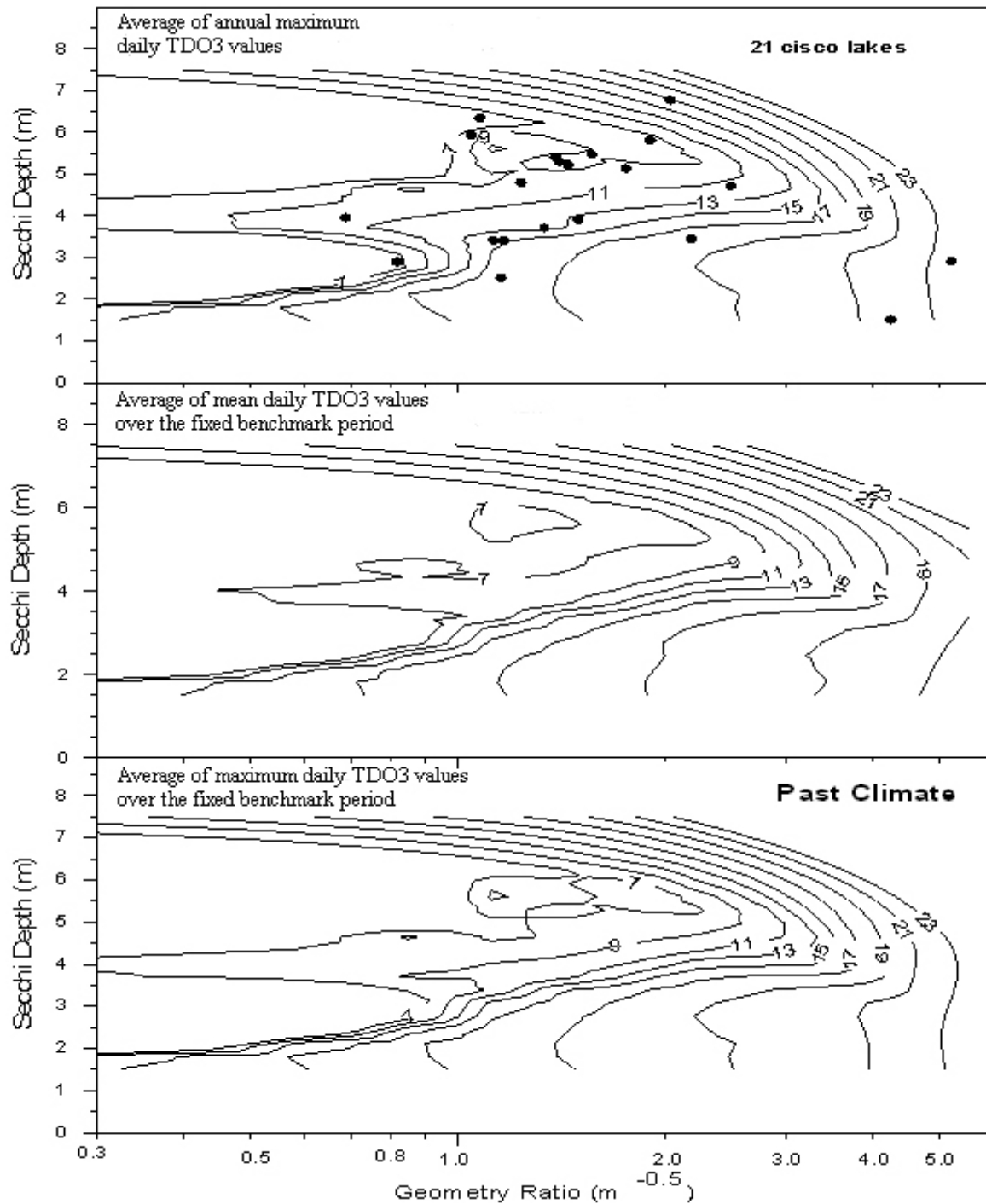


Figure 4.1 Contour plots of  $AvgTDO3_{AM}$  (top panel, Table 3.1, line 3),  $AvgATDO3_{FB}$  (middle panel, Table 3.1, line 6), and  $AvgMTDO3_{FB}$  (bottom panel, Table 3.1, line 9). Simulations are for the period from 1992 to 2008 using weather data from the weather station closest to each of the 21 cisco study lakes. Contours were derived by interpolation of simulated data points for 21 cisco lakes.

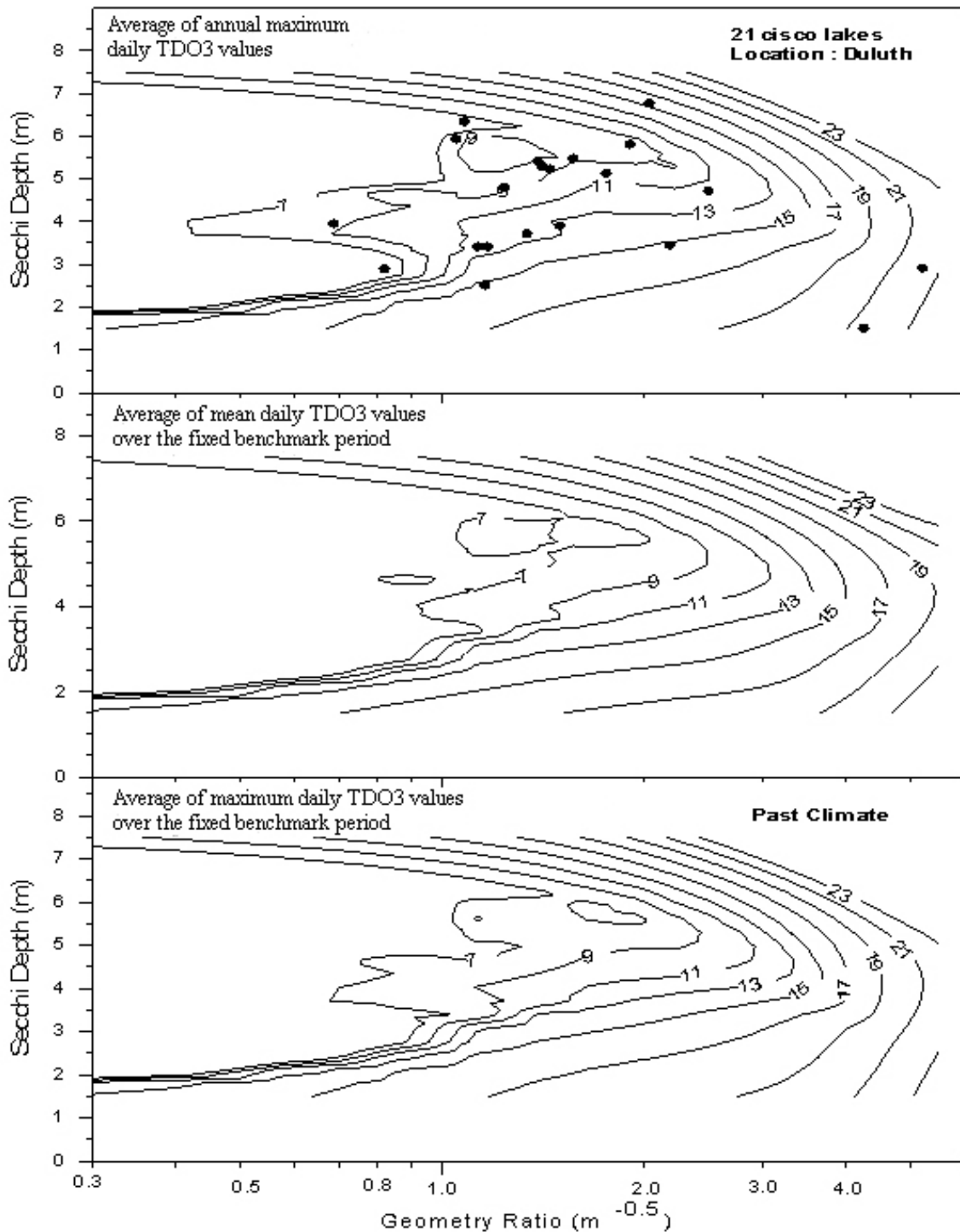


Figure 4.2 Contour plots of  $\text{AvgTDO3}_{\text{AM}}$  (top panel, Table 3.1, line 3),  $\text{AvgATDO3}_{\text{FB}}$  (middle panel, Table 3.1, line 6), and  $\text{AvgMTDO3}_{\text{FB}}$  (bottom panel, Table 3.1, line 9). Simulations are for the period **from 1962 to 2008** using **Duluth weather data**. Contours were derived by interpolation of simulated data points for **21 cisco lakes**.

## 4.2 Contour plots of selected TDO3 parameters for past (1962 to 2008) climate conditions

Averages of annual maximum daily TDO3 values ( $\text{AvgTDO3}_{\text{AM}}$ ), mean and maximum daily TDO3 values over the fixed benchmark period ( $\text{AvgATDO3}_{\text{FB}}$ , and  $\text{AvgMTDO3}_{\text{FB}}$ ) in the 47-year simulation period under past climate (1962 to 2008) and the CGCM 3.1 future climate scenario are summarized in Table 4.2 for the 21 cisco study lakes and in Table 4.3 for the 30 virtual cisco lakes. The fixed benchmark period for stratified lakes is from DOY 209 to DOY 239. Results presented in Tables 4.2 and 4.3 are also plotted in Figure 4.3, and were calculated from daily temperature and DO profiles simulated using International Falls weather data. Results simulated with Duluth and St. Cloud weather data as model input are given in Appendix C (Tables C.1 to C.11).

Figure 4.3 shows contour plots of averages of annual maximum daily TDO3 values ( $\text{AvgTDO3}_{\text{AM}}$ ), mean and maximum daily TDO3 values over the fixed benchmark period ( $\text{AvgATDO3}_{\text{FB}}$ , and  $\text{AvgMTDO3}_{\text{FB}}$ ) in the 47-year simulation period under past climate conditions (1962 – 2008) using International Falls weather data. Contours in Fig. 4.3 were derived by interpolation from simulated data points for 21 cisco lakes and 30 virtual cisco lakes. Similar contours in Figure 4.4 were derived by interpolation from simulated data points for the 30 virtual cisco lakes only. When combined results of these TDO3 parameter values for the 21 cisco study lakes and the 30 virtual cisco lakes were used in Figure 4.3 to develop contour plots, some contour islands appeared, because the 21 cisco study lakes are not distributed uniformly on the plot of Secchi depth versus geometry ratio. Figure 4.3 does show, however, that the contours derived from the 21 cisco study lakes using calibrated model parameters are largely consistent with contours derived from the 30 virtual cisco lakes using generalized model parameters. Contour plots in Figure 4.4 derived by interpolation from simulated data points for the 30 virtual cisco lakes only, show a clearer pattern of changes of TDO3 parameters as a function of lake geometry ratio and Secchi depth than the contour plots in Figure 4.3. Similar contour plots of TDO3 parameters derived from simulated data points using Duluth and St. Cloud weather data are presented in Appendix C (Figures C.1 to C.4).

Figures 4.3 and 4.4 provide additional insights. The pattern of the contour lines indicates that the dependence of  $\text{AvgTDO3}_{\text{AM}}$ ,  $\text{AvgATDO3}_{\text{FB}}$ , and  $\text{AvgMTDO3}_{\text{FB}}$  on lake geometry ratio GR and Secchi depth SD shifts, when lake stratification shifts from dimictic (seasonal) to polymictic. The transition occurs at GR values  $\approx 2$  to 3.

The TDO3 parameters strongly depend on lake geometry ratio GR and weakly on Secchi depth SD when the GR is on the order of 3 or larger (weakly stratified, polymictic lakes). Above  $\text{GR} > 3$  the values of all three TDO3 parameters ( $\text{AvgTDO3}_{\text{AM}}$ ,  $\text{AvgATDO3}_{\text{FB}}$ , and

AvgMTDO3<sub>FB</sub>) rise when GR increases. Virtual lakes LakeC26 to LakeC30 have lake geometry ratios of 3.5 and averages of annual maximum daily TDO3 values (AvgTDO3<sub>AM</sub>) from 16.3 to 18.0 °C under past climate conditions using International Falls weather data (Table 4.3 and Fig. 4.4).

On the other hand, in lakes with  $GR < 2$  (seasonally stratified, dimictic lakes) the TDO3 parameters depend significantly on SD, provided that SD is low (less transparent, mesotrophic or eutrophic lakes). Virtual lakes LakeC01 to LakeC05 have a lake geometry ratio of 0.74 and are strongly stratified lakes; their averages of AvgTDO3<sub>AM</sub> ranged from 7.9 to 15.6 °C (Table 4.3). Figure 4.4 shows that TDO3 parameter values in lakes with low geometry ratio (LakeC01 to LakeC05) depend more strongly on Secchi depth or lake trophic status than TDO3 parameter values in lakes with high lake geometry ratio (LakeC25 to LakeC30).

Table 4.2 Values of GR, SD, and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively) . Past **climate conditions (1962-2008)** and the **CGCM 3.1 climate scenario**, and **International Falls weather** data have been used in the simulations of the **21 cisco study lakes**.

Lake Name	Geometry ratio (m <sup>-0.5</sup> )	Secchi depth (m)	Past climate (1962 – 2008)			Future CGCM 3.1 climate scenario		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Six	0.69	3.94	9.12	6.62	7.42	10.89	7.45	8.39
Grindstone	0.82	2.88	5.22	4.52	4.55	5.63	4.79	4.85
Ten Mile	1.05	5.92	9.78	8.01	8.54	11.59	8.80	9.34
Little Trout	1.08	6.33	5.72	5.42	5.49	6.30	5.73	5.82
Carlos	1.13	3.40	11.78	6.37	7.47	15.31	8.11	10.57
Elk	1.16	2.50	14.55	12.69	14.11	18.46	16.91	18.20
Cedar	1.17	3.40	12.52	9.24	10.78	16.43	12.44	14.52
Big Trout	1.24	4.78	8.00	5.94	6.30	10.23	6.98	7.54
Kabekona	1.34	3.70	11.55	7.67	9.04	14.61	9.94	12.02
Trout (Cook)	1.39	5.40	10.20	6.51	7.36	12.95	7.50	8.83
Snowbank	1.41	5.28	8.09	6.44	6.74	10.05	7.31	7.74
Little Sand	1.45	5.22	7.65	6.06	6.38	10.07	6.85	7.55
Siseebakwet	1.50	3.89	14.14	10.30	12.30	17.64	13.85	16.38
Greenwood	1.57	5.46	8.09	6.47	6.81	11.33	7.48	8.47
Mukooda	1.76	5.12	9.41	7.04	7.51	12.01	8.43	9.33
Burntside	1.91	5.80	7.41	6.30	6.52	8.29	6.89	7.08
Blue	2.04	6.76	14.93	11.88	13.64	18.66	14.79	17.38
Fish Hook	2.19	3.44	15.06	12.26	14.33	18.54	16.35	18.11
Trout (St. Louis)	2.50	4.71	11.23	8.91	9.51	14.95	10.77	13.17
White Iron	4.26	1.50	21.95	20.47	21.71	25.32	23.46	24.93
South Twin	5.22	2.90	22.95	20.31	22.23	26.15	23.20	25.31

Note: Annual maximum is average of annual maximum daily TDO3 values in the simulation period, and is AvgTDO3<sub>AM</sub> defined in Table 3.1. Benchmark mean is average of mean daily TDO3 values over the fixed benchmark period, and is AvgATDO3<sub>FB</sub> defined in Table 3.1. Benchmark maximum is average of maximum daily TDO3 values over the fixed benchmark period, and is MaxATDO3<sub>FB</sub> defined in Table 3.1

Table 4.3 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively). Past **climate conditions (1962-2008)** and the **CGCM 3.1 climate scenario**, and **International Falls weather** data have been used in the simulation of the **30 virtual cisco lakes**.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	Past climate (1962-2008)			Future CGCM 3.1 climate scenario		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
LakeC01	0.74	1.25	15.60	14.33	15.44	18.05	17.07	17.93
LakeC02	0.74	2.50	12.51	9.66	11.31	15.13	10.76	13.08
LakeC03	0.74	4.50	9.10	6.50	7.12	10.53	7.05	7.77
LakeC04	0.74	7.00	8.01	6.29	6.58	8.92	6.58	6.93
LakeC05	0.74	8.50	7.92	6.35	7.10	8.65	6.98	7.37
LakeC06	1.11	1.25	16.72	15.12	16.64	20.87	19.24	20.79
LakeC07	1.11	2.50	13.30	10.62	12.55	16.90	13.60	16.07
LakeC08	1.11	4.50	9.73	6.50	7.32	12.20	7.57	8.75
LakeC09	1.11	7.00	7.99	6.41	6.68	9.16	6.83	7.12
LakeC10	1.11	8.50	8.29	7.40	7.68	8.91	7.90	8.16
LakeC11	1.46	1.25	16.97	15.40	16.88	21.68	19.25	21.35
LakeC12	1.46	2.50	14.37	12.02	13.88	18.73	16.98	18.47
LakeC13	1.46	4.50	11.03	7.35	8.63	14.73	9.71	12.06
LakeC14	1.46	7.00	8.46	7.16	7.43	10.05	7.84	8.12
LakeC15	1.46	8.50	9.36	8.12	8.48	10.34	8.95	9.30
LakeC16	1.97	1.25	17.22	15.87	17.13	21.71	19.73	21.41
LakeC17	1.97	2.50	15.24	13.67	15.00	20.04	18.69	19.96
LakeC18	1.97	4.50	13.06	9.53	11.56	17.73	14.56	17.06
LakeC19	1.97	7.00	10.52	8.84	9.27	12.82	9.93	10.48
LakeC20	1.97	8.50	11.64	9.81	10.35	13.08	11.00	11.56
LakeC21	2.50	1.25	17.16	16.02	17.08	21.52	19.91	21.28
LakeC22	2.50	2.50	15.35	13.91	15.14	19.87	18.67	19.78
LakeC23	2.50	4.50	14.03	11.04	13.01	18.54	16.25	18.15
LakeC24	2.50	7.00	12.98	10.82	11.48	15.28	12.38	13.20
LakeC25	2.50	8.50	14.16	11.89	12.69	16.13	13.55	14.38
LakeC26	3.50	1.25	17.97	16.96	17.88	21.98	20.65	21.82
LakeC27	3.50	2.50	16.63	15.37	16.40	20.61	19.59	20.52
LakeC28	3.50	4.50	16.30	14.05	15.65	20.04	18.57	19.80
LakeC29	3.50	7.00	17.07	14.71	15.93	19.47	16.87	18.14
LakeC30	3.50	8.50	18.02	15.84	17.16	20.55	18.13	19.49

Note: Annual maximum is average of annual maximum daily TDO3 values in the simulation period, and is AvgTDO3<sub>AM</sub> defined in Table 3.1. Benchmark mean is average of mean daily TDO3 values over the fixed benchmark period, and is AvgATDO3<sub>FB</sub> defined in Table 3.1. Benchmark maximum is average of maximum daily TDO3 values over the fixed benchmark period, and is MaxATDO3<sub>FB</sub> defined in Table 3.1



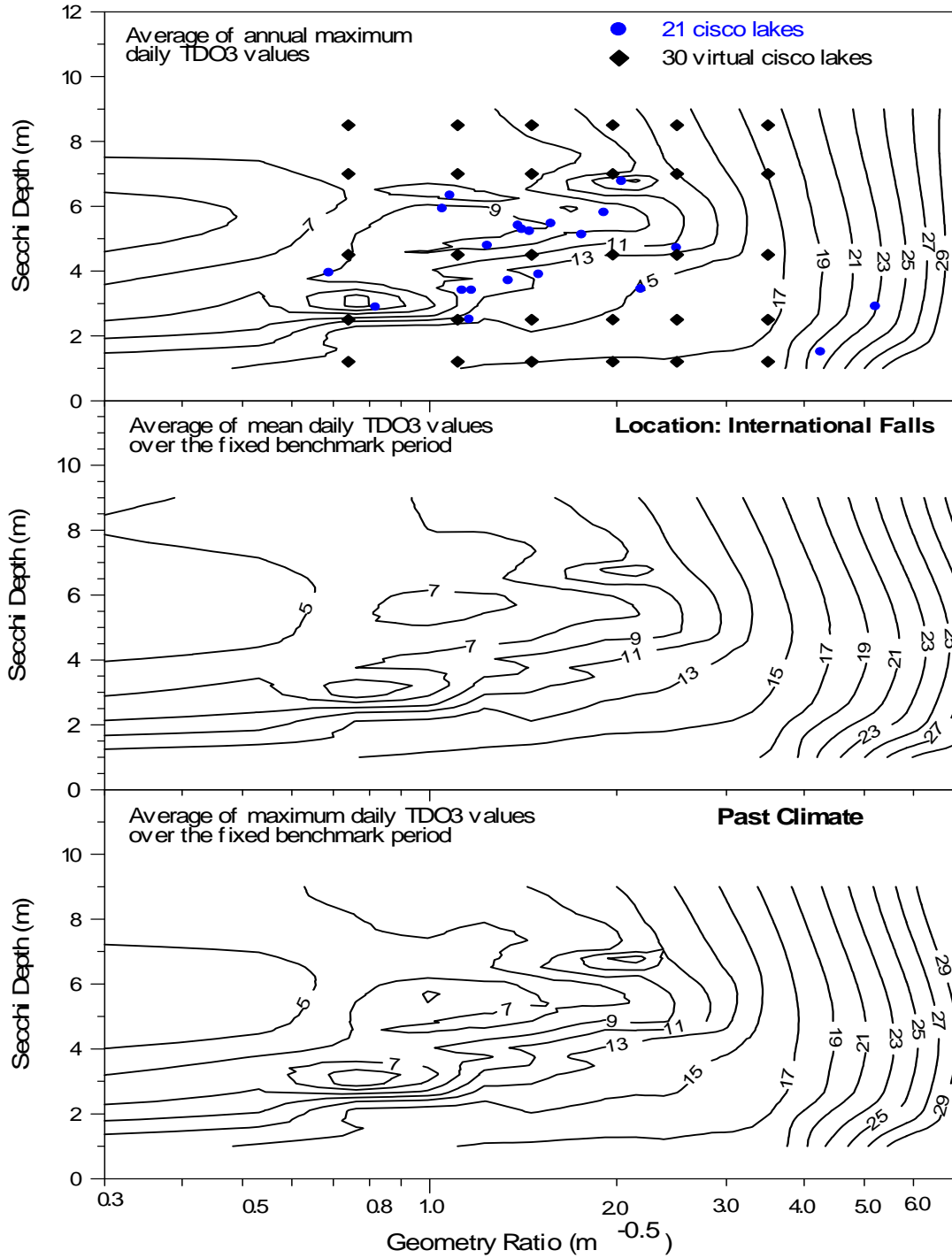


Figure 4.3 Contour plots of  $\text{AvgTDO3}_{\text{AM}}$  (Table 3.1, line 3),  $\text{AvgATDO3}_{\text{FB}}$ , and  $\text{AvgMTDO3}_{\text{FB}}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239). Simulations are for **past climate conditions (1962 to 2008)** using **International Falls weather** data. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.

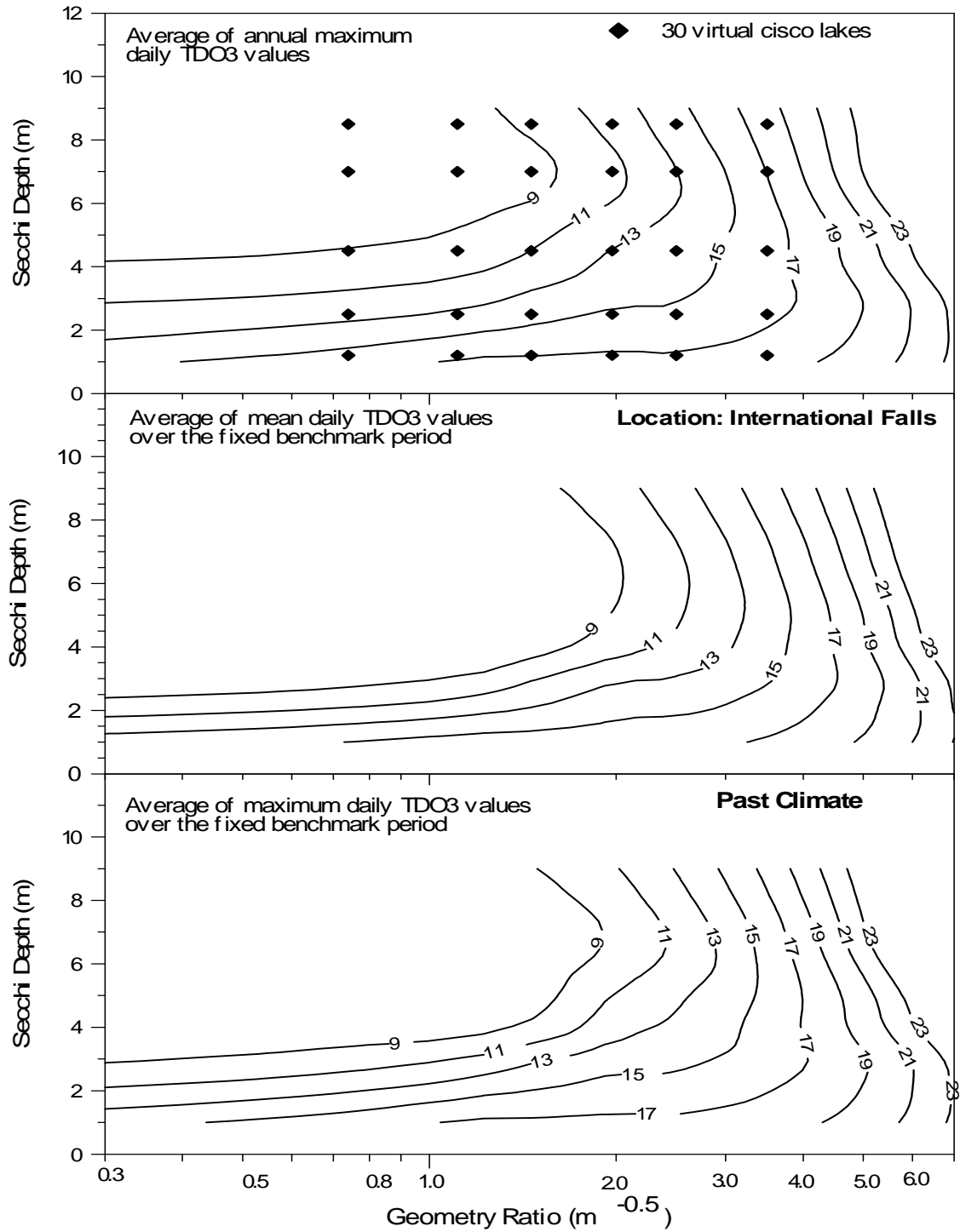


Figure 4.4 Contour plots of  $AvgTDO3_{AM}$  (Table 3.1, line 3), and  $AvgATDO3_{FB}$ , and  $AvgMTDO3_{FB}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239). Simulations are for **past climate conditions (1962 to 2008)** using **International Falls weather** data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

### 4.3 Contour plots of selected TDO3 parameters for future climate scenarios

Output from two recent GCM models (CGCM 3.1 and MIROC 3.2) was used to generate two future climate scenarios. Daily water temperature and DO profiles were simulated by using the CGCM 3.1 and MIROC 3.2 climate scenarios as input to the MINLAKE2010 simulations of 21 cisco study lakes and 30 virtual cisco lakes. Figures 4.5, 4.6, and 4.7 show results in the form of contour plots for averages of annual maximum daily TDO3 values ( $AvgTDO3_{AM}$ ), mean and maximum daily TDO3 values over the benchmark period ( $AvgATDO3_{FB}$ , and  $AvgMTDO3_{FB}$ ) for the future 47-year simulation period. These contour plots were derived by applying the MIROC 3.2 climate change scenario to the International Falls, Duluth, and St. Cloud weather data, respectively; lines were obtained by interpolation from simulated data points for 30 virtual cisco lakes only. Similar contour plots were derived by interpolation from simulated data points for 21 cisco lakes and 30 virtual cisco lakes under the CGCM 3.1 climate change scenario at all three weather stations; these plots are given in Appendix C (Figures C.5 to C.13). A comparison of Figure 4.3 with 4.5 reveals that under future climate conditions TDO3 parameter values rise by around 2.0 to 3.0 °C. The contour plots in Figures 4.5 to 4.7 are useful to select refuge lakes for cisco in consideration of future climate warming.

Tables 4.4, 4.5, and 4.6 list statistical differences for the three TDO3 parameters ( $AvgTDO3_{AM}$ ,  $AvgATDO3_{FB}$ , and  $AvgMTDO3_{FB}$ ) between the CGCM 3.1 future climate scenario and past (1962-2008) climate conditions. The differences of  $AvgTDO3_{AM}$  for the 21 cisco lakes ranged from 0.41 to 3.91 °C with a mean of 2.67 °C and a standard deviation of 1.09 °C when International Falls weather data were used (Table 4.4). A similar magnitude of increases was projected for the 30 virtual cisco lakes and at other weather stations (Tables 4.5 and 4.6). The maximum and minimum increases of the three TDO3 parameters from past climate to the CGCM 3.1 future scenario were projected to be from 3.91 to 6.51 °C, and from 0.00 to 0.78 °C, respectively.

Almost the same values were projected for 21 cisco lakes and 30 virtual cisco lakes for increases from past climate (1962 to 2008) to the MIROC 3.2 future scenario and at all three weather stations (Tables 4.7, 4.8, and 4.9). The maximum and minimum increases of the three TDO3 parameters were projected to be from 4.07 to 6.40 °C, and from 0.14 to 0.81 °C, respectively.

The mean increases of all three TDO3 parameters from past climate to the CGCM 3.1 or the MIROC 3.2 future scenarios for 21 cisco lakes and 30 virtual cisco lakes were projected to be from 1.84 to 3.47 °C and from 1.84 to 3.56 °C, respectively. All these increases were slightly larger when St. Cloud weather data were used instead of International Falls weather data (Tables 4.6 and 4.9).

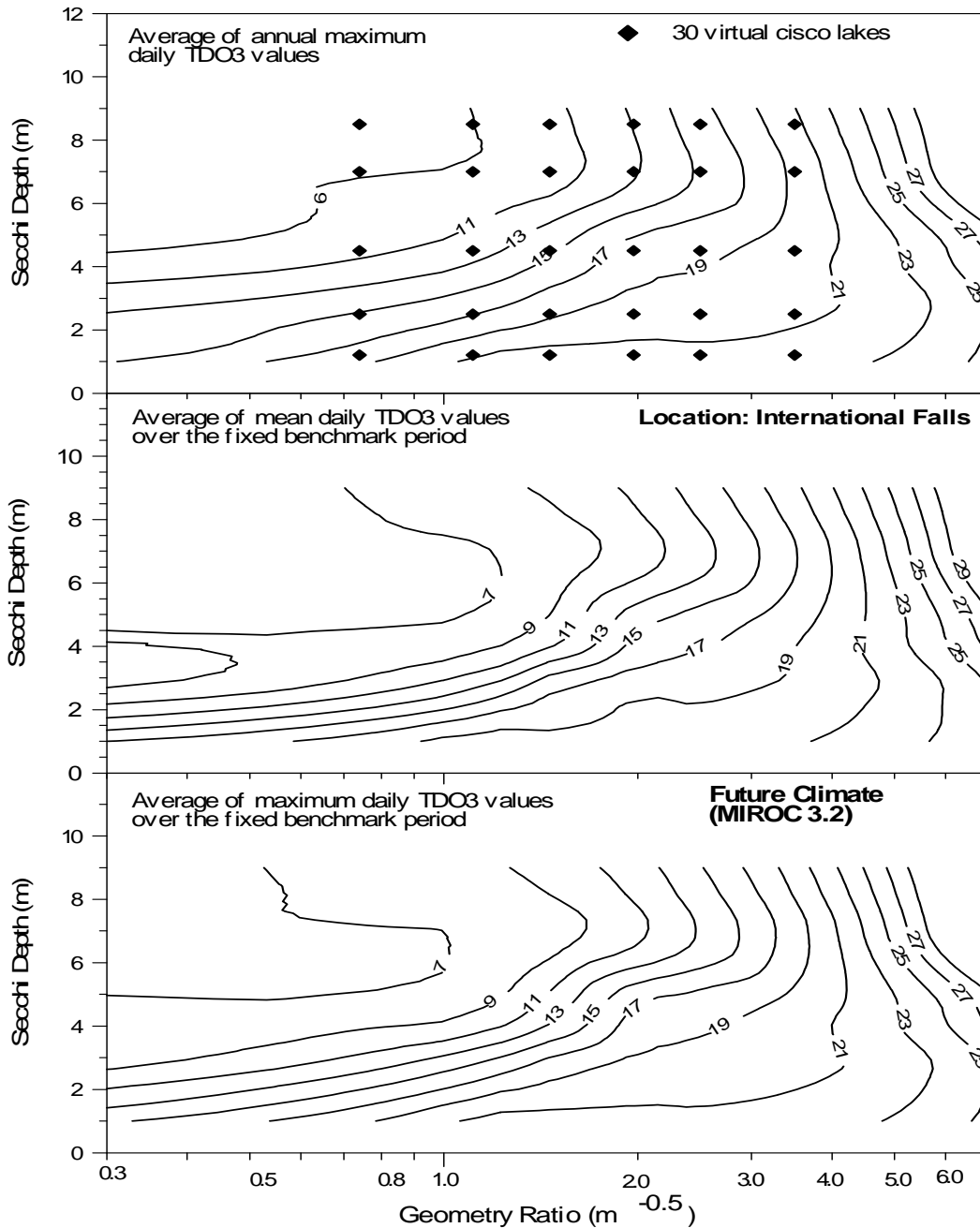


Figure 4.5 Contour plots of  $\text{AvgTDO3}_{\text{AM}}$  (Table 3.1, line 3), and  $\text{AvgATDO3}_{\text{FB}}$  and  $\text{AvgMTDO3}_{\text{FB}}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated for the **MIROC 3.2 future climate scenario** using **International Falls weather** data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

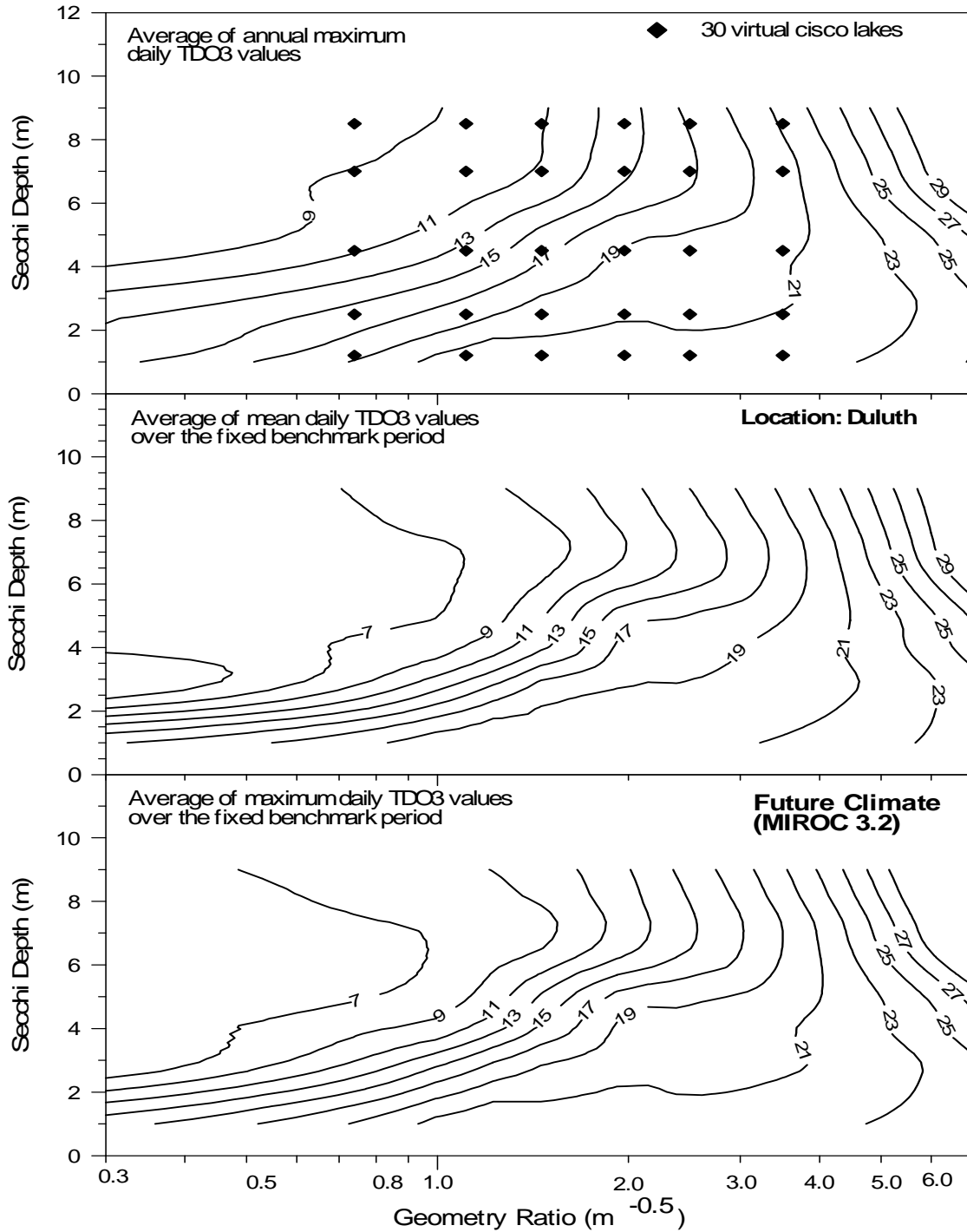


Figure 4.6 Contour plots of  $AvgTDO3_{AM}$  (Table 3.1, line 3), and  $AvgATDO3_{FB}$  and  $AvgMTDO3_{FB}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **MIROC 3.2 future climate scenario** using **Duluth weather** data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

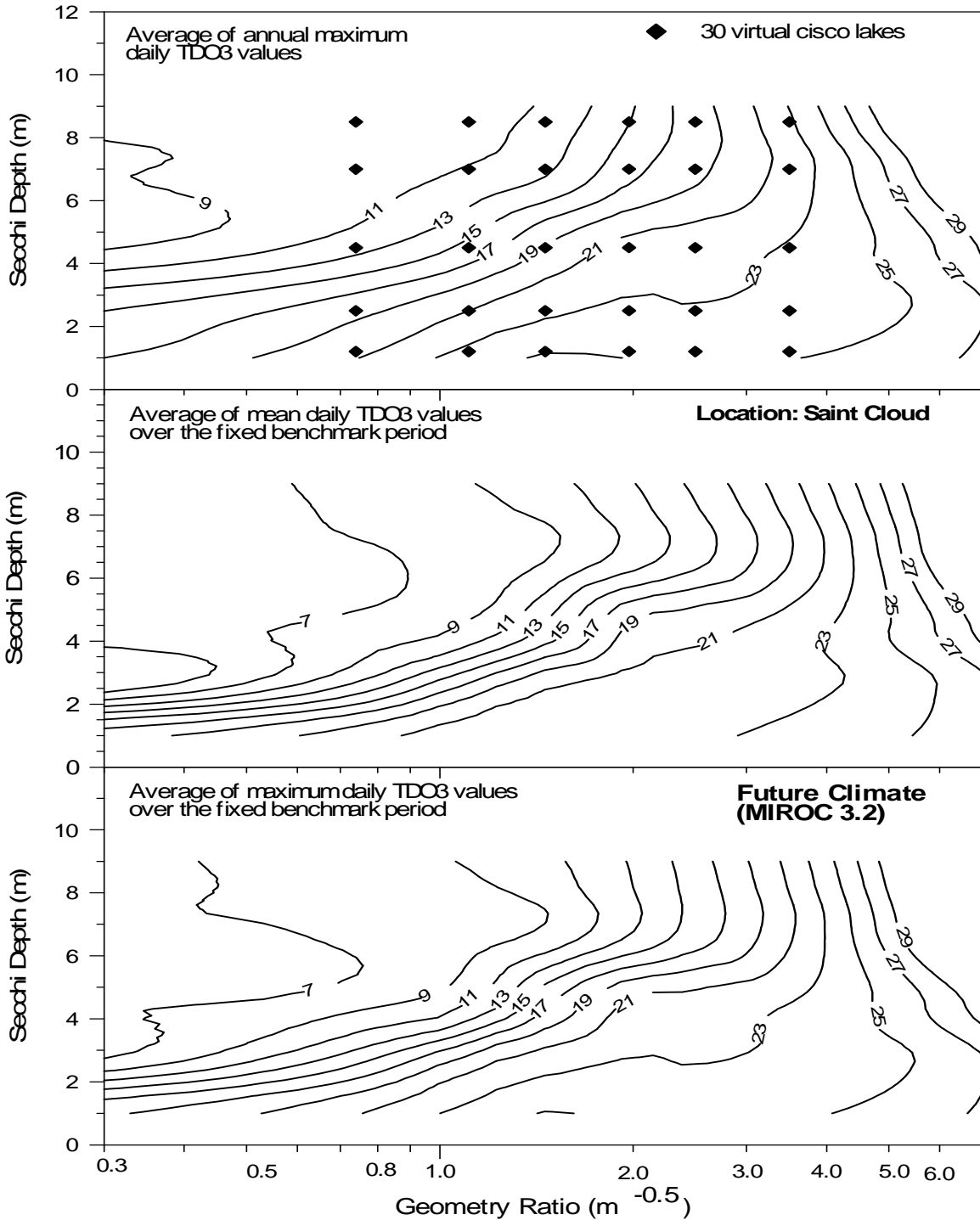


Figure 4.7 Contour plots of  $AvgTDO3_{AM}$  (Table 3.1, line 3), and  $AvgATDO3_{FB}$  and  $AvgMTDO3_{FB}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **MIROC 3.2 future climate scenario** using **St. Cloud weather data**. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

Table 4.4 Statistical differences for three TDO3 parameters (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively) between the **future CGCM 3.1 climate scenario and past climate conditions (1962 to 2008)** at the **International Falls** weather station.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	3.91	4.22	4.09	4.80	5.21	5.50
Minimum	0.41	0.27	0.30	0.62	0.29	0.27
Mean	2.67	1.84	2.23	2.92	2.57	2.70
Standard Deviation	1.09	1.27	1.37	1.40	1.70	1.72

Table 4.5 Statistical differences for three TDO3 parameters (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively) between the **future CGCM 3.1 climate scenario and past climate conditions (1962 to 2008)** at the **Duluth** weather station.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	4.81	5.34	5.18	4.80	5.58	5.42
Minimum	0.78	0.55	0.60	0.49	0.13	0.15
Mean	3.45	2.72	3.11	3.11	2.82	2.91
Standard Deviation	1.17	1.49	1.50	1.26	1.63	1.56

Table 4.6 Statistical differences for three TDO3 parameters (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively) between the **future CGCM 3.1 climate scenario and past climate conditions (1962 to 2008)** at the **St. Cloud** weather station.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	5.14	5.13	6.13	5.41	6.51	6.18
Minimum	0.77	0.39	0.44	0.44	0.00	0.01
Mean	3.47	2.79	3.26	3.16	2.75	2.89
Standard Deviation	1.12	1.52	1.74	1.40	1.79	1.74

Table 4.7 Statistical differences for three TDO3 parameters (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively) between the **future MIROC 3.2 climate scenario and past climate conditions (1962 to 2008)** at the **International Falls weather station**.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	4.26	4.19	4.07	4.80	5.21	5.50
Minimum	0.69	0.14	0.17	0.62	0.29	0.27
Mean	2.92	1.84	2.28	2.92	2.57	2.70
Standard Deviation	1.11	1.32	1.47	1.40	1.70	1.72

Table 4.8 Statistical differences for three TDO3 parameters (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively) between the **future MIROC 3.2 climate scenario and past climate conditions (1962 to 2008)** at the **Duluth weather station**.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	4.77	4.77	4.83	4.99	5.53	5.29
Minimum	0.46	0.23	0.26	0.82	0.28	0.32
Mean	3.24	2.24	2.66	3.32	2.83	2.97
Standard Deviation	1.24	1.54	1.57	1.35	1.75	1.71

Table 4.9 Statistical differences for three TDO3 parameters (**AvgTDO3<sub>AM</sub>**, **AvgATDO3<sub>FB</sub>** and **AvgMTDO3<sub>FB</sub>**, Table 3.1, lines 3, 6 and 9, respectively) between the **future MIROC 3.2 climate scenario and past climate conditions (1962 to 2008)** at the **St. Cloud weather station**.

	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameter	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	5.27	5.20	6.11	5.63	6.40	6.04
Minimum	0.81	0.27	0.28	1.02	0.34	0.40
Mean	3.56	2.55	3.10	3.55	2.93	3.12
Standard Deviation	1.13	1.52	1.79	1.37	1.81	1.80



#### 4.4 Contour plots of TDO3 parameters using variable benchmark periods

The benchmark period is the period of greatest oxythermal stress for coldwater fish. It is defined as the 31-day period with the highest value of TDO3 (Jacobson et al. 2010). In addition to using a fixed benchmark period (from DOY 209 to DOY 239) introduced by Jacobson et al. (2010), variable (sliding) benchmark periods were explored to compute TDO3 parameters. The sliding 31-day benchmark period retained in this study must contain the day when the annual maximum daily TDO3 ( $TDO3_{AM}$  in Table 3.1) occurs in that year. Over each sliding benchmark period the mean daily TDO3 was calculated, and only the highest mean value in any of the sliding benchmark periods of a year ( $ATDO3_{VB}$  in Table 3.1) was retained. Averages of the beginning dates of sliding benchmark periods for  $ATDO3_{VB}$  ranged from DOY 210 (July 29) to DOY 280 (October 7) for 30 virtual lakes and past climate conditions (1962 to 2008) (Figs 3.9 to 3.11). Because of this wide variation of beginning dates, it is necessary and recommended to calculate mean daily TDO3 values using variable (sliding) benchmark periods for each lake in order to identify the greatest oxythermal stress for coldwater fish.

Figure 4.8 shows contour plots of averages of highest mean daily TDO3 over variable benchmark periods ( $AvgATDO3_{VB}$  in Table 3.1) under past climate conditions (1962 to 2008), and the CGCM 3.1 and MIROC 3.2 future climate scenarios. Contours were derived by interpolation from simulated data points for the 30 virtual cisco lakes (dots in top frame of Figure 4.8), and simulated  $AvgATDO3_{VB}$  values given in Appendix B (Tables B.1 to B.3). Duluth weather data was used for the model simulations in Fig. 4.8, and similar contour plots derived from model simulations using International Falls and St. Cloud weather data are given in Figure 4.9 and 4.10, respectively. Statistics for  $AvgATDO3_{VB}$  values under past climate and future scenarios at all three weather stations (International Falls, Duluth, and St. Cloud) are given in Table 4.10. The  $AvgATDO3_{VB}$  values ranged from 7.28 to 19.91°C under past climate conditions and from 8.02 to 23.28°C under two future climate scenarios at three weather stations for 30 virtual cisco lakes (Table 4.10). Statistical differences of  $AvgATDO3_{VB}$  values between future climate scenarios and past climate (1962-2008) are given in Table 4.11 for the three principal weather stations. The projected increases of  $AvgATDO3_{VB}$  values from past climate to future scenarios ranged from 0.30 to 5.11°C (Table 4.11), and average increases were projected to be from 2.79 to 3.40°C. Because of these increases, it is important to use TDO3 parameter values projected for future climate scenarios to select cisco refuge lakes in Minnesota.

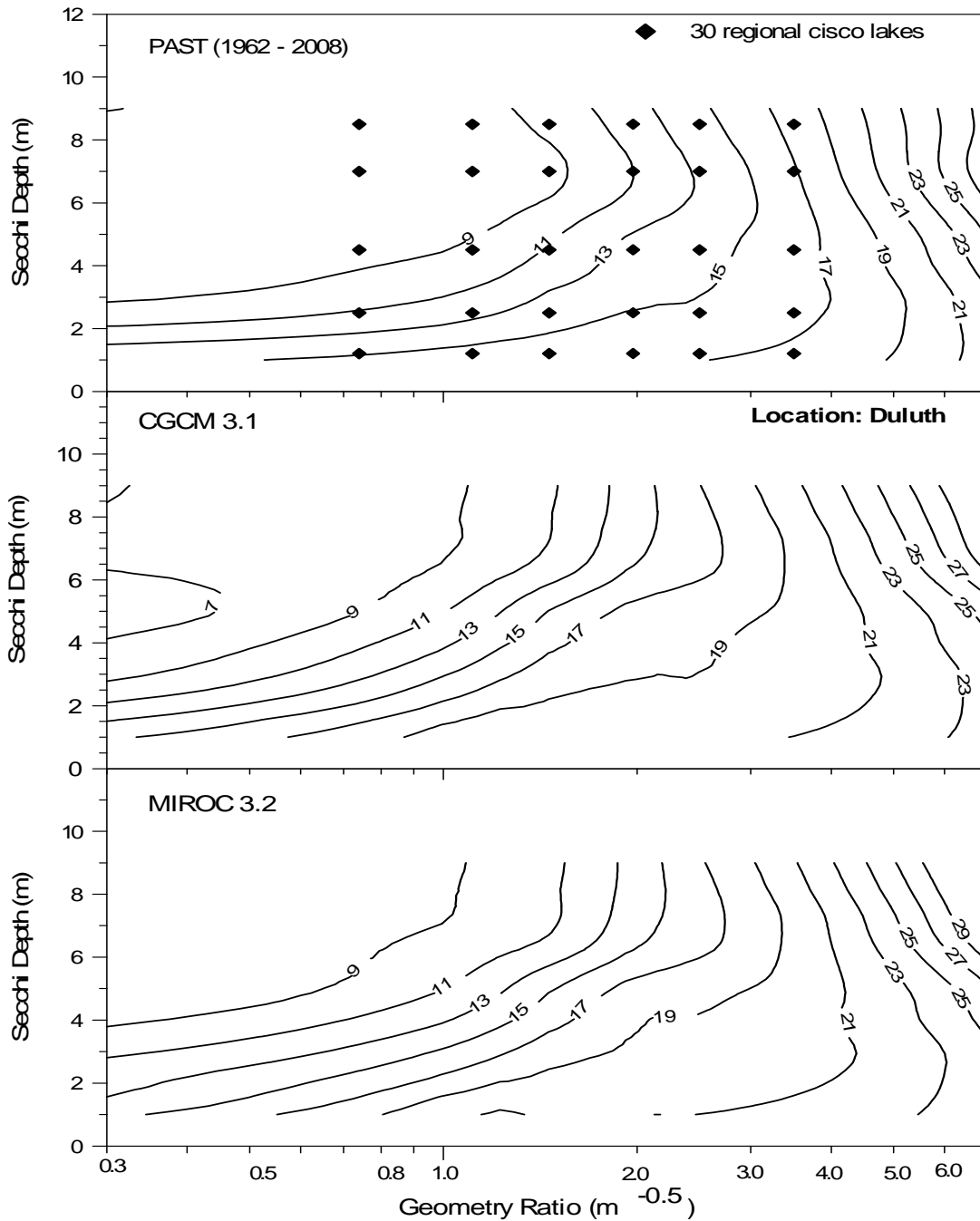


Figure 4.8 Contour plots of averages of highest mean daily TDO3 over variable benchmark periods ( $ATDO3_{VB}$ , Table 3.1, line 10) under **past climate (1962-2008)**, and **CGCM 3.1 and MIROC 3.2 future climate scenarios**. **Duluth weather** data were used for the model simulations. Contours were derived by interpolation from simulated points for **30 virtual lakes**.

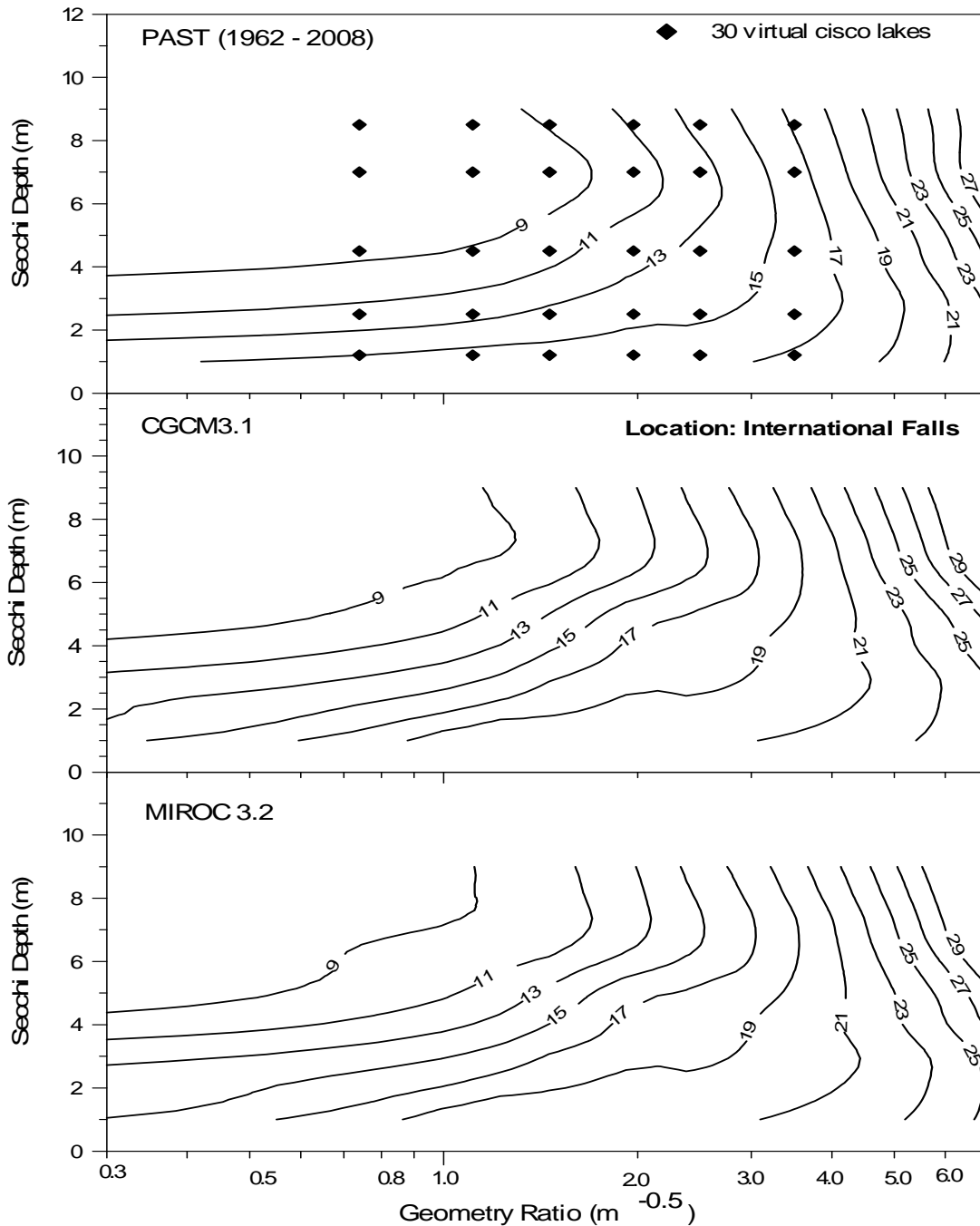


Figure 4.9 Contour plots of averages of highest mean daily TDO3 over variable benchmark periods ( $ATDO3_{VB}$ , Table 3.1, line 10) under **past climate (1962-2008)**, and **CGCM 3.1 and MIROC 3.2 future climate scenarios**. **International Falls** weather data were used for the model simulations. Contours were derived by interpolation from simulated points for **30 virtual lakes**.

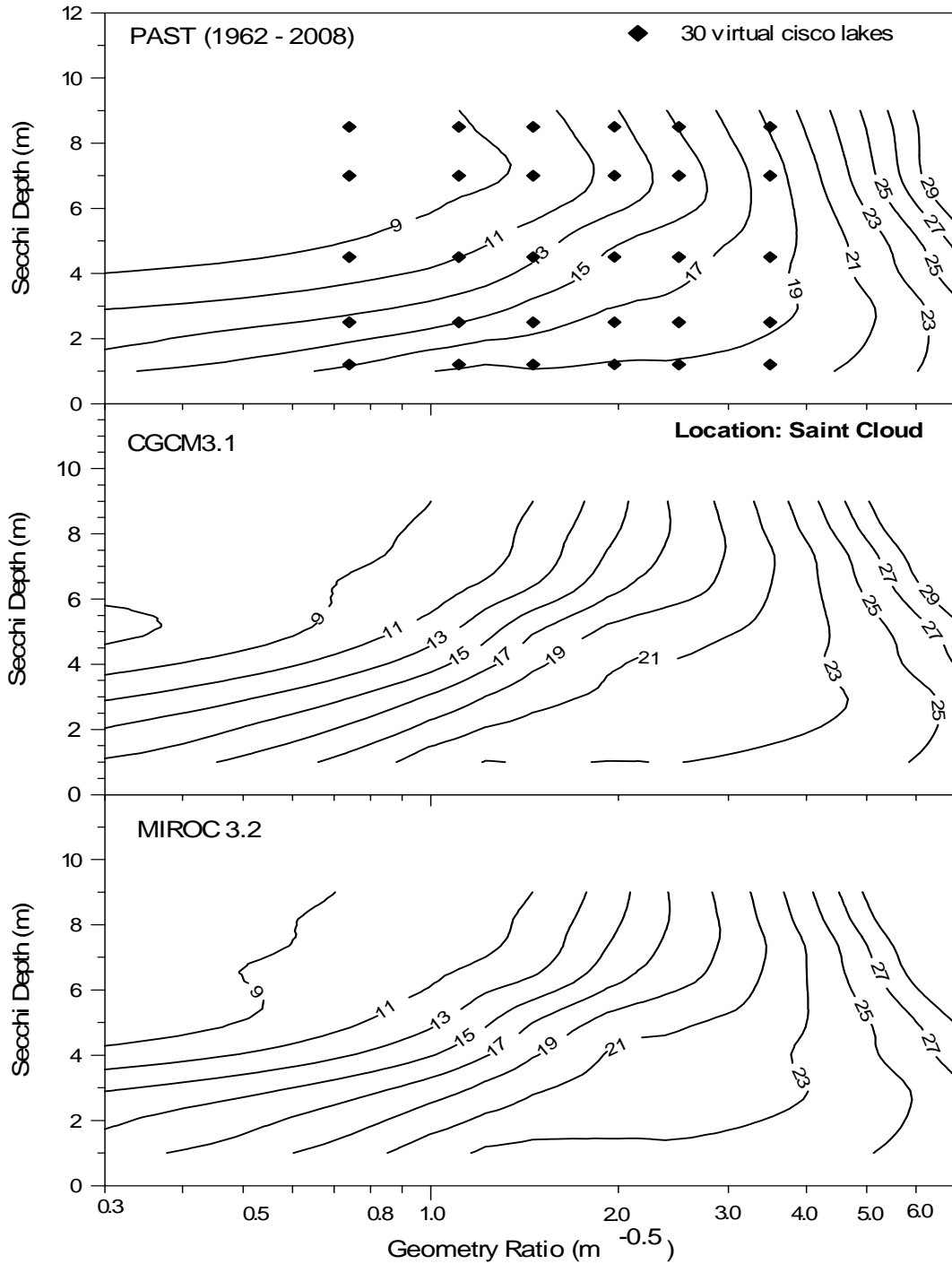


Figure 4.10 Contour plots of averages of highest mean daily TDO3 over variable benchmark periods ( $ATDO3_{VB}$ , Table 3.1, line 10) under **past climate (1962-2008)**, and **CGCM 3.1 and MIROC 3.2 future climate scenarios**. **St. Cloud** weather data were used for the model simulations. Contours were derived by interpolation from simulated points for **30 virtual lakes**.

Table 4.10 Statistics of AvgATDO3<sub>VB</sub> (Table 3.1, line 12) under **past climate conditions (1962-2008) and future climate scenarios** at three weather stations.

Statistical parameter	International Falls			Duluth			St. Cloud		
	Past	CGCM	MIROC	Past	CGCM	MIROC	Past	CGCM	MIROC
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
Standard Deviation	3.25	4.34	4.26	3.39	4.25	4.38	3.96	4.90	4.89

Table 4.11 Statistical differences of AvgATDO3<sub>VB</sub> (Table 3.1, line 12) **between future climate scenarios and past climate conditions (1962-2008)** at three weather stations.

Statistical parameter	CGCM 3.1 minus past			MIROC 3.2 minus 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
Standard Deviation	1.33	1.22	1.33	1.30	1.32	1.31

## **Chapter 5 Selection of Cisco Refuge Lakes**

This is the final chapter of the project report. It is about the identification, selection and ranking of cisco habitat in potential refuge lakes under future (warmer) climate scenarios in Minnesota. The selection was based on the oxythermal parameter TDO3, which is a temperature that measures survival stress on adult cisco: the lower the TDO3, the lower the stress.

Time series of daily TDO3 values had to be calculated from simulated daily profiles of water temperature and DO in each lake. The simulations were made for two future climate scenarios, CGCM 3.1 and MIROC 3.2. From these time series one or several TDO3 characteristic parameters had to be obtained and used to identify and select refuge lakes from approximately 620 cisco lakes (Table D.1) in Minnesota. Table 3.1 identifies twelve different options for the calculation of TDO3 characteristic parameters, ranging from a single annual daily maximum value to an average over a fixed or variable benchmark period of 31 days length. An acceptable frequency of occurrence of a critical TDO3 value had to be selected.

The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to 2008 were used. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes in Minnesota.

One associated weather station had to be selected for the simulation of each lake, but data from only three Class I NWS weather stations were useful and available. 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.

Two upper TDO3 boundaries for cisco refuge lakes were selected, and the pool of 620 Minnesota cisco lakes was divided into three tiers accordingly: Lakes in Tier 1 have the most suitable cisco habitat, those in Tier 2 have suitable habitat, and those in Tier 3 are marginal or non-cisco lakes. This decision was based on Jacobson et al. (2010).

### **5.1 Criteria for refuge lake selection**

#### ***5.1.1 Choice of TDO3 parameter***

In Table 3.1 twelve TDO3 characteristic parameters were defined. Each can be calculated from simulated daily water temperature and DO profiles over the multi-year simulation period. Although simulations are continuous, and give daily profiles of water temperature and DO in a lake year-round, only the summer results (May 1 to October 31) were used to determine TDO3

values. Simulations could be made for the 21 actual cisco study lakes for which the MINLAKE2010 model had been calibrated, or for the 30 virtual cisco lakes modeled with generalized calibration parameters as described in Project Report 2 (Fang et al. 2010). As an example, Table 5.1 gives values and ranges of the twelve TDO3 characteristic parameters defined in Table 3.1 calculated for two virtual cisco lakes (LakeC06 and LakeC08) using Duluth weather data under past climate conditions (1992 to 2008) and under the CGCM 3.1 climate scenario.

Table 5.1 Values and ranges (in °C) of twelve TDO3 parameters (defined in Table 3.1) extracted from simulated daily temperature and DO profiles in two virtual cisco lakes (LakeC06 and LakeC08) using **Duluth weather data under past climate conditions (1992-2008)** and the **CGCM 3.1 climate scenario**.

TDO3 Parameter		LakeC06 (Past)	LakeC06 (CGCM 3.1)	LakeC08 (Past)	LakeC08 (CGCM 3.1)
<b>TDO3<sub>AM</sub></b>	TDO3 <sub>A</sub>	12.71–20.43	18.26–23.70	7.75–12.98	10.23–17.94
<b>MaxTDO3<sub>AM</sub></b>	TDO3 <sub>B</sub>	20.43	23.70	12.98	17.94
<b>AvgTDO3<sub>AM</sub></b>	TDO3 <sub>C</sub>	17.16	21.58	9.93	13.52
<b>ATDO3<sub>FB</sub></b>	TDO3 <sub>D</sub>	11.71–19.21	16.97–22.98	5.09–8.68	6.34–12.02
<b>MaxATDO3<sub>FB</sub></b>	TDO3 <sub>E</sub>	19.21	22.98	8.68	12.02
<b>AvgATDO3<sub>FB</sub></b>	TDO3 <sub>F</sub>	15.26	19.42	6.54	8.46
<b>MTDO3<sub>FB</sub></b>	TDO3 <sub>G</sub>	12.38–20.01	18.26–23.70	5.48–10.03	7.40–14.36
<b>MaxMTDO3<sub>FB</sub></b>	TDO3 <sub>H</sub>	20.01	23.7	10.03	14.36
<b>AvgMTDO3<sub>FB</sub></b>	TDO3 <sub>I</sub>	17.03	21.49	7.40	9.95
<b>ATDO3<sub>VB</sub></b>	TDO3 <sub>J</sub>	11.80–19.86	17.08–23.16	7.28–12.10	9.62–16.47
<b>MaxATDO3<sub>VB</sub></b>	TDO3 <sub>K</sub>	19.86	23.16	12.10	16.47
<b>AvgMTDO3<sub>VB</sub></b>	TDO3 <sub>L</sub>	15.59	20.00	9.32	12.65

Which TDO3 characteristic parameter(s) should be used to identify and select refuge lakes from the 620 cisco lakes in Minnesota?

Calculation of the four TDO3 parameters TDO3<sub>AM</sub>, ATDO3<sub>FB</sub>, MTDO3<sub>FB</sub>, and ATDO3<sub>VB</sub>, for each simulated year in the 47-year simulation period, is not a good option because there would be four times 47 values in the simulation period for each lake. The values of these TDO3 parameters would vary due to weather variations in the 47-year simulation period. Annual maximum daily TDO3 values (TDO3<sub>AM</sub>) and maximum daily TDO3 values (MTDO3<sub>FB</sub>) over the fixed benchmark period (DOY 209 to DOY 239) are the highest TDO3 values that occur on a particular day or in the fixed benchmark period of a particular simulated year.

Another four maximum TDO3 parameter values calculated over the 47-year simulation period, i.e., MaxTDO3<sub>AM</sub>, MaxATDO3<sub>FB</sub>, MaxMTDO3<sub>FB</sub>, MaxATDO3<sub>VB</sub>, are not good options either, because they are the highest values that occur in a particularly warm years for each lake.

For example, in LakeC06 (Table 5.1) and under past climate conditions  $\text{MaxTDO3}_{\text{AM}}$  was  $20.43^{\circ}\text{C}$  and occurred on August 7, 1983; the range of  $\text{TDO3}_{\text{AM}}$  values in the 47-year simulation period was from  $12.71$  to  $20.43^{\circ}\text{C}$ .

Average TDO3 parameter values in the 47-year simulation period, i.e.,  $\text{AvgTDO3}_{\text{AM}}$ ,  $\text{AvgATDO3}_{\text{FB}}$ ,  $\text{AvgMTDO3}_{\text{FB}}$ ,  $\text{AvgATDO3}_{\text{VB}}$ , are better choices than maximum TDO3 parameter values, and good candidates of TDO3 characteristic parameters to be used to identify and select cisco refuge lakes. Contour plots of four average TDO3 parameters ( $\text{AvgTDO3}_{\text{AM}}$ ,  $\text{AvgATDO3}_{\text{FB}}$ ,  $\text{AvgMTDO3}_{\text{FB}}$ , and  $\text{AvgMTDO3}_{\text{VB}}$ ) using lake geometry ratio and Secchi depth as independent variables were presented and discussed in Chapter 4.

Jacobson et al. (2010) studied coldwater fish oxythermal habitat in Minnesota lakes, and introduced and calculated TDO3, temperature at 3 mg/L of dissolved oxygen, from measured temperature and DO profiles. The oxythermal habitat variable was calculated by Jacobson et al. (2010) as a mean TDO3 value (not a daily maximum) over the greatest oxythermal stress period or benchmark period. Using the findings of the study by Jacobson et al. (2010),  $\text{AvgATDO3}_{\text{FB}}$  and  $\text{AvgATDO3}_{\text{VB}}$  were chosen as TDO3 parameters for the selection of cisco refuge lakes.

As discussed in Chapter 3 summer benchmark periods with the greatest oxythermal stress shift greatly from one lake type to another, and also with climate warming. Therefore, the first choice for the TDO3 parameter to be used to identify and select cisco refuge lakes was  $\text{AvgATDO3}_{\text{VB}}$  (or  $\text{TDO3}_{\text{L}}$ , Table 3.1, line 12). The research team members decided that the second choice was  $\text{AvgATDO3}_{\text{FB}}$  (or  $\text{TDO3}_{\text{F}}$ , Table 3.1, line 6).  $\text{AvgATDO3}_{\text{VB}}$  is the average of the highest mean daily TDO3 values over a variable (sliding) 31-day benchmark period in each simulated year over the 47-year simulation period. There is one  $\text{AvgATDO3}_{\text{VB}}$  value for each lake in the 1962-2008 simulation period. Similarly there is only one  $\text{AvgATDO3}_{\text{FB}}$  value, and it is the average of the mean daily TDO3 values over the fixed 31-day benchmark period (DOY 209 to DOY 239) in each simulated year over the 47-year simulation period. So the only difference between  $\text{AvgTDO3}_{\text{FB}}$  and  $\text{AvgTDO3}_{\text{VB}}$  is that one is from values in the same fixed benchmarked period of every year, whereas the other is from values in a benchmark period that shifts from year to year.

The multi-year average values,  $\text{AvgATDO3}_{\text{FB}}$  and  $\text{AvgATDO3}_{\text{VB}}$  calculated over 47-year periods, were the final choices. They are defined in Table 3.1, lines 6 and 12. Each of these two TDO3 parameters is calculated over the length of a 31-day benchmark period; one uses a fixed benchmark period from DOY 209 to DOY 239 (July 28 to August 27); the other uses a variable (sliding) benchmark period.

### ***5.1.2 Choice of limiting TDO3 values: Sub-division of 620 cisco lakes into Tiers***

The oxythermal parameter TDO3 measures environmental conditions and stress in a lake. 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 ( $\text{maxT}_{\text{DO3}}$ ), to illustrate oxythermal habitat differences in four coldwater taxa common in Minnesota. Lake Trout were present in lakes with the lowest values of  $\text{maxT}_{\text{DO3}}$  and were represented by central species response borders of  $\text{maxT}_{\text{DO3}}$  from  $4.0$  to  $5.1^{\circ}\text{C}$



(Jacobson et al. 2010). Cisco were present in lakes with a broad range of  $\max T_{\text{DO}_3}$ , with central species response borders of  $\max T_{\text{DO}_3}$  from 4.0 to 16.9°C (Jacobson et al. 2010). Species response curves of lake whitefish and burbot were between lake trout and cisco, with central borders of 4.0 to 11.1°C for lake whitefish and 4.0 to 8.8°C for burbot (Jacobson et al. 2010). Through discussion among the researcher team members, it was decided that cisco refuge lakes should be selected and identified in two categories (Table 5.2): 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 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 upper of the lake whitefish central response borders of TDO3. Therefore, Tier 1 refuge lakes identified for cisco in this study are also useful to the management of lake whitefish in Minnesota. Tier 1 cisco refuge lakes allow for a wider margin of error and are therefore a safer choice than Tier 2 cisco refuge lakes.

The TDO3 parameters and their values used to identify and classify Minnesota’s cisco lakes into three tiers are summarized in Table 5.2.

Table 5.2 Categories of refuge lakes and criteria for classification.

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

### 5.1.3 Choice of weather stations

It is noteworthy that cisco lakes in Minnesota are primarily found in two ecoregions: North Central Hardwood Forests and Northern Lakes and Forests (Fig. 5.1). In this study, effects of climate on cisco were considered in model simulations using daily weather data at eight weather stations (Table 2.3). Weather stations at International Falls, Duluth, St. Cloud, and Minneapolis in Minnesota and Fargo in North Dakota are the Class I NWS stations. We were able to retrieve daily data from 1961 to 2008 from the Class I stations. Weather stations at Bemidji, Brainerd, and Grand Rapids in Minnesota are Class II NWS stations. They have daily data available for the period from 1991 to 2008.

Weather data from Minneapolis were used only to calibrate the MINLAKE2010 model for two non-cisco lakes in southern Minnesota. Similarly, Class II weather stations were used only to calibrate the MINLAKE2010 model for cisco and non-cisco lakes in central and north central Minnesota.

For identifying cisco refuge lakes in Minnesota, the three (principal) Class I weather stations located at International Falls, Duluth, and St. Cloud (Fig. 5.1) were used to cover all

cisco lakes. These three Class I NWS station had long-term (48 years) high quality weather data for the model simulations of daily temperature and DO profiles in cisco lakes.

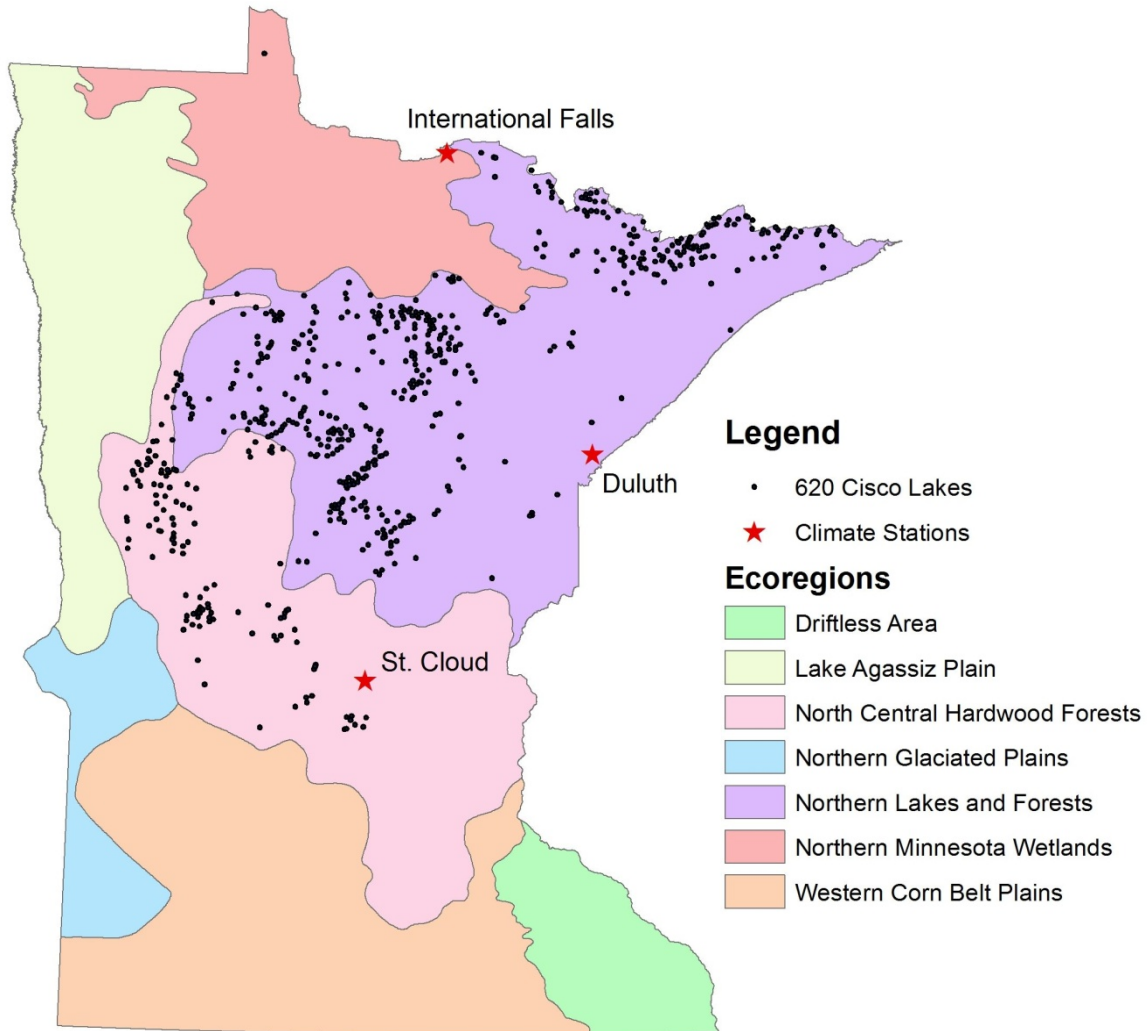


Figure 5.1 Distributions of 620 cisco lakes in the ecoregions of Minnesota. Three Class I weather stations used to identify cisco refuge lakes are also shown.

#### 5.1.4 Choice of simulation period

The length of the multi-year simulation period depended on the availability of weather data as MINLAKE2010 model input. The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to

2008 were used. The three principal weather stations used were in International Falls, Duluth and St. Cloud, Minnesota. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles and associated AvgATDO3<sub>FB</sub> and AvgATDO3<sub>VB</sub> for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes.

### ***5.1.5 Choice of weather station pairing with lakes***

Each lake had to be simulated with daily weather data as model input. Three Class I weather stations (International Falls, Duluth, and St. Cloud) had been selected, but which station to use for each lake was unclear. Three options were explored for the pairing of lakes and principal weather stations, and simulation results were obtained for each option. The options are: (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. Actually, the option (3) contains three options: associating all lakes with one of the three principal weather stations, International Falls, Duluth, and St. Cloud, respectively. Therefore, five options to associate each cisco lake to a weather station were used and explored in the cisco habitat simulations.

## **5.2 Selection of refuge lakes paired with a single principal weather station - for past climate and two future climate scenarios**

Contour lines of 11°C and 17°C in the contour plots of AvgATDO3<sub>FB</sub> and AvgTDO3<sub>VB</sub> were used to identify cisco refuge lakes in the database of 620 Minnesota cisco lakes (Table D.1 in Appendix D). These contour lines were derived by interpolation from simulated points for the 30 virtual lakes. The final selection of cisco refuge lakes was based on TDO3 parameters projected under the two future climate scenarios. Selections of cisco refuge lakes were also performed for past climate conditions (1962 - 2008) because the results are useful to understand the impact of climate warming on cisco refuge lakes in Minnesota.

Figure 5.2 shows the distribution of the 620 cisco lakes on a plot of Secchi depth versus lake geometry ratio. Based on Figure 5.2 there are 94 Tier 1 refuge lakes (green circles with cross), 429 Tier 2 refuge lakes (blue rhombuses with cross), and 97 non-refuge lakes (filled black rhombuses) out of 620 cisco lakes in Minnesota. Contour lines based on the parameter AvgATDO3<sub>VB</sub> (or TDO3<sub>L</sub> defined in Table 3.1, line 12), were used to identify refuge lakes, and AvgATDO3<sub>VB</sub> values for constructing contour lines (green and blue dashed lines) were simulated under past climate conditions (1962 – 2008) using Duluth weather data. The two contour lines are from Fig. 4.8 (top).

Figure 5.3 shows the distribution of selected refuge lakes and non-refuge cisco lakes based on contour lines of the other selected parameter AvgATDO3<sub>FB</sub> (TDO3<sub>F</sub>, defined in Table

3.1, line 6). Values of  $\text{AvgATDO3}_{\text{FB}}$  for constructing contour lines in Fig. 5.3 were simulated under the CGCM 3.1 future climate scenario using Duluth weather data. The two contour lines are from Fig. C.4 (Appendix C). Based on Figure 5.3 it is projected that there are 79 Tier 1 refuge lakes, 134 Tier 2 refuge lakes, and 407 non-refuge lakes out of 620 cisco lakes in Minnesota.

The difference in the number of Tier 1 plus Tier 2 cisco refuge lakes between Figs. 5.2 and 5.3 is substantial, 523 versus 213. The dramatic drop reflects the simulated or projected effect of climate change, because the data in both figures were obtained by identical simulations, except that the weather data used for Fig. 5.2 were historical data from 1962 to 2008, and those used for Fig 3.2 were historical data incremented by the predictions of the CGCM 3.1 future climate scenario model.

Figure 5.4 shows distribution of refuge and non-refuge cisco lakes using contour lines of  $\text{AvgATDO3}_{\text{VB}}$  for variable (sliding) benchmark periods instead of a fixed benchmark period as shown in Fig. 5.3. The simulations were again made for the CGCM 3.1 future climate scenario using Duluth weather data. Using the contour lines of  $\text{AvgATDO3}_{\text{VB}}$ , it is projected from Fig. 5.4 to have 25 Tier 1 refuge lakes, 54 less than identified using contour lines of  $\text{AvgATDO3}_{\text{FB}}$  from Fig. 5.3 for the fixed benchmark period under the same climate scenario (CGCM 3.1). Because  $\text{AvgATDO3}_{\text{VB}}$  (over the sliding benchmark periods) is always greater than  $\text{AvgATDO3}_{\text{FB}}$  (over the fixed benchmark period), the variable benchmark method always projects a smaller number of refuge lakes. For example, in Table 5.1,  $\text{AvgATDO3}_{\text{VB}} = 12.65^{\circ}\text{C}$  and  $\text{AvgATDO3}_{\text{FB}} = 8.46^{\circ}\text{C}$  for LakeC08.

Figure 5.5 shows the distribution of refuge and non-refuge cisco lakes identified by using again contour lines of  $\text{AvgATDO3}_{\text{VB}}$  ( $\text{TDO3}_{\text{L}} = 11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  (for Tier 1 and Tier 2, respectively), however, the MIROC 3.2 future climate scenario and Duluth weather data were used in the simulations. The number of Tier 1 plus Tier 2 refuge lakes identified under the MIROC 3.2 and CGCM 3.1 future climate scenarios is almost the same (154 in Fig. 5.4 versus 155 in Fig. 5.5). Table D.1 in Appendix D lists all 620 cisco lakes by MN DNR DOW number and lake name and four lake characteristic parameters (surface area, maximum depth, lake geometry ratio, and Secchi depth). Refuge lake types identified in Fig. 5.5 for each of 620 cisco lakes are listed in the last column of Table D.1. Refugee lakes are identified by 1, 2, and 3 in Table D.1; the numbers stand for Tier 1 refuge lake, Tier 2 refuge lake, and Tier 3 or non-refuge lake. Refuge lakes were selected using contour lines of averages of mean daily TDO3 for **fixed and variable** benchmark periods ( $\text{AvgATDO3}_{\text{FB}}$ ,  $\text{AvgATDO3}_{\text{VB}}$ , Table 3.1, lines 6 and 12) for the MIROC 3.2 future climate scenario using Duluth weather data for all 620 cisco lakes. Lakes in Table D.1 are sorted by refuge lake type selected using fixed benchmark period and then by lake name.

The geographic distribution of refuge lakes and non-refuge lakes in Minnesota based on the results in Figure 5.5 is shown in Figure 5.6 (green circles for Tier 1 refuge lakes, pink pentagons for Tier 2 refuge lakes, and black rhombuses for non-refuge lakes).

Tables 5.3 and 5.4 summarize the numbers of Tier 1 and Tier 2 refuge lakes and non-refuge lakes out of 620 cisco lakes in Minnesota using contour lines of AvgATDO3<sub>VB</sub> (variable benchmark periods) and AvgATDO3<sub>FB</sub> (fixed benchmark period) as boundary limits between tiers. Results in Tables 5.3 and 5.4 are for past climate and two future climate scenarios. All 620 cisco lakes were simulated with weather data from three weather stations (International Falls, Duluth and St. Cloud). The numbers of refuge lakes in Tables 5.3 and 5.4, were simulated by applying three different sets of weather data to all 620 cisco lakes, even though some of the cisco lakes are far away from a particular weather station. This is not the final selection of refuge cisco lakes in Minnesota but the results provide insight into the impact of weather station location and climate scenarios. For example, under the MIROC 3.2 future climate scenario, when weather data at International Fall, Duluth, and St. Cloud are used, Minnesota is projected to have 199, 155, and 86 refuge lakes (Tier 1 plus Tier 2), respectively. By comparison there were 534, 523, and 340 refuge lakes, respectively, under past climate conditions (Table 5.3). Climate warming is projected to decrease by 335, 368, and 254 the number of refuge lakes, respectively, when weather data from International Fall, Duluth, and St. Cloud are used to determine the contour lines for AvgATDO3<sub>VB</sub> for variable benchmark periods.

More refuge lakes (Tier 1 plus Tier 2) were found using AvgATDO3<sub>FB</sub> (Table 5.4) than using AvgATDO3<sub>VB</sub> (Table 5.3) under the same climate conditions because AvgATDO3<sub>FB</sub> can only be equal to or less than AvgATDO3<sub>VB</sub>. Under the MIROC 3.2 future climate scenario, when weather data at International Fall, Duluth, and St. Cloud were used, Minnesota was projected to have 298, 218, and 163 refuge lakes (Tier 1 plus Tier 2) out of 620 cisco lakes, respectively, when contour lines of AvgATDO3<sub>FB</sub> for the fixed benchmark period (DOY 209 to DOY 239) were used (Table 5.4). The number of refuge lakes increased from 63 to 99 lakes when the fixed benchmark period (AvgATDO3<sub>FB</sub> or TDO3<sub>F</sub> in Table 3.1) was used instead of the variable benchmark period (AvgATDO3<sub>VB</sub> or TDO3<sub>L</sub> in Table 3.1). Table D.1 in Appendix D also shows that 61 lakes were identified as Tier 1 refuge lakes using the fixed benchmark period but were identified as Tier 2 refuge lakes using the variable benchmark periods, and 63 lakes were identified as Tier 2 refuge lakes using the fixed benchmark period but were identified as Tier 3 or non-refuge lakes using the variable benchmark periods.

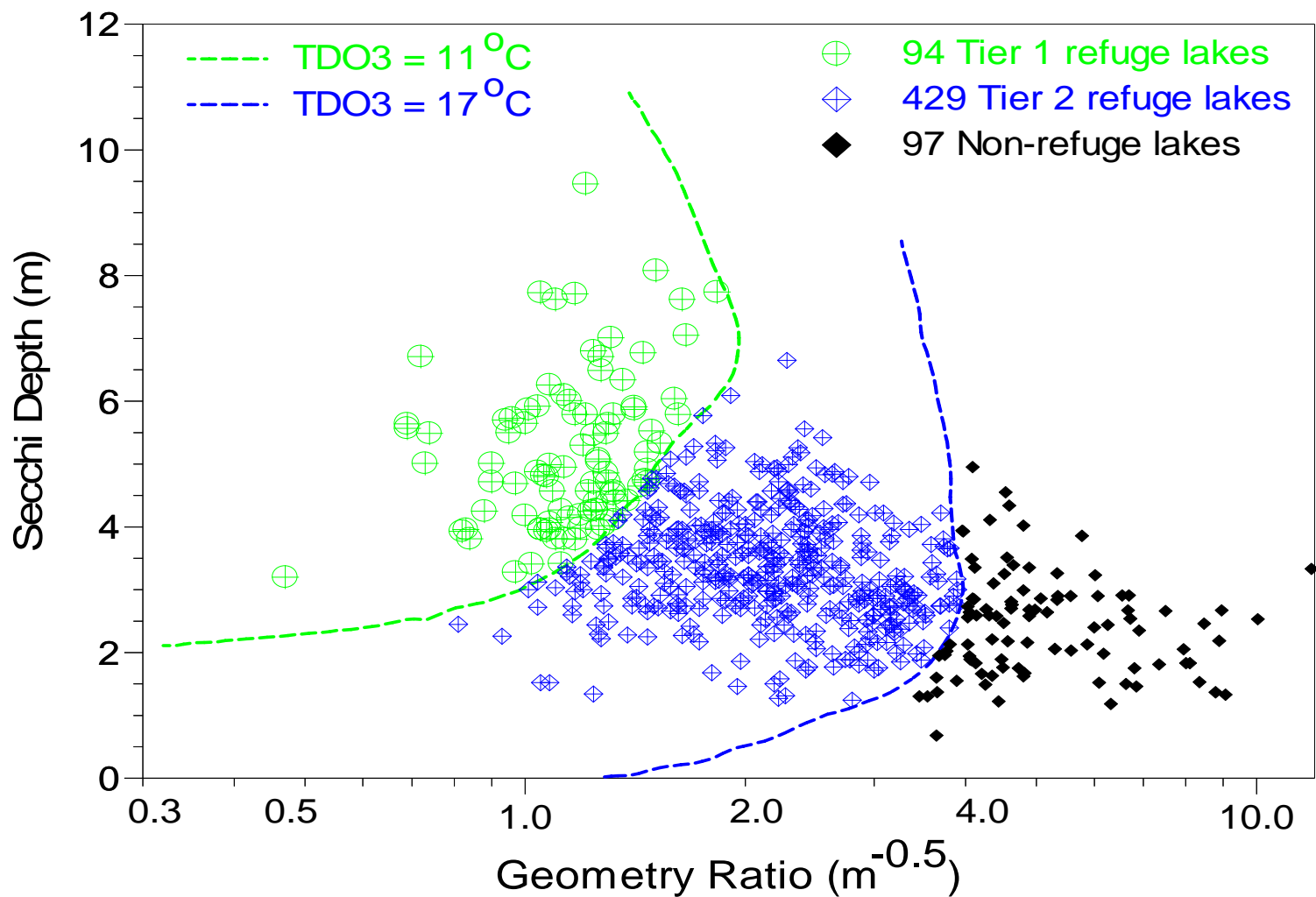


Figure 5.2 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for AvgATDO3<sub>VB</sub> (TDO3<sub>L</sub>) and were derived for **variable benchmark periods** simulated for **past climate conditions (1962-2008)** using **Duluth weather data**.

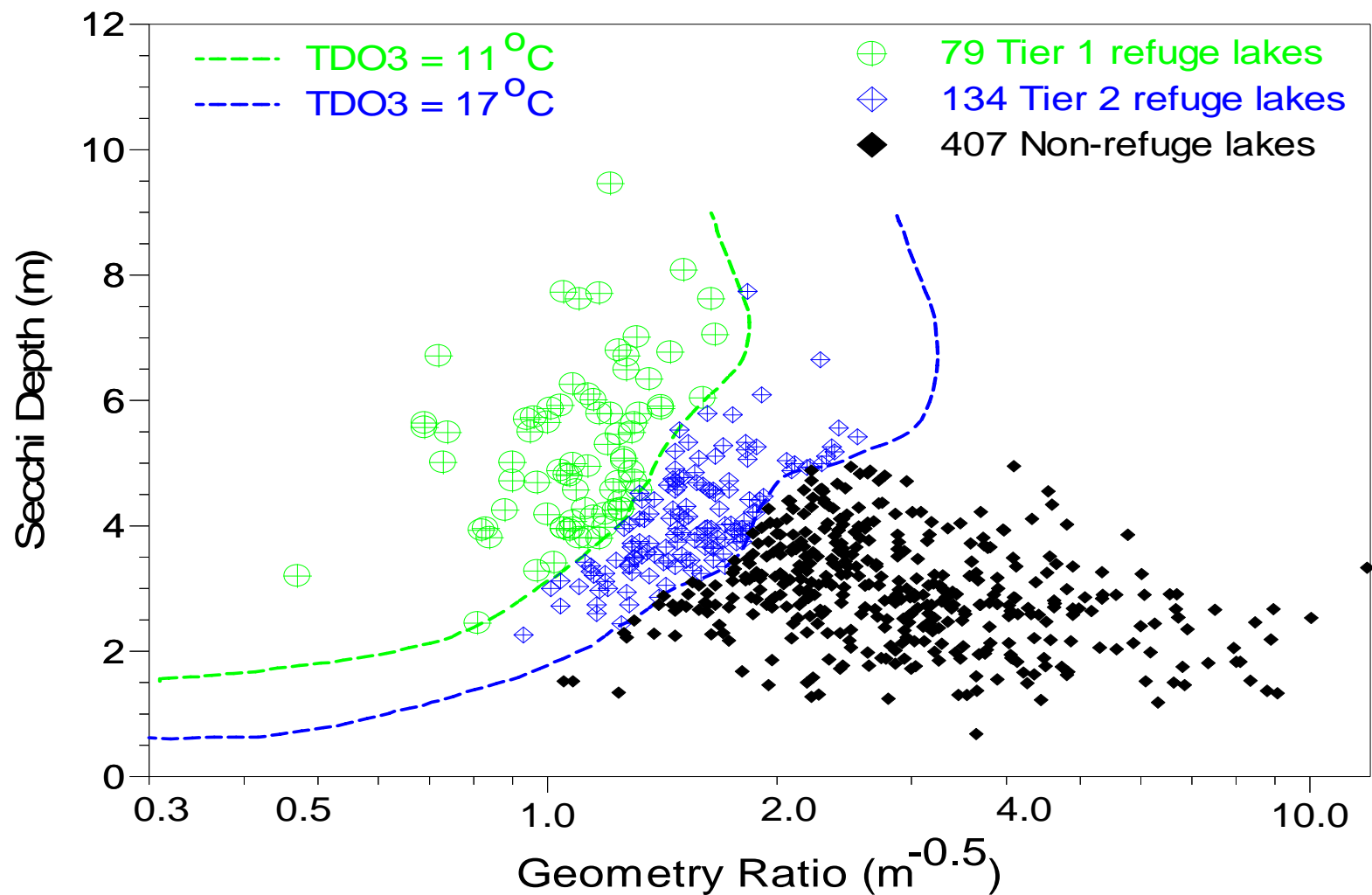


Figure 5.3 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for  $\text{AvgATDO3}_{\text{FB}}$  ( $\text{TDO3}_{\text{F}}$ ) and were derived for the **fixed benchmark period** (DOY 209 to DOY 239) simulated for the **CGCM 3.1 future climate scenario** using **Duluth weather data**.

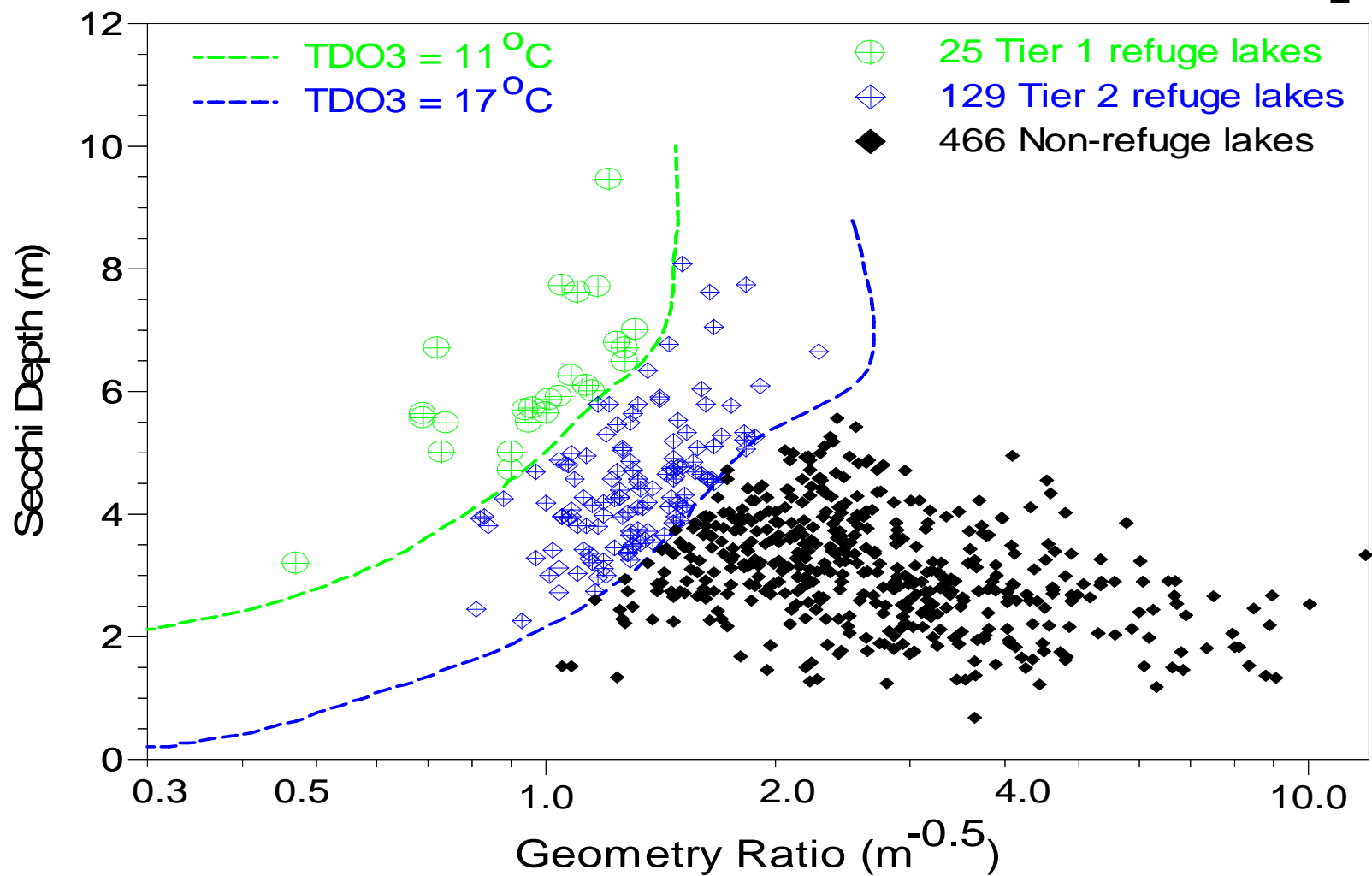


Figure 5.4 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for  $\text{AvgATDO3}_{\text{VB}}$  ( $\text{TDO3}_{\text{L}}$ ) and were derived for **variable benchmark periods** simulated for the **CGCM 3.1 future climate scenario** using **Duluth weather data**.



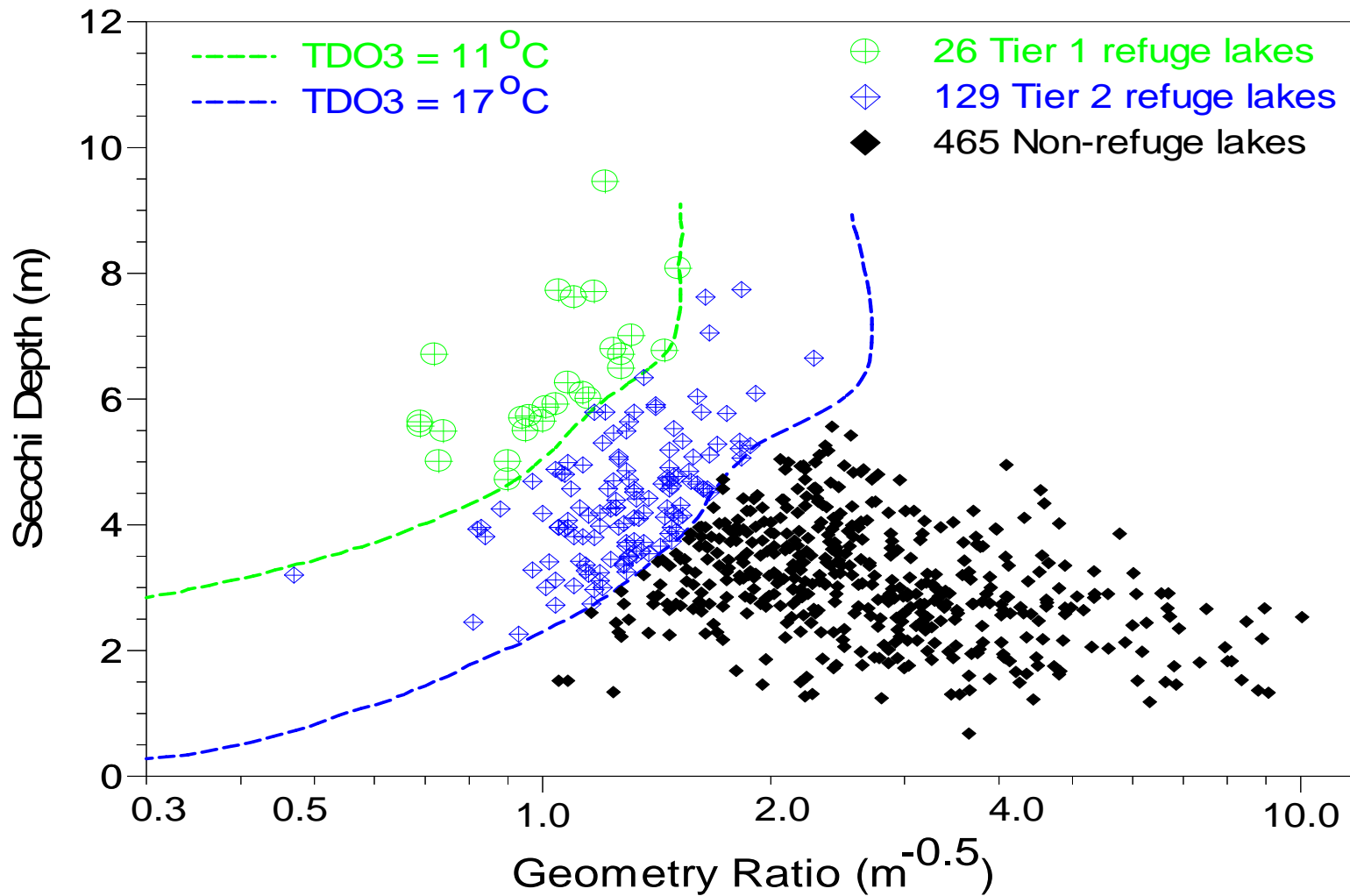


Figure 5.5 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of 620 cisco lakes. The boundary contour lines are for  $AvgATDO3_{VB}$  ( $TDO3_L$ ) and were derived for variable benchmark periods were simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

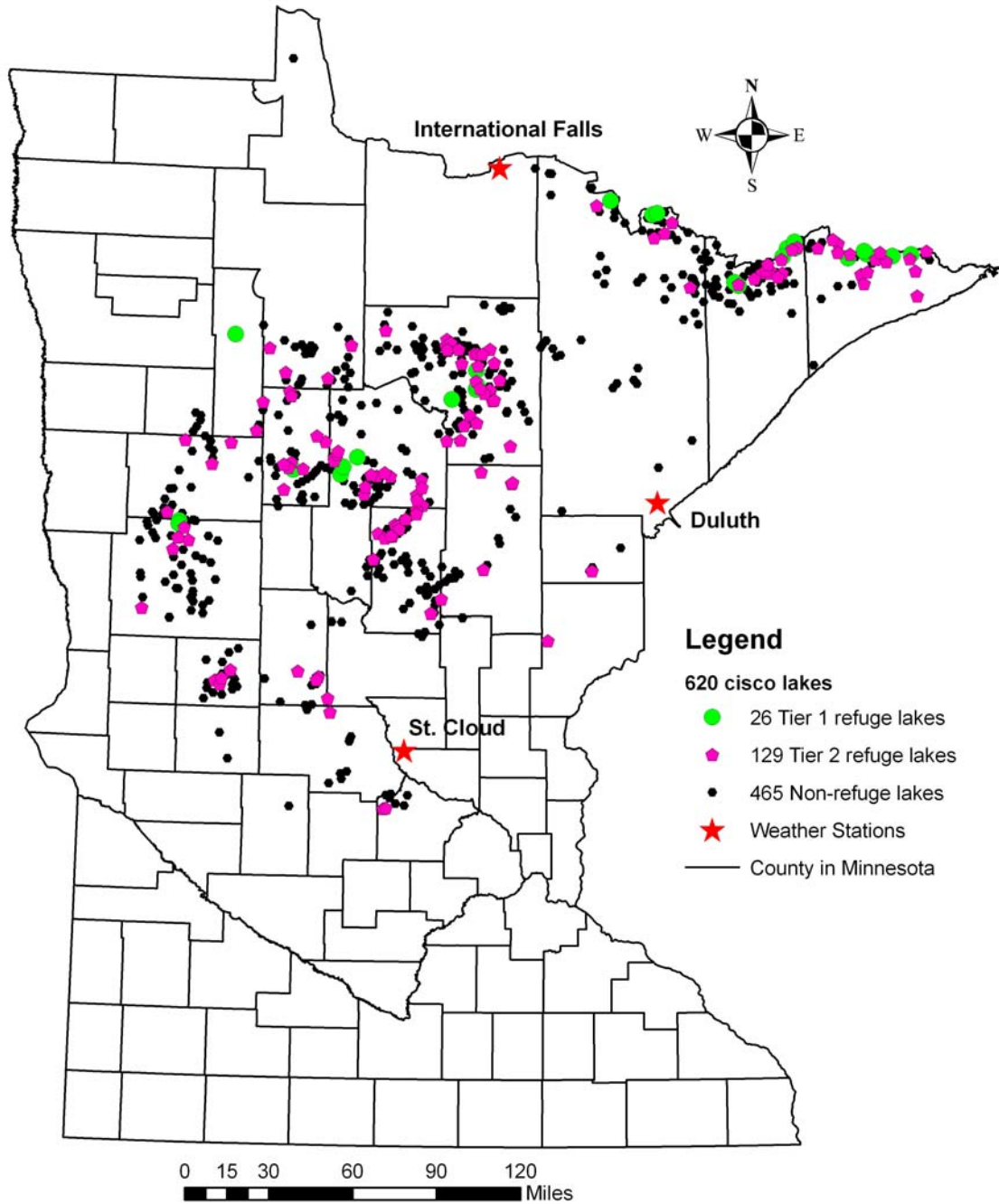


Figure 5.6 Geographic distribution of Tier 1 and Tier 2 refuge lakes and non-refuge cisco lakes simulated with the **MIROC 3.2 future climate scenario**. The boundary limits for selection of refuge lakes were contour lines of  $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 17^{\circ}\text{C}$  and  $11^{\circ}\text{C}$ , respectively. Variable benchmark periods and **Duluth weather** data were used in the simulations.

Table 5.3 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from 620 cisco lakes in Minnesota using  $\text{AvgATDO3}_{\text{VB}} = 11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  as boundary limits for Tier 1 and Tier 2, respectively, for variable benchmark periods defined in Table 3.1, line 12). A single weather station was used to simulate all 620 cisco lakes.

One weather station for all 620 lakes	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
<b>International Falls</b>	Past	117	417	534	86	620
	CGCM 3.1	44	174	218	402	620
	MIROC 3.2	31	168	199	421	620
<b>Duluth</b>	Past	94	429	523	97	620
	CGCM 3.1	25	129	154	466	620
	MIROC 3.2	26	129	155	465	620
<b>St. Cloud</b>	Past	50	290	340	280	620
	CGCM 3.1	17	70	87	533	620
	MIROC 3.2	9	77	86	534	620

Table 5.4 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from 620 cisco lakes in Minnesota using  $\text{AvgATDO3}_{\text{FB}} = 11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  as boundary limits for Tier 1 and Tier 2, respectively, for the fixed benchmark period (defined in Table 3.1, line 6). A single weather station was used to simulate all 620 cisco lakes.

One weather station for all 620 lakes	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
<b>International Falls</b>	Past	247	305	552	68	620
	CGCM 3.1	118	181	299	321	620
	MIROC 3.2	117	181	298	322	620
<b>Duluth</b>	Past	182	361	543	77	620
	CGCM 3.1	79	134	213	407	620
	MIROC 3.2	87	131	218	402	620
<b>St. Cloud</b>	Past	144	258	402	218	620
	CGCM 3.1	65	97	162	458	620
	MIROC 3.2	68	95	163	457	620

### 5.3 Selection of refuge lakes paired with one of three principal weather stations by shortest distance

Each of the 620 cisco lakes in Minnesota shown on Figure 5.1 is closer to one weather station than another. It therefore makes sense to group cisco lakes by distance to the principal weather stations used for the selection of refuge lakes. The simplest method to associate cisco lakes with the principal weather stations is based on distance between weather station and lake. Figure 5.7 shows the distribution of the 620 cisco lakes as well as the three principal weather stations used for the selection of refuge lakes. There are 169, 189, and 262 cisco lakes associated with International Falls, Duluth, and St. Cloud weather station, respectively.

The selection process for refuge lakes used in the previous section was repeated for cisco lakes grouped by weather station. We used again contour lines of  $\text{AvgATDO3}_{\text{VB}}$  ( $\text{TDO3}_{\text{L}}$ ) for variable benchmark periods and  $\text{AvgATDO3}_{\text{FB}}$  ( $\text{TDO3}_{\text{F}}$ ) for the fixed benchmark period as boundary limits for Tier 1 and Tier 2, and we simulated past climate condition (1962 to 2008) and two future climate scenarios. The  $\text{TDO3}$  contour lines of  $11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  used to identify refuge lakes were derived by interpolation from simulated points for the 30 virtual lakes. Results are summarized in Table 5.5 (using  $\text{TDO3}_{\text{L}}$ ) and 5.6 (using  $\text{TDO3}_{\text{F}}$ ). Figures 5.8, 5.9, and 5.10 show distributions of Tier 1 and Tier 2 refuge lakes and non-refuge lakes for cisco lakes near International Falls, Duluth, and St. Cloud, respectively. The selection of refuge lakes on Figs. 5.8, 5.9, and 5.10 was again based on contour lines of  $\text{AvgTDO3}_{\text{VB}}$  ( $\text{TDO3}_{\text{L}}$ ) for variable benchmark periods simulated under the MIROC 3.2 future climate scenario. Tables 5.5 and 5.6 also include information on the total number of selected refuge lakes associated with each of the three weather stations.

Under the MIROC 3.2 future climate scenario, Minnesota was projected to have 41, 70, and 26 refuge lakes (Tier 1 plus Tier 2) out of 169, 189, and 262 cisco lakes associated with International Fall, Duluth, and St. Cloud weather station, respectively, when contour lines of  $\text{AvgATDO3}_{\text{VB}}$  are used for the selection. Minnesota was projected to have 137 and 207 refuge lakes (Tier 1 plus Tier 2) out of 620 cisco lakes under the MIROC 3.2 future climate scenario when contour lines of  $\text{AvgATDO3}_{\text{VB}}$  (Table 5.3) and  $\text{AvgATDO3}_{\text{FB}}$  (Table 5.6) were used, respectively. Climate warming under the MIROC 3.2 future climate scenario is projected to decrease by 312 the number of refuge lakes from past climate conditions when contour lines of  $\text{AvgATDO3}_{\text{VB}}$  are used (Table 5.5).

The geographic distribution of refuge lakes and non-refuge lakes in Minnesota based on results in Figures 5.8, 5.9 and 5.10 is shown in Figure 5.11. Minnesota is projected to have 22 Tier 1 refuge lakes, 115 Tier 2 refuge lakes, and 483 non-refuge lakes out of the 620 cisco lakes in Minnesota under the MIROC 3.2 future climate scenario when contour lines of  $\text{AvgATDO3}_{\text{VB}}$  are used (Fig. 5.11) and refuge lakes are associated by weather stations. These results are not much different from results presented in Fig. 5.6 when the selection of refuge lakes was performed using Duluth weather data for all lakes.

Figure 5.12 shows the geographic distribution and number of Tier 1 and Tier 2 refuge lakes and non-refuge cisco lakes associated with each of the three weather stations for the MIROC 3.2 future climate scenario.

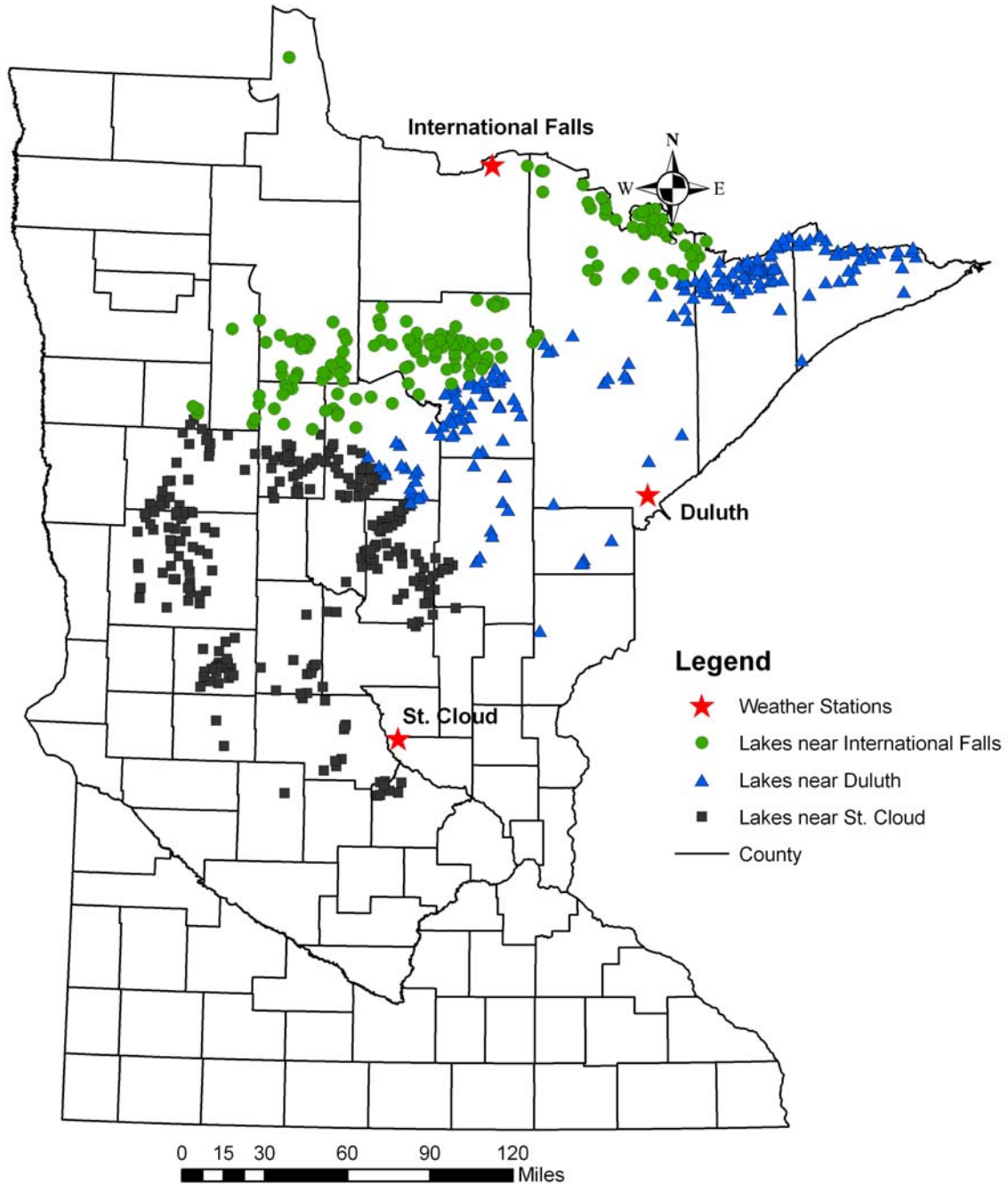


Figure 5.7 Geographic distribution of 620 cisco lakes paired with weather stations based on the shortest distance between weather station and lake location.

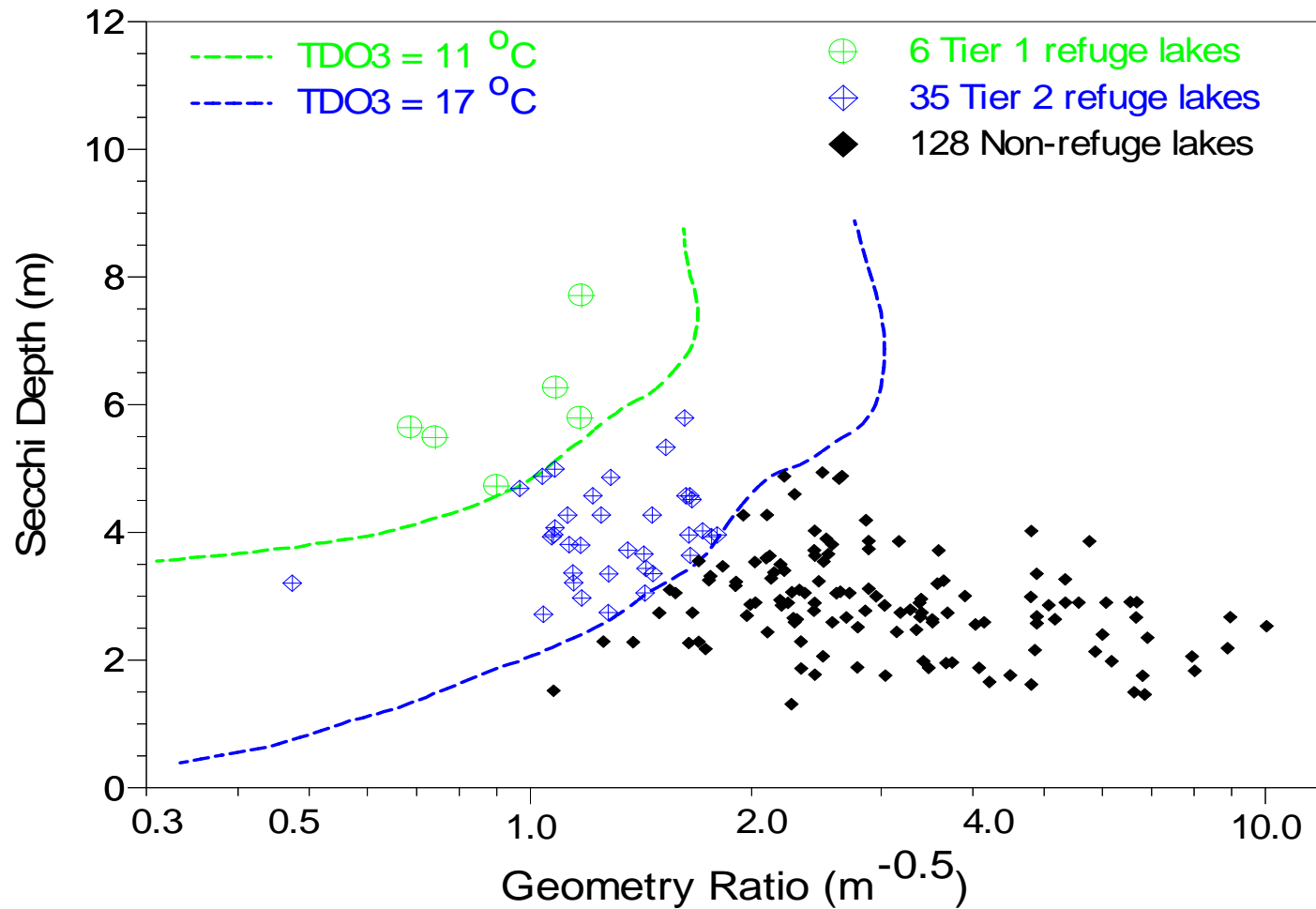


Figure 5.8 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **169** cisco lakes associated with the **International Falls weather station**. The boundary limits for selection of refuge lakes were contour lines of  $AvgATDO3_{VB}$  ( $TDO3_L$ ) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **International Falls weather data**.

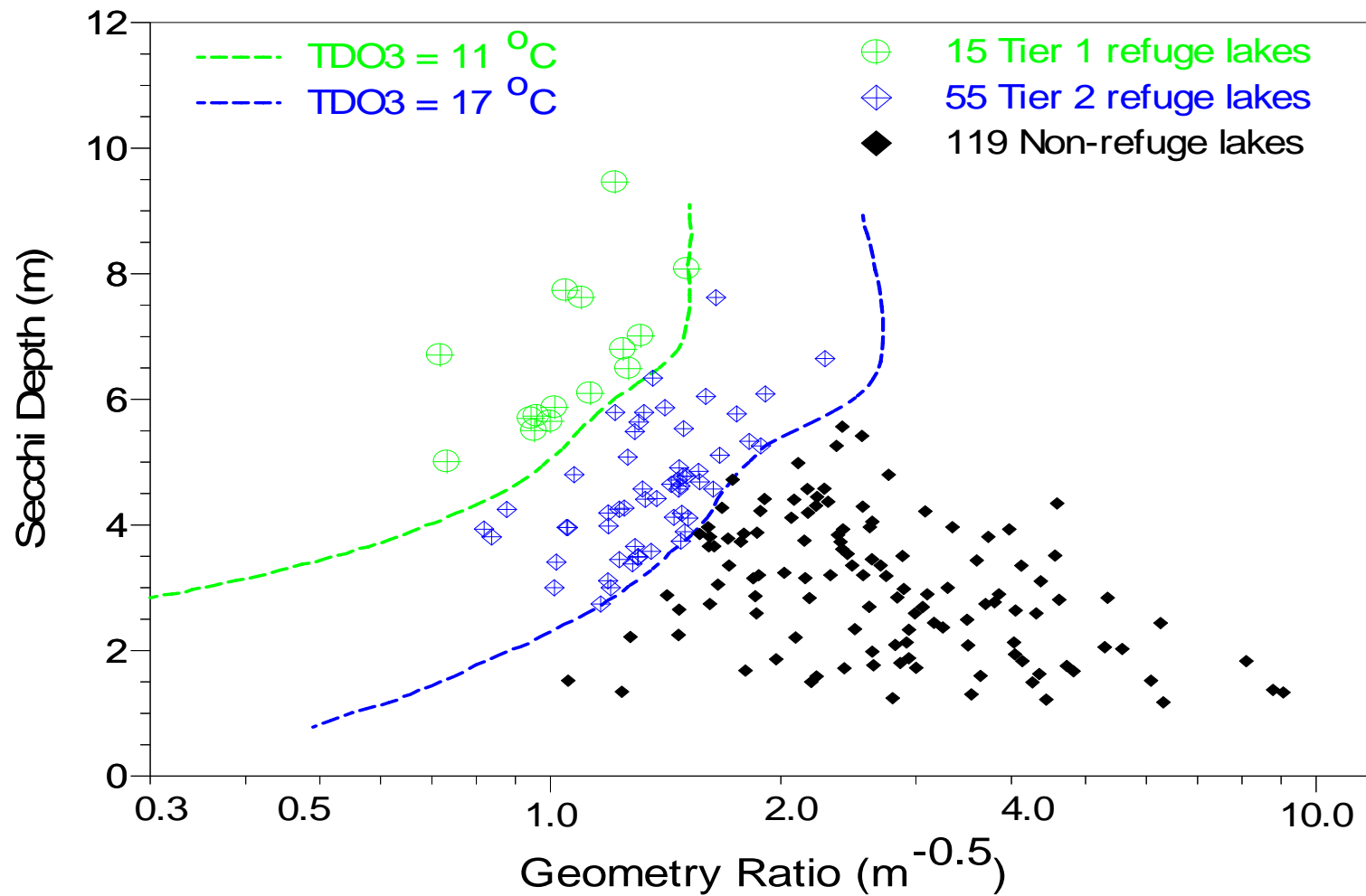


Figure 5.9 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **189** cisco lakes associated with the **Duluth weather station**. The boundary limits for selection of refuge lakes were contour lines of  $\text{AvgATDO3}_{\text{VB}}$  ( $\text{TDO3}_L$ ) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

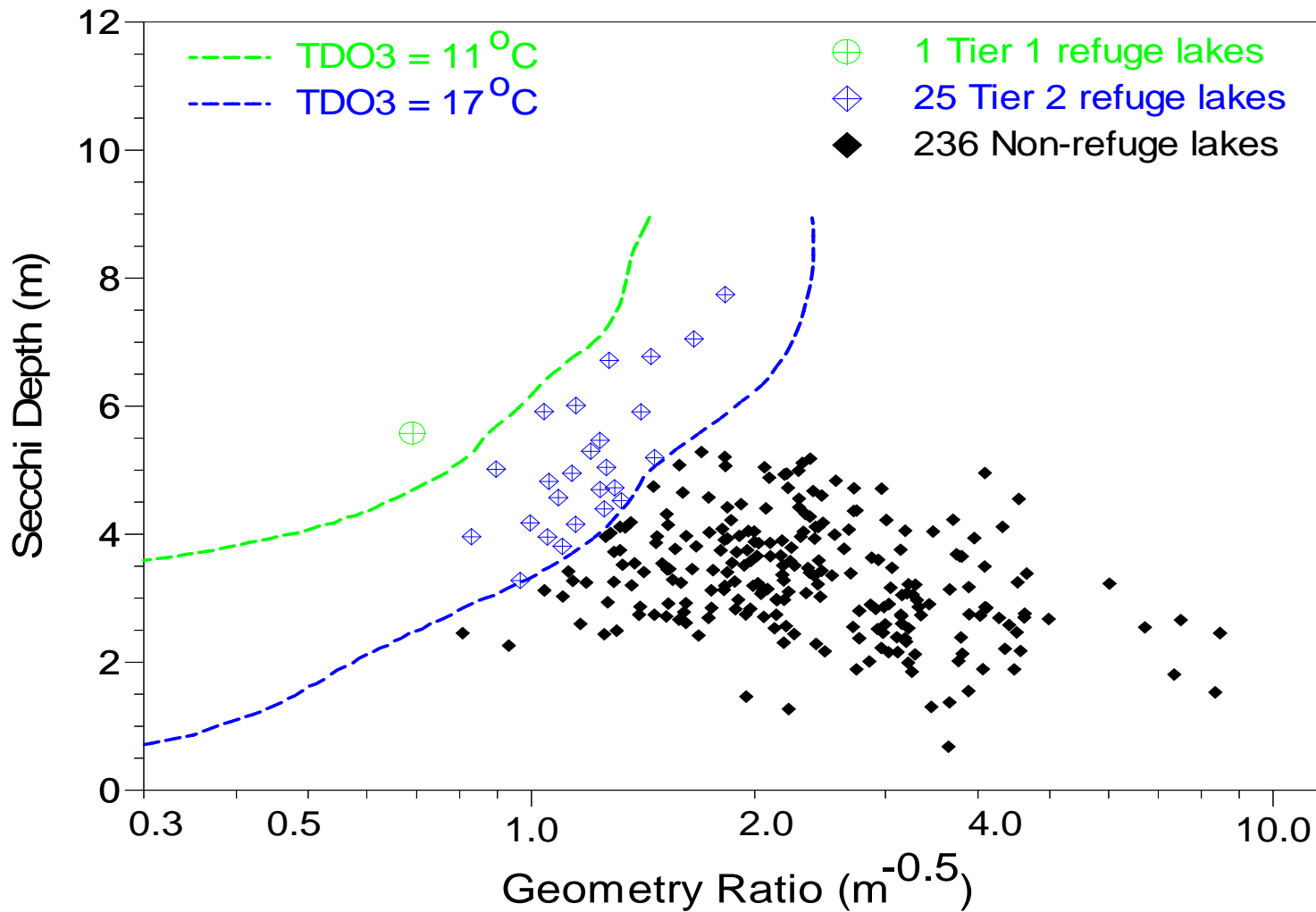


Figure 5.10 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **262** cisco lakes associated with the **St. Cloud weather station**. The boundary limits for selection of refuge lakes were contour lines of  $AvgATDO3_{VB}$  ( $TDO3_L$ ) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **St. Cloud weather data**.



Table 5.5 Number of Tier 1 and Tier 2 refuge lakes and non-refuge lakes selected from **cisco lakes paired by shortest distance to one of the three principal weather stations** using  $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  as boundary limits for Tier 1 and Tier 2, respectively, for variable benchmark periods (defined in Table 3.1, line 12). Three principal weather stations are used separately to simulate their paired cisco lakes.

<b>Closest weather station</b>	<b>Climate scenario</b>	<b>Tier 1 refuge lakes</b>	<b>Tier 2 refuge lakes</b>	<b>Total number of refuge lakes</b>	<b>Non-refuge lakes</b>	<b>Total number of lakes</b>
<b>International Falls</b>	Past	23	112	135	34	169
	CGCM 3.1	9	36	45	124	169
	MIROC 3.2	6	35	41	128	169
<b>Duluth</b>	Past	42	120	162	27	189
	CGCM 3.1	14	55	69	120	189
	MIROC 3.2	15	55	70	119	189
<b>St. Cloud</b>	Past	15	137	152	110	262
	CGCM 3.1	2	25	27	235	262
	MIROC 3.2	1	25	26	236	262
All three stations	Past	80	369	449	171	620
	CGCM 3.1	25	116	141	479	620
	MIROC 3.2	22	115	137	483	620

Table 5.6 Number of Tier 1 and Tier 2 refuge lakes and non-refuge lakes selected from **cisco lakes associated by distance to one of the three principal weather stations** using  $\text{AvgATDO3}_{\text{FB}} (\text{TDO3}_{\text{F}}) = 11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  as boundary limits for Tier 1 and Tier 2, respectively, for the fixed benchmark period (defined in Table 3.1, line 6). Three principal weather stations are used separately to simulate their associated cisco lakes.

<b>Closest weather station</b>	<b>Climate scenario</b>	<b>Tier 1 refuge lakes</b>	<b>Tier 2 refuge lakes</b>	<b>Total number of refuge lakes</b>	<b>Non-refuge lakes</b>	<b>Total number of lakes</b>
<b>International Falls</b>	Past	49	88	137	31	169
	CGCM 3.1	23	39	62	106	169
	MIROC 3.2	23	39	62	106	169
<b>Duluth</b>	Past	78	91	169	20	189
	CGCM 3.1	36	51	87	102	189
	MIROC 3.2	39	50	89	100	189
<b>St. Cloud</b>	Past	49	128	177	85	262
	CGCM 3.1	19	37	56	206	262
	MIROC 3.2	22	34	56	206	262
All three stations	Past	176	307	483	137	620
	CGCM 3.1	78	127	205	415	620
	MIROC 3.2	84	123	207	413	620

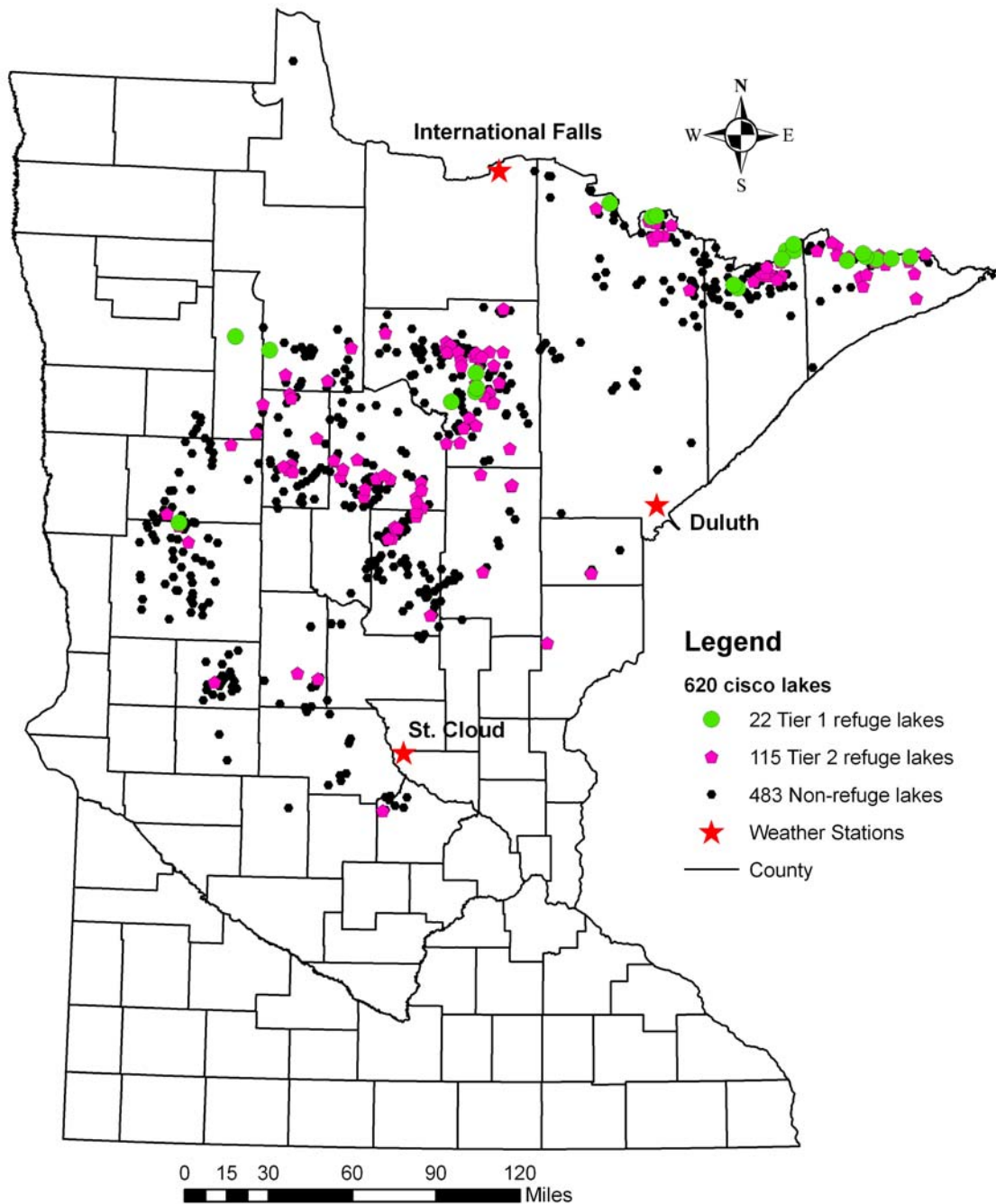


Figure 5.11 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and non-refuge cisco lakes simulated with the **MIROC 3.2 future climate scenario**. The boundary limits for selection of refuge lakes were contour lines of  $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 17^{\circ}\text{C}$  and  $11^{\circ}\text{C}$ , for Tier 1 and Tier 2, respectively. Variable benchmark periods and weather data from the three associated weather stations (**International Falls, Duluth, and St. Cloud**) were used in the simulations.

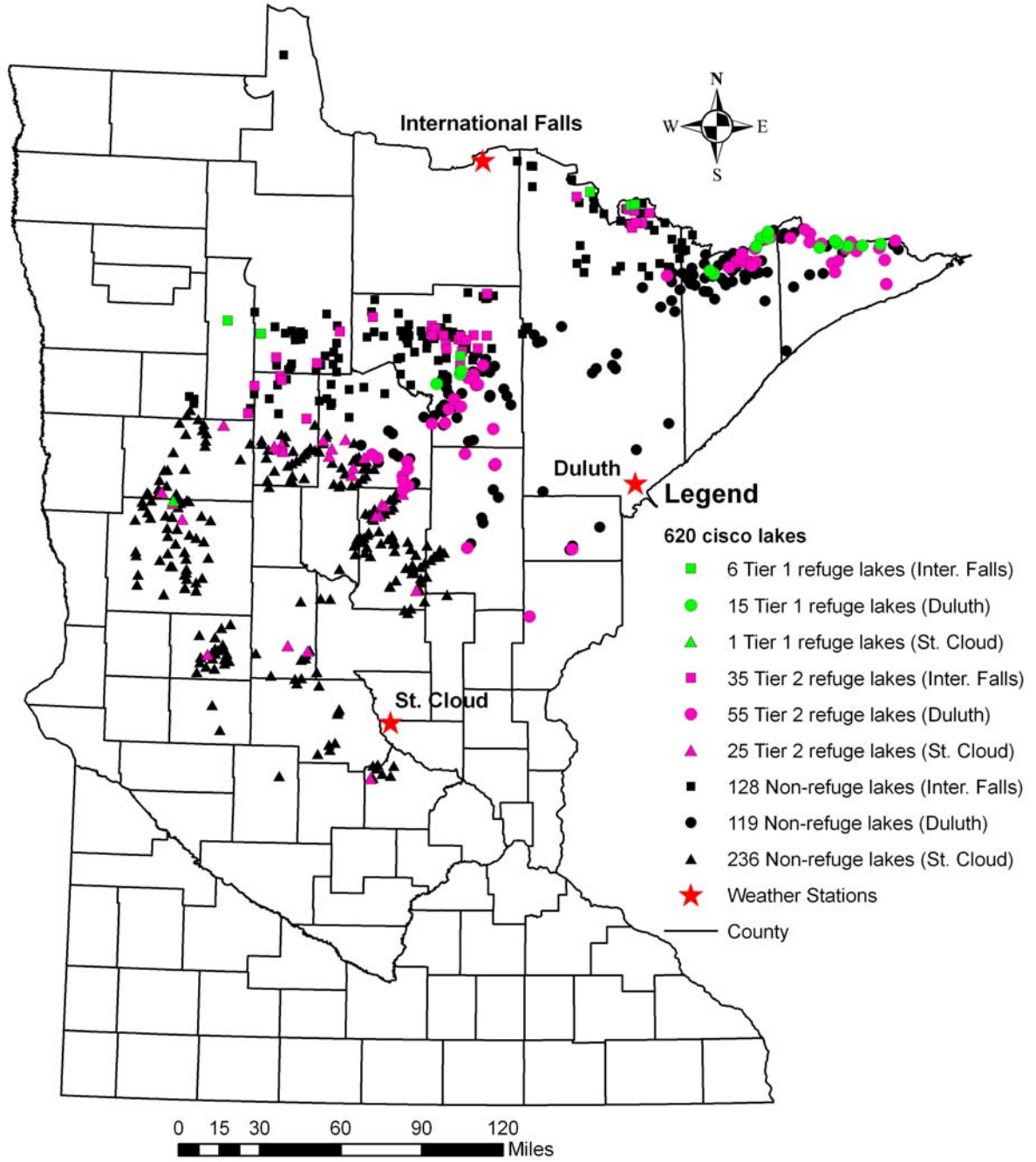


Figure 5.12 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and non-refuge cisco lakes simulated under the same conditions as lakes in Figure 5.11. The pairing of each lake with a specific weather station is shown more clearly than in Figure 5.11.

## 5.4 Selection of refuge lakes paired by latitude with one of three principal weather stations

Using distance from the lake to a weather station, as the criterion to associate a cisco lake with a weather station may not be the best approach. 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 1993). Therefore, two constant latitudes were proposed as boundary limits to associate cisco lakes with weather stations (Figure 5.13). The latitudes proposed as dividing lines are 46.10°N and 47.65°N. 46.10°N runs through central Minnesota (Figure 5.13). There are 55 cisco lakes below 46.10°N through central Minnesota that were assigned to the St. Cloud weather station. There are 166 lakes above the dividing line of 47.65°N through northern Minnesota that were assigned to the International Falls weather station. There are 399 lakes between the dividing lines of 47.65°N and 46.10°N latitudes that were assigned to the Duluth weather station. In Figure 5.13 and in the following discussion, the three groups of cisco lakes are named “northern cisco lakes” assigned to International Falls, “mid-latitude cisco lakes” assigned to Duluth, and “southern cisco lakes” assigned to St. Cloud.

The refuge lake selection process was repeated for cisco lakes grouped by latitude with weather stations. Contour lines of  $\text{AvgATDO3}_{\text{VB}}$  ( $\text{TDO3}_{\text{L}}$ ) = 11°C and 17°C were again used for variable benchmark periods and  $\text{AvgATDO3}_{\text{FB}}$  ( $\text{TDO3}_{\text{F}}$ ) = 11°C and 17°C for the fixed benchmark period as boundary limits for Tier 1 and Tier 2 refuge lakes, and again simulations were made for past climate conditions (1962 – 2008) and for two future climate scenarios. The TDO3 contour lines of 11°C and 17°C used to identify refuge lakes were derived by interpolation from simulated points for the 30 virtual lakes.

The results are summarized in Table 5.7 (using  $\text{TDO3}_{\text{L}}$ ) and 5.8 (using  $\text{TDO3}_{\text{F}}$ ). Figures 5.14, 5.15, and 5.16 show distributions of Tier 1 and Tier 2 refuge lakes and non-refuge lakes for the 166 northern, 399 mid-latitude, and 55 southern cisco lakes, respectively. The selections of refuge lakes for Figs. 5.14, 5.15, and 5.16 were again based on contour lines of  $\text{AvgATDO3}_{\text{VB}}$  ( $\text{TDO3}_{\text{L}}$ ) for variable benchmark periods simulated under the MIROC 3.2 future climate scenario, which has finer spatial resolution (Fig. 2.3) than the CGCM 3.1 scenario (Fig. 2.2).

Under the MIROC 3.2 future climate 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, when contour lines of  $\text{AvgATDO3}_{\text{VB}}$  for variable benchmark periods were used (Table 5.7 and Figs. 5.14 to 5.16). It was projected to have 160 and 229 refuge lakes (Tier 1 plus Tier 2) out of 620 cisco lakes under the MIROC 3.2 future climate scenario when contour lines of  $\text{AvgATDO3}_{\text{VB}}$  (Table 5.7) and  $\text{AvgATDO3}_{\text{FB}}$  (Table 5.8) were used, respectively. Climate warming under the MIROC 3.2 future climate scenario is projected to decrease by 346 the number of refuge lakes from past climate conditions when contour lines of  $\text{AvgATDO3}_{\text{VB}}$  were used (Table 5.7).

The geographic distribution of refuge lakes and non-refuge lakes in Minnesota based on results in Figures 5.14, 5.15 and 5.16 is shown in Figure 5.17. A division of the 620 Minnesota

cisco lakes into 29 Tier 1 refuge lakes, 131 Tier 2 refuge lakes, and 460 non-refuge cisco lakes was projected for the MIROC 3.2 future climate scenario when contour lines of AvgATDO3<sub>VB</sub> were used as boundary limits (Fig. 5.17) and refuge lakes were selected separately from three cisco lakes groups divided by latitude. Overall, the results are not much different from the results presented in Fig. 5.6 for all 620 cisco lakes and Fig. 5.11 for the three lake groups obtained by using minimum distance.

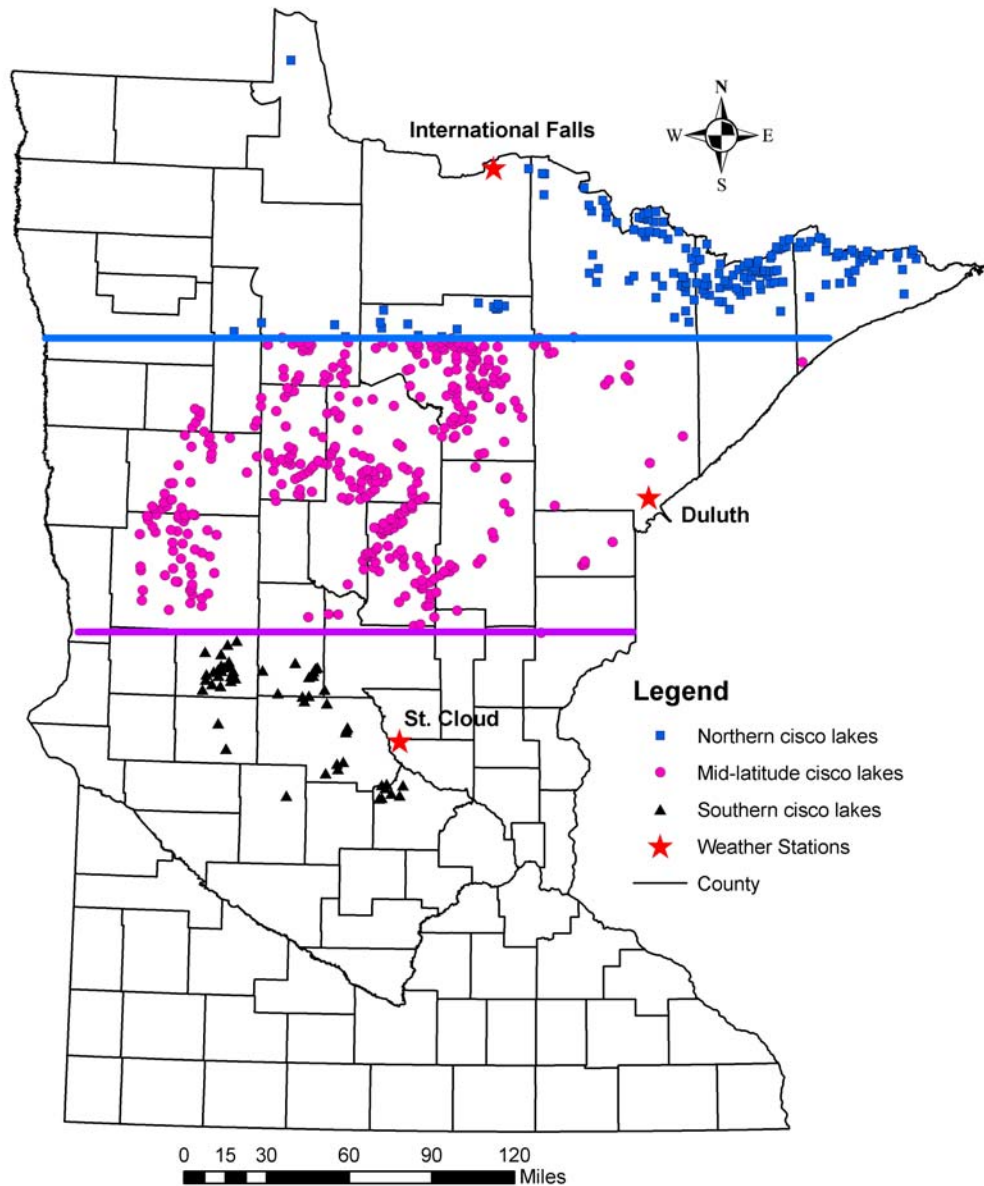


Figure 5.13 Geographic distribution of 620 cisco lakes in Minnesota relative to latitudes 46.10°N and 47.65°N. The two latitudes divide the 620 cisco lakes into 166 northern cisco lakes, 399 mid-latitude cisco lakes, and 55 southern cisco lakes.

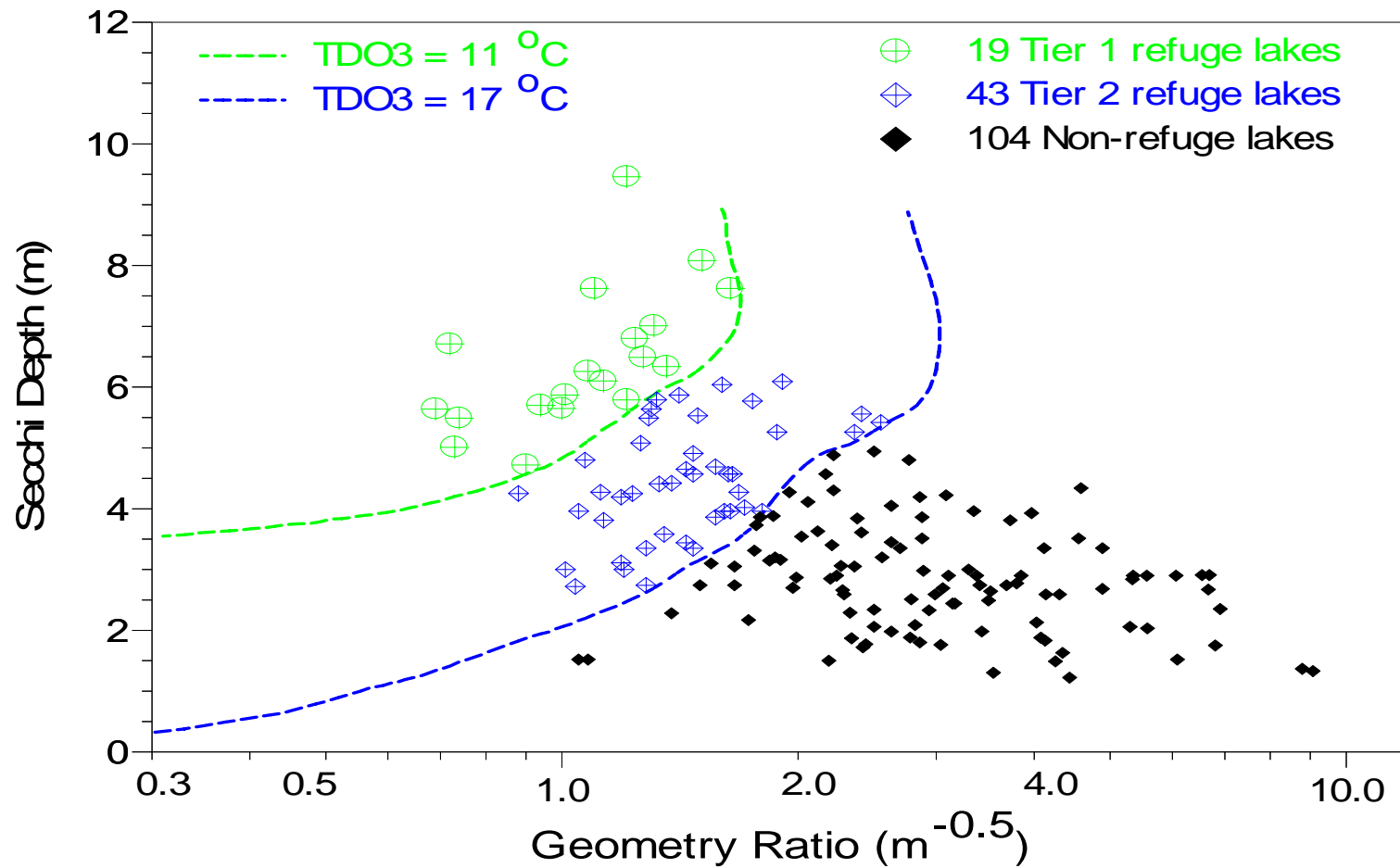


Figure 5.14 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **166 northern cisco lakes**. The boundary limits for selection of refuge lakes were contour lines of  $AvgATDO3_{VB}$  ( $TDO3_L$ ) for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **International Falls weather data**.

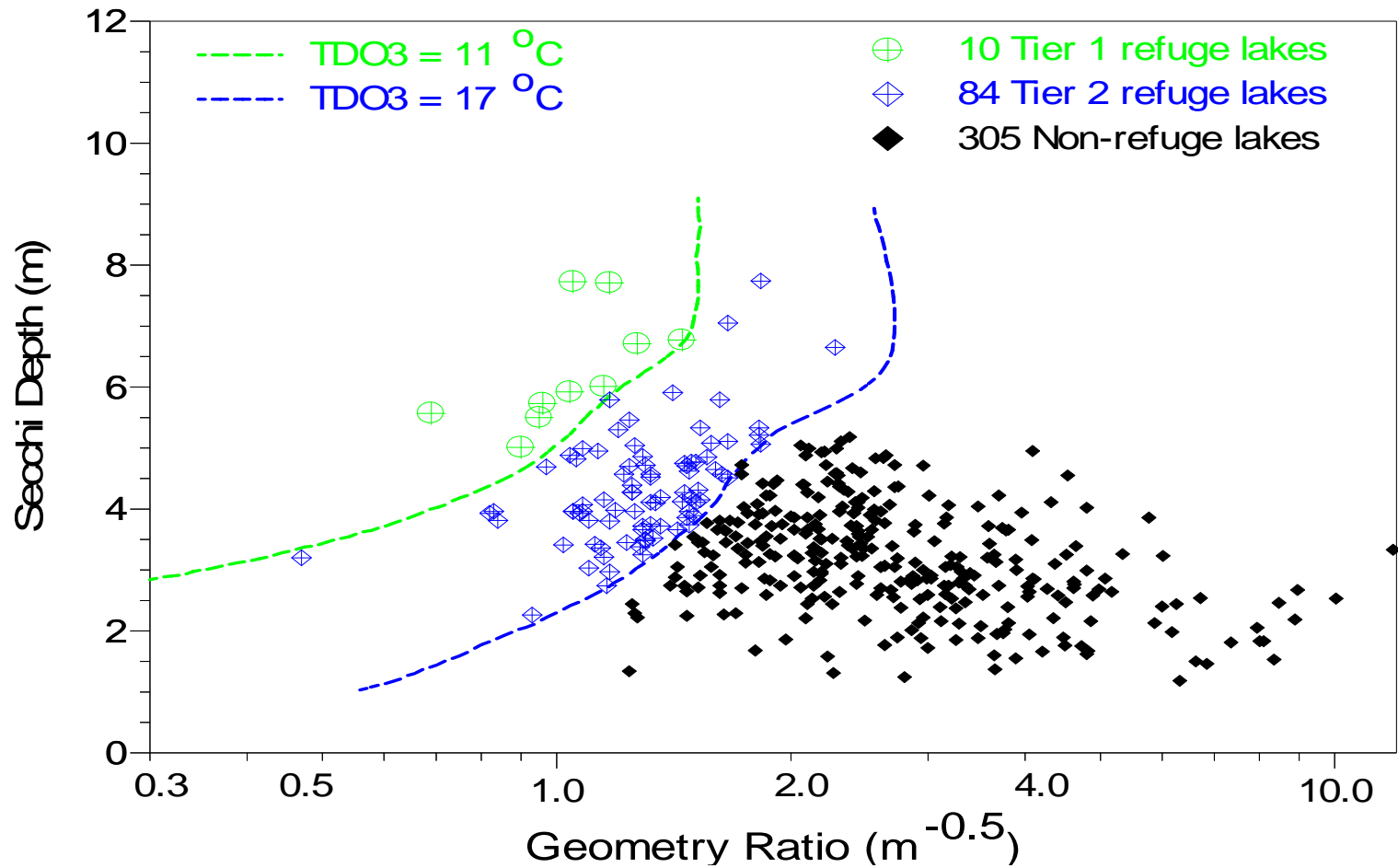


Figure 5.15 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **399 mid-latitude cisco lakes**. The boundary limits for selection of refuge lakes were contour lines of **AvgTDO3<sub>VB</sub> (TDO3<sub>L</sub>)** for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather** data.

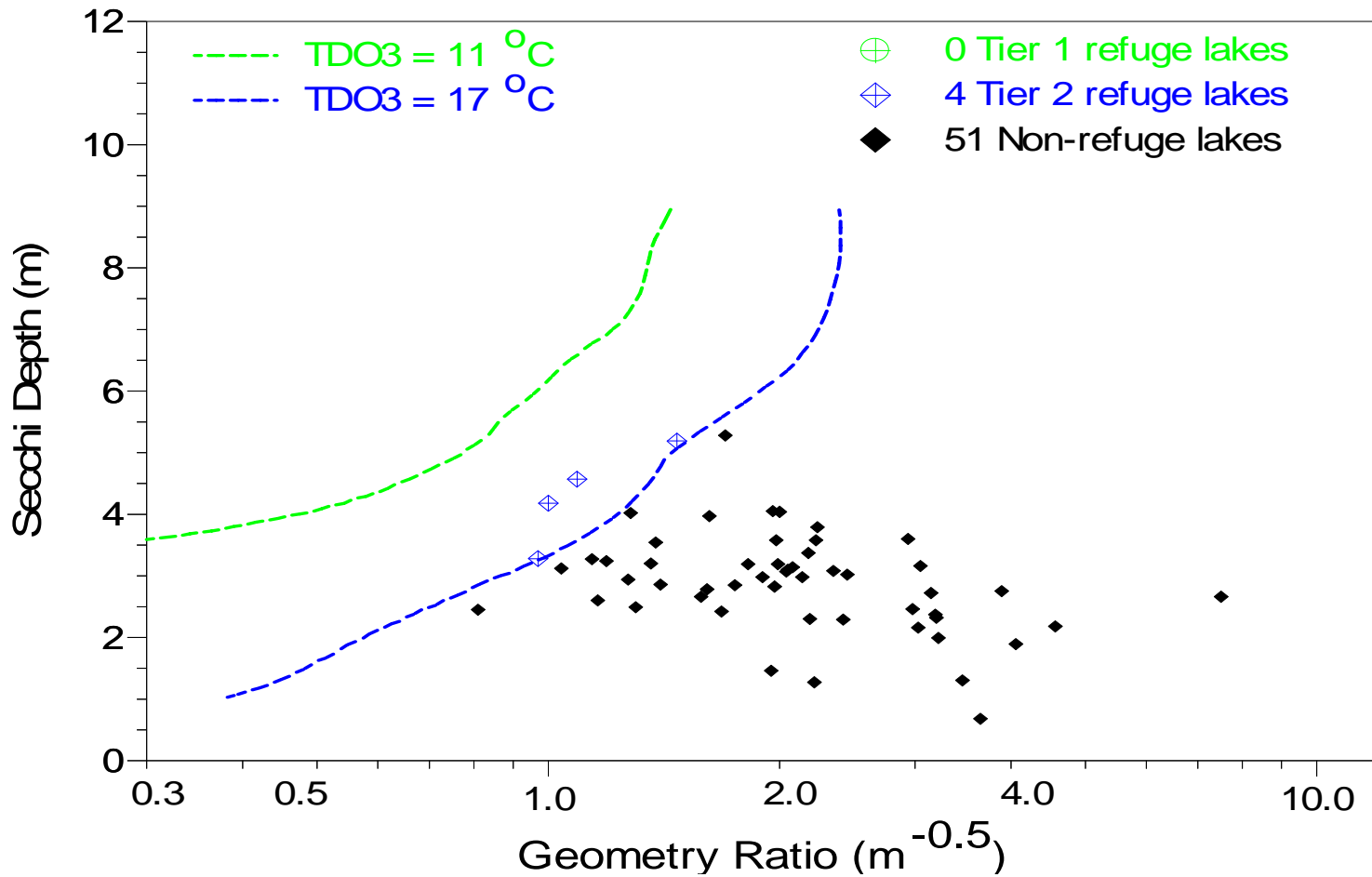


Figure 5.16 Distribution of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes out of **55 southern cisco lakes**. The boundary limits for selection of refuge lakes were contour lines of **AvgTDO3<sub>VB</sub> (TDO3<sub>L</sub>)** for variable benchmark periods simulated for the **MIROC 3.2 future climate scenario** using **St. Cloud weather** data.



Table 5.7 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from **cisco lakes grouped by latitude** using  $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  as boundary limits for Tier 1 and Tier 2, respectively, for variable benchmark periods (defined in Table 3.1, line 12). Three principal weather stations each assigned to a different range of latitudes are used to simulate all 620 lakes.

Weather station by latitude	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
<b>Northern (International Falls)</b>	Past	41	96	137	29	166
	CGCM 3.1	24	43	67	99	166
	MIROC 3.2	19	43	62	104	166
<b>Mid-latitude (Duluth)</b>	Past	52	285	337	62	399
	CGCM 3.1	10	83	93	306	399
	MIROC 3.2	10	84	94	305	399
<b>Southern (St. Cloud)</b>	Past	1	31	32	23	55
	CGCM 3.1	0	4	4	51	55
	MIROC 3.2	0	4	4	51	55
All three latitudes	Past	94	412	506	114	620
	CGCM 3.1	34	130	164	456	620
	MIROC 3.2	29	131	160	460	620

Table 5.8 Number of lakes selected as Tier 1 and Tier 2 refuge lakes and non-refuge lakes from **cisco lakes grouped by latitude** using  $\text{AvgATDO3}_{\text{FB}} (\text{TDO3}_{\text{F}}) = 11^{\circ}\text{C}$  and  $17^{\circ}\text{C}$  as boundary limits for Tier 1 and Tier 2, respectively, for the fixed benchmark period (defined in Table 3.1, line 6). Three principal weather stations each assigned to a different range of latitudes are used to simulate all 620 lakes.

Weather station by latitude	Climate scenario	Tier 1 refuge lakes	Tier 2 refuge lakes	Total number of refuge lakes	Non-refuge lakes	Total number of lakes
<b>Northern (International Falls)</b>	Past	72	71	143	23	166
	CGCM 3.1	42	40	82	84	166
	MIROC 3.2	42	40	82	84	166
<b>Mid-latitude (Duluth)</b>	Past	109	243	352	47	399
	CGCM 3.1	43	90	133	266	399
	MIROC 3.2	47	88	135	264	399
<b>Southern (St. Cloud)</b>	Past	9	29	38	17	55
	CGCM 3.1	2	10	12	43	55
	MIROC 3.2	2	10	12	43	55
All three latitudes	Past	190	343	533	86	620
	CGCM 3.1	87	140	227	392	620
	MIROC 3.2	91	138	229	390	620

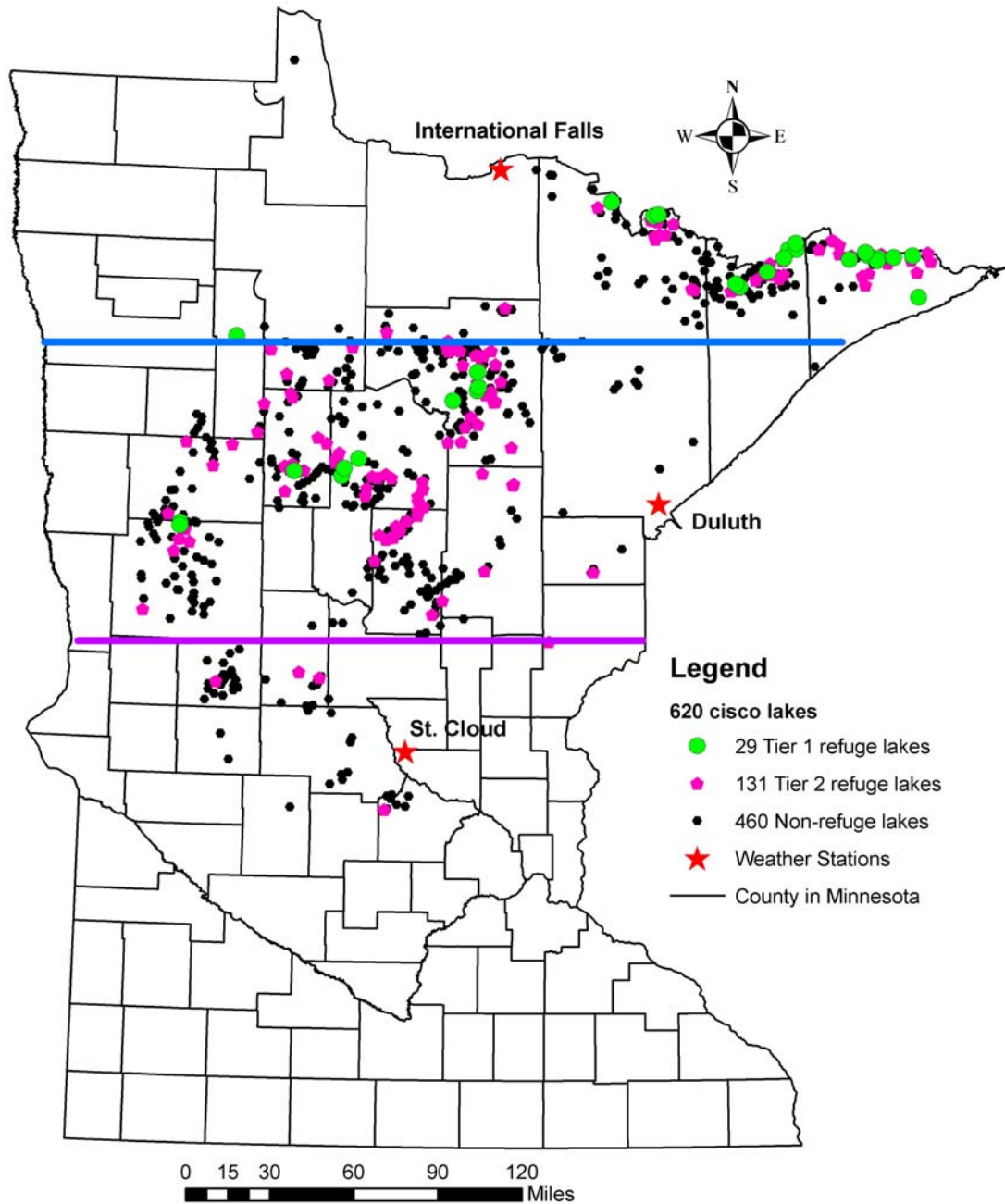


Figure 5.17 Geographic distribution of Tier 1 and Tier 2 cisco refuge lakes and non-refuge cisco lakes simulated with the **MIROC 3.2 future climate scenario**. Lakes are grouped by latitude into 166 northern, 399 mid-latitude, and 55 southern cisco lakes. The boundary limits for selection of refuge lakes were contour lines of  $\text{AvgATDO3}_{\text{VB}} (\text{TDO3}_{\text{L}}) = 17^{\circ}\text{C}$  and  $11^{\circ}\text{C}$ , for Tier 1 and Tier 2, respectively. Variable benchmark periods were used, and principal weather stations (**International Falls**, **Duluth**, and **St. Cloud**) were associated by latitude with each lake group.

## 5.5 Characteristics of cisco refuge lakes in Minnesota: Statistics of geometry ratios, Secchi depths, maximum depths, and surface areas

Bathymetric and other limnological characteristics of 620 Minnesota cisco lakes (Table D.1) had been analyzed and compared with the same characteristics in another and larger Minnesota lake database (Schupp, MNDNR) consisting of 3002 lakes (Fang et al. 2009). It was found that, on average, cisco lakes in Minnesota are deeper, more transparent and less trophic than other lakes. They are preferentially located in north central and northeastern Minnesota (Figure 5.1). To explore the characteristics of the selected cisco **refuge** lakes, we analyzed the statistical distributions of lake surface area  $A_s$ , maximum depth  $H_{\max}$ , geometry ratio GR (=  $A_s^{0.25}/H_{\max}$ ) and mean Secchi depth SD of the selected refuge lakes. Tables 5.9 to 5.11 list the statistics of these lake parameters for Tier 1 and Tier 2 refuge lakes, and for comparison for non-refuge lakes as well. These lakes had been classified based on simulated values of  $\text{AvgATDO3}_{\text{VB}}$  ( $\text{TDO3}_{\text{L}}$ ) under the MIROC 3.2 future climate scenario and by pairing lakes and weather stations by shortest distance (Table 5.10) or by latitude (Table 5.11).

Table 5.12 summarizes the statistics of the four lake parameters for refuge lakes only (Tier 1 plus Tier 2). For the simulations, lakes had been paired with weather stations by latitude or by shortest distance. The statistical results for the four lake characteristics were hardly affected by the distinction, although the number of refuge lakes was different (160 versus 137). For the 160 refuge lakes, the mean Secchi depths were from 2.26 to 9.46 m, lake geometry ratios from 0.47 to 2.55  $\text{m}^{-0.5}$ , and maximum depths from 13.1 to 64.9 m. The first, second (median), and third quartile values of bathymetric parameters and Secchi depths are reported in Tables 5.9 to 5.12. For example, from quartile values, we know that 75%, 50% and 25% of the 160 refuge cisco lakes (Table 5.12) have Secchi depths greater than 4.0, 4.6, and 5.5 m, respectively, and that 50% of these lakes have maximum depths greater than 25.6 m, and geometry ratios less than 1.29  $\text{m}^{-0.5}$ . On the other hand, of the 460 non-refuge lakes in Table 5.11, 50% have maximum depths less than 14.32 m, geometry ratios greater than 2.54  $\text{m}^{-0.5}$ , and mean Secchi depths less than 3.0 m (Table 5.11).

Figures 5.18, 5.19, 5.20, and 5.21 give graphical representations of the cumulative distributions of, summer mean Secchi depth SD, lake geometry ratio GR, lake maximum depth  $H_{\max}$ , and lake surface area  $A_s$ , respectively, for all cisco refuge lakes (Tier 1 plus Tier 2) under a future climate scenario, as well as for all 620 cisco lakes (Table D.1). Refuge lakes for the cumulative distribution curves were identified by three choices: using Duluth weather data for all lakes or by pairing cisco lakes with weather stations by latitude or by distance as discussed in the previous sections. As can be clearly seen, the choice did not matter, because the three cumulative distributions for the cisco **refuge** lakes under the MIROC 3.2 future climate scenario in Figures 5.18 to 5.21 are very similar, but are substantially different from distributions of SD, GR, and  $H_{\max}$  for all 620 cisco lakes. Refuge lakes selected under the MIROC 3.2 climate scenario have Secchi depths greater than  $\approx 2.5$  m (Fig. 5.18), lake geometry ratio less than  $\approx 2.5$   $\text{m}^{-0.5}$  (Fig. 5.19), and maximum depths greater than  $\approx 15$  m (Fig. 5.20). The cumulative distributions of surface areas of cisco refuge lakes and all 620 lakes are not significantly different. Refuge lakes selected for the MIROC 3.2 climate scenario have surface area up to 28.9  $\text{km}^2$ , and only 3.2% or 20 cisco

lakes out of 620 cisco lakes in the MN DNR database have a surface area greater than 28.9 km<sup>2</sup>. These 20 large surface area lakes are identified as non-refuge lakes.

We have identified major and significant differences between cisco refuge lakes and non-refuge lakes. Refuge lakes are highly transparent and deep lakes. Their size (surface area) is somewhat, but not much smaller than that of the non-refuge lakes. The twenty largest current cisco lakes are not projected to be refuge lakes. Overall it appears that the cisco refuge lakes are a very special group among Minnesota lakes in general.

It can be concluded that the cisco refuge lakes (Tier 1 and Tier 2) identified in this report have bathymetric and transparency characteristics that are different from the ensemble of 620 cisco lakes in Minnesota. In the first project report of this study (Fang et al. 2009) it was shown that the 620 cisco lakes in Minnesota are substantially different from the bulk of Minnesota's lakes. In this third project report of the study it has been shown that refuge lakes are even more exceptional.

Table 5.9 Statistics of characteristics of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes under the **MIROC 3.2 future climate scenario**, identified by **AvgATDO3<sub>VB</sub>** (TDO3<sub>L</sub> in Table 3.1, line 12). Simulations used **Duluth weather data for all 620 cisco lakes**.

Statistical Parameter	26 Tier 1 Refuge Lakes				129 Tier 2 Refuge Lakes				465 Non-refuge lakes			
	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)
Maximum	21.27	63.40	1.51	9.46	28.90	64.92	2.28	7.74	3847.77	56.08	22.70	5.56
Minimum	0.19	22.25	0.69	4.72	0.04	13.11	0.47	2.26	0.05	3.05	1.05	0.68
Average	3.55	36.98	1.05	6.36	2.60	27.12	1.32	4.40	17.84	15.66	3.04	3.08
Standard deviation	5.39	11.73	0.23	1.09	4.01	9.70	0.26	0.98	186.02	7.74	1.78	0.90
3rd Quartile	3.84	42.29	1.20	6.79	3.11	32.61	1.48	4.91	4.80	19.51	3.51	3.72
Median	1.40	35.97	1.05	6.06	0.97	25.30	1.29	4.27	1.79	14.32	2.51	3.05
1st Quartile	0.82	27.43	0.91	5.64	0.51	19.81	1.14	3.75	0.80	10.36	2.02	2.52

Table 5.10 Statistics of characteristics of Tier 1 and Tier 2 refuge lakes, and non-refuge lakes under the **MIROC 3.2 future climate scenario**, identified by **AvgATDO3<sub>VB</sub>** (TDO3<sub>L</sub> in Table 3.1, line 12). Simulations for **cisco lakes grouped by paired by shortest distance from the International Falls, Duluth, and St. Cloud weather stations**.

	<b>23 Tier 1 Refuge Lakes</b>				<b>115 Tier 2 Refuge Lakes</b>				<b>484 Non-refuge lakes</b>			
Statistical Parameter	<b>A<sub>s</sub> (km<sup>2</sup>)</b>	<b>H<sub>max</sub> (m)</b>	<b>GR (m<sup>-0.5</sup>)</b>	<b>SD (m)</b>	<b>A<sub>s</sub> (km<sup>2</sup>)</b>	<b>H<sub>max</sub> (m)</b>	<b>GR (m<sup>-0.5</sup>)</b>	<b>SD (m)</b>	<b>A<sub>s</sub> (km<sup>2</sup>)</b>	<b>H<sub>max</sub> (m)</b>	<b>GR (m<sup>-0.5</sup>)</b>	<b>SD (m)</b>
Maximum	21.27	61.57	1.51	9.46	28.90	64.92	2.28	7.74	3847.77	56.08	22.70	5.56
Minimum	0.19	22.25	0.69	4.72	0.04	13.11	0.47	2.72	0.05	3.05	0.81	0.68
Average	3.16	36.93	1.03	6.39	2.62	26.85	1.32	4.52	17.90	16.07	3.03	3.11
Standard deviation	4.74	10.88	0.22	1.15	4.37	10.27	0.27	1.03	186.02	8.30	1.79	0.91
3rd Quartile	3.84	42.29	1.17	6.96	2.49	32.31	1.48	5.03	4.91	19.81	3.51	3.75
Median	1.40	36.57	1.03	5.98	0.96	24.99	1.29	4.41	1.91	14.32	2.51	3.05
1st Quartile	0.76	27.81	0.91	5.64	0.52	19.36	1.14	3.81	0.83	10.36	2.02	2.53

Table 5.11 Statistics of characteristics of Tier 1 and Tier 2 cisco refuge lakes, and non-refuge lakes under the **MIROC 3.2 future climate scenario**, identified by **AvgATDO3<sub>VB</sub>** (TDO3<sub>L</sub> in Table 3.1, line 12). Simulations for **cisco lakes grouped by latitude** (166 northern, 399 mid-latitude, and 55 southern cisco lakes).

Statistical Parameter	29 Tier 1 Refuge Lakes				131 Tier 2 Refuge Lakes				460 Non-refuge lakes			
	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)
Maximum	21.27	63.40	1.64	9.46	28.90	64.92	2.55	7.74	3847.77	56.08	22.70	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	18.05	15.83	3.04	3.06
Standard deviation	5.16	12.00	0.25	1.06	3.93	9.78	0.31	0.91	187.02	8.03	1.79	0.88
3rd Quartile	2.89	41.15	1.24	6.80	2.82	32.00	1.51	4.87	4.92	19.81	3.52	3.66
Median	1.13	35.05	1.08	6.10	0.97	24.69	1.32	4.27	1.86	14.32	2.54	3.00
1st Quartile	0.81	26.21	0.94	5.65	0.51	18.60	1.17	3.81	0.80	10.36	2.02	2.49

Table 5.12 Statistics of characteristics of cisco **refuge lakes** (combined Tier 1 plus Tier 2) under the **MIROC 3.2 future climate scenario**, identified by AvgATDO3<sub>VB</sub> (TDO3<sub>L</sub> in Table 3.1, line 12) simulated for **cisco lakes grouped by latitude or shortest distance**.

Statistical Parameter	160 Refuge Lakes (lakes grouped by latitude)				137 Refuge Lakes (lakes grouped by shortest distance)			
	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)	A <sub>s</sub> (km <sup>2</sup> )	H <sub>max</sub> (m)	GR (m <sup>-0.5</sup> )	SD (m)
Maximum	28.90	64.92	2.55	9.46	28.90	64.92	2.28	9.46
Minimum	0.04	13.11	0.47	2.26	0.04	13.11	0.47	2.72
Average	2.63	27.89	1.31	4.74	2.70	28.47	1.28	4.82
Standard deviation	4.18	10.79	0.32	1.21	4.42	10.98	0.28	1.26
3rd Quartile	2.87	34.14	1.48	5.49	2.89	34.44	1.47	5.64
Median	1.01	25.60	1.29	4.57	0.98	25.60	1.26	4.62
1st Quartile	0.59	19.74	1.10	3.95	0.59	21.03	1.08	3.96

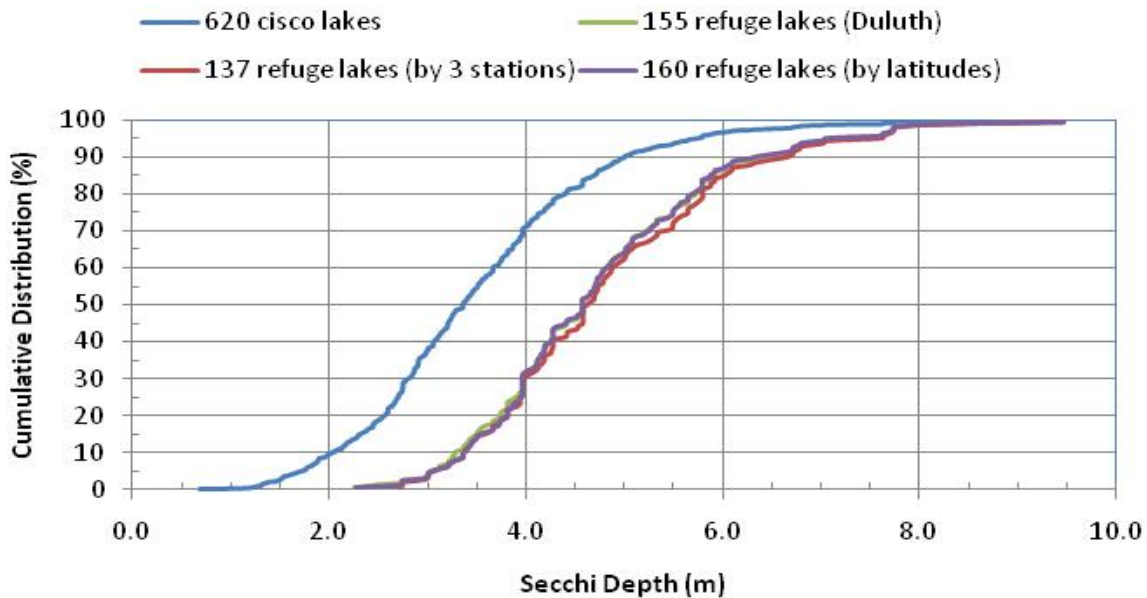


Figure 5.18 Cumulative distributions of **mean Secchi depth** for 620 cisco lakes and refuge lakes simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.



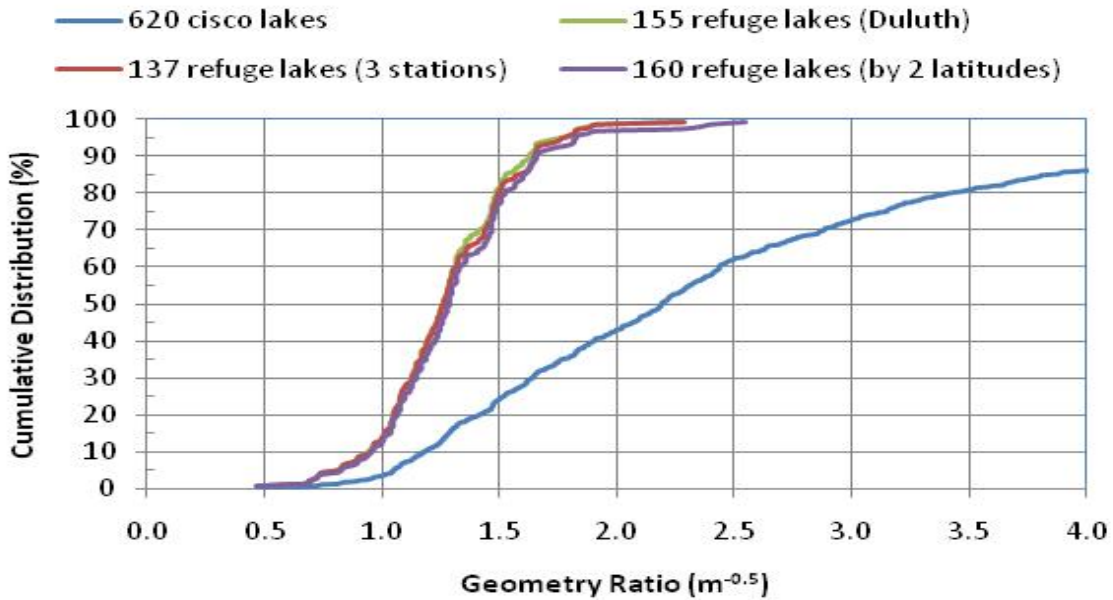


Figure 5.19 Cumulative distributions of **lake geometry ratio** for 620 cisco lakes and refuge lakes simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.

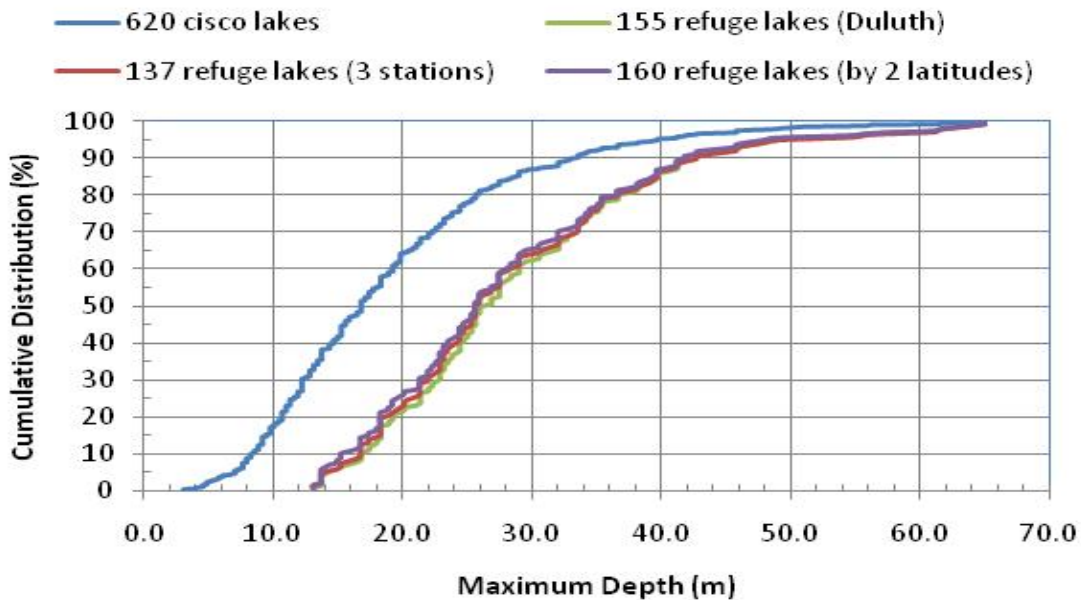


Figure 5.20 Cumulative distributions of **lake maximum depth** for 620 cisco lakes and refuge lakes simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.

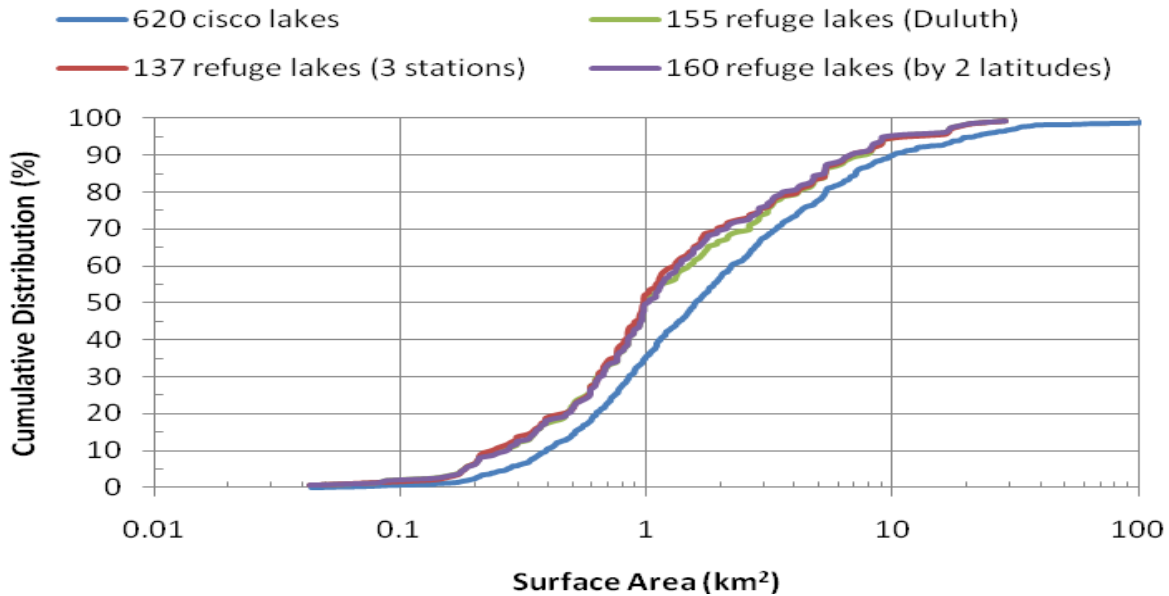


Figure 5.21 Cumulative distributions of **lake surface area** for 620 cisco lakes and refuge lakes selected simulated for the **MIROC 3.2 future climate scenario** using three methods to pair each lake with a weather station.

## 5.6 Validation (hindcasting) of cisco lake numbers for past climate

We cannot validate the number of refuge lakes predicted for future climate scenarios, but we can compare the number of refuge lakes **projected (hindcast)** for past climate conditions to 620, the number of **known** cisco lakes in Minnesota. Ten different projections of refuge lakes for past climate from 1962 to 2008 were made, and individual results are listed in Tables 5.3 to 5.8. The ten projections were made with variable and fixed benchmark periods, and by five different pairings of lakes with the principal weather stations, as described earlier. The five pairings were (1) International Falls for all 620 lakes, (2) Duluth for all 620 lakes, and (3) St. Cloud for all 620 lakes, (4) shortest distance to a weather station, and (5) most similar latitude with a weather station. To make the comparison easier, results from Tables 5.3 to 5.8 have been summarized in Table 5.13.

Tier 1 and Tier 2 refuge lakes identified for cisco under historical climate conditions (1961-2008) may be called viable cisco lakes where cisco is capable of living, developing, or spawning under favorable conditions. Cisco can still persist in lakes with TDO3 values greater than 17 °C but at a reduced probability of occurrence (Jacobson et al. 2010).

Table 5.13 Number (percentage of 620) of cisco refuge lakes projected (hindcast) for past (1962-2008) climate conditions.

Lake and weather station pairing	Variable Benchmark	Fixed Benchmark
International Falls weather for all 620 lakes	534 (86%)	552 (89%)
Duluth weather for all 620 lakes	523 (84%)	543 (77%)
St. Cloud weather for all 620 lakes	340 (55%)	402 (65%)
Shortest distance from lake to weather station	449 (72%)	483 (78%)
Similar latitude of lake and weather station	506 (82%)	533 (86%)
Average	470 (76%)	503 (81%)

The analysis and modeling procedure applied in this study was able to identify (hindcast) from 340 to 552 cisco lakes (55% to 89%) or on average 487 cisco lakes (78%) out of the 620 cisco lakes in the Minnesota data base as viable cisco (refuge) lakes. This means that on average the methodology underpredicted the viability of lakes as cisco refuge lakes. There were no overpredictions of viability. This may be interpreted as conservative in the context of this study. We used a long simulation period from 1962 to 2008 to make the projections and the results reflect averages for this period, as does the number 620 of documented cisco lakes. We did not account for trends in recent Minnesota climate.

Adult cisco mortality (see Fig. 1.1) was reported in 18 lakes in Minnesota during the unusually warm summer of 2006 (Jacobson et al. 2008). Water temperature and dissolved oxygen profiles in 22 cisco lakes, including 17 of the 18 lakes in which cisco mortality was reported, and 5 reference lakes without cisco mortality, were measured and analyzed by Jacobson et al. (2008). The data were used to determine the lethal oxythermal niche boundary. With the exception of two lakes (Lake Bemidji and Long Lake), all 21 cisco study lakes used by Jacobson et al. (2008) are in the MN DNR cisco lake database.

Lake names and DOW numbers of Jacobson et al.'s (2008) 21 study lakes are listed in Table 5.14 with an indication whether cisco mortality occurred in 2006 or not. Table 5.14 also lists the number of times that these 21 study lakes were identified as Tier 1 or Tier 1 plus Tier 2 refuge lakes by the five different methods discussed earlier in this report. AvgATDO3<sub>VB</sub> (Table 3.1, line 12) contour lines for variable benchmark periods were used to rank the 21 study lakes as refuge lakes. A comparison of the model predictions with actual observations gave the following results: Of the 16 study lakes with adult cisco mortality in 2006, none was identified as a Tier 1 refuge lakes by any of the five methods (red "0" in Table 5.14), and three (Cotton Lake, Little Turtle Lake, and Mille Lacs Lake) were not identified as either Tier 1 or Tier 2 refuge lakes by

any of the five methods (Table 5.14). All five reference lakes that did not experience adult cisco mortality in 2006, were identified as either Tier 1 or Tier 2 refuge lakes by all of the five methods (bold “5” Table 5.14). These are remarkable agreements between model predictions of refuge lakes and observed adult cisco mortality events in 2006.

Table 5.14 Number of times that each of the 21 study lakes (Jacobson et al. 2008) is identified as Tier 1 or Tier 1 plus Tier 2 refuge lake under **past climate conditions (1962 to 2008)** by the five pairing methods presented above. **AvgATDO3<sub>VB</sub>** (Table 3.1, line 12) was used for the identification of refuge lakes.

<b>DOW Number</b>	<b>Lake Name</b>	<b>Cisco mortality in 2006</b>	<b>Number of times as Tier 1 refuge lake</b>	<b>Number of times as Tier 1 plus Tier 2 refuge lake</b>
04003800	Andrusia	Yes	<b>0</b>	4
21005700	Carlos	Yes	<b>0</b>	5
03028600	Cotton	Yes	<b>0</b>	<b>0</b>
29007200	8th Crow Wing	Yes	<b>0</b>	1
11030500	Gull	Yes	<b>0</b>	3
15001600	Itasca	Yes	<b>0</b>	2
11020300	Leech	Yes	<b>0</b>	4
18026600	Little Pine (Cass)	Yes	<b>0</b>	3
56014200	Little Pine (Ottetail)	Yes	<b>0</b>	3
31077900	Little Turtle	Yes	<b>0</b>	<b>0</b>
48000200	Mille Lacs	Yes	<b>0</b>	<b>0</b>
11041100	Pine Mountain	Yes	<b>0</b>	3
29009100	7th Crow Wing	Yes	<b>0</b>	3
56038500	Star	Yes	<b>0</b>	5
03001000	Straight	Yes	<b>0</b>	3
11020100	Woman	Yes	<b>0</b>	1
18031500	Big Trout	No	3	<b>5</b>
29007500	Kabekona	No	0	<b>5</b>
56036000	Rose	No	3	<b>5</b>
56035800	Scalp	No	5	<b>5</b>
11041300	Ten Mile	No	5	<b>5</b>

However, some disagreement between the prediction (of the refuge lakes) and the observed cisco mortality does exist. For example, 13 of the 16 study lakes with adult cisco mortality in 2006 were identified as Tier 2 refuge lakes by one to five methods. One reference lake (Lake Kabekona) was not identified as a Tier 1 refuge lake by any of five methods, although it had no mortality. One cause for the discrepancies may be that long-term (47 year) averages of highest mean daily TDO3 values (AvgATDO3<sub>VB</sub> for variable benchmark periods) were used to

make the refuge lake predictions, while the observed mortality events were for one specific year and an unknown recurrence interval. If TDO3 parameters that are averages of 47 years are too conservative predictors, shorter averaging periods and recurrence intervals that pair fish growth cycles with weather cycles can be considered. The agreement between projections and observations may become even better.

## 5.7 Summary of cisco refuge lake projections for future climate scenarios

### 5.7.1 Number of Tier 1, Tier 2, and total refuge lakes

Tables 5.3 to 5.8 give the number of refuge lakes projected by 10 different methods (using TDO3s for fixed or variable benchmark periods and different pairings of lakes with weather stations). The numbers for Tier 1, Tier 2, and the total number of projected refuge lakes (Tier 1 plus Tier 2) are summarized in Table 5.15. The TDO3 contour lines of 11°C and 17°C used to identify refuge lakes were derived by interpolation from simulated points for the 30 virtual lakes.

Table 5.15 Projected number of Tier 1, Tier 2, and total cisco refuge lakes under two future climate scenarios (CGCM 3.1 and MIROC 3.2).

Weather station and lake pairing	Climate scenario	Variable benchmark			Fixed benchmark		
		Tier 1	Tier 2	Total	Tier 1	Tier 2	Total
International Falls for all 620 lakes	CGCM 3.1	44	174	218	118	181	299
	MIROC 3.2	31	168	199	117	181	298
Duluth for all 620 lakes	CGCM 3.1	25	129	154	79	134	213
	MIROC 3.2	26	129	155	87	131	218
St. Cloud for all 620 lakes	CGCM 3.1	17	70	87	65	97	162
	MIROC 3.2	9	77	86	68	95	163
Shortest distance	CGCM 3.1	25	116	141	78	127	205
	MIROC 3.2	22	115	137	84	123	207
Similar latitude	CGCM 3.1	34	130	164	87	140	227
	MIROC 3.2	29	131	160	91	138	229
Average	Number	26	124	150	88	134	222
	(% of 620)	4%	20%	24%	14%	22%	36%

The numbers obtained by the variable benchmark and the fixed benchmark method are significantly different for Tier 1 and total refuge lakes, but the two climate scenarios (CGCM 3.1 and MIROC 3.2) gave mostly similar results. Tier 1 cisco refuge lakes obtained for a very

stringent water temperature constraint ( $\leq 11.0$  °C, Table 5.2) numbered only 4% to 14% of the total 620 cisco lakes in the Minnesota database. Tier 2 cisco refuge lakes for the water temperature range from 11.0 °C to 17.0 °C comprised from 20 to 22% of the 620 cisco lakes. In total, projected cisco refuge lakes comprise from 24% to 36% of all current 620 cisco lakes (Table 5.15). Consequently 76% to 64% of all current 620 cisco lakes are projected to lose cisco habitat under the two future climate scenarios investigated, if the stringent water temperature constraint of 17.0 °C is used as a criterion (lethal temperature for coldwater fish used in previous studies was as high as 23.4 °C).

### ***5.7.2 Names and locations of Tier 1 and Tier 2 cisco refuge lakes***

The number of Tier 1 and Tier 2 cisco refuge lakes determined for the future climate scenario MIROC 3.2 varies depending on the chosen lake and weather station pairing (Table 5.15). Although the numbers are different, many lakes are the same. Therefore, refuge lakes were listed by name and geographic coordinates in Table 5.16 for Tier 1 and in Appendix E for Tier 1 plus Tier 2. They were first ordered by the number of times that they were found by the five different methods (listed in the first column of Table 5.14) using the fixed benchmark period and the MIROC 3.2 future climate scenario and were then listed by lake name in alphabetical order. The number of times that they were identified as Tier 1 refuge lakes by the five methods is also listed in Table 5.16 when the fixed benchmark and the variable benchmark were used with the future climate scenarios MIROC 3.2 and CGCM 3.1.

Lakes that were identified most often are on top of the list. For example, when the fixed benchmark period and the MIROC 3.2 future climate scenario were used to identify Tier 1 refuge lakes, a total of 68, 12, 4, 14, and 19 cisco lakes were identified as Tier 1 refuge lakes by 5 methods, 4 methods, 3 methods, 2 methods, and 1 method, respectively (Fig. 5.22). In total, 117 Tier 1 cisco refuge lakes, with the geographic distribution shown in Fig. 5.22, were identified at least by one method. Similar information for all refuge lakes (Tier 1 plus Tier 2) is given in Table E.1 in Appendix E. In total, 298 cisco lakes were identified as either Tier 1 or Tier 2 refuge lakes at least by one method, and 163 cisco lakes were identified as either Tier 1 or Tier 2 refuge lakes by all five methods that associate a cisco lake to weather station (Table 5.14). These two lists (Table 5.16 and Table E.1 in Appendix E) give recommended cisco refuge lakes independent of method used for their determination. The Tier 1 cisco refuge lakes from Table 5.16 are plotted on a map of Minnesota in Figure 5.22 and the Tier 1 plus Tier 2 refuge lakes from figure E.1 are plotted in Figure 5.23. The number of times that they were identified as refuge lakes is given in the legend.

Table 5.16 Names and geographic locations of Tier 1 cisco refuge lakes in Minnesota and number of times identified as Tier 1 cisco refuge lakes by five different methods.

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
31034900	Antler	466207.0	5275090.0	5	5	0	0
38050200	Ashigan	624749.0	5320500.0	5	5	2	2
03008500	Bad Medicine	317655.0	5221710.0	5	5	1	1
18003000	Barbour	432303.0	5123450.0	5	3	0	0
11027700	Big Deep	394595.0	5196110.0	5	5	0	0
29018500	Big Sand	350361.0	5207040.0	5	5	0	1
31079300	Big Too Much	440872.0	5277200.0	5	5	0	0
18031500	Big Trout	411532.0	5174230.0	5	5	0	0
18021100	Blue	423977.0	5180350.0	5	1	0	0
31039500	Bluewater	458235.0	5252040.0	5	5	4	5
04029700	Buzzle	339646.0	5276030.0	5	5	2	2
77012000	Charlotte	355635.0	5090450.0	5	5	0	0
31074900	Chase	444194.0	5246180.0	5	5	5	5
38016600	Cherry	641319.0	5333210.0	5	5	4	5
16013900	Clearwater	697251.0	5328720.0	5	5	5	5
31054000	Clubhouse	457155.0	5272470.0	5	5	0	2
15009000	Deep	320013.0	5283860.0	5	5	4	4
11023700	Deep Portage	393944.0	5191690.0	5	5	0	0
16023200	Duncan	688691.0	5328360.0	5	5	4	5
11046600	Fifth	376618.0	5212610.0	5	5	0	1
04021700	Grant	348931.0	5261900.0	5	5	0	0
58012300	Grindstone	499427.0	5107650.0	5	5	0	0
69048700	Gun	559422.0	5352420.0	5	5	5	5
16035600	Gunflint	672943.0	5329800.0	5	5	0	0
31045200	Gunn	459357.0	5265500.0	5	5	0	0
31091100	Hamrey	406242.0	5285940.0	5	5	0	0
38020600	Hanson	642735.0	5333610.0	5	5	0	2
18026900	Island Loon	413256.0	5173460.0	5	3	0	0
11040000	Jack	390145.0	5213090.0	5	5	3	3
18036100	Kimball	408024.0	5167390.0	5	5	0	0
38022900	Little Knife	636926.0	5333150.0	5	5	5	5
56032800	Little McDonald	292892.0	5165460.0	5	5	0	1
29015000	Little Sand	353063.0	5205920.0	5	5	3	1
31039400	Little Trout	458897.0	5254040.0	5	5	4	5
69068200	Little Trout	535431.0	5360490.0	5	5	4	5
16044800	Loon	671907.0	5327530.0	5	5	5	5
29018000	Lower Bottle	352030.0	5210180.0	5	5	0	1
31023900	Lower Hanson	466217.0	5250430.0	5	5	0	0
16046300	Magnetic	665952.0	5330660.0	5	5	0	2
03037100	Meadow	280699.0	5181750.0	5	5	0	0

Table 5.16 (cont'd.)

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
77002200	Mons	367464.0	5087210.0	5	5	0	0
16004300	Moose	716878.0	5331470.0	5	5	0	2
16023400	Moss	687734.0	5326820.0	5	5	2	2
29023700	Newman	351221.0	5250800.0	5	5	0	2
16033100	North	681002.0	5331430.0	5	5	4	2
38064000	Ojibway	608799.0	5311710.0	5	5	4	5
38021100	Ottertrack	641140.0	5336920.0	5	5	4	4
11047600	Portage	381932.0	5207450.0	5	5	3	3
31042200	Ruby	458339.0	5262900.0	5	5	5	5
56035800	Scalp	287474.0	5174890.0	5	5	3	3
38071400	Section Twelve	608813.0	5312520.0	5	5	0	0
56036900	Six	287670.0	5176620.0	5	5	5	5
38052900	Snowbank	617945.0	5315770.0	5	5	0	2
16024400	South	682582.0	5329800.0	5	5	5	5
38038800	Spoon	633501.0	5326830.0	5	5	0	0
18035900	Star	410022.0	5167710.0	5	5	0	1
69036900	Takucmich	562210.0	5353350.0	5	5	5	5
01010900	Taylor	460999.0	5204520.0	5	5	0	0
11041300	Ten Mile	380379.0	5203110.0	5	5	3	5
38072400	Tofte	606653.0	5313510.0	5	5	4	4
38017200	Topaz	639601.0	5332420.0	5	5	0	0
16004900	Trout	711435.0	5305720.0	5	5	2	2
31041000	Trout	458192.0	5256660.0	5	5	0	2
31072500	Turtle	448327.0	5275130.0	5	5	0	0
16008600	West Pike	708128.0	5329680.0	5	5	4	4
16035400	Winchell	679256.0	5318140.0	5	5	0	2
01004600	Ball Bluff	478651.0	5197700.0	4	4	0	0
16014700	Flour	693783.0	5325350.0	4	2	0	0
38037200	Fraser	634053.0	5318890.0	4	2	0	0
16031900	Gaskin	682846.0	5319510.0	4	2	0	0
16058000	Granite	666146.0	5335850.0	4	4	0	0
31077800	Little Too Much	441738.0	5274880.0	4	4	0	0
01008900	Long	462404.0	5148280.0	4	4	0	0
31078100	Long	441433.0	5280740.0	4	4	0	0
31021900	O'Reilly	467570.0	5245500.0	4	4	0	0
16004100	Pine	707341.0	5327100.0	4	4	0	0
31021800	Shamrock	468692.0	5245840.0	4	4	0	0
29023900	Spearhead	352132.0	5248390.0	4	4	0	0
11046900	Anway	376737.0	5211040.0	3	1	0	0
29004800	Benedict	371657.0	5221980.0	3	1	0	0



Table 5.16 (cont'd.)

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
29018400	Blue	347677.0	5209100.0	3	1	0	0
11086600	Tamarack	401048.0	5202160.0	3	3	0	0
31027800	Barwise	468711.0	5267270.0	2	2	0	0
69011800	Burntside	581302.0	5310720.0	2	2	0	0
15001000	Elk	331973.0	5228580.0	2	2	0	0
16061700	Gneiss	662965.0	5338100.0	2	2	0	0
16007700	Greenwood	710490.0	5320110.0	2	2	0	0
31046600	Horseshoe	461830.0	5272270.0	2	2	0	0
21010600	Latoka	310959.0	5082980.0	2	1	0	0
21010800	Mina	307985.0	5085170.0	2	2	0	0
16023000	Rose	690083.0	5330660.0	2	2	0	0
16062900	Sea Gull	654464.0	5333260.0	2	2	0	0
04008500	Swenson	373092.0	5258540.0	2	2	0	0
38035100	Thomas	631603.0	5316590.0	2	2	0	0
16026700	Vernon	680957.0	5312910.0	2	2	0	0
86027900	West Lake Sylvia	404790.0	5011290.0	2	1	0	0
77002400	Bass	366498.0	5085360.0	1	1	0	0
21005700	Carlos	316947.0	5091130.0	1	1	0	0
18029800	East Fox	417710.0	5177450.0	1	1	0	0
18039600	Edna	399225.0	5154230.0	1	1	0	0
11017400	Girl	405649.0	5204090.0	1	1	0	0
31037300	Hale	458520.0	5232670.0	1	1	0	0
01005700	Little Ball Bluff	479174.0	5198320.0	1	1	0	0
31057500	Little Bass	454599.0	5237110.0	1	1	0	0
09003500	Little Hanging Horn	524719.0	5147700.0	1	1	0	0
31039900	Little Wabana	462902.0	5249760.0	1	1	0	0
31057100	Loon	451222.0	5231220.0	1	1	0	0
18037800	Lower Hay	401812.0	5169230.0	1	1	0	0
11028200	Mann	397848.0	5203010.0	1	1	0	0
56082900	Pebble	265969.0	5126590.0	1	1	0	0
56036000	Rose	290565.0	5172740.0	1	1	0	0
18031100	Rush-Hen	413972.0	5171730.0	1	1	0	0
31008400	Shallow	477729.0	5219260.0	1	1	0	0
29011700	Spider	358726.0	5206440.0	1	1	0	0
31039200	Wabana	460476.0	5252590.0	1	1	0	0

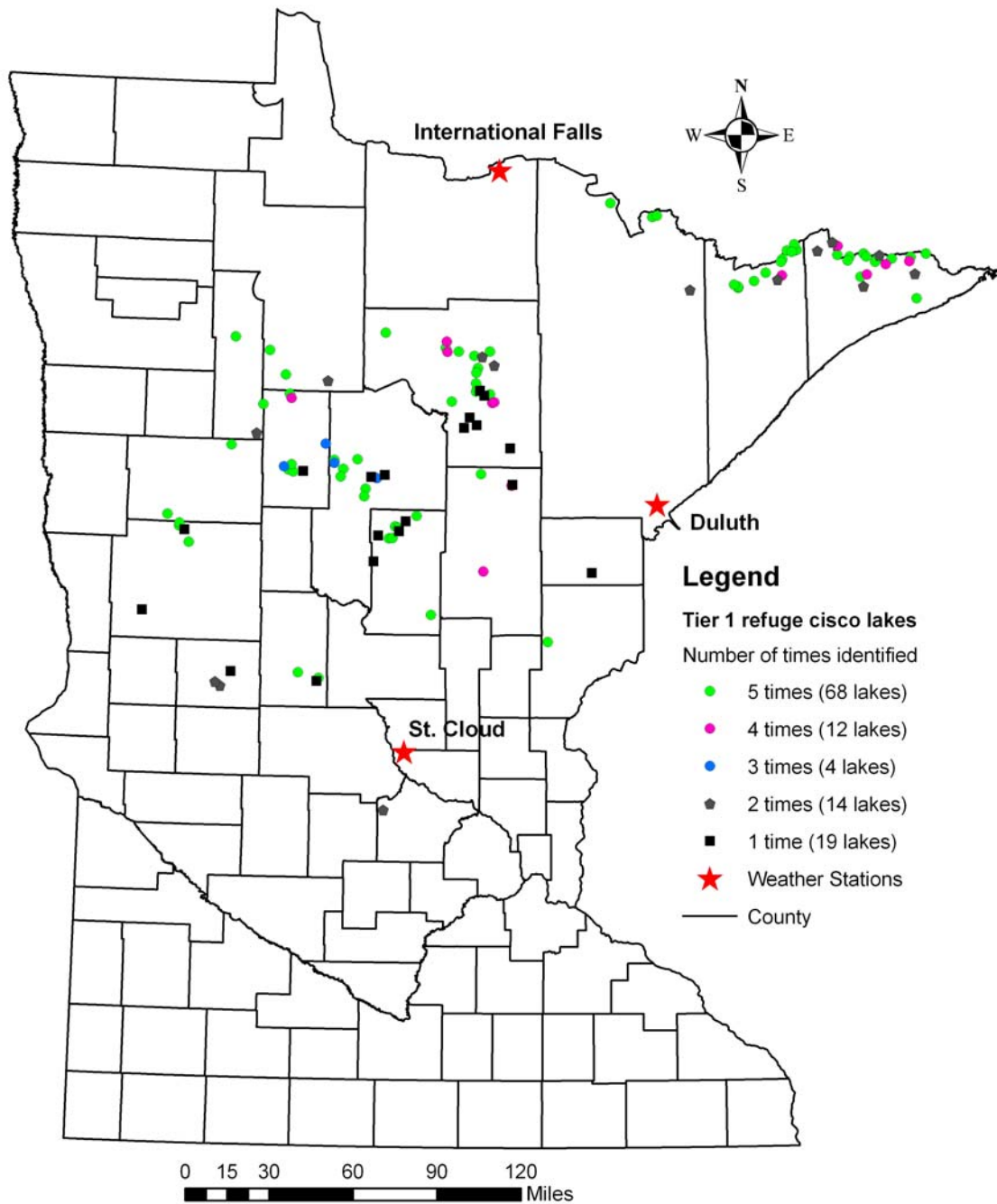


Figure 5.22 Geographic distribution of **Tier 1 cisco refuge lakes** for the **MIROC 3.2 future climate scenario** using  $AvgATDO3_{FB}$  (Table 3.1 line 6) in the fixed benchmark period and **five options for the pairing of a lake with a weather station**. The number of times that a lake was identified as Tier 1 refuge lake is indicated in the legend.

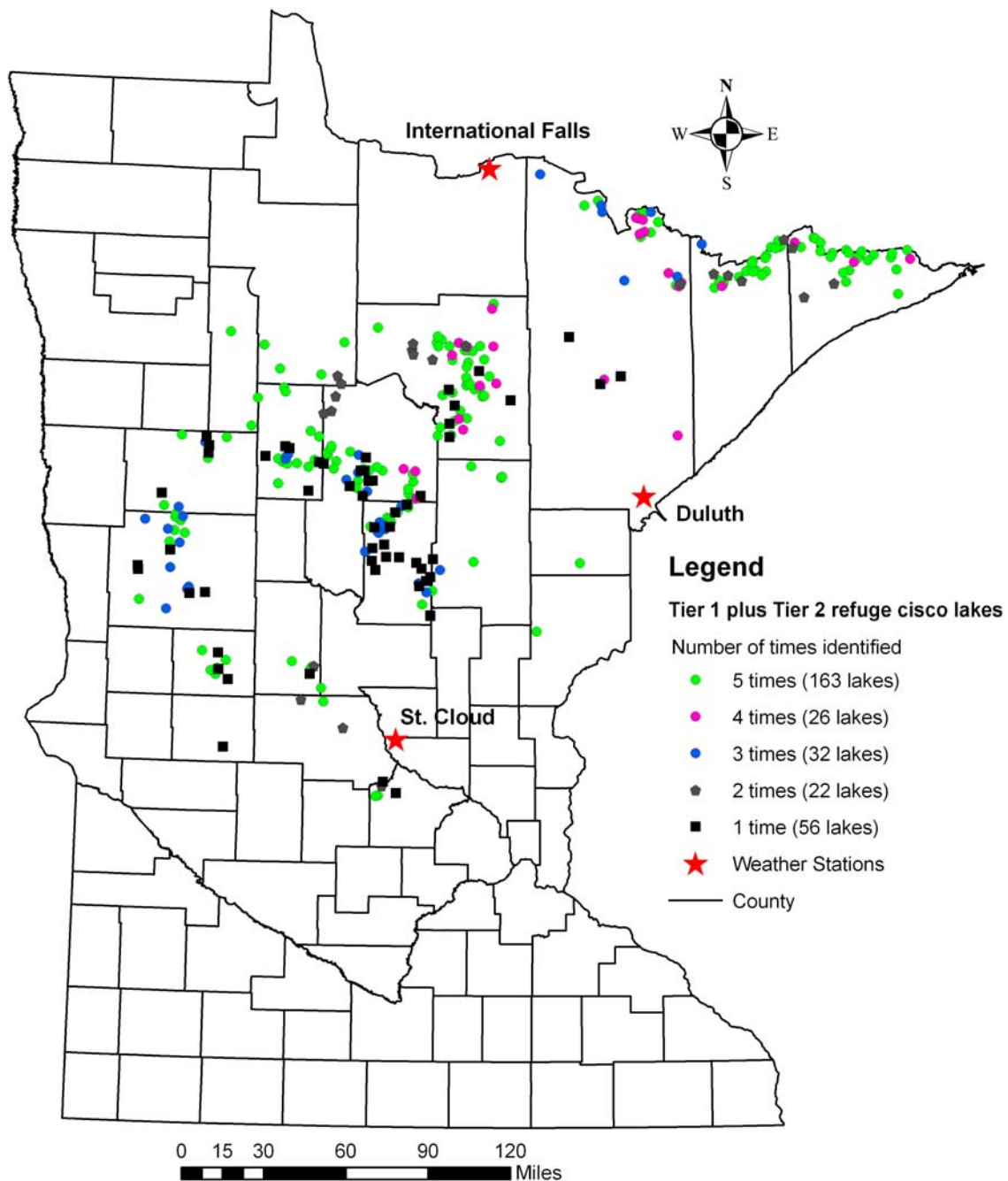


Figure 5.23 Geographic distribution of **Tier 1 plus Tier 2** cisco refuge lakes for the **MIROC 3.2 future climate scenario** using  $AvgATDO3_{FB}$  (Table 3.1 line 6) in the fixed benchmark period and **five options for the pairing of a lake with a weather station**. The number of times that a lake was identified as a Tier 1 or a Tier 2 refuge lake is indicated in the legend.

### 5.7.3 Cisco lakes within 2°C bands of TDO3 contour lines (isotherms)

Another approach to the selection of refuge lakes is to rank all cisco lakes according to where a cisco lake is located between TDO3 contour lines. For the selection of Tier 1 and Tier 2 refuge lakes, and Tier 3 or non-refuge lakes, we used only two TDO3 contour lines or isotherms (11°C and 17°C). To refine the ranking of the 620 cisco lakes in Minnesota we divided them into narrower bands between contour lines. Increments of 2°C between TDO3 contour lines from 5°C to 23°C were first selected. Cisco lakes in Minnesota were therefore grouped into the following ten TDO3 intervals: 5 – 7°C, 7 – 9°C, 9 – 11°C, 11 – 13°C, 13 – 15°C, 15 – 17°C, 17 – 19°C, 19 – 21°C, 21 – 23°C, and > 23°C. Nine TDO3 contour lines (from 5 to 25 °C in 2°C increments) and 620 cisco lakes were plotted in the previously used coordinate system of Secchi depth (SD) versus lake geometry ratio (GR) (Figs. 5.24 and 5.25). The TDO3 contour lines from 5°C to 23°C used to group cisco lakes were derived by interpolation from simulated points for the 30 virtual lakes.

Figure 5.24 and 5.25 show the distribution of all 620 cisco lakes between contour lines of **AvgATDO3<sub>FB</sub>** and **AvgATDO3<sub>VB</sub>** (Table 3.1, lines 6 and 12) for fixed and variable benchmark periods, respectively, simulated using Duluth weather data and the MIROC 3.2 future climate scenario. There are some contour lines of TDO3 with values greater than 23°C in Figs. 5.24 and 5.25, but we did not rank cisco lakes for TDO3 > 23°C. The geographic distribution of all 620 cisco lakes grouped between contour lines of **AvgATDO3<sub>FB</sub>** (Table 3.1, line 6) in Fig. 5.24 is shown in Fig. 5.26. TDO3 intervals and the number of cisco lakes in each interval (2°C increment) are shown in the legend.

Table 5.17 Number of cisco lakes between 2°C TDO3 contour lines simulated using Duluth weather data for the MIROC 3.2 future climate scenario for fixed and variable benchmark periods (**AvgATDO3<sub>FB</sub>**, **AvgATDO3<sub>VB</sub>**, Table 3.1, lines 6 and 12).

Fixed Benchmark Period		Variable Benchmark Periods	
TDO3 values	Number of lakes	TDO3 values	Number of lakes
5 - 7°C	15	N/A	
7 – 9°C	42	< 9°C	3
9 – 11°C	30	9 – 11°C	23
11 – 13°C	39	11 – 13°C	27
13 – 15°C	41	13 – 15°C	35
15 – 17°C	51	15 – 17°C	67
17 – 19°C	162	17 – 19°C	123
19 – 21°C	169	19 – 21°C	261
21 – 23°C	43	21 – 23°C	52
>23°C	28	>23°C	29

Table 5.17 gives the number of cisco lakes that are found in each of the ten TDO3 intervals (2°C increment). The results of TDO3 are from the same simulations used in Figs. 5.24 and 5.25. As many as 169 and 261 cisco lakes (or 27% and 42% of the 620 cisco lakes) fall within the interval 19–21°C when fixed and variable benchmark periods were used to calculate TDO3 values, respectively. If number of lakes between 2°C contour lines is regrouped as two contour lines (11°C and 17°C) for identifying Tier 1 to 3 refuge lakes, results presented in Table 5.17 are consistent with results presented in Tables 5.3 and 5.4 for Duluth weather station.

Names and geographic locations of all 620 cisco lakes in Minnesota grouped by 2°C TDO3 contour lines are listed in Appendix F. Lakes in Table F.1 are sorted from lowest to highest TDO3 interval first and then sorted by lake name alphabetically for lakes within the same contour interval. Table F.1 can be very useful cisco lake management program to develop a strategy conservation and protection efforts on different cisco lakes.



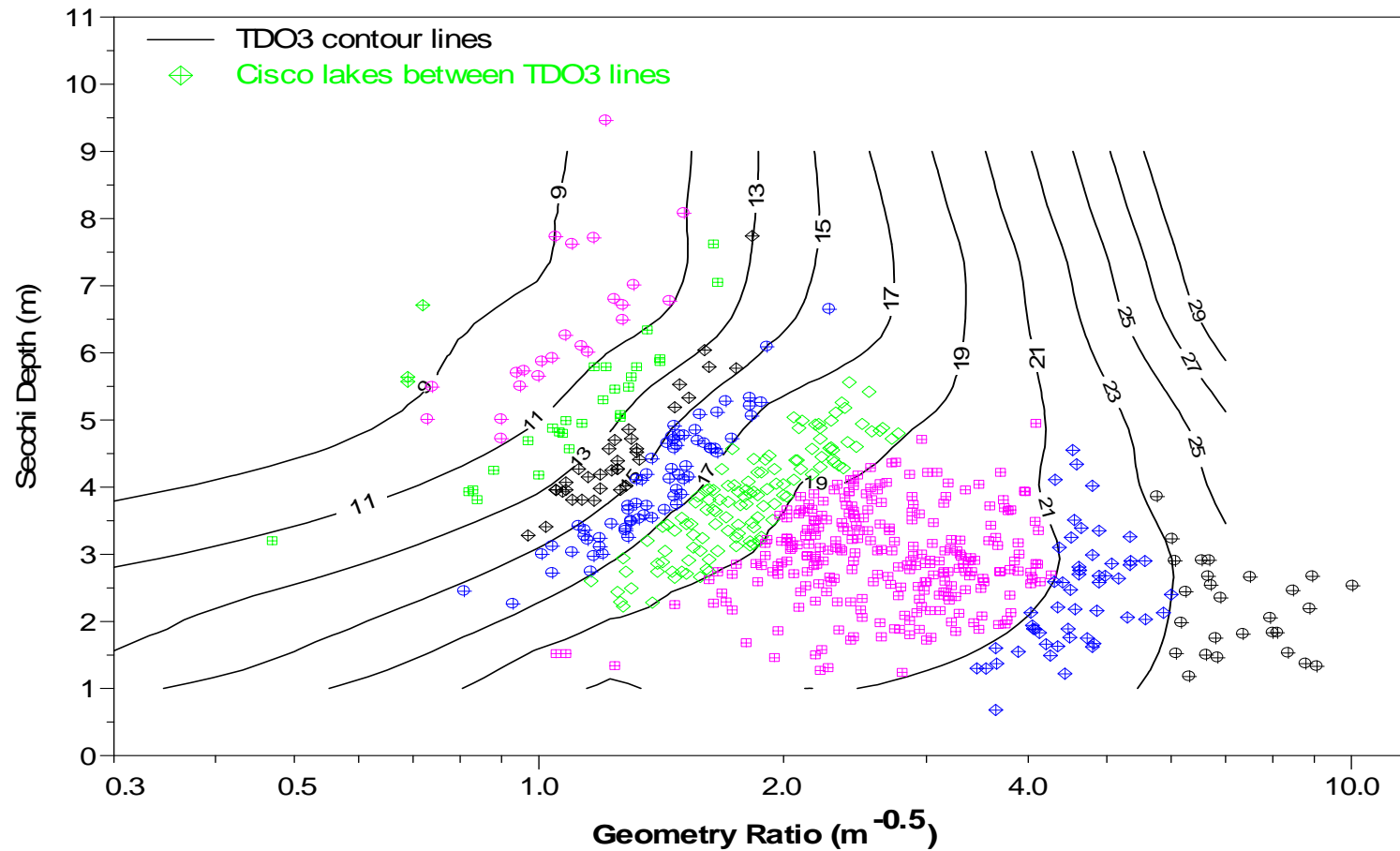


Figure 5.25 Distribution of 620 cisco lakes between  $2^{\circ}\text{C}$  contour lines of  $\text{AvgATDO3}_{\text{VB}}$  (Table 3.1, line 12) for **variable benchmark periods** simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

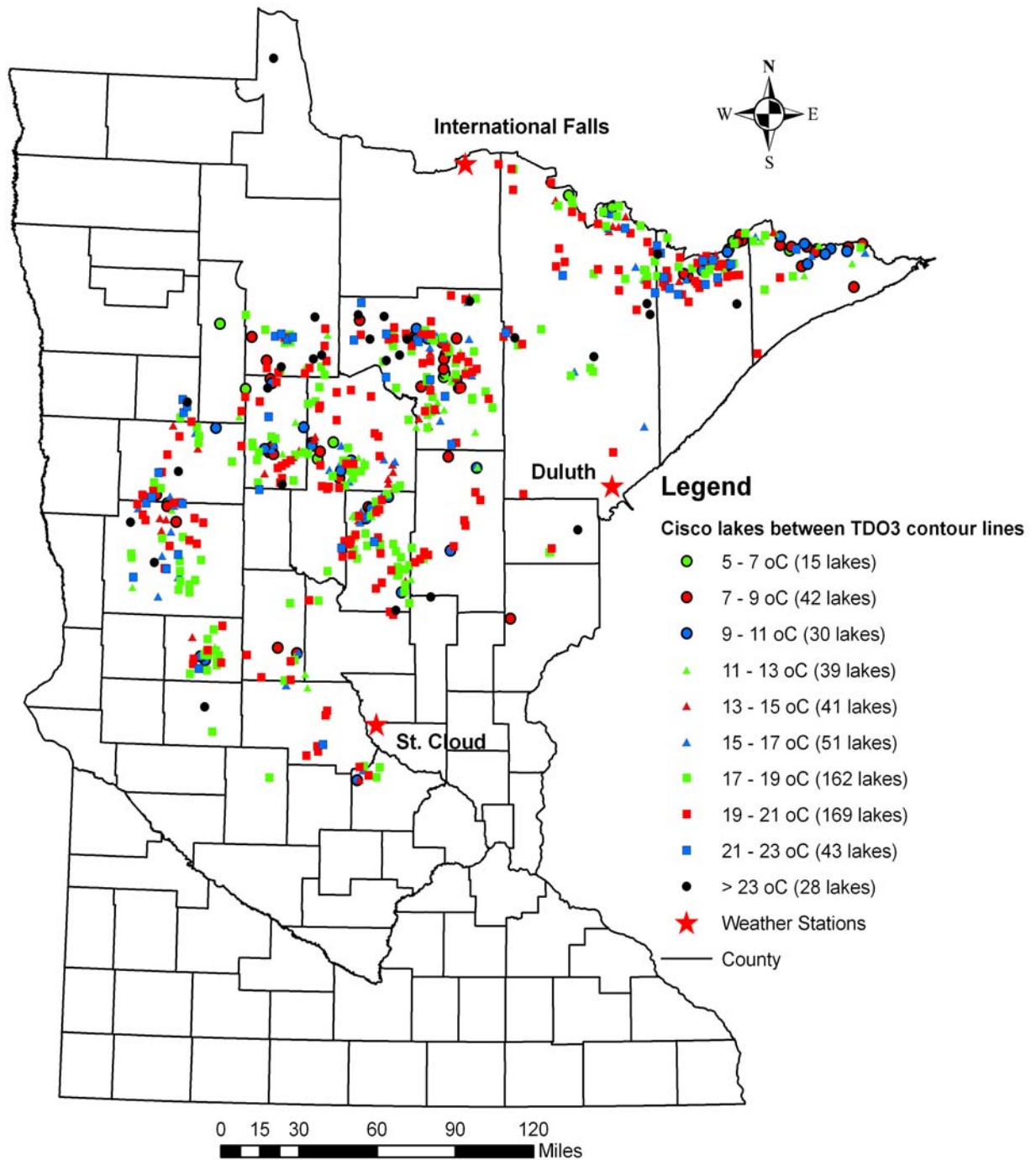


Figure 5.26 Geographical distribution of 620 cisco lakes with different  $\text{AvgATDO3}_{\text{FB}}$  (Table 3.1, line 6) values in a fixed benchmark period. Results are for the **MIROC 3.2 future climate scenario** using **Duluth weather data**. Bands of  $2^{\circ}\text{C}$  TDO3 increment values and numbers of cisco lakes that fall within a band are given in the legend.



#### ***5.7.4 Cisco lakes within 1°C bands of TDO3 contour lines (isotherms)***

To further refine the ranking of the 620 cisco lakes in Minnesota we divided them into further narrower bands between contour lines. Increments of 1°C between TDO3 contour lines from 5°C to 24°C were selected. Cisco lakes in Minnesota were therefore grouped into the following 25 TDO3 intervals: 5 – 6°C, 6 – 7°C, ..., 23 – 24°C and > 24°C (Table 5.18). For 1°C increment of TDO3 values, e.g., 5 – 6°C, lakes were grouped for TDO3 > 5°C but ≤ 6°C. Twenty-five TDO3 contour lines (from 5 to 24 °C in 1°C increments) and 620 cisco lakes were plotted in the previously used coordinate system of Secchi depth (SD) versus lake geometry ratio (GR) (Figs. 5.27 and 5.28). The TDO3 contour lines from 5°C to 24°C used to group cisco lakes were derived by interpolation from simulated points for the 30 virtual lakes.

Figure 5.27 and 5.28 show the distribution of all 620 cisco lakes between 1°C contour lines of **AvgATDO3<sub>FB</sub>** and **AvgATDO3<sub>VB</sub>** (Table 3.1, lines 6 and 12) for fixed and variable benchmark periods, respectively, simulated using Duluth weather data and the MIROC 3.2 future climate scenario. There are some contour lines of TDO3 with values greater than 24°C that are not shown in Figs. 5.27 and 5.28, but we did not rank cisco lakes for TDO3 > 24°C because the lethal temperature for coldwater fish species was 23.4°C (Stefan et al. 2001). The results of TDO3 in Figs. 5.27 and 5.28 are from the same simulations used in Figs. 5.24 and 5.25 but are plotted for 1°C increment.

Table 5.18 gives the number of cisco lakes that are found in each of the 25 TDO3 intervals (1°C increment). As many as 107 and 90 cisco lakes (or 17% and 15% of the 620 cisco lakes) fall within the interval 18 – 19°C when fixed and variable benchmark periods were used to calculate TDO3 values, respectively. Results presented in Table 5.18 are consistent with results presented in Tables 5.3, Table 5.4 (for Duluth weather station) and 5.17 if number of lakes between 1°C contour lines is regrouped as two contour lines (11°C and 17°C) for identifying Tier 1 to 3 refuge lakes or 2°C bands for ranking cisco lakes.

Table 5.18 Number of cisco lakes between 1°C TDO3 contour lines simulated using Duluth weather data for the MIROC 3.2 future climate scenario for fixed and variable benchmark periods ( $AvgATDO3_{FB}$ ,  $AvgATDO3_{VB}$ , Table 3.1, lines 6 and 12).

<b>Fixed Benchmark Period</b>		<b>Variable Benchmark Periods</b>	
TDO3 values	Number of lakes	TDO3 values	Number of lakes
5 - 6 °C	1	5 - 6 °C	0
6 - 7 °C	13	6 - 7 °C	0
7 - 8 °C	23	7 - 8 °C	0
8 - 9 °C	17	8 - 9 °C	3
9 - 10 °C	18	9 - 10 °C	10
10 - 11 °C	18	10 - 11 °C	14
11 - 12 °C	18	11 - 12 °C	15
12 - 13 °C	23	12 - 13 °C	11
13 - 14 °C	20	13 - 14 °C	18
14 - 15 °C	18	14 - 15 °C	19
15 - 16 °C	16	15 - 16 °C	31
16 - 17 °C	36	16 - 17 °C	35
17 - 18 °C	54	17 - 18 °C	36
18 - 19 °C	107	18 - 19 °C	90
19 - 20 °C	107	19 - 20 °C	164
20 - 21 °C	64	20 - 21 °C	93
21 - 22 °C	32	21 - 22 °C	43
22 - 23 °C	7	22 - 23 °C	9
23 - 24 °C	12	23 - 24 °C	12
> 24 °C	15	> 24 °C	16

Names and geographic locations of all 620 cisco lakes in Minnesota grouped by 1°C TDO3 contour lines are listed in Appendix G. Lakes in Table G.1 are sorted from lowest to highest TDO3 interval first and then sorted by lake name alphabetically for lakes within the same contour interval. Table G.1 can be very useful cisco lake management program to develop a strategy conservation and protection efforts on different cisco lakes.

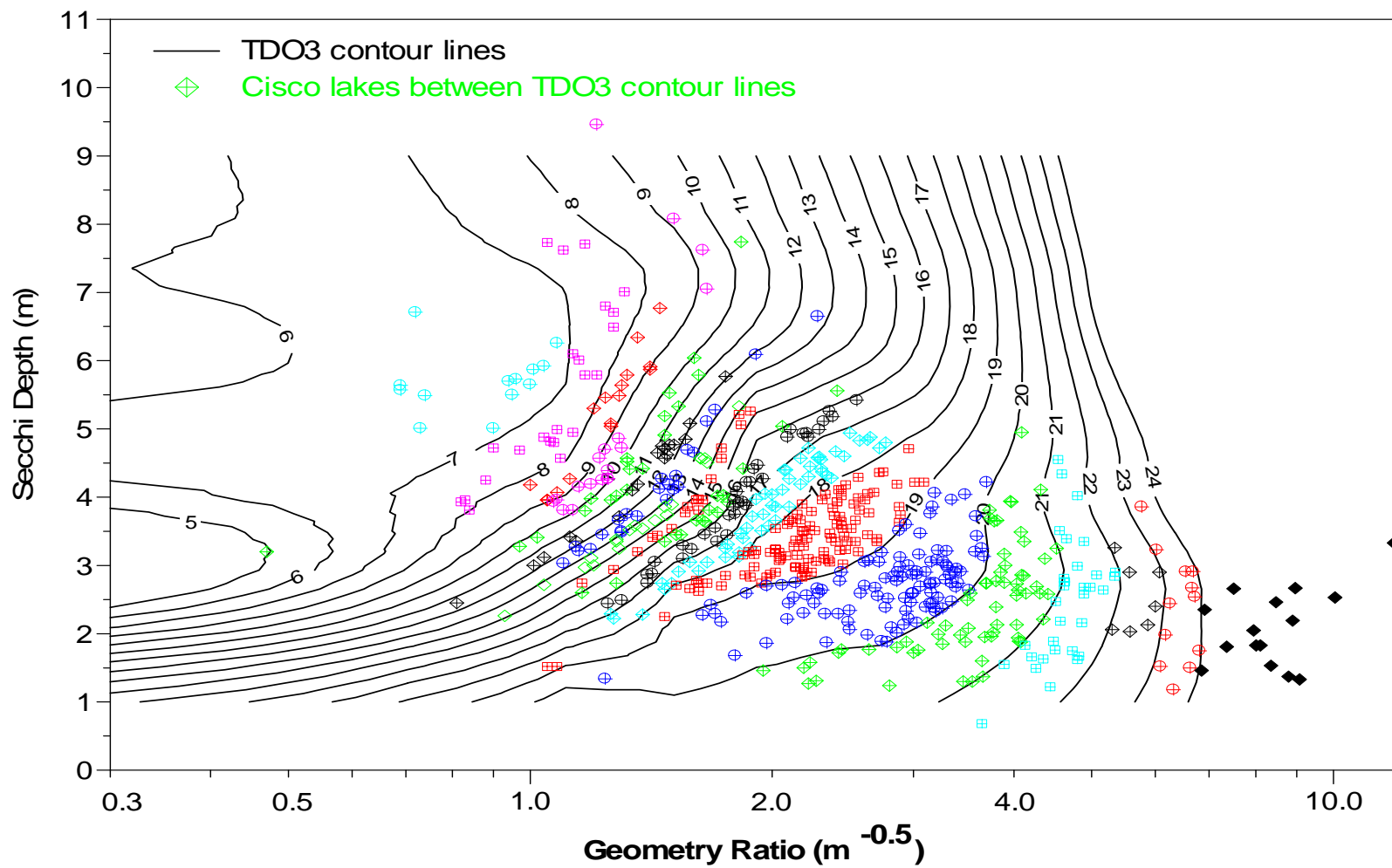


Figure 5.27 Distribution of 620 cisco lakes between  $1^{\circ}\text{C}$  contour lines of  $\text{AvgATDO3}_{\text{FB}}$  (Table 3.1, line 6) for **fixed benchmark period** simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

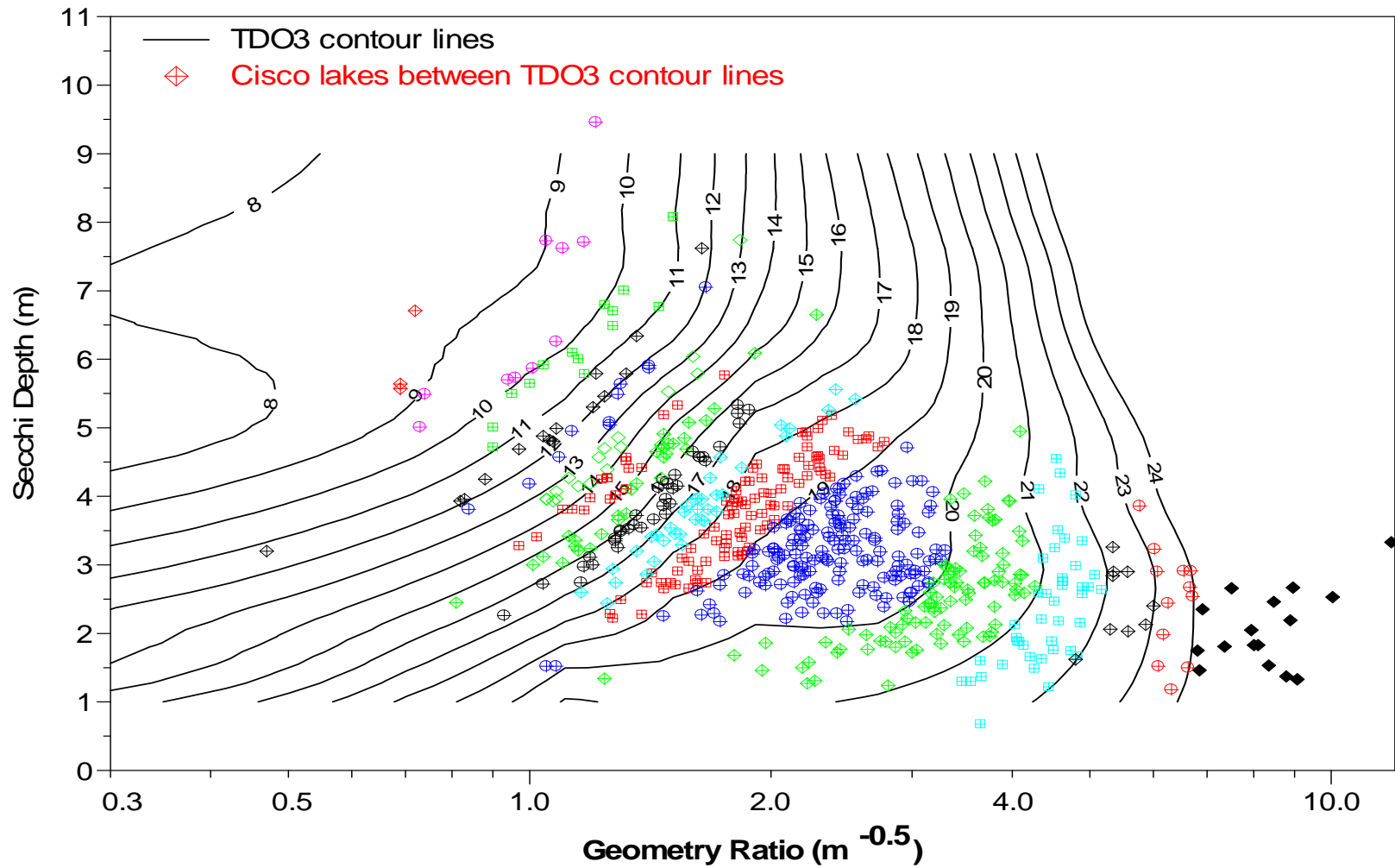


Figure 5.28 Distribution of 620 cisco lakes between  $1^{\circ}\text{C}$  contour lines of  $\text{AvgATDO3}_{\text{VB}}$  (Table 3.1, line 12) for **variable benchmark periods** simulated for the **MIROC 3.2 future climate scenario** using **Duluth weather data**.

## Chapter 6 Summary and Conclusion

### 6.1 Summary

This is the third and final project report of the project “Identification of potential coldwater refuge lakes important for sustaining cisco habitat under climate warming scenarios in Minnesota” for the Minnesota Department of Natural Resources. Cisco (tullibee, lake herring), is a valuable coldwater fish in Minnesota lakes.

The first project report (Fang et al. 2009) gave an overview of the characteristics of cisco lakes in Minnesota. The second project report (Fang et al. 2010) described the development of the water quality model MINLAKE2010 and results of water temperature and dissolved oxygen (DO) model simulations for selected Minnesota (cisco) lakes. This third report gives the numbers and names of Minnesota lakes in which cisco habitat is most likely to continue to exist under global warming scenarios. The current cisco lakes are ranked by an oxythermal parameter (TDO3) that measures stress on adult cisco. This third report describes the methodology and results of computer model simulations of cisco habitat in Minnesota lakes. The results are projections of potential cisco ‘refuge lakes’ under projected warmer climate scenarios in Minnesota.

This report has six chapters. Chapter 1 introduces the concepts and general methodology used to evaluate cisco habitat in lakes. It also introduces 21 actual cisco study lakes and 30 virtual cisco lakes in Minnesota. Both were used in the model simulations of water quality and cisco habitat.

Chapter 2 is about future climate scenarios. The chapter introduces General Circulation Models (GCMs) of the earth’s atmosphere, and how the results of these models are used to quantify the many available future climate scenarios. Options for the selection of climate scenarios are presented, and the selection of the GCM 2.0, CGCM 3.1 and the MIROC 3.2 future climate scenarios for this projected is discussed. In the end, the chapter explains how climate input data are generated for the MINLAKE2010 simulation model that was used to simulate daily water temperature and DO profiles in a lake.

Chapter 3 gives a general discussion of the oxythermal habitat descriptors or parameters that can be used to characterize fish habitat in a lake. Adult cisco habitat is severely limited by critical water temperature and dissolved oxygen (DO) conditions in different strata of a cisco lake. The oxythermal variable TDO3 (Jacobson et al. 2010) that is used in this study to separate viable from non-viable cisco habitat is introduced. TDO3 relates to the survival stress of adult cisco; the lower the TDO3, the lower the stress is to cisco. TDO3 is a water temperature that occurs where DO = 3 mg/L (Jacobson et al. 2010).

Methods to determine time series of daily TDO3 values from simulated daily temperature and DO profiles are discussed. Because fish are unlikely to respond to daily TDO3 values alone, biologically meaningful ‘TDO3 parameters’ must be extracted from the daily TDO3 time series.

These ‘TDO3 parameters’ can be averages or extreme values of daily TDO3 values over monthly and multi-year timescales. This is a central issue of this study, because the ‘TDO3 parameters’ relate daily water quality characteristics in a lake to long-term fish responses.

Twelve options for TDO3 parameters were identified (Table 3.1), although there are more. They range from single-day values to multi-year averages, and from extreme values to average values. They were defined in Table 3.1 and calculated from simulated daily temperature and DO profiles. Two TDO3 parameters (AvgATDO3<sub>FB</sub> and AvgATDO3<sub>VB</sub>) were selected to characterize cisco habitat in this study following the analysis of field data by Jacobson et al (2010). The selected TDO3 parameters are averages of daily TDO3 over 31-day benchmark periods. Annual maxima of these benchmark averages and multi-year averages over the entire simulation period of 47 years were also considered as options. Benchmark periods were either between fixed calendar days (DOY 209 to DOY 239, i.e. July 28 to August 27, 31 days) or sliding 31-day periods from which the highest TDO3 parameter values were selected.

At the end of Chapter 3 time-series of the selected TDO3 parameters in selected lakes and ranges of TDO3 parameter values in selected lakes are analyzed to project if a lake can be a cisco refuge lake. The short length of available weather data records (1991 to 2008) from Class II NWS weather stations made their use in the refuge lake selection simulations prohibitive. Only Class I NWS weather stations with daily weather data records from 1961 to 2008 were used. The first year of simulation results was discarded because of uncertain initial conditions. Useful simulated time series of lake temperature and DO profiles for the 47-year period from 1962 to 2008 were obtained and used to identify and select cisco refuge lakes in Chapter 5.

Chapter 4 presents the results of numerous simulations of selected TDO3 parameters in tabular or graphical form. The graphs are in a format that was used very successfully in previous studies: TDO3-values are presented as isolines on a coordinate system of lake geometry ratio GR vs. Secchi depth SD. 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. Numerical values of TDO3 given in tables and graphs of Chapter 4 were generated by MINLAKE2010 with daily weather data input representative of past climate and the above mentioned three future climate scenarios.

Cisco habitat simulations were first made for continuous, year-round weather time series from 1962 to 2008 (47 years) at the daily time scale. Simulations were then extended to projected future climate scenarios. A year-round water quality model MINLAKE 2010, that had previously been calibrated against 7384 pairs of temperature and DO data points measured in 28 cisco study lakes between 1979 and 2008 with overall standard errors of 1.47 °C for water temperature, and 1.5 mg/L for DO, was used in all cisco habitat simulations. Year-round water temperatures and DO concentrations in Minnesota cisco lakes ranged from 0 to 26 °C and 0 to 16 mg/L, respectively.

In Chapter 5 of this report the key and final results are presented. Refuge lakes for cisco are selected (identified). Each simulated lake had to be paired with a weather station, but useful

data were available only from three Class I NWS weather stations. Three options (methods) were used to pair each lake with one of the three weather stations: (1) using one single weather station for all lakes, (2) assigning a lake according to the shortest distance to a weather station, and (3) by pairing lakes and weather stations according to latitude. Refuge lakes were determined using all three options.

For refuge lake selection, the pool of 620 Minnesota cisco lakes was divided into three tiers. Tier 1 for a  $TDO3 \leq 11^{\circ}\text{C}$ , Tier 2 for the range  $11^{\circ}\text{C} < TDO3 \leq 17^{\circ}\text{C}$ , and Tier 3 for  $TDO3 > 17^{\circ}\text{C}$ . Tier 1 and Tier 2 were identified as cisco refuge lakes, Tier 3 as non-refuge lakes for cisco. This decision was based on Jacobson et al. (2010). Tier 1 has the most suitable coldwater fish habitat, Tier 2 has suitable coldwater fish habitat, and Tier 3 is considered unsuitable for coldwater fish. These ranges are defined by fairly stringent limiting TDO3 temperatures. Tier 1 and Tier 2 refuge lakes identified may be called viable cisco lakes where cisco is capable of living, developing, or spawning under favorable conditions. Cisco can still persist in lakes with TDO3 values greater than  $17^{\circ}\text{C}$  but at a reduced probability of occurrence (Jacobson et al. 2010). The TDO3s used for the refuge lake selection were simulated for the future climate scenarios CGCM 3.1 and MIROC 3.2. The  $\text{AvgATDO3}_{\text{FB}}$  and  $\text{AvgATDO3}_{\text{VB}}$  values, defined in Table 3.1, lines 6 and 12, were the actual ‘TDO3 parameters’ applied to select the refuge lakes.

Results are presented in tables or in graphical form. Graphs use isolines of selected TDO3 parameter values in a diagram of Secchi depth (as an indicator of lake trophic state) vs. lake geometry ratio (as an indicator of lake stratification and mixing dynamics), as described in Chapter 4. These contour plots of selected TDO3 values were interpolated from data points for the 30 virtual cisco lakes for both past climate conditions and two future climate scenarios. Cisco refuge lakes in Minnesota were identified for the two future climate scenarios CGCM 3.1 and MIROC 3.2 as Tier 1 or Tier 2 refuge lakes as defined above.

The number of lakes that qualify as cisco refuge lakes depends, of course, on the assumptions and choices made in the method of selection and the climate scenarios. Projections made for past climate conditions (1962 to 2008) identified on average 487 lakes or 78% of 620 cisco lakes investigated as viable (Table 5.13). This hindcasting is considered to be a good validation of the methodology used for refuge lake selection. It is also indication of a conservative approach for the projection of cisco refuge lakes under future climate warming scenarios, because no overpredictions were made by any of the methods used.

Another model validation was made by comparing the names of the 16 lakes that experienced cisco mortality in the exceptionally warm summer of 2006 to the names of identified cisco refuge lakes (Table 5.14). None of the 16 lakes had been identified as a Tier 1 refuge lake, but 10 had been identified as Tier 2 refuge lakes by more than 2 methods. Five other cisco lakes that had no documented cisco kill in 2006 had all been identified as Tier 1 cisco refuge lakes. The comparison is not very rigorous, because the projections were made with 47-year averages of TDO3s, whereas the recurrence interval of the single year cisco kill event occurred in is unknown.

## 6.2 Conclusion

The conclusion of this study is that under fairly stringent selection criteria ( $DO > 3$  mg/L and  $TDO3 \leq 17^{\circ}\text{C}$ ) at least one fourth to one third of the lakes that currently have cisco populations, are projected to maintain cisco habitat under projected future climate scenarios (Table 5.15). Many such ‘refuge’ lakes are located in northeastern and central Minnesota (Figures 5.22 and 5.23).

Tier 1 plus Tier 2 refuge lakes selected e.g. under the future climate scenario MIROC 3.2 have Secchi depths greater than  $\approx 2.5$  m (Fig. 5.18), lake geometry ratio less than  $\approx 2.5 \text{ m}^{-0.5}$  (Fig. 5.19), maximum depths greater than  $\approx 15$  m (Figure 5.20), and surface areas less than  $\approx 30 \text{ km}^2$  (Figure 5.21).

The number of refuge lakes determined, e.g., for the future climate scenarios MIROC 3.2, varies depending on the selection method used (Tables 5.3 to 5.13). Tier 1 refuge lakes are listed by name in Table 5.16 and are grouped in five batches according to the number of methods by which they were identified. Lakes on top of Table 5.16 are presumed to be the best candidates for cisco refuge lakes. The lakes on the list have been plotted on a map of Minnesota in Figure 5.22.

Instead of dividing the 620 cisco lakes into three tiers, individual cisco lakes can be ordered (ranked) by the number of times that they were identified as Tier 1 plus Tier 2 refuge lakes by the five options to pair a lake with a weather station (Appendix E) and their respective TDO3 values. Therefore, 620 cisco lakes in Minnesota were assembled in narrow ( $2^{\circ}\text{C}$  and  $1^{\circ}\text{C}$ ) bands of TDO3 values (Figures 5.24, 5.25, 5.27, and 5.28). Names and locations of lakes in each band are given in Appendix F ( $2^{\circ}\text{C}$  band) and Appendix G ( $1^{\circ}\text{C}$  band). Lakes on top of the list (Tables F.1 and G.1) are again presumed to be the best candidates for cisco refuge lakes because they are for the lowest TDO3 values, and low TDO3 values are presumed to reflect the least stress on adult cisco. The number of lakes in each band of TDO3 values is given in Tables 5.17 and 5.18.



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## **Appendix A. Simulations of Cisco Survival Conditions in Selected Minnesota Lakes**

In this study, oxythermal habitat limits for fish, especially water temperature and dissolved oxygen (DO) conditions for cisco fish kill to occur, are used to make projections for cisco survival in Minnesota lakes that currently have populations of cisco.

Two methods were considered to determine oxythermal habitat limits for cisco. The first method was used in a previous and broader regional fish habitat study in Minnesota and in the contiguous U.S.A (Fang et al. 1998). This method will be called constant value method (CVM) in this study because non-survival limits for a fish species are specified as constant values, i.e., a constant lethal temperature (thermal limit) and a constant minimum DO concentration required for long-term survival of a fish species. Based on the previous study, the non-survival limits to identify “cisco kill” by this method are a maximum temperature  $T_{\max} = 23.4^{\circ}\text{C}$  and minimum  $\text{DO}_{\min} = 3.0 \text{ mg/L}$ . A non survival period of length (NSL) is defined as the total number of days when either the temperature or the DO in vertical lake profiles do not meet these fish survival criteria at all depths (Eaton et al. (1995). NSL measures the number of days with cisco kill conditions in a lake in a year. NSL values are calculated for every year of the simulation period.

The second method uses variable, non-survival limits, i.e., lethal temperature and minimum DO are coupled. This approach has been proposed by Jacobson et al. (2008). For each value of minimum DO required for fish to survive, a water temperature is calculated using an equation developed by Jacobson et al. (2008) for some of the coldwater fish species (cisco, burbot, lake whitefish and lake trout); this method is therefore referred to in this study as the equation method (EM). In a stratified lake, temperature and DO typically vary with depth. The required minimum DO at the measured or simulated temperature at a specific depth in a lake is compared with the measured or simulated DO in that respective layer. When the minimum DO required is not met by the actual DO - in all layers of a lake, fish kill in that lake is projected for that day. Fish kill is determined day by day, and year by year for an entire multi-year simulation period. The procedure can also be reversed, and the allowable maximum temperature at the measured or simulated DO at a specific depth in a lake is compared with the measured or simulated temperature in that respective layer.

### **A.1. Simulation of Cisco Habitat by the Constant Values Method (CVM)**

In this method, the water depth where the simulated  $\text{DO} = 3 \text{ mg/L}$  in the simulated daily DO profile is identified, and then the simulated water temperature at that depth is determined. If this temperature is more than  $23.4^{\circ}\text{C}$  then cisco fish kill is assumed for that particular day. This process is carried out for the whole year, to find the total number of fish kill days for that year. Figure A1 shows the process in a schematic diagram. An isotherm of the lethal temperature  $T_{\max} = 23.4^{\circ}\text{C}$  developed from the simulated water temperature profiles is drawn in a depth vs. time plot of a lake. This isotherm develops from the water surface downwards as the summer

progresses, and similarly an isopleth of the minimum  $DO_{min} = 3.0$  mg/l derived from the simulated DO profiles develops from the lake bottom upwards, as shown in Figure A.1. As the summer progresses, the isotherm of the lethal temperature and the isopleth of the DO survival limit may intersect each other. After this has occurred, fish kill is projected for each of the following days (Figure A.1). In winter, DO can drop to less than 3.0 mg/L below the ice cover of a lake. When the 3mg/L DO isopleths touches the ice cover, winter kill is projected.

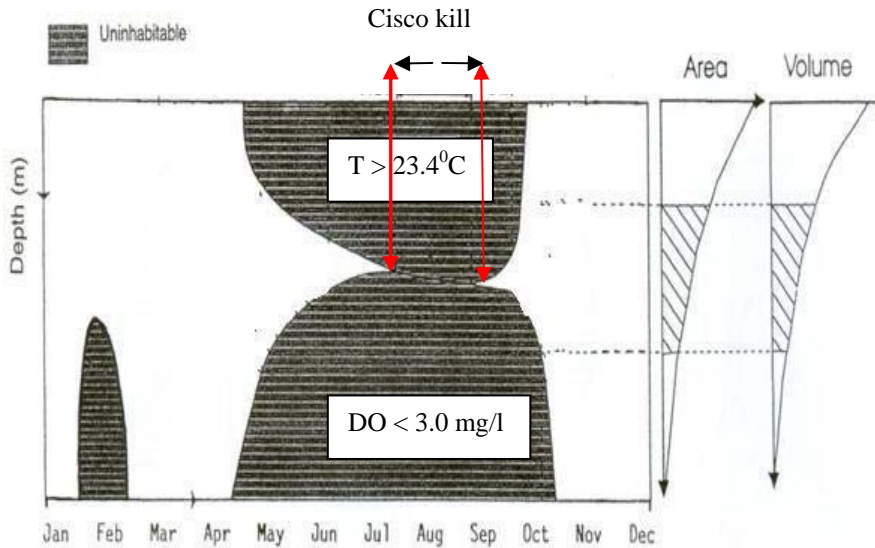


Figure A.1 Depth vs. time plot of the critical isotherm and DO isopleth, showing projected cisco kill in a seasonally stratified lake as dark shaded areas

Contour plots that delineate non-survival fish habitat in a coordinate system of lake depth vs. time can be developed by the CVM to illustrate if fish can survive in a specific lake. Examples of depth vs. time contours of coldwater fish habitat in 10 study lakes are shown for selected years in Figure A.2 for cisco lakes, and in Figures A.3 and A.4 for non-cisco lakes. Isotherms at the lethal temperature of  $23.4^{\circ}C$  are drawn as black lines and isopleths at the DO limit of 3.0 mg/L are drawn as red lines. After isotherms of the lethal temperature and isopleths of the DO survival limit intersect, fish kill is projected to occur on the following days. During the simulation period, 2006 was the warmest year, and 1997 was the coldest year. Therefore, depth vs. time contours for these two years were included on these plots. Winter fish kill in Carrie Lake, a shallow lake, is shown in Figure A.3 for four selected years. Winter fish kill is also shown in 1997 for Madison Lake and St. Olaf Lake. Cisco fish kill would have occurred (was projected) in summer of 2006 in all non-cisco lakes, except Bear Head Lake. Summer kill in 2006 was also projected for two cisco lakes (South Twin and White Iron).

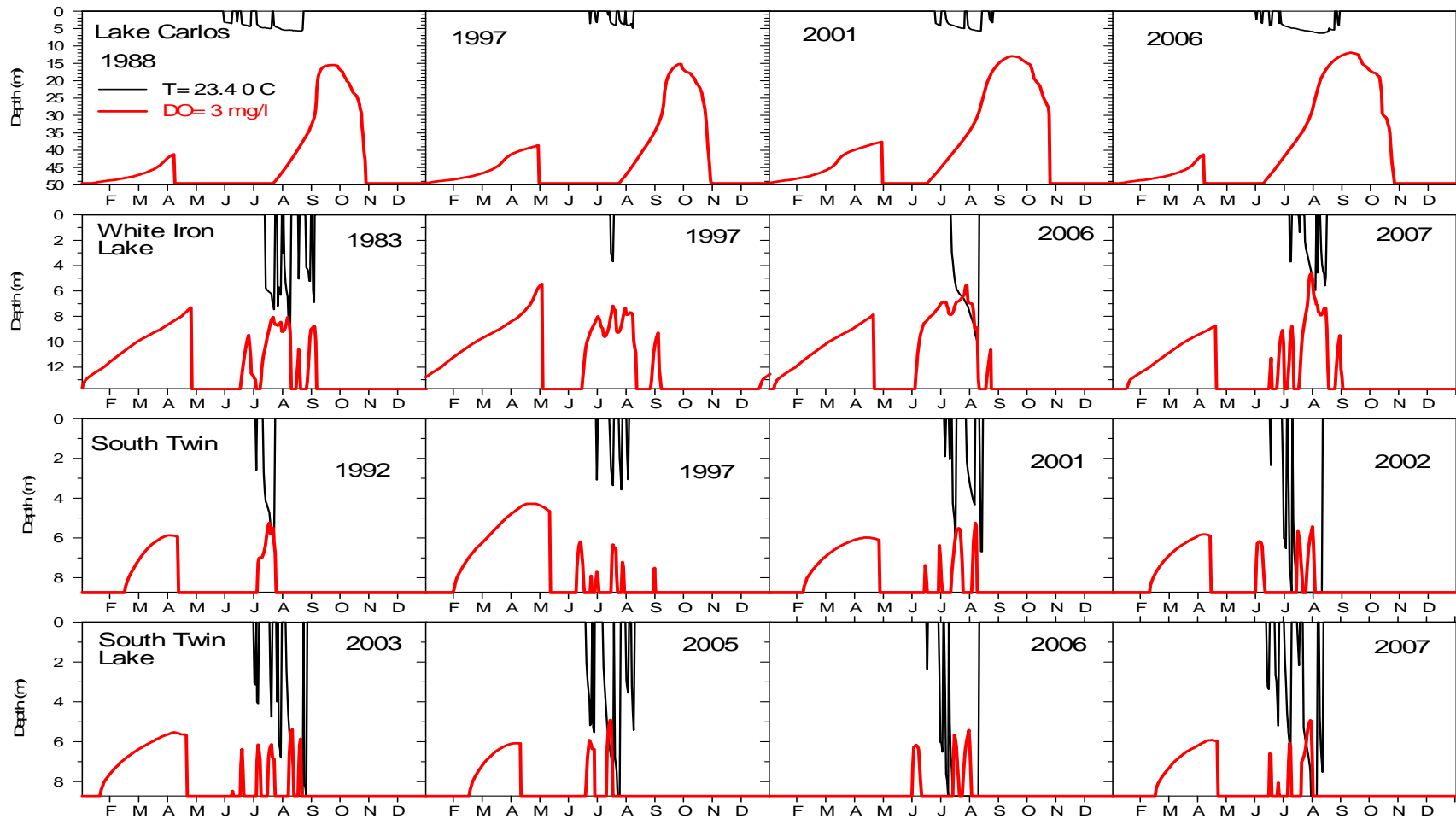


Figure A.2 Depth vs. time contours of cold-water (cisco) fish habitat in cisco lakes (Lake Carlos, White Iron Lake, and South Twin Lake) for selected years. Isotherms at the lethal temperature of  $23.4\text{ }^{\circ}\text{C}$  are black lines and isopleths at the DO limit of  $3.0\text{ mg/L}$  are red lines.

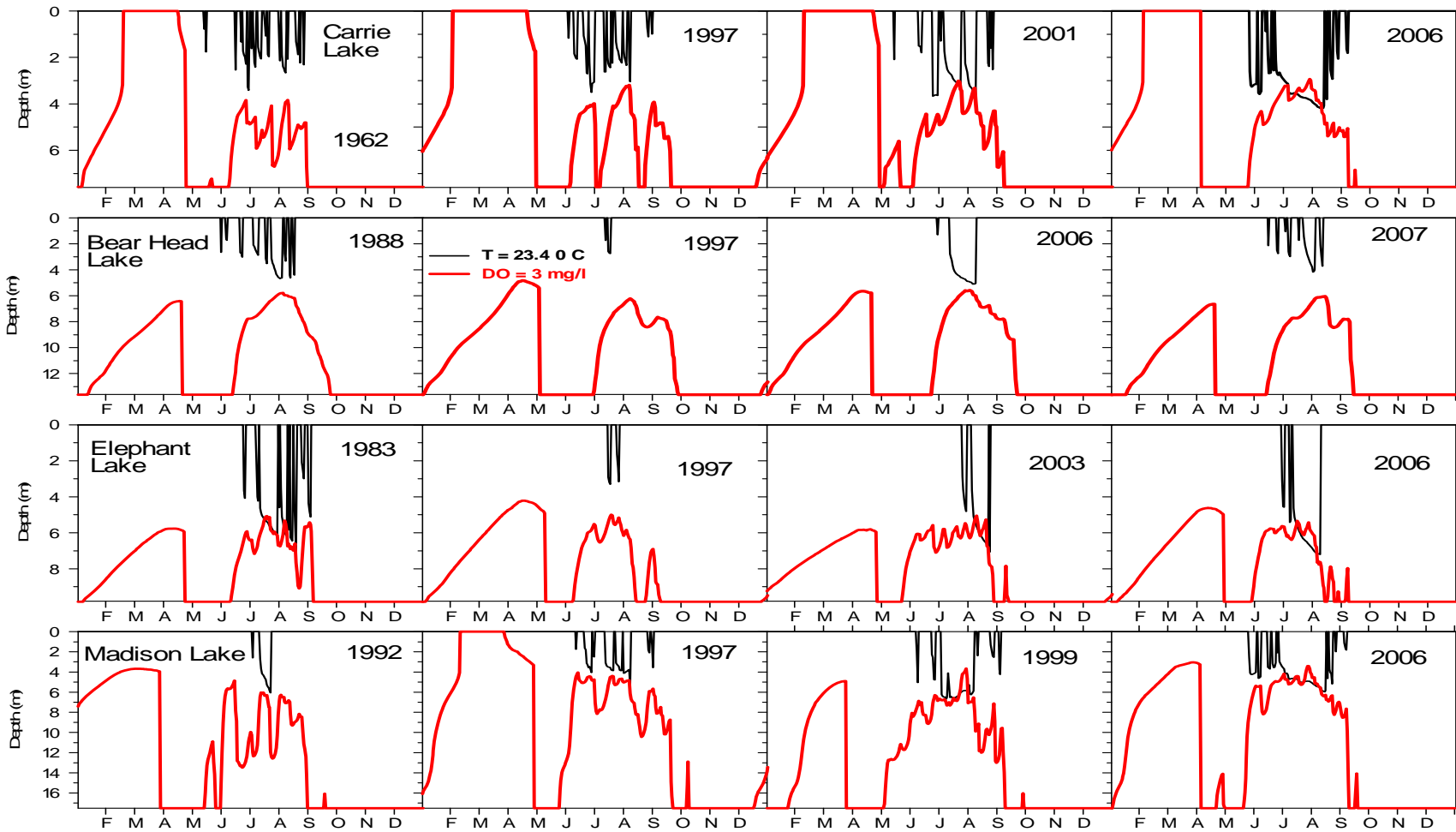


Figure A.3 Depth vs. time contours of cold-water (cisco) fish habitat in non-cisco lakes (Carrie Lake, Bear Head Lake, Elephant Lake, and Madison Lake) for selected years. Isotherms at the lethal temperature of 23.4 °C are black lines and isopleths at the DO limit of 3.0 mg/L are red lines.

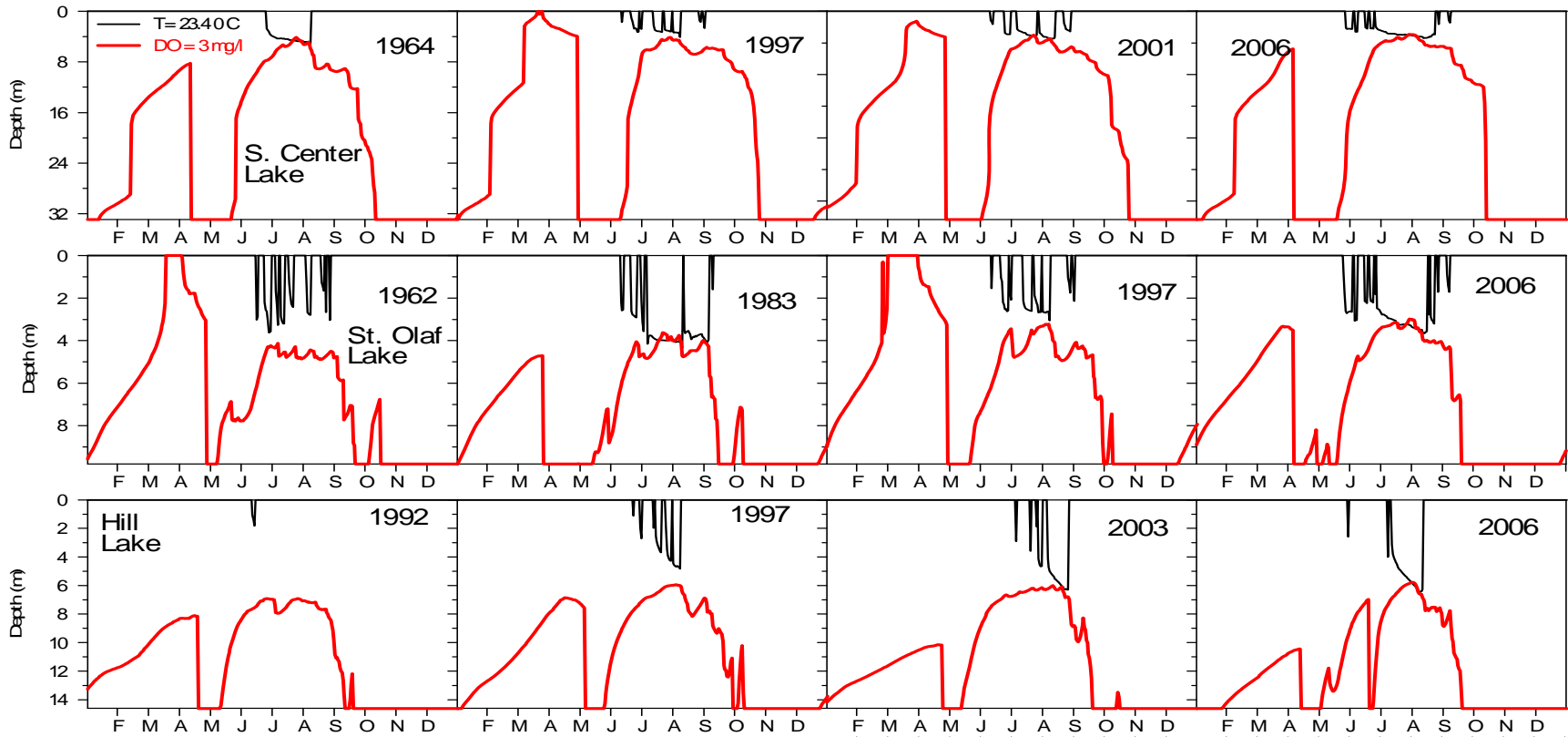


Figure A.4 Depth vs. time contours of cold-water (cisco) fish habitat in non-cisco lakes (South Center Lake, St. Olaf Lake, and Hill Lake) for selected years. Isotherms at the lethal temperature of 23.4 °C are black lines and isopleths at the DO limit of 3.0 mg/L are red lines.



## A.2 Simulation of Cisco Habitat by the Coupled Oxythermal Limit - Equation Method (EM)

Constant lethal temperature and minimum DO concentration values for fish to survive were developed in a previous study (Eaton et al. 1995; Stefan et al. 1996). More recently Jacobson et al. (2008) developed an equation for the lethal niche boundary of adult cisco by remapping the measured oxygen concentrations and temperatures from the profiles measured in 16 Minnesota lakes that experienced cisco mortality in mid-summer of 2006. The equation is given as

$$DO_{lethal} = 0.40 + 0.000006 e^{0.59T_{lethal}} \quad (A.1)$$

where  $DO_{lethal}$  and  $T_{lethal}$  are the dissolved oxygen concentration and the water temperature that define the lethal niche boundary (Jacobson et al. 2008).  $DO_{lethal}$  is the required or needed minimum DO concentration at a given temperature  $T_{lethal}$  for cisco to survive. Equation (A.1) gives a DO survival limit for cisco that is not constant, but instead depends on water temperature. The equation method (EM), therefore, uses survival limits for temperature and DO that are variable and related to each other.

Table A.1 illustrates the difference between the CVM and the EM. A notable difference between these two methods is that the CVM uses 3.0 mg/L as DO survival limit, and 23.4°C as the lethal temperature for cisco (Eaton et al.1995), whereas the EM with 3.0 mg/L as DO survival limit as input gives a lethal temperature for cisco from equation A.1 (Jacobson et al. 2008) as 22.0°C only. The difference of 1.4°C is significant.

Table A.1 Cisco survival criteria used in two different studies.

Previous study (Eaton et al. 1995; Stefan et al. 1996) on cold-water fish		Recent study (Jacobson et al. 2008) on cisco mortality	
Minimum DO requirement (mg/L)	Lethal temperature (°C)	Minimum DO requirement (mg/L)	Lethal temperature (°C)
3.0 mg/l	23.4	0.4	<12.0
		2.0	21.8
		3.0	22.0
		4.0	22.6
		6.3	23.4
		8.9	24.0

Note: The recent study by Jacobson et al. (2008) was done specifically for cisco, whereas the past study by Eaton et al. (1995) was done on the entire coldwater fish guild and not specifically on cisco (though cisco is a coldwater fish). We have therefore relied on the EM in this study for cisco refuge lake selection.

Equation (A.1) indicates that the required DO concentration for adult cisco is about 0.4 mg/L when water temperature is less than 15°C, and increases to 3 mg/L at a water temperature of 22°C. The required DO concentration becomes 8.9 mg/L at 24°C. Equation (A.1) was implemented in the fish habitat simulation program to determine potential fish mortality in 15 study lakes selected in the first phase of this study. For each simulation day, the required DO concentrations,  $DO_{lethal}$ , were computed from simulated water temperatures in all water layers using equation (A.1), and compared with DO concentrations simulated by MINLAKE2010 in the same layers. Fish kill was assumed to occur if the simulated DO was less than the  $DO_{lethal}$  value at all water depths on that day. If simulated DO was larger than  $DO_{lethal}$  in some of the water layers, fish mortality was not assumed to occur because cisco could swim to the water layers with suitable DO and temperature conditions.

Sample plots of simulated DO concentrations versus simulated temperatures in four study lakes on selected summer days when cisco mortality (kill) potential was high are shown in Figures A.5 and A.6. The lethal-niche-boundary curve (Equation A.1) developed by Jacobson et al. 2008) has been added for reference. All simulated data points are located to the right of the curve, indicating that adult cisco kill could indeed occur in all water layers (depths) on the days shown. Figure A.5 shows that fish kill of adult cisco is projected to occur on some days in Carrie Lake, Hill Lake, South Center Lake and Madison Lake. This agrees with field observations because no cisco have been found in those four lakes. They are identified as non-cisco lakes.

South Twin and White Iron are two cisco lakes, but Figure A6 shows that there is cisco kill potential in these two lakes on some days in some years. Other available measured temperature and DO profile data in White Iron Lake and South Twin Lake (Figure A.7) do not indicate that cisco kill would occur. Field data are not available for most of the days when simulated temperature and DO values projected cisco kill. For example, simulated temperature and DO values projected cisco kill in South Twin Lake on some days in 1992, 1995, 1998, 1999, 2000 and 2006, but field data are only available in 2008 for South Twin Lake. There is one exception: simulated temperature and DO on July 25, 2006 in White Iron Lake indicate a possible kill of adult cisco (Fig. A.6), but measured temperature and DO profiles did not suggest cisco kill potential. This suggests that the model may have overpredicted water temperature and/or under predicted DO concentration on July 25 in White Iron Lake. Figure A.7 shows that some but not all data points from measurements on July 25, 2006, are on the right side of the lethal niche boundary curve. It means that July 25, 2006 was a stressful day for cisco in White Iron Lake due to hot weather. Indeed significant cisco kills occurred in the summer of 2006 in 16 Minnesota cisco lakes.

Figures A.8 and A.9 show that there are many days in summer when lakes identified as 'non-cisco lakes' would not support cisco habitat, i.e., have cisco kill. There is one exception for non-cisco lakes: Bear Head Lake is classified as non-cisco lake by the MN DNR, but Figure A.9 shows there are favorable environmental conditions to support cisco, and maybe cisco was not introduced to the lake (isolated lake in the northern border region of Minnesota).

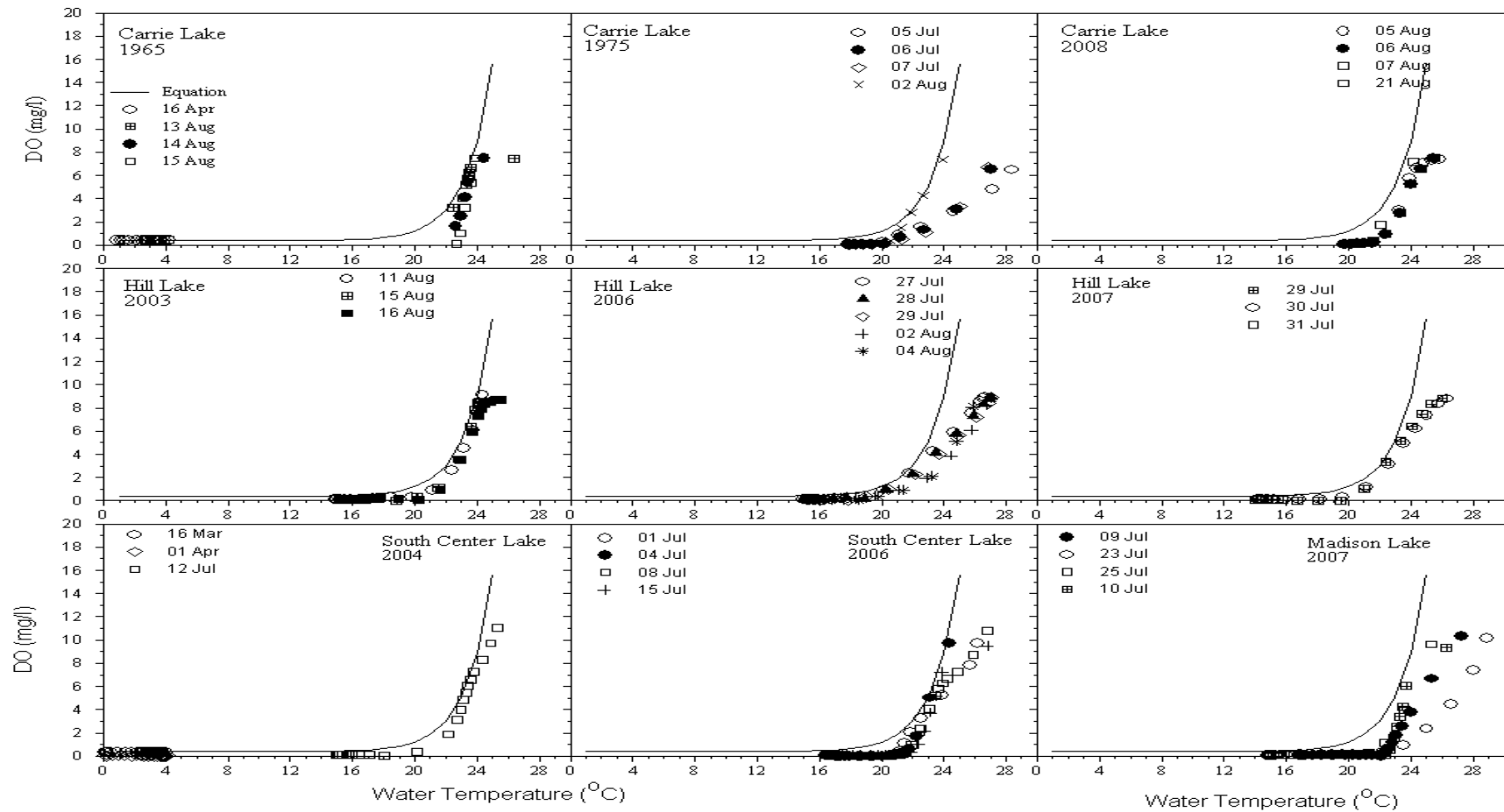


Figure A.5 Simulated DO concentration versus simulated temperature in selected non-cisco lakes (Carrie Lake, Hill Lake, South Center Lake, and Madison Lake) on selected summer days with potential cisco mortality against the lethal-niche-boundary curve developed by Jacobson et al. (2008).

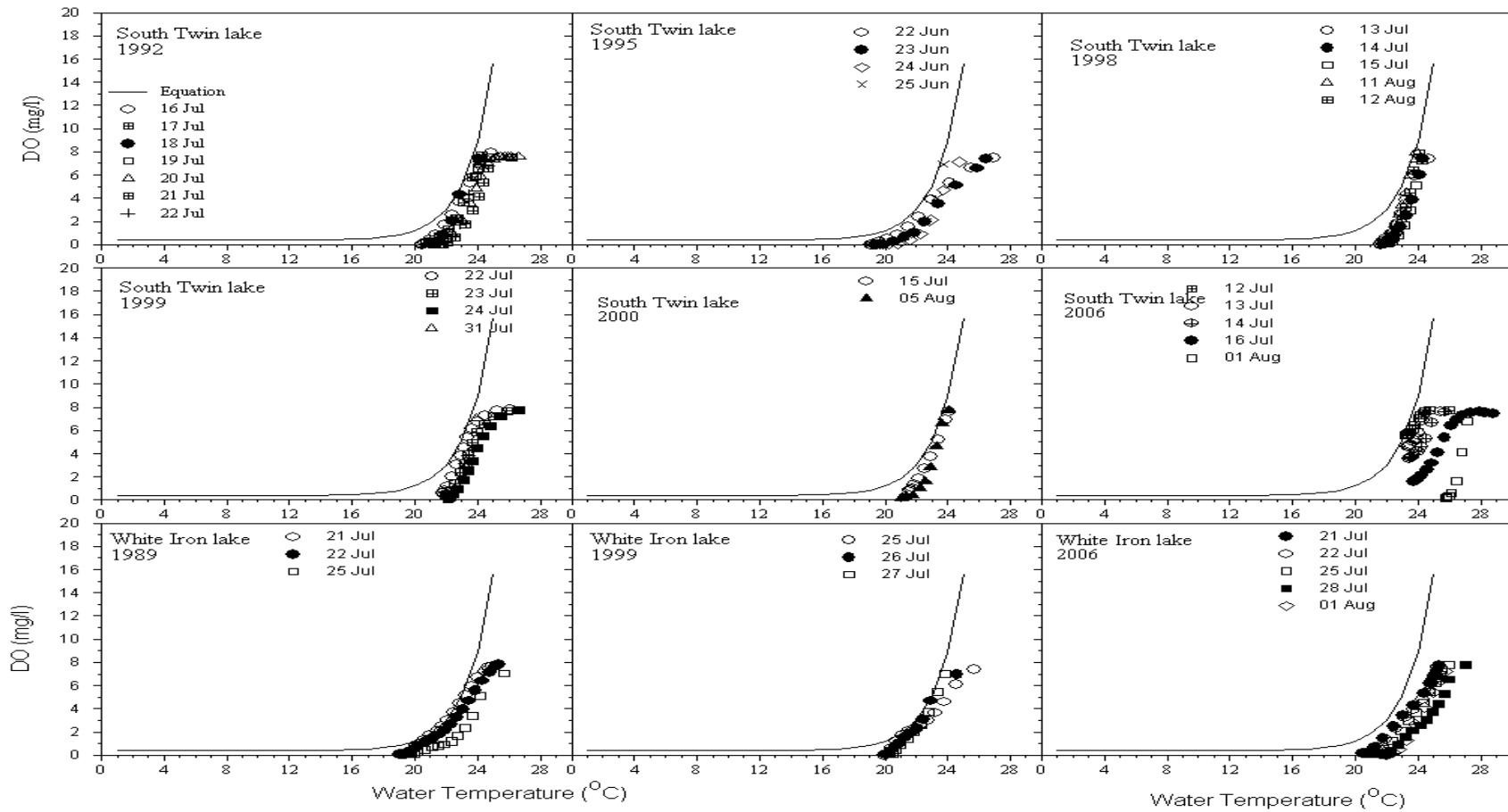


Figure A.6 Simulated DO concentration versus simulated temperature in cisco lakes (South Center Lake, and White Iron) on selected summer days with potential cisco mortality against the lethal-niche-boundary curve developed by Jacobson et al. (2008).

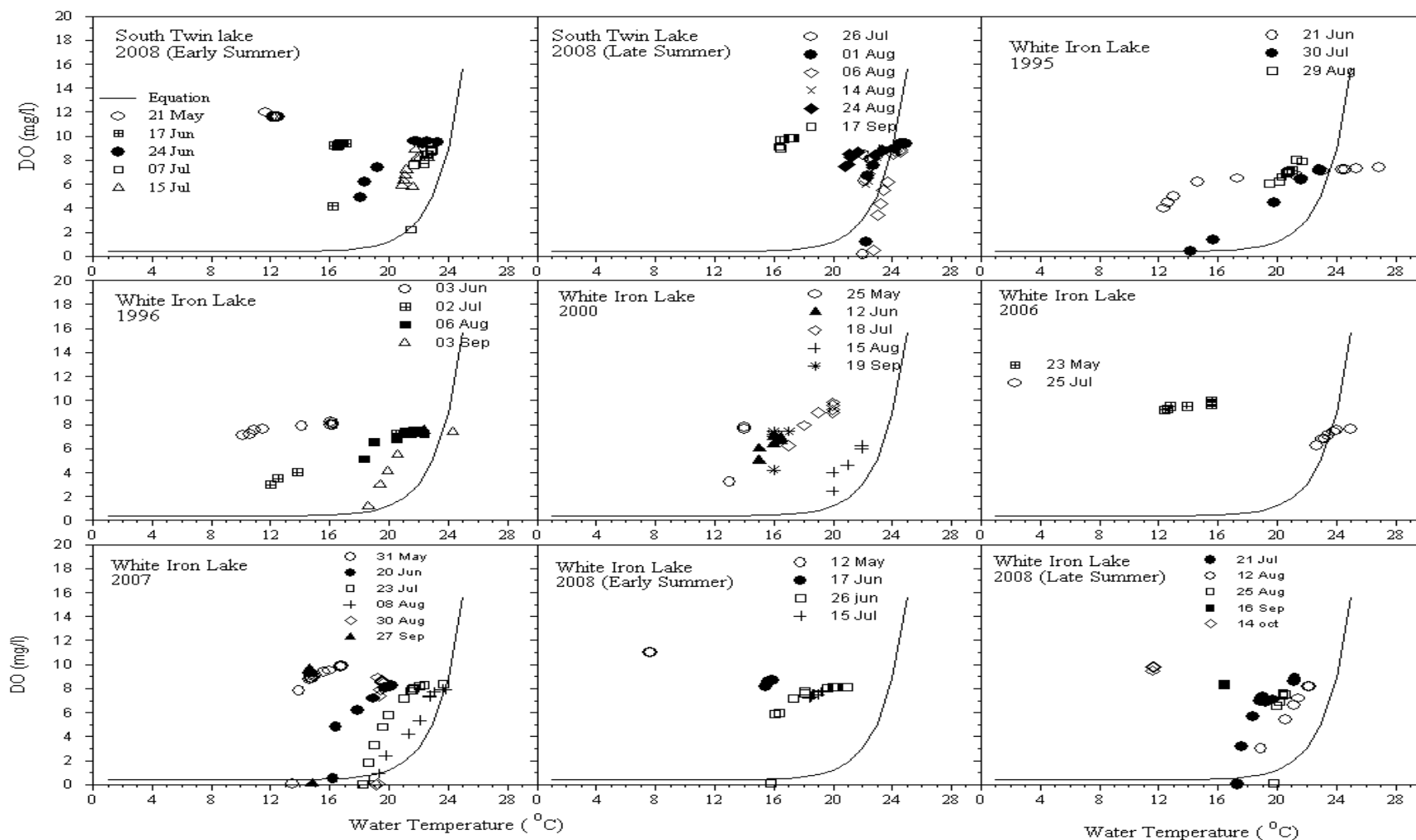


Figure A.7 Measured DO concentration versus measured temperature in cisco lakes (South Twin Lake and White Iron Lake) on summer days with potential cisco mortality against the lethal-niche-boundary curve developed by Jacobson et al. (2008).

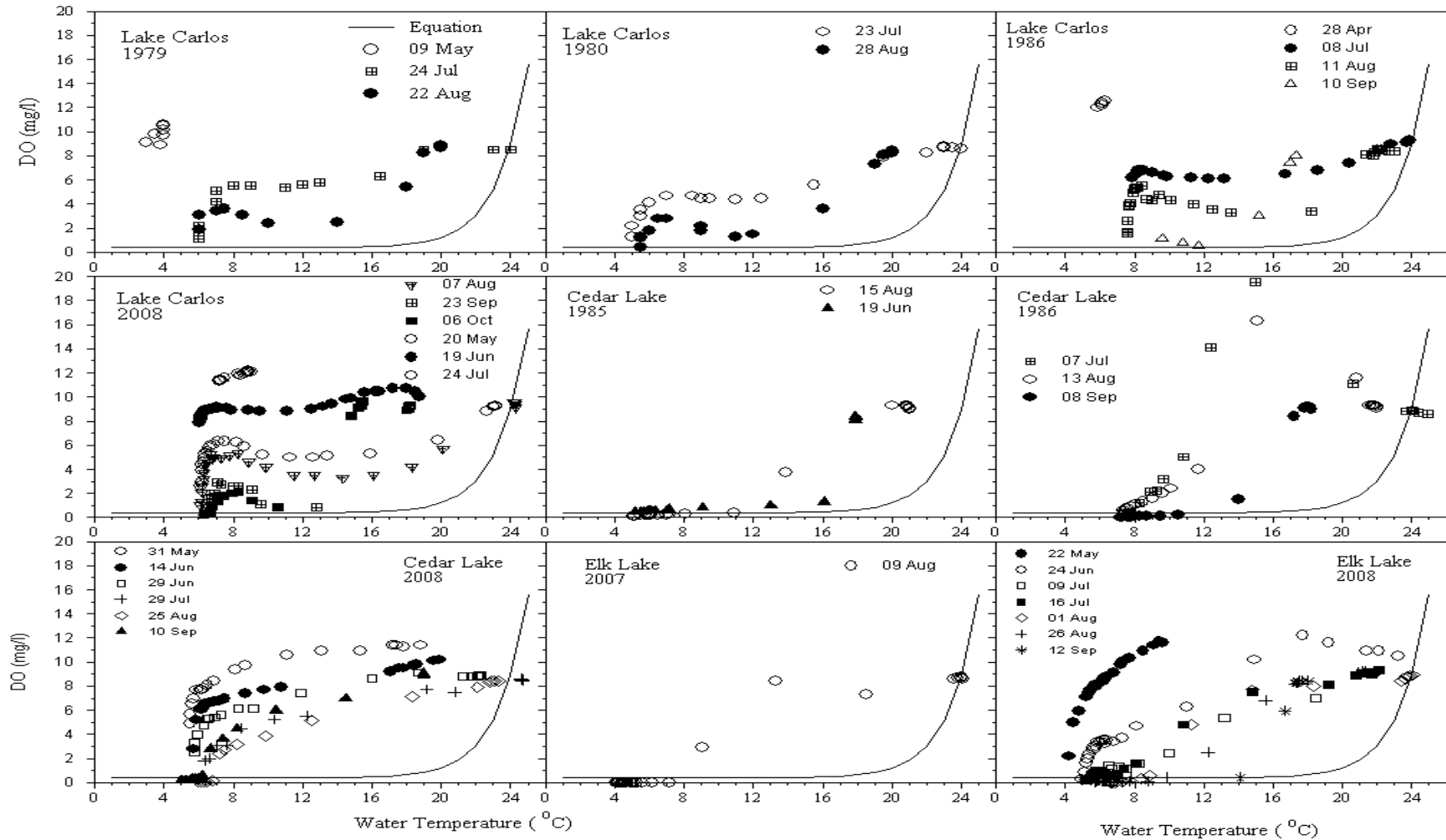


Figure A.8 Measured DO concentration versus measured temperature in cisco lakes (Lake Carlos, Cedar Lake, and Elk Lake) on summer days with potential cisco mortality against the lethal-niche-boundary curve developed by Jacobson et al. (2008).

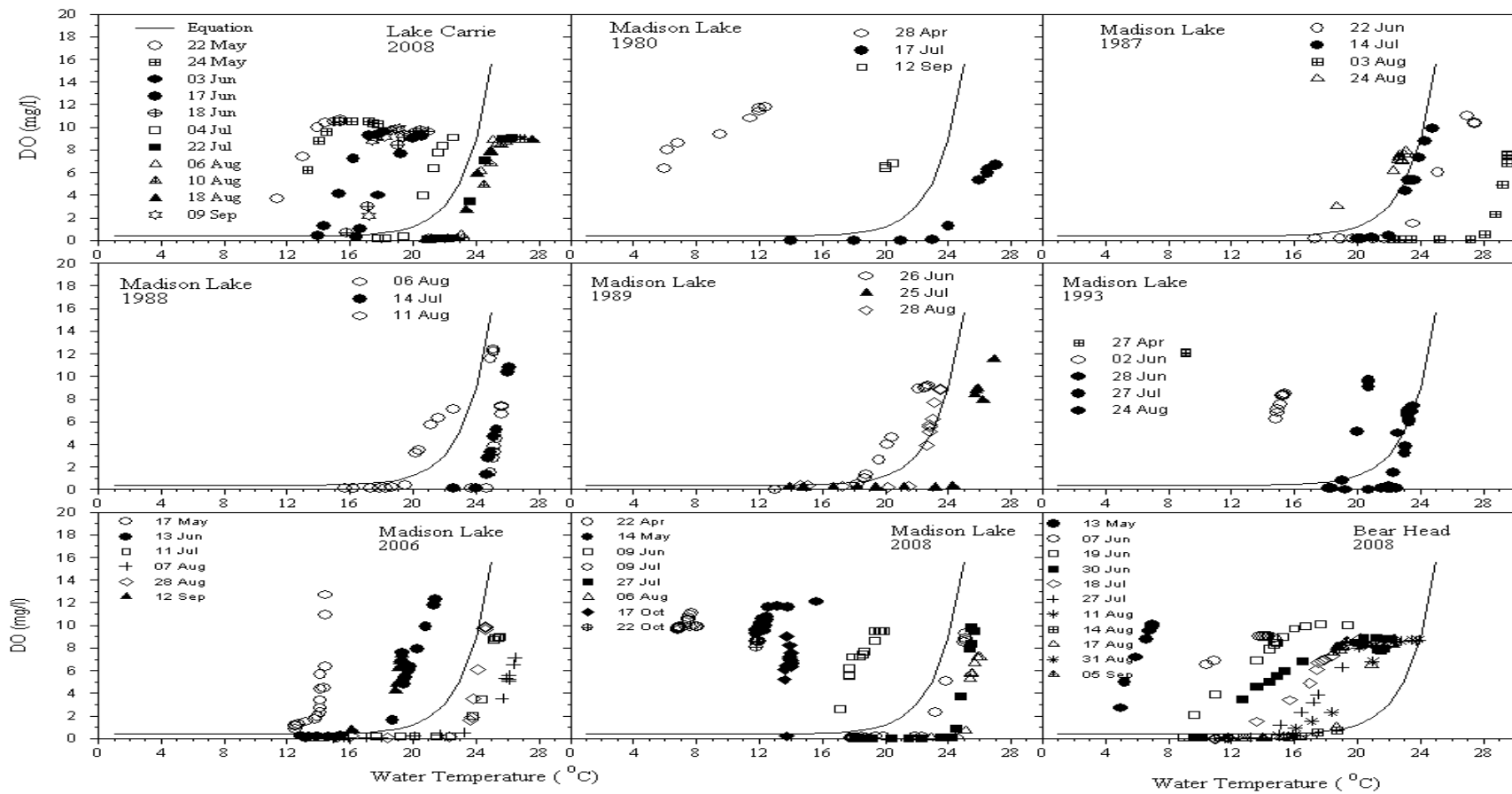


Figure A.9 Measured DO concentration versus measured temperature in non-cisco lakes (Carrie Lake, Madison Lake, and Bear Head Lake) on summer days with potential cisco mortality against the lethal-niche-boundary curve developed by Jacobson et al. (2008).

### **A.3 Results of Cisco Habitat Simulations and Cisco Kill Projections for Past Climate**

Cisco habitat and cisco kill projections for the 15 study lakes used in the first phase of the study are summarized in Tables A.2 to A.5. Simulations of water temperature and DO profiles were performed for either 47 years (1961 to 2008) or 17 years (1991 to 2008). Lakes with \* in Tables A.2 to A.5 were simulated for 17 years due to limited available climate data. The number of days with cisco kill determined by the constant value method (CVM) or the equation method (EM) (for DO equal 3.0 mg/l) is given in Tables A.2 and A.3.

Both the CVM and the EM projected no cisco kill in any of the simulated years in the following six lakes: Carols, Cedar, Elk, Kabekona, Ten Mile, and Trout. All of these six lakes are classified by MN DNR as cisco habitat lakes. South Twin and White Iron are also classified as cisco habitat lakes but both the CVM and the EM projected some days with adult cisco kill. Statistics (average, standard deviation, maximum and minimum) of the number of days with cisco kill are also reported in Tables A.2 and A.3.

Seven of the 15 study lakes have no known cisco populations, and we have listed them as “non-cisco lakes”. Both cisco habitat assessment methods were applied to these seven lakes, and cisco kill conditions for six of the seven lakes were projected on a recurring basis; a viable cisco habitat was projected by the simulations for Bear Head although no cisco has been recorded in the lake. The maximum number of days with cisco kill in any of the 15 study lakes was projected to be 2673 days in 46 years or 57 days per year in Carrie Lake (including both summer kill and winterkill). Tables A.2 and A.3 not only present the number or percent of years with cisco kill and the total number of days with fish kill, but also the total number of days with winter kill.

The number of days with cisco kills estimated using DO limits of 2.0 mg/l and 4.0 mg/L are summarized in Table A.4 for eight cisco lakes and in Table A.5 for seven non-cisco lakes. For the first six cisco lakes no fish kill conditions were projected, even when the higher DO limit of 4.0 mg/L was used. A lower DO limit (DO = 2 mg/L) resulted in a smaller number of days with cisco kill conditions. Consistent fish kill projections were obtained for all six non-cisco lakes in Table A.5, except Hill Lake which had no cisco kill conditions except when DO = 2 mg/l was used.

Tables A.2 to A.3 show that the projected number of years and the total number of days with fish kill are different when either the CVM ( $T_{\max} = 23.4^{\circ}\text{C}$  and  $\text{DO}_{\min} = 3 \text{ mg/L}$ ) or EM are used. For summer kill, the CVM always projected fewer years and days with fish kill than the EM did. For example, Elephant Lake was projected to have 12 years or 94 days (total) with summer kill (no winter kill) by the CVM, but the projection shifted to 27 years or 263 days (total) when the EM was used. This is because the CVM would not project fish kill until the temperature reaches  $23.4^{\circ}\text{C}$  at  $\text{DO} = 3 \text{ mg/L}$ , whereas the EM has a lethal-niche-boundary temperature of  $22.0^{\circ}\text{C}$  at  $\text{DO} = 3.0 \text{ mg/L}$ . For projecting winterkill the situation is just opposite. The EM projected fewer days with winterkill than the CVM with  $T_{\max} = 23.4^{\circ}\text{C}$  and  $\text{DO}_{\min} = 3 \text{ mg/L}$  did. EM projects no winterkill until DO is less than 0.4 mg/l when water temperature is low (2 to  $5^{\circ}\text{C}$ ), while the critical DO in the CVM is fixed at 3.0 mg/L. For example, Carrie Lake



was projected to have 2556 days (total) of winterkill (Table A3) based on the non-survival limit of DO = 3.0 mg/L (CVM), while only 947 days (total) of winterkill were projected by EM.

It is still an open question how many days of non-survival need to be simulated to match actual cisco kill observations. In previous projections of regional fish habitat under past and future climate scenarios (Stefan et al. 1996) long-term averages of water temperatures and DO concentrations were used, and fish kill was assumed to occur when the total number of simulated non-survival days was greater or equal to 7 (either consecutive or discontinuous 7 days). In this study, daily profiles of simulated temperature and DO (not long-term averages) were used to project potential fish kill. Therefore, additional information on fish kill days and years were abstracted and reported in Tables A.2 to A.5. The information includes (1) number of years with more than 7 days of projected cisco kill (days do not have to be continuous or consecutive 7 days), (2) number of years with more than 7 consecutive days of projected cisco kill, and (3) maximum number of consecutive days of projected fish kill in the year when the cisco kill was project to occur (e.g., in 2006).

South Twin Lake was projected to have five years out of 47 years with possible cisco kill over consecutive seven days (Table A2), while White Iron Lakes was projected to have only one year with possible cisco kill with consecutive seven days when CVM is used. The maximum number of continuous kill days in South Twin Lake and White Iron Lake (Table A.2) were projected to be 12 to 28 days using CVM and to occur in 2006 (the hottest year of the simulation period). South Twin Lake and White Iron Lake are relative shallow lakes with maximum depths of 8.8 m and 14.0 m, respectively. For the non-cisco lakes (Table A3) the maximum continuous kill days were projected to occur either in 2006 for summer kill (with a few exceptions) or in 1996 or 1997 for winterkill (the coldest two years of the simulation period).

The annual number of cisco kill days is plotted lake by lake and year by year in Figures A.10 and A.11 for the full length of the simulation periods (1962-2008) or (1992-2008). The top two rows are for cisco lakes and the bottom two rows are for non-cisco lakes. Results were obtained using both the CVM (Fig. A.10) and the EM (Fig. A.11).

Table A.2 Number of days when cisco kill is projected to occur in eight cisco lakes (DO Limit = 3.0 mg/L) under past climate conditions.

Name of lake	Method used to calculate cisco kill	No of years with cisco kill	Percent of years with cisco kill	No of days with cisco kills	No of days with winter -kill	Number of cisco kill days in a year for the years with cisco kill				Max no of consecutive cisco kill days in a year	No of years with > 7 cisco kill days	No of years with > 7 consecutive cisco kill days
						Avg.	Std.D.	Max.	Min.			
Carlos	EM <sup>2</sup>	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM <sup>3</sup>	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Cedar	EM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Elk <sup>1</sup>	EM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Kabekona <sup>1</sup>	EM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Ten Mile <sup>1</sup>	EM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Trout	EM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
South Twin <sup>1</sup>	EM	12	88	141	0	12	9	30	1	30 (2006)	9	8
	CVM	9	53	99	0	11	8	29	1	28 (2006)	6	5
White Iron	EM	10	21	75	0	8	4	24	1	24 (2006)	6	5
	CVM	4	32	19	0	5	2	15	1	12 (2006)	1	1

<sup>1</sup> The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008.<sup>2</sup> 'EM' indicates Equation method, <sup>3</sup> 'CVM' (Constant value method) indicates that  $T_{\max} = 23.4^{\circ}\text{C}$  and  $\text{DO}_{\min} = 3.0 \text{ mg/L}$  was used to limit coldwater fish habitat.

Table A.3 Number of days when cisco kill is projected to occur in seven non-cisco lakes under past climate conditions.

Name of lake	Method used to calculate cisco kill	No of years with cisco kill	Percent of years with cisco kill	No of days with cisco kill	No of days with winter-kill	Number of cisco kill days in a year for the years with cisco kill				Max no of consecutive cisco kill days in a year	No of years with > 7 cisco kill days	No of years with > 7 consecutive cisco kill days
						Avg.	Std.D	Max.	Min.			
Bear Head	EM <sup>2</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM <sup>3</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Carrie	EM	47	100	1327	947	28	13	71	7	45 (1996)	47	46
	CVM	47	100	2673	2556	57	12	88	23	79 (1997)	47	47
Elephant	EM	27	57	263	0	10	8	30	1	28 (2006)	15	11
	CVM	12	26	94	0	8	4	21	1	21 (2006)	6	4
Hill <sup>1</sup>	EM	3	18	47	0	16	6	18	14	18 (2007)	3	3
	CVM	1	6	5	0	5	1	5	5	5 (2006)	0	0
Madison	EM	42	89	935	75	22	13	56	2	34 (2006)	38	34
	CVM	36	77	609	214	17	14	50	1	39 (2001)	29	23
South Center	EM	22	47	228	0	10	8	32	1	29 (1988)	14	11
	CVM	10	21	41	2	4	2	9	1	9	3	3
St. Olaf	EM	34	72	575	0	17	11	38	2	37 (2006)	30	28
	CVM	22	47	247	108	11	9	40	2	30 (1997)	11	10

<sup>1</sup> The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008. <sup>2</sup> 'EM' indicates Equation method, <sup>3</sup> 'CVM' (Constant value method) indicates that  $T_{\max} = 23.4^{\circ}\text{C}$  and  $\text{DO}_{\min} = 3.0 \text{ mg/L}$  was used to limit coldwater fish habitat.

Table A.4 Number of days when cisco kill is projected to occur in eight cisco lakes for fixed DO limits of 2.0 or 4.0 mg/L under past climate conditions.

Name of lake	Method used to calculate cisco kill	No of years with cisco kill	Perce nt of years with cisco kill	Total no of days with cisco kill	Total no of days with winter -kill	Number of days cisco kill occurs in a year for the years with cisco kill				Max no of consecutive cisco kill days in a year	No of years with > 7 cisco kill days	No of years with > 7 consecutive cisco kill days
						Avg.	Std.D.	Max.	Min.			
Carlos	CVM (DO=2) <sup>2</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Cedar	CVM (DO=2)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Elk <sup>1</sup>	CVM (DO=2)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Kabekona <sup>1</sup>	CVM (DO=2)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Ten Mile <sup>1</sup>	CVM (DO=2)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Trout	CVM (DO=2)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
South Twin <sup>1</sup>	CVM (DO=2)	10	59	1133	0	10	8	29	2	28	7	7
	CVM (DO=4)	9	53	79	0	11	8	29	3	28	5	4
White Iron	CVM (DO=2)	5	11	31	0	6	3	20	2	20	1	1
	CVM (DO=4)	1	2	10	0	10	1	10	10	6	1	0

<sup>1</sup> The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008.

<sup>2</sup> 'CVM' (Constant value method) indicates that  $T_{max}=23.4^{\circ}C$  and  $DO_{min} = 2.0$  mg/L or  $DO_{min} = 4.0$  mg/L was used to limit coldwater fish habitat.

Table A.5 Number of days when cisco kill is projected to occur in seven non-cisco lakes for DO limits of 2.0 or 4.0 mg/L under past climate conditions.

Name of lake	Method used to calculate cisco kill	No of years with cisco kill	Percent of years with cisco kill	No of days with cisco kills	No of days with winter -kill	Number of days cisco kill occurs in a year for the years with cisco kill				Max no of consecutive cisco kill days in a year	No of years with > 7 cisco kill days	No of years with > 7 consecutive cisco kill days
						Avg.	Std.D.	Max.	Min.			
Bear Head	CVM(DO=2) <sup>2</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Carrie	CVM (DO=2)	47	100	3215	3017	68	13	104	34	89	47	47
	CVM (DO=4)	47	100	2105	2456	45	14	76	12	58(1965)	47	47
Elephant	CVM (DO=2)	16	34	139	0	9	5	22	1	22	9	7
	CVM (DO=4)	10	21	54	0	5	3	16	1	13	3	2
Hill <sup>1</sup>	CVM (DO=2)	3	18	25	0	8	4	13	2	13	2	1
	CVM (DO=4)	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Madison	CVM (DO=2)	42	89	834	283	19	15	60	2	54	35	31
	CVM (DO=4)	32	68	412	158	12	11	42	1	38(1997)	18	11
South Center	CVM (DO=2)	22	47	147	16	8	5	20	1	16	10	7
	CVM (DO=4)	2	4	8	0	4	1	5	3	5 (1987)	0	0
St. Olaf	CVM (DO=2)	34	72	488	214	14	13	56	1	41	24	19
	CVM (DO=4)	12	26	92	51	8	5	19	1	19	6	5

<sup>1</sup> The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008.

<sup>2</sup> 'CVM' (Constant value method) indicates that  $T_{max} = 23.4^{\circ}C$  and  $DO_{min} = 2.0$  mg/L or  $DO_{min} = 4.0$  mg/L was used to limit coldwater fish habitat.

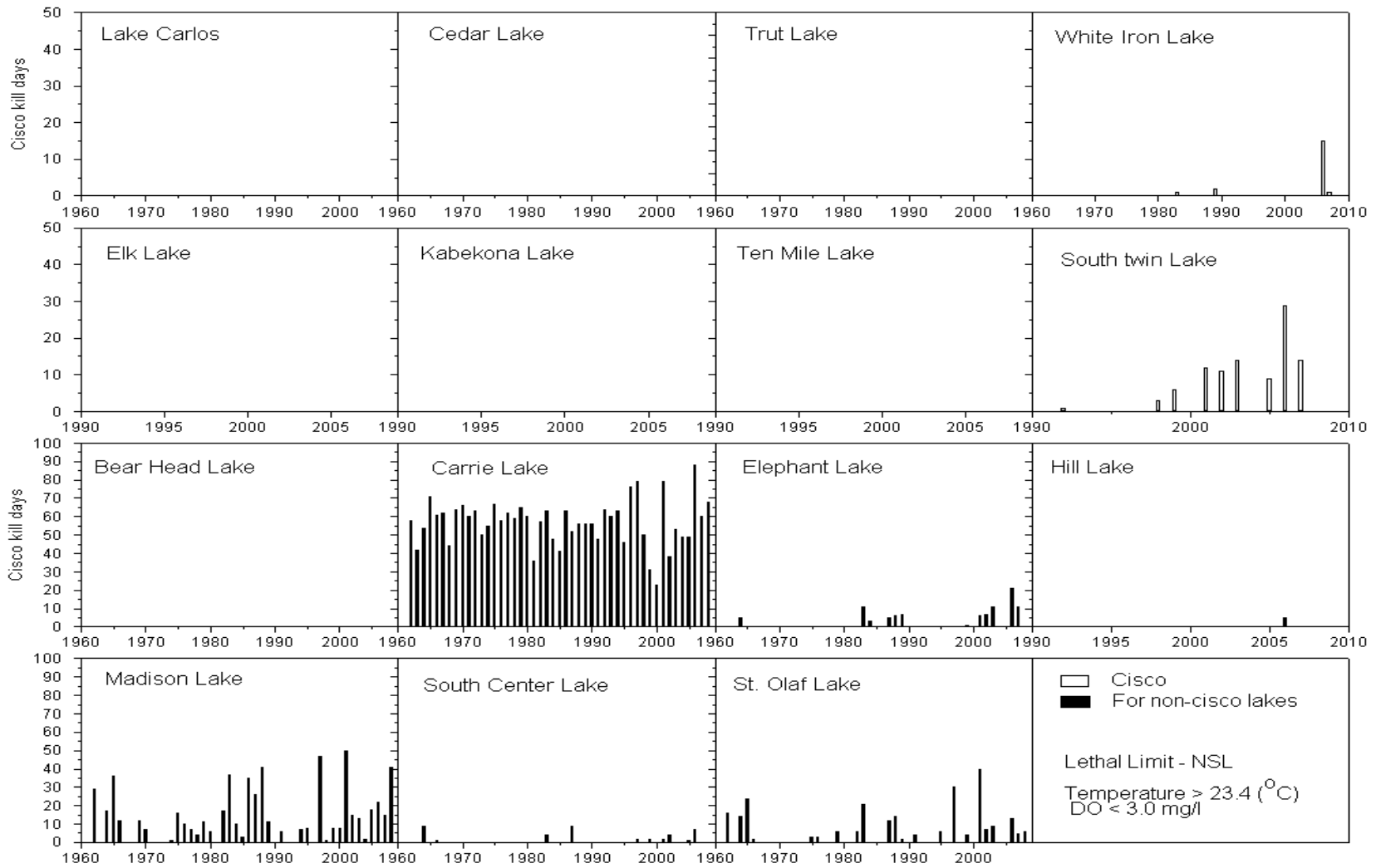


Figure A.10 Number of cisco fish kill days during simulation period (1962-2008 or 1992-2008) determined using NSL lethal temperature (23.4 °C) and minimum DO (3.0 mg/L) limits. Lakes in top two rows are cisco lakes and others are non-cisco lakes.



#### **A.4 Results of Cisco Habitat Simulations and Cisco Kill Projections Under Future Climate Scenarios**

Cisco kill in the first set of 15 study lakes was determined using projected water temperatures and DO concentrations under three future climate scenarios based on the output of three GCM models: CCCma GCM 2.0, CCCma CGCM 3.1 (A1B scenario), and MIROC 3.2 (A1B scenario). The projected numbers of annual cisco kill days obtained by the CVM, and by the EM are presented in Figures A.12 and A.13, respectively. Both figures show that under the future climate scenarios CGCM 3.1 and MIROC 3.2 there is a considerable increase in the number of possible kill days in two of the cisco lakes, South Twin Lake and White Iron Lake; these two were previously identified to have high cisco kill potential under past climate conditions (Figs. A.9 and A.11). For other cisco lakes (in top two rows) no fish kill is projected under future climate scenarios (one exception: the EM projects a few days of cisco kill for Cedar Lake).

Model simulations were also performed for a set of 13 additional cisco lakes selected in the second stage of the study. The projected numbers of annual cisco kill days in the 13 additional cisco lakes were explored under a CCCma CGCM 3.1 future climate scenario. For 12 cisco lakes no fish kill was projected under the future climate scenario; only Blue Lake, one of the 13 additional lakes, was projected to have a few days with cisco kill potential. In consideration of various uncertainties (e.g., model accuracy, fish habitat limits, and future climate scenarios), we suggested as a preliminary conclusion, that all 19 cisco study lakes - after excluding White Iron Lake and South Twin Lake - are likely to support cisco habitat under future climate conditions, and can therefore be considered as cisco refuge lakes. Figure A.14 shows distribution of 558 cisco lakes and the 21 selected cisco study lakes: under the CCCma CGCM 3.1 future climate scenario, 19 cisco lakes were projected to have no cisco kill, and the remaining two cisco lake were projected to have cisco kill or unfavorable conditions for cisco to survive. Because projected annual cisco kill days are all zero for the 19 cisco lakes, it is impossible to rank the 19 cisco lakes, but Figure A14 does provide valuable information: there is a region on the SD versus GR plot where lakes can support cisco habitat under future climate scenarios. Figure A14 gives us a preliminary idea of that region, i.e., refuge lakes that may sustain cisco habitat under climate warming scenarios should have a Secchi depth SD greater than 2 m (mesotrophic or oligotrophic lakes) and a lake geometry ratio GR less than  $3 \text{ m}^{-0.5}$  (typically seasonally stratified lakes).

For non-cisco lakes (bottom two rows in Figs. A.12 and A.13) both the CVM and the EM show a considerable increase in the number of annual cisco kill days under future climate scenarios. Projections of the number of annual kill days under all three future climate scenarios are consistent (Figs. A.12 and A.13). The GCM 2.0 scenario projects relatively higher values of cisco kill days, because assumed future CO<sub>2</sub> emissions were higher for this earlier climate scenario model. Future climate scenarios based on the two more recent GCM models (CCCma CGCM 3.1 and MIROC 3.2) project almost the same numbers of cisco kill days. Tables A.6 and A.7 list cisco kill results under the CCCma CGCM 3.1 future climate scenario.



All three future climate scenarios project fewer cisco kill days in Carrie Lake (Table A.7) because Carrie Lake is a shallow lake and most of its projected kill days are winterkill days (simulated DO concentrations are lower than the DO survival limits from surface to bottom of the lake during winter). This is consistent with previous projections of winterkill in shallow lakes over the contiguous United States (Fang and Stefan 2000) because of the projected decrease in ice cover days during winter (Fang and Stefan. 1998). Table A.3 shows that there were 2556 days of winterkill out of a total 2673 days of kill during the simulation period (47 years) in Carrie Lake. The rise in water temperature under projected future climate conditions eliminates the possibility of winterkill for Carrie Lake. Table A.7 shows there is no more cisco kill in winter in Carrie Lake, and the total number of days with cisco kill in Carrie Lake is projected to be much less under all three future climate scenarios than the past number.

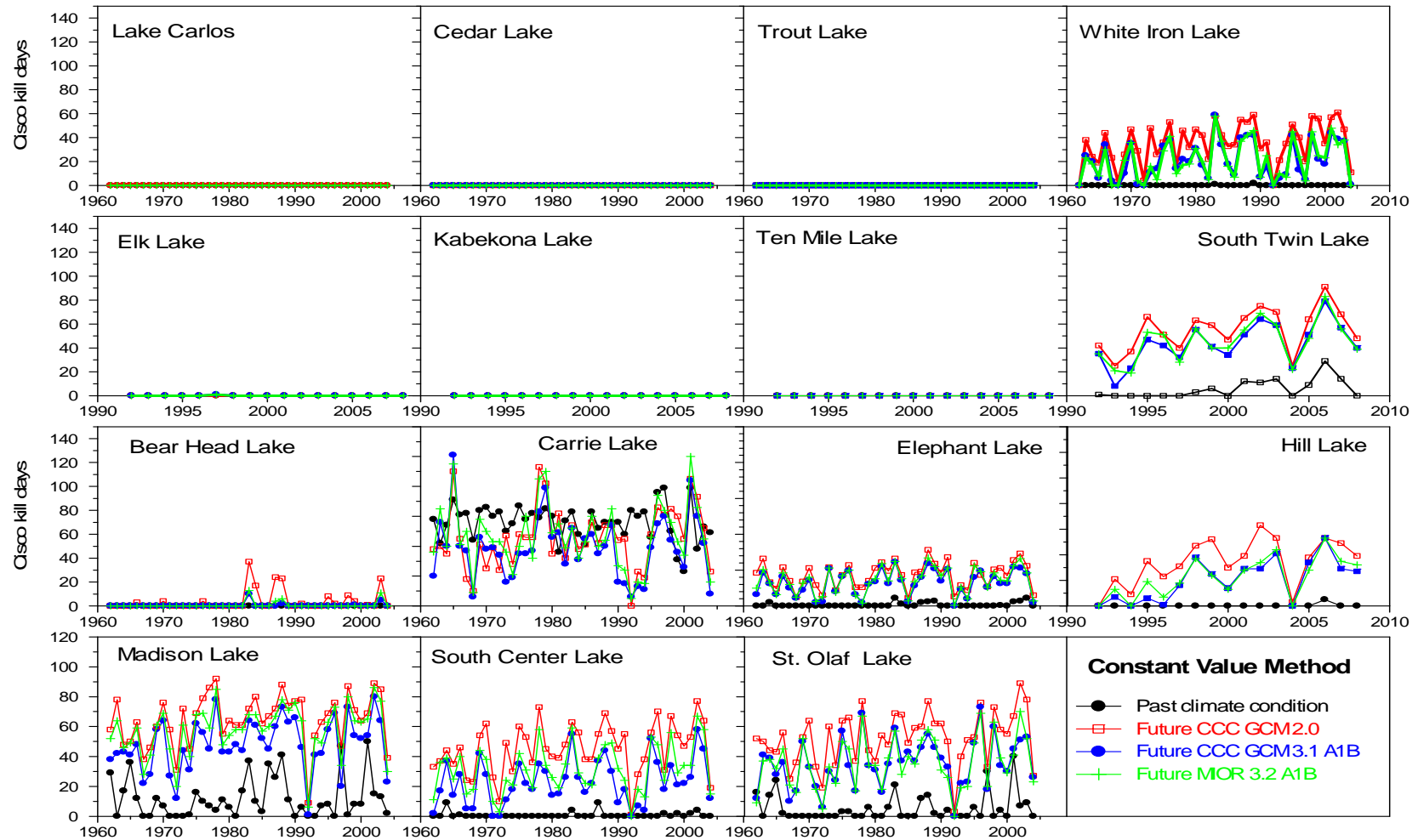


Figure A.12 Number of cisco kill days during the simulation period (1962-2008 or 1992-2008) under future climate conditions determined using the constant value method (CVM). Lakes in the top two rows are cisco lakes and those in the bottom two rows are non-cisco lakes.

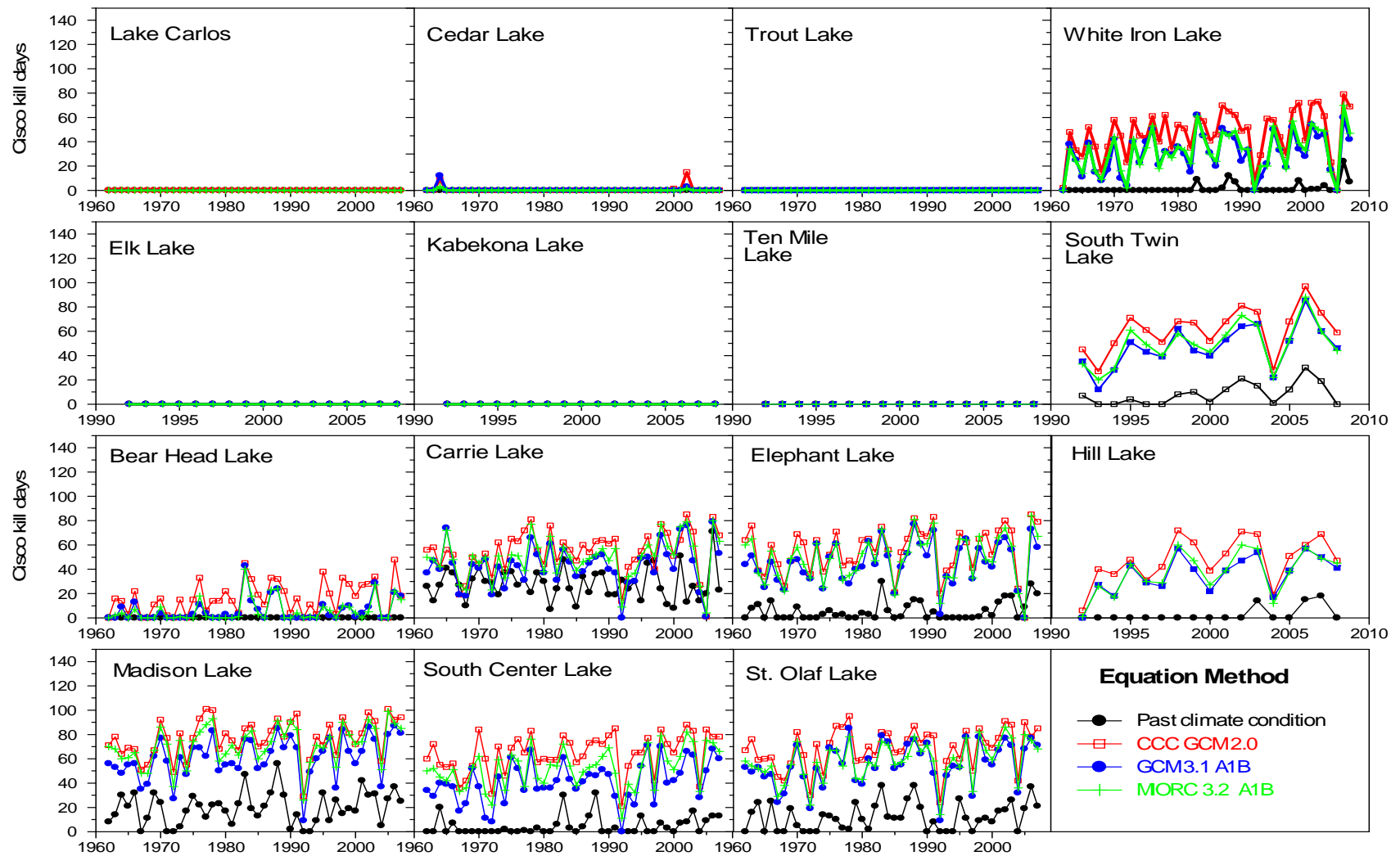


Figure A.13 Number of cisco kill days during the simulation period (1962-2008 or 1992-2008) under future climate conditions determined using the equation method (EM). Lakes in the top two rows are cisco lakes and those in the bottom two rows are non-cisco lakes.

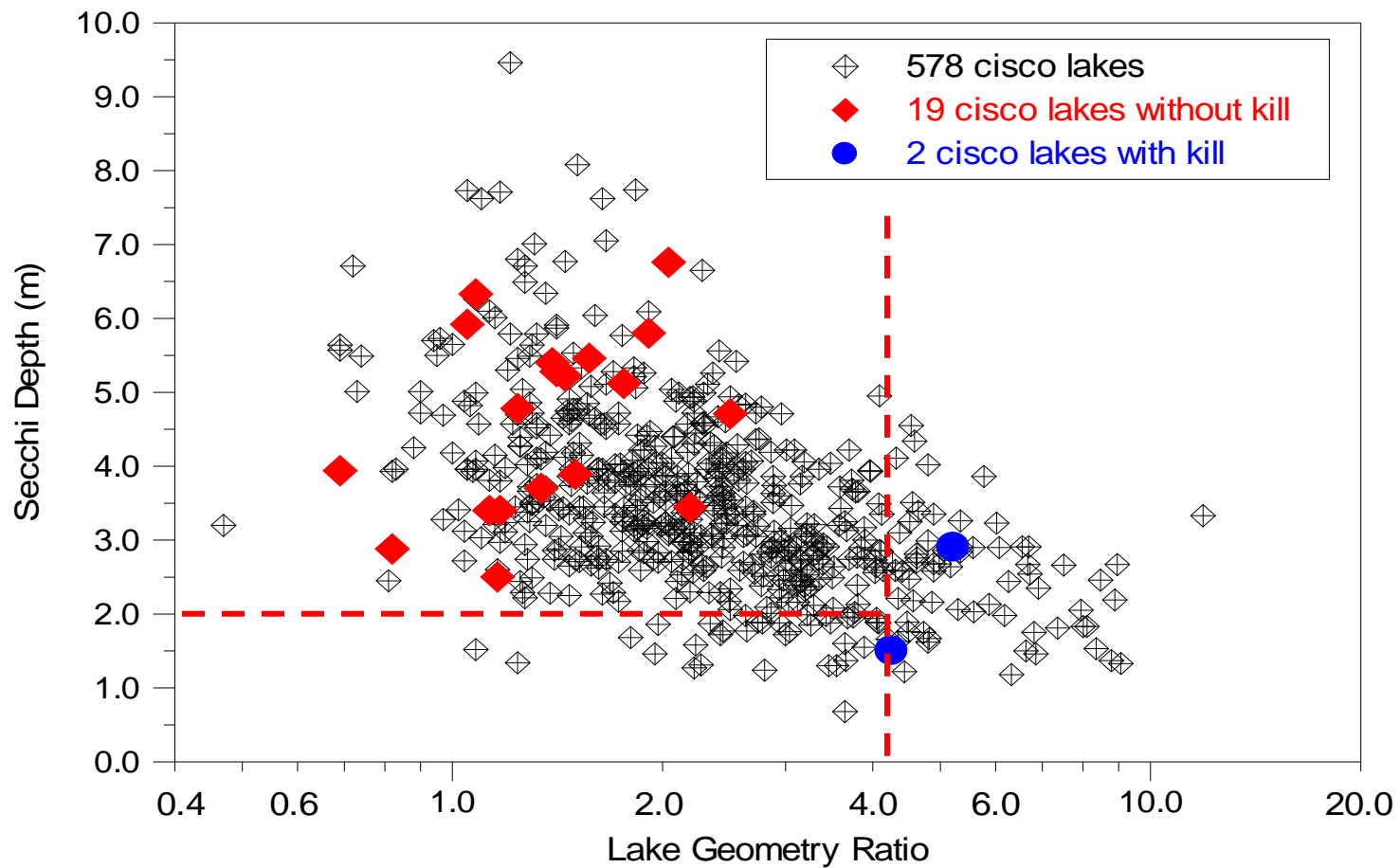


Figure A.14 Distribution of 21 cisco study lakes among 578 cisco lakes showing no cisco kill and two cisco study lakes that have potential cisco kill. Under the CCCma CGCM 3.1 future climate scenario 19 study lakes show no potential cisco kill and can therefore be considered as refuge lakes, while two study lakes are projected to experience potential cisco kill.

Table A.6 Number of days when cisco kill is projected to occur in eight cisco lakes (DO Limit = 3.0 mg/L) under the CCC CGCM 3.1 future climate scenario.

Name of lake	Method used to calculate cisco kill	No of years with cisco kill	Percent of years with cisco kill	No of days with cisco kills	No of days with winter -kill	Number of cisco kill days in a year for the years with cisco kill				Max no of consecutive cisco kill days in a year	No of years with > 7 cisco kill days	No of years with > 7 consecutive cisco kill days
						Avg.	Std.D.	Max.	Min.			
Carlos	EM <sup>2</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM <sup>3</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Cedar	EM	2	4	10	0	5	1	8	2	8 (1964)	1	1
	CVM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Elk <sup>1</sup>	EM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	1	6	1	0	1	0	1	1	1 (1997)	0	0
Kabekona <sup>1</sup>	EM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Ten Mile <sup>1</sup>	EM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Trout	EM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
South Twin1	EM	17	100	802	0	47	18	85	12	69 (2006)	17	16
	CVM	17	100	741	0	44	17	79	8	75 (2006)	17	17
White Iron	EM	44	94	1440	0	33	17	62	4	56 (2006)	43	41
	CVM	42	89	1001	0	24	16	59	1	52 (2006)	35	33

<sup>1</sup> The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008.

<sup>2</sup> 'EM' indicates Equation method,

<sup>3</sup> 'CVM' (Constant value method) indicates that  $T_{\max} = 23.4^{\circ}\text{C}$  and  $\text{DO}_{\min} = 3.0 \text{ mg/L}$  was used to limit coldwater fish habitat.

Table A.7 Number of days when cisco kill is projected to occur in seven non-cisco lakes (DO limit = 3.0 mg/L) under the CCC CGCM 3.1 future climate scenario

Name of lake	Method used to calculate cisco kill	No of years with cisco kill	Percent of years with cisco kill	No of days with cisco kill	No of days with winter-kill	Number of cisco kill days in a year for the years with cisco kill				Max no of consecutive cisco kill days in a year	No of years with > 7 cisco kill days	No of years with > 7 consecutive cisco kill days
						Avg.	Std.D.	Max.	Min.			
Bear Head	EM <sup>2</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
	CVM <sup>3</sup>	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill	No Kill
Carrie	EM	47	100	2181	89	46	16	81	19	79 (2006)	47	47
	CVM	47	100	2040	598	43	11	103	7	81 (1979)	47	46
Elephant	EM	46	98	2030	0	43	17	79	1	77 (2006)	45	45
	CVM	47	100	1885	0	40	21	101	6	73 (2006)	45	44
Hill <sup>1</sup>	EM	16	94	606	0	36	16	57	17	64 (2007)	16	16
	CVM	14	82	349	0	21	16	53	1	61 (2002)	12	11
Madison	EM	47	100	2883	0	61	17	87	9	87 (1978)	47	46
	CVM	47	100	2355	0	50	18	80	1	81 (1978)	46	45
South Center	EM	46	98	1832	0	39	13	70	0	70 (1996)	47	45
	CVM	43	91	1001	0	21	12	55	1	55 (1983)	38	37
St. Olaf	EM	46	98	1945	0	41	17	71	8	82 (2002)	46	45
	CVM	44	94	1144	0	24	15	58	2	61 (2006)	40	38

<sup>1</sup> The simulation period for the lake is from 1992 to 2008; for other lakes, it is from 1962 to 2008. <sup>2</sup> 'EM' indicates equation method, <sup>3</sup> 'CVM' (Constant value method) indicates that  $T_{\max} = 23.4^{\circ}\text{C}$  and  $\text{DO}_{\min} = 3.0 \text{ mg/L}$  was used to limit coldwater fish habitat

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## Appendix B TDO3 Values and Beginning Dates of Variable Benchmark Periods for the 30 Virtual Cisco Lakes

Table B.1 Averages of highest mean daily TDO3 values (AvgATDO3<sub>VB</sub> in Table 3.1) and beginning dates for variable (sliding) 31-day benchmark periods under **past climate** conditions (1962-2008), and the **CGCM 3.1** and **MIROC 3.2** future climate scenarios at the **Duluth** weather station. Results are for the **30 virtual** cisco lakes.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	AvgATDO3 <sub>VB</sub>			Beginning Date of Variable Benchmark Period (DOY)		
			Past	CGCM	MIROC	Past	CGCM	MIROC
LakeC01	0.74	1.25	14.90	17.67	17.96	222	218	218
LakeC02	0.74	2.50	11.18	13.83	14.74	239	242	242
LakeC03	0.74	4.50	8.30	9.75	10.26	259	267	269
LakeC04	0.74	7.00	7.48	8.20	8.61	267	279	281
LakeC05	0.74	8.50	7.60	8.02	8.35	269	277	282
LakeC06	1.11	1.25	15.59	20.00	20.70	210	205	205
LakeC07	1.11	2.50	12.48	16.92	17.16	231	225	228
LakeC08	1.11	4.50	9.32	12.65	12.59	253	251	255
LakeC09	1.11	7.00	7.53	9.20	9.31	266	274	278
LakeC10	1.11	8.50	8.19	9.09	9.08	263	276	279
LakeC11	1.46	1.25	15.94	19.80	20.49	208	204	204
LakeC12	1.46	2.50	14.07	18.68	18.92	223	215	216
LakeC13	1.46	4.50	11.22	15.84	15.59	243	235	239
LakeC14	1.46	7.00	8.52	11.15	10.74	262	264	271
LakeC15	1.46	8.50	9.44	10.81	10.58	259	269	274
LakeC16	1.97	1.25	16.58	20.35	20.79	207	205	204
LakeC17	1.97	2.50	15.11	19.29	19.70	218	210	211
LakeC18	1.97	4.50	13.57	18.17	18.33	231	222	224
LakeC19	1.97	7.00	11.00	14.53	14.13	253	248	253
LakeC20	1.97	8.50	11.96	14.02	13.65	249	254	260
LakeC21	2.50	1.25	16.72	20.40	20.82	209	205	205
LakeC22	2.50	2.50	15.31	19.23	19.62	219	211	212
LakeC23	2.50	4.50	14.40	18.55	18.80	230	221	222
LakeC24	2.50	7.00	13.28	16.37	16.24	245	244	247
LakeC25	2.50	8.50	14.33	16.73	16.53	240	244	249
LakeC26	3.50	1.25	17.42	20.86	21.34	212	208	208
LakeC27	3.50	2.50	16.48	19.94	20.35	222	214	214
LakeC28	3.50	4.50	16.30	19.66	20.03	230	222	222
LakeC29	3.50	7.00	16.83	19.38	19.49	229	232	235
LakeC30	3.50	8.50	17.66	20.27	20.45	226	228	231



Table B.2 Averages of highest mean daily TDO3 values (AvgATDO3<sub>VB</sub> in Table 3.1) and beginning dates for variable (sliding) 31-day benchmark periods under **past climate** conditions (1962-2008), and the **CGCM 3.1** and **MIROC 3.2** future climate scenarios at the **International Falls** weather station. Results are for the **30 virtual** cisco lakes.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	AvgATDO3 <sub>VB</sub>			Beginning Date of Variable Benchmark Period (DOY)		
			Past	CGCM	MIROC	Past	CGCM	MIROC
LakeC01	0.74	1.25	15.01	17.40	17.68	222	218	219
LakeC02	0.74	2.50	11.75	14.16	15.02	235	238	239
LakeC03	0.74	4.50	8.61	9.95	10.45	256	262	266
LakeC04	0.74	7.00	7.65	8.55	8.82	264	274	278
LakeC05	0.74	8.50	7.66	8.33	8.46	265	278	284
LakeC06	1.11	1.25	15.55	19.89	19.94	210	209	212
LakeC07	1.11	2.50	12.51	15.80	16.44	230	229	230
LakeC08	1.11	4.50	9.15	11.44	12.06	252	254	256
LakeC09	1.11	7.00	7.64	8.75	9.21	264	273	276
LakeC10	1.11	8.50	8.15	8.76	8.93	262	274	279
LakeC11	1.46	1.25	15.77	20.05	20.24	206	201	204
LakeC12	1.46	2.50	13.46	17.69	18.04	225	217	220
LakeC13	1.46	4.50	10.34	13.84	14.24	247	242	244
LakeC14	1.46	7.00	8.15	9.60	9.98	262	270	273
LakeC15	1.46	8.50	9.12	10.10	10.18	258	268	274
LakeC16	1.97	1.25	16.21	20.40	20.39	207	200	205
LakeC17	1.97	2.50	14.46	19.00	19.14	220	210	213
LakeC18	1.97	4.50	12.34	16.79	17.13	237	228	231
LakeC19	1.97	7.00	10.10	12.27	12.47	255	258	261
LakeC20	1.97	8.50	11.19	12.62	12.69	251	257	262
LakeC21	2.50	1.25	16.31	20.46	20.39	209	203	206
LakeC22	2.50	2.50	14.69	18.96	19.07	221	212	214
LakeC23	2.50	4.50	13.43	17.71	17.87	235	224	228
LakeC24	2.50	7.00	12.41	14.74	14.86	248	250	254
LakeC25	2.50	8.50	13.53	15.48	15.53	243	247	252
LakeC26	3.50	1.25	17.23	21.06	21.12	211	206	208
LakeC27	3.50	2.50	16.09	19.87	20.03	223	212	216
LakeC28	3.50	4.50	15.77	19.39	19.65	233	222	225
LakeC29	3.50	7.00	16.27	18.67	18.80	232	234	238
LakeC30	3.50	8.50	17.22	19.70	19.85	229	230	233

Table B.3. Averages of highest mean daily TDO3 values (AvgATDO3<sub>VB</sub> in Table 3.1) and beginning dates for variable (sliding) 31-day benchmark periods under **past climate** conditions (1962-2008), and the **CGCM 3.1** and **MIROC 3.2** future climate scenarios at the **St. Cloud** weather station. Results are for the **30 virtual** cisco lakes.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	AvgATDO3 <sub>VB</sub>			Beginning Date of Variable Benchmark Period (DOY)		
			Past	CGCM	MIROC	Past	CGCM	MIROC
LakeC01	0.74	1.25	16.91	19.28	19.70	221	216	216
LakeC02	0.74	2.50	13.52	16.20	17.24	237	241	241
LakeC03	0.74	4.50	9.62	10.88	11.71	261	269	271
LakeC04	0.74	7.00	8.35	8.88	9.53	272	282	284
LakeC05	0.74	8.50	8.24	8.54	9.14	276	288	288
LakeC06	1.11	1.25	18.87	22.38	22.50	209	206	210
LakeC07	1.11	2.50	14.96	19.36	19.79	229	225	226
LakeC08	1.11	4.50	10.93	14.16	14.60	254	252	254
LakeC09	1.11	7.00	8.65	9.98	10.61	270	277	279
LakeC10	1.11	8.50	8.82	9.48	9.83	271	281	283
LakeC11	1.46	1.25	18.74	22.65	23.31	203	200	201
LakeC12	1.46	2.50	16.36	21.04	21.42	222	214	214
LakeC13	1.46	4.50	12.79	17.80	18.00	245	236	238
LakeC14	1.46	7.00	9.32	12.10	12.10	269	267	272
LakeC15	1.46	8.50	10.05	11.33	11.33	265	274	279
LakeC16	1.97	1.25	19.15	22.85	23.23	202	199	200
LakeC17	1.97	2.50	17.61	21.82	22.33	214	207	208
LakeC18	1.97	4.50	15.42	20.37	20.69	232	222	224
LakeC19	1.97	7.00	11.69	15.77	15.63	259	250	254
LakeC20	1.97	8.50	12.47	14.57	14.47	255	260	266
LakeC21	2.50	1.25	19.19	22.81	23.17	205	201	203
LakeC22	2.50	2.50	17.68	21.72	22.12	215	209	209
LakeC23	2.50	4.50	16.39	20.76	21.21	229	220	222
LakeC24	2.50	7.00	13.97	17.75	17.89	251	243	246
LakeC25	2.50	8.50	15.09	17.35	17.39	247	250	253
LakeC26	3.50	1.25	19.91	23.28	23.70	207	203	205
LakeC27	3.50	2.50	18.74	22.27	22.74	216	210	211
LakeC28	3.50	4.50	18.34	21.89	22.44	227	218	220
LakeC29	3.50	7.00	18.09	20.81	21.21	235	235	237
LakeC30	3.50	8.50	19.16	21.59	21.87	230	232	235

## Appendix C Contour Plots and Tables for Three TDO3 Parameters

Daily water temperature and DO profiles were simulated using MINLAKE2010 under past climate conditions (1962 to 2008) and two future climate scenarios (CGCM 3.1 and MIROC 3.2) using weather data at three principle weather stations (International Falls, Duluth, and St. Cloud) in Minnesota. Three TDO3 parameters, AvgTDO<sub>AM</sub>, AvgATDO<sub>FB</sub>, and AvgMTDO<sub>FB</sub> defined in Table 3.1 (line 3, 6, and 12, respectively), were calculated from simulated daily temperature and DO profiles in the 21 cisco study lakes (Table 1.1) and 30 virtual cisco lakes (Table 1.2) under past climate conditions (1962-2008) and two future climate scenarios (CGCM 3.1 and MIROC 3.2). In this appendix, the simulated and computed results for selected TDO3 parameters are presented as tabulated results and in contour plots (Figs. C.1 to C.15) as a function of two principal lake characteristic parameters, i.e., lake geometry ratio (GR) (Boyce and Gorham, 1989) as a measure of the strength of stratification, and Secchi depth (SD) as a measure of transparency and lake trophic status. These results provide the basis for the selection of cisco refuge lakes presented in Chapter 5. Five similar contour plots presented in Chapter 4 (Figs. 4.3 to 4.8) are not repeated here. Values of the three TDO3 parameters for each of the 21 cisco lakes and the 30 virtual cisco lakes are listed in Tables C.1 to C.2, and two similar tables (Tables 4.2 and 4.3) are not repeated here.

“Annual maximum” in all tables (C.1 to C.11) is average of annual maximum daily TDO3 values in the 47-year simulation period, i.e., AvgTDO<sub>3AM</sub> defined in Table 3.1 (line 3). “Benchmark mean” in all tables is average of mean daily TDO3 values over the fixed benchmark period (DOY 209 to DOY 239), i.e., AvgATDO<sub>3FB</sub> defined in Table 3.1 (line 6). “Benchmark maximum” in all tables is average of maximum daily TDO3 values over the fixed benchmark period, i.e., MaxATDO<sub>3FB</sub> defined in Table 3.1 (line 5).

Secchi depths reported for the 21 cisco study lakes were summer averages computed from measured Secchi depths on dates having measured temperature and DO profiles. For example, Secchi depth reported for Grindstone Lake is 2.88 m in Table C.1 and 3.93 m in MN DNR database, and 2.50 m in Table C.1 and 3.36 m for Lake Elk in MN DNR database.

Table C.11 shows statistical differences of the TDO3 parameters between Duluth and International Falls weather station under the CGCM 3.1 future climate scenario. All mean differences are greater than zero (higher TDO3 at the more southern latitude), but some of the differences are negative presumably due to lake effects in Duluth and/or climate variations.

All TDO3 values in the figures and tables of this appendix are in degrees Celsius (°C).

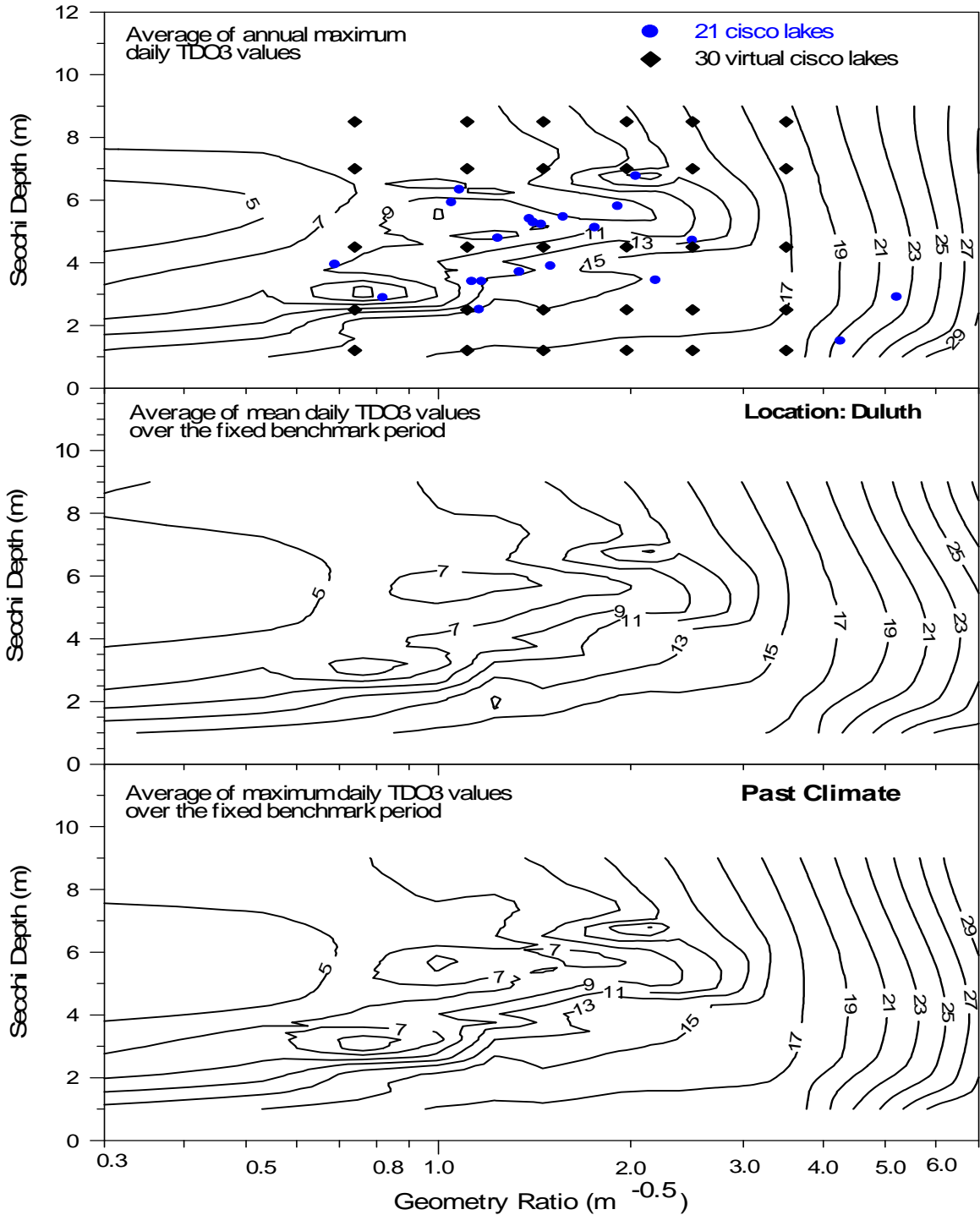


Figure C.1. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), AvgATDO3<sub>FB</sub>, and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239). Simulations are for **past climate conditions (1962 to 2008)** using **Duluth weather data**. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.

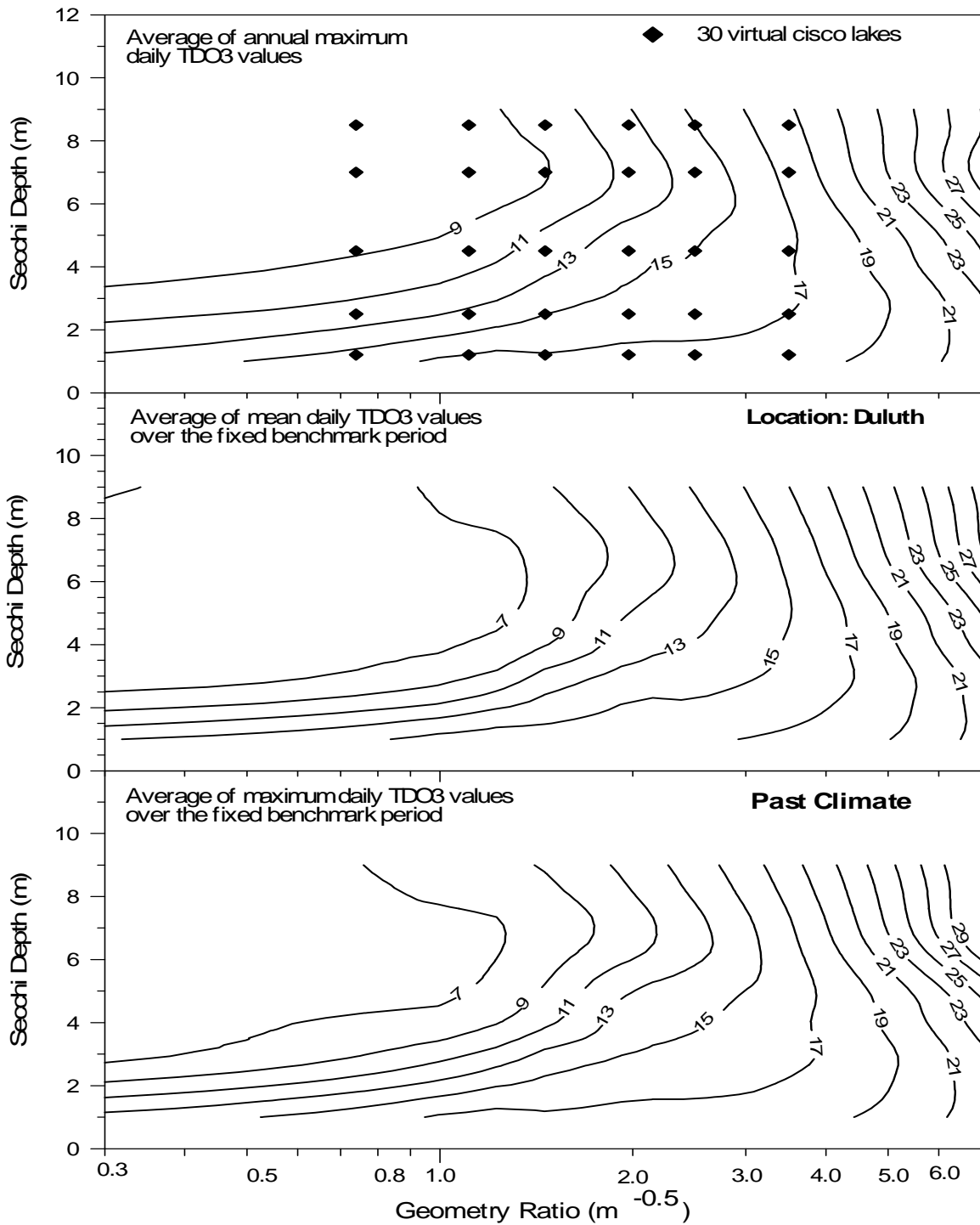


Figure C.2. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), AvgATDO3<sub>FB</sub>, and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239). Simulations are for **past climate conditions (1962 to 2008)** using **Duluth weather data**. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

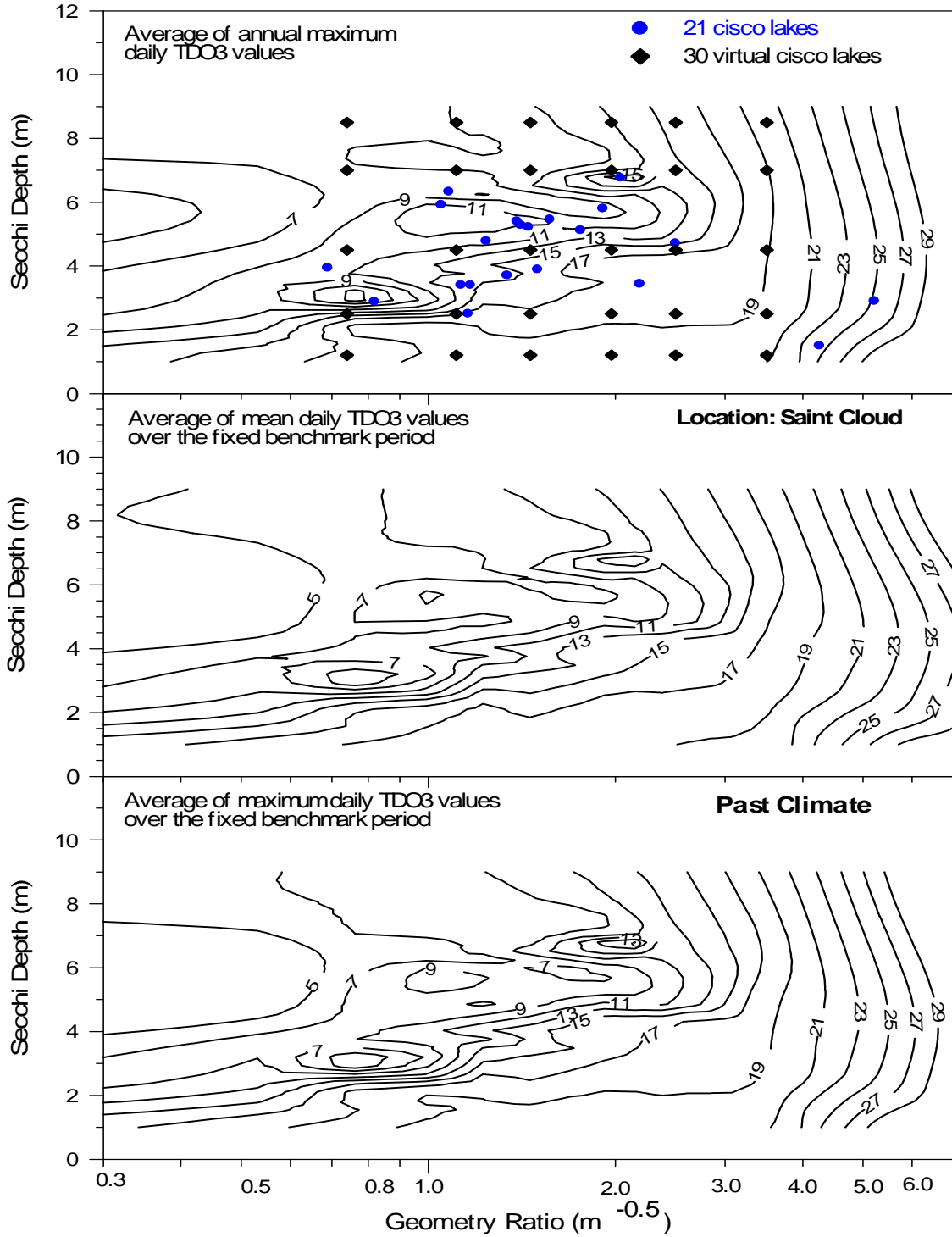


Figure C.3. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), AvgATDO3<sub>FB</sub>, and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239). Simulations are for **past climate conditions (1962 to 2008)** using **St. Cloud weather data**. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.

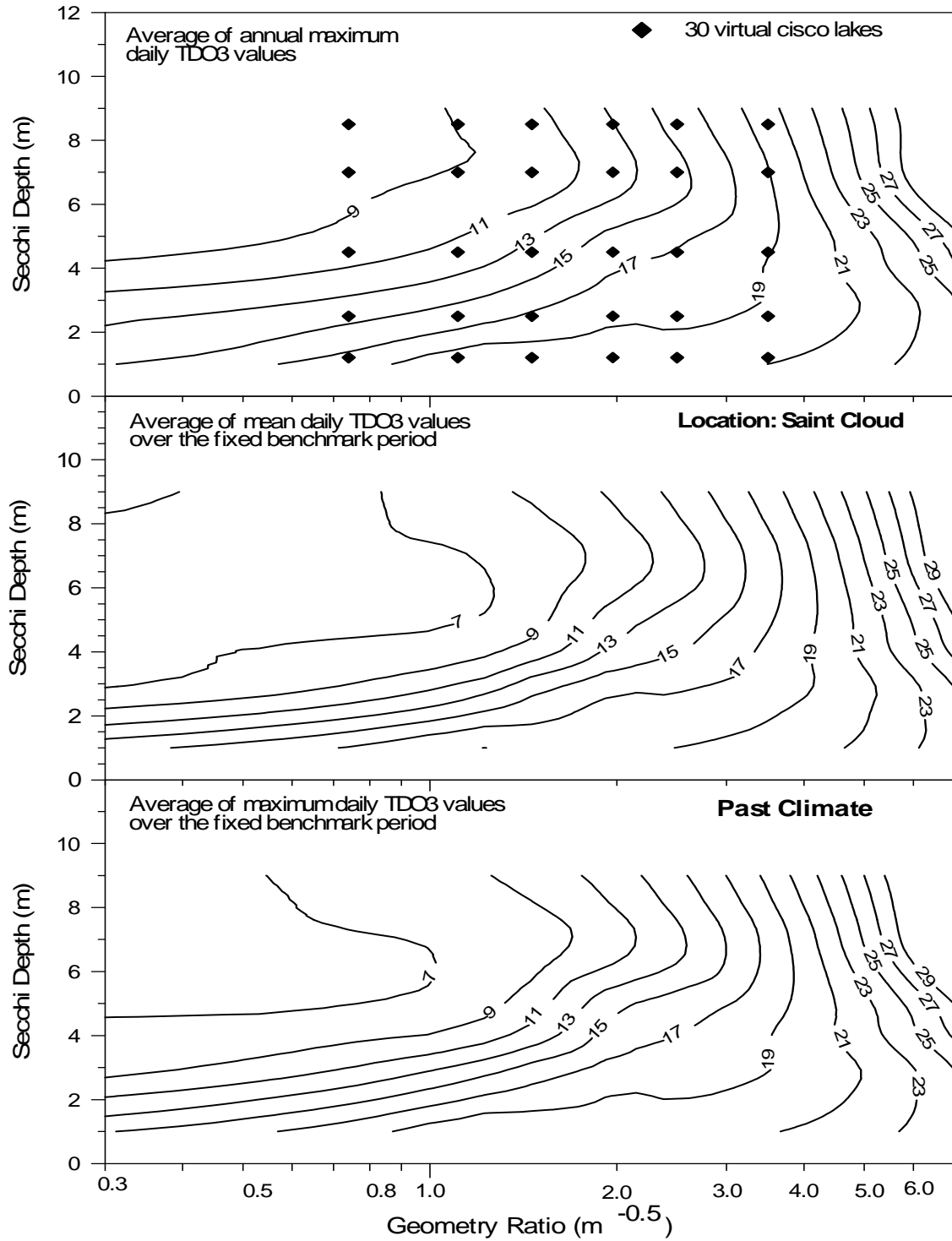


Figure C.4. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), AvgATDO3<sub>FB</sub>, and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239). Simulations are for **past climate conditions (1962 to 2008)** using **St. Cloud weather data**. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

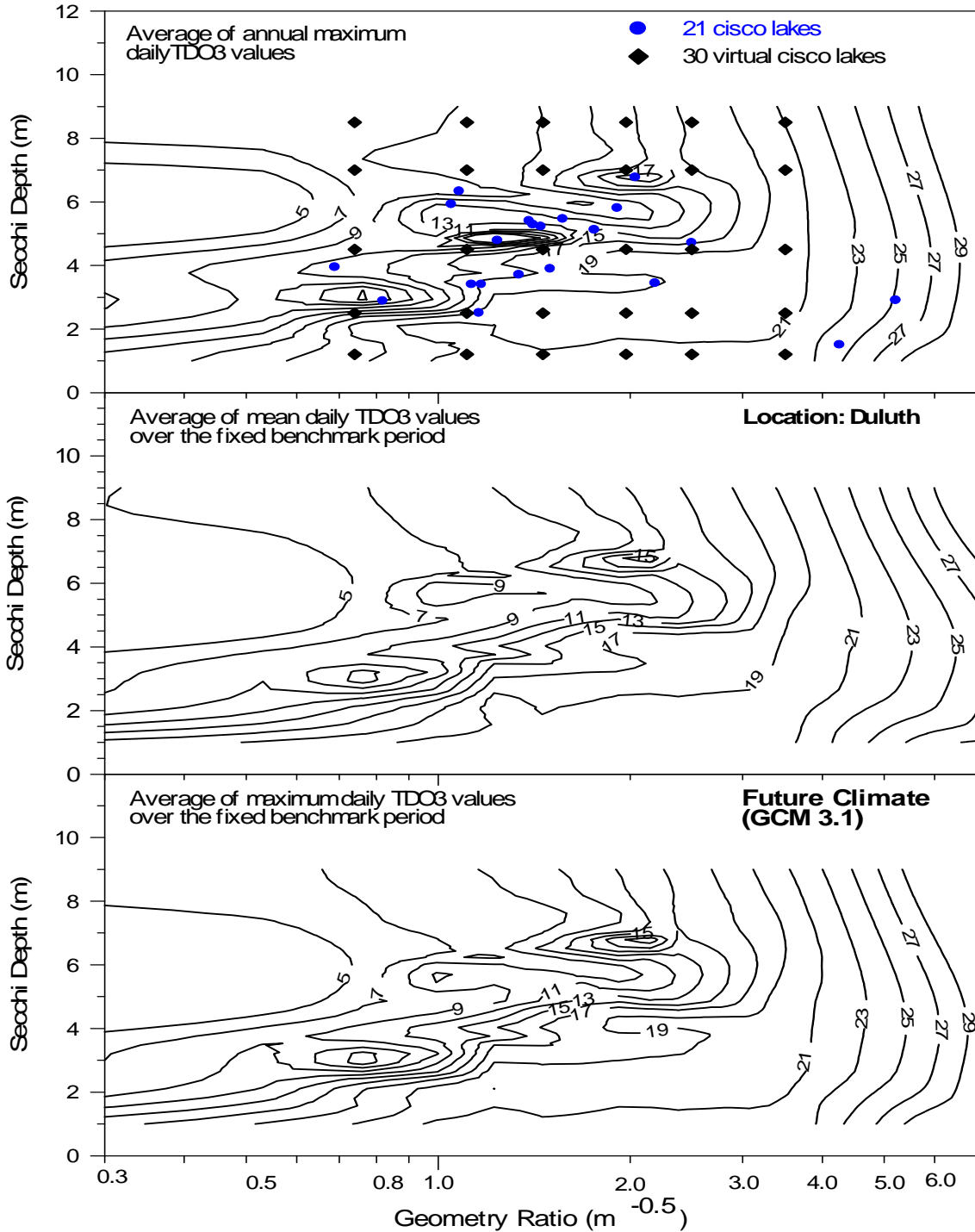


Figure C.5. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), and AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated for the **CGCM 3.1 future climate scenario** using **Duluth** weather data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.



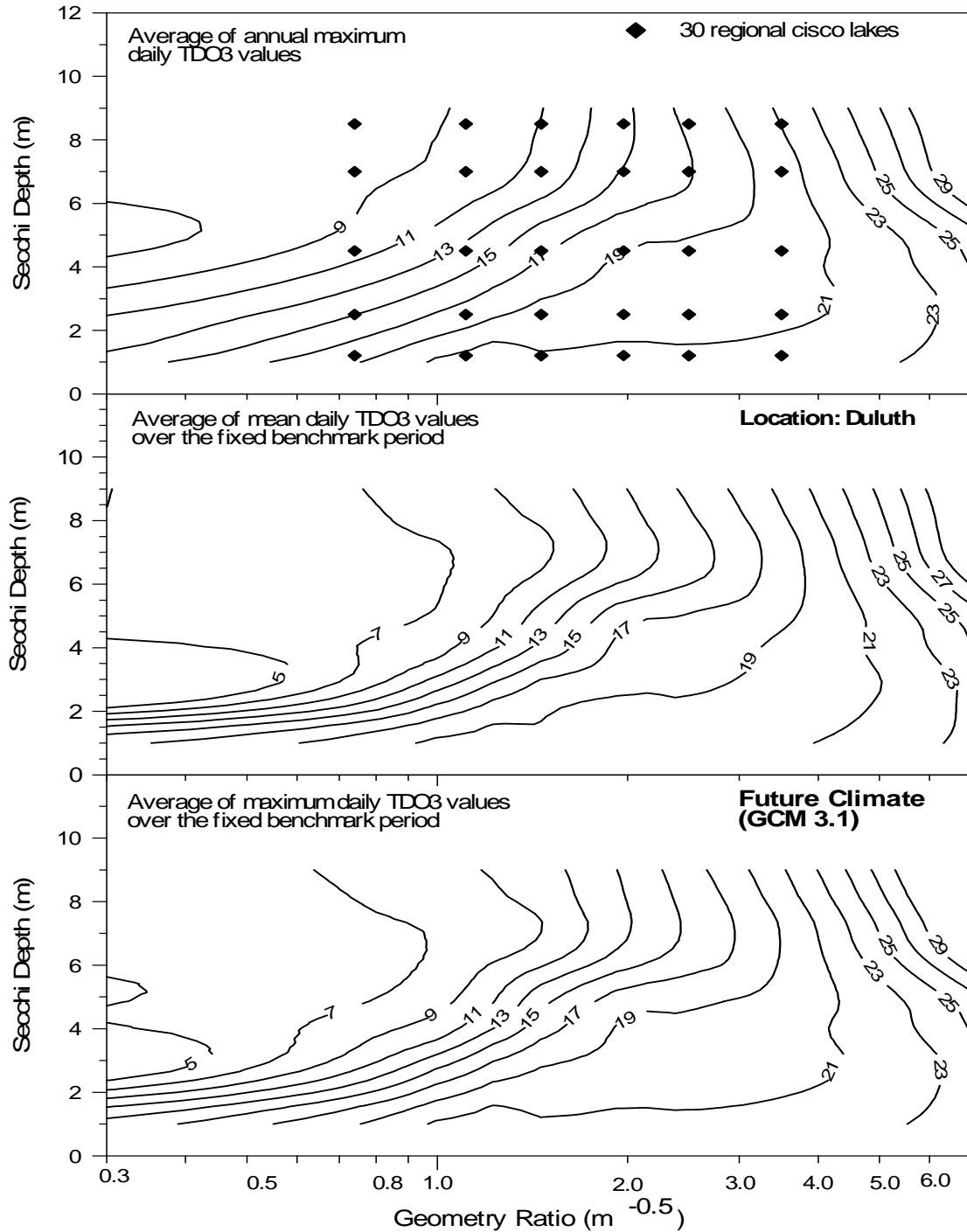


Figure C.6. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), and AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **CGCM 3.1 future climate scenario** using **Duluth** weather data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

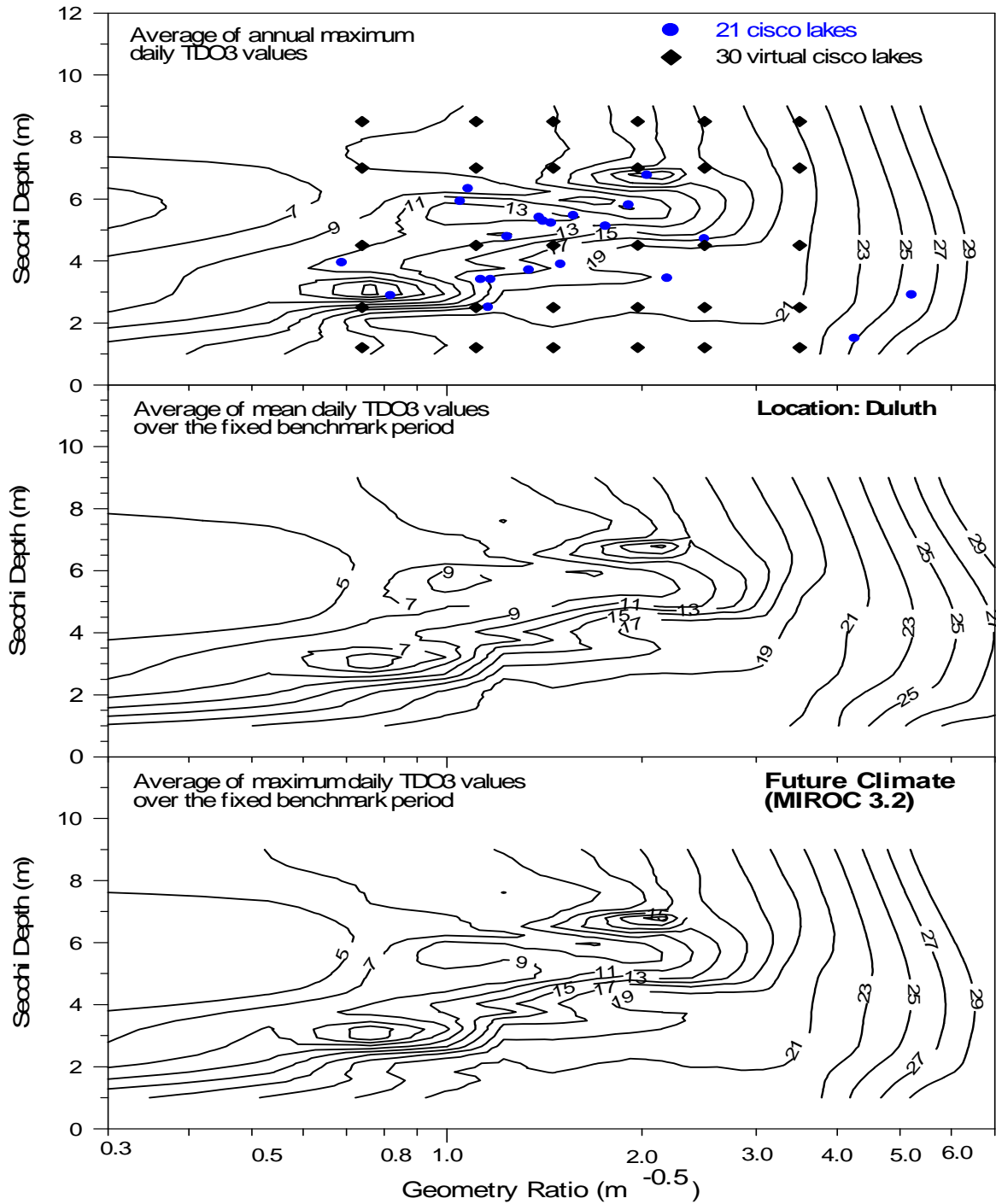


Figure C.7. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), and AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **MIROC 3.2 future climate scenario** using **Duluth** weather data. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.

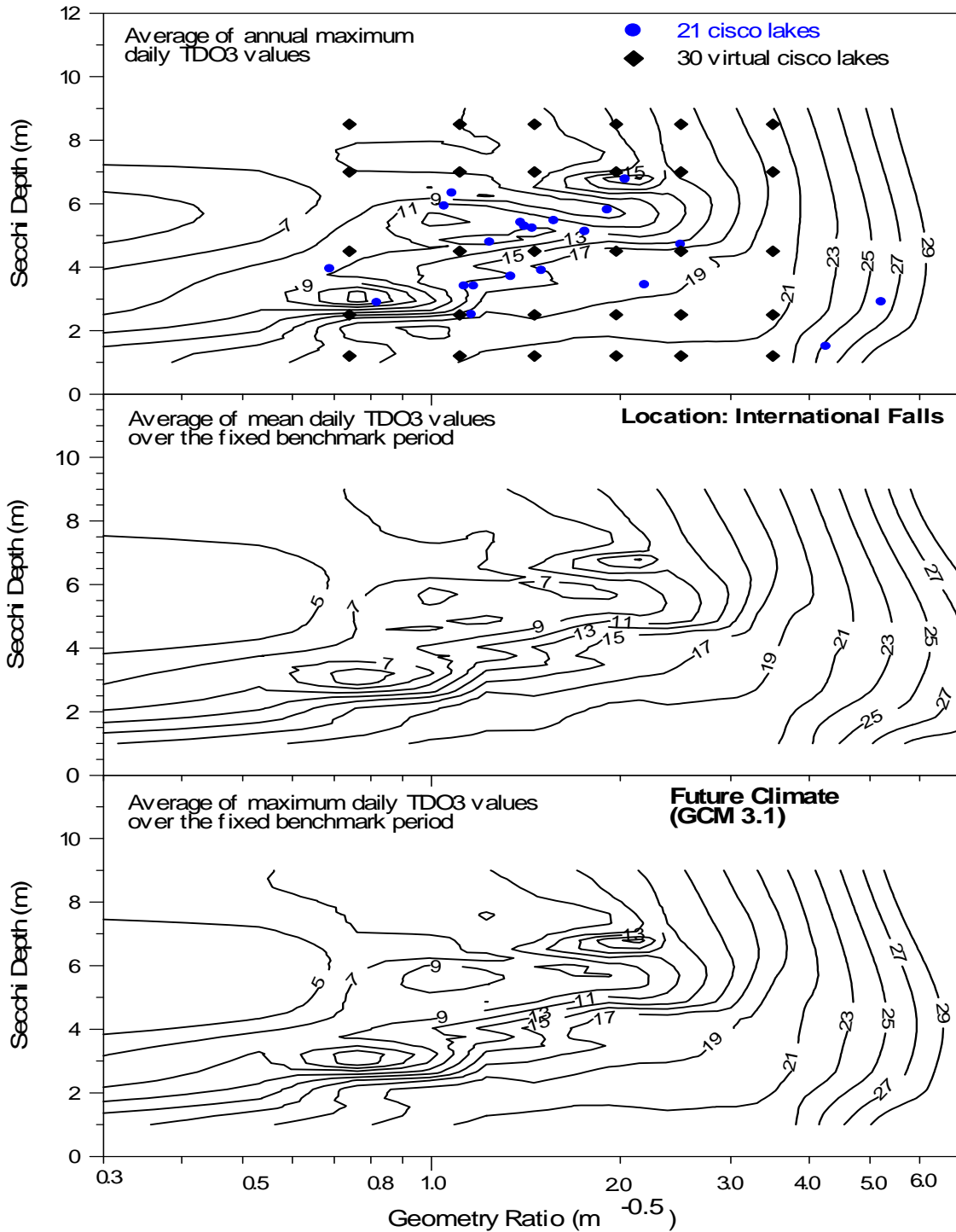


Figure C.8. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), and AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **CGCM 3.1 future climate scenario** using **International Falls** weather data. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.

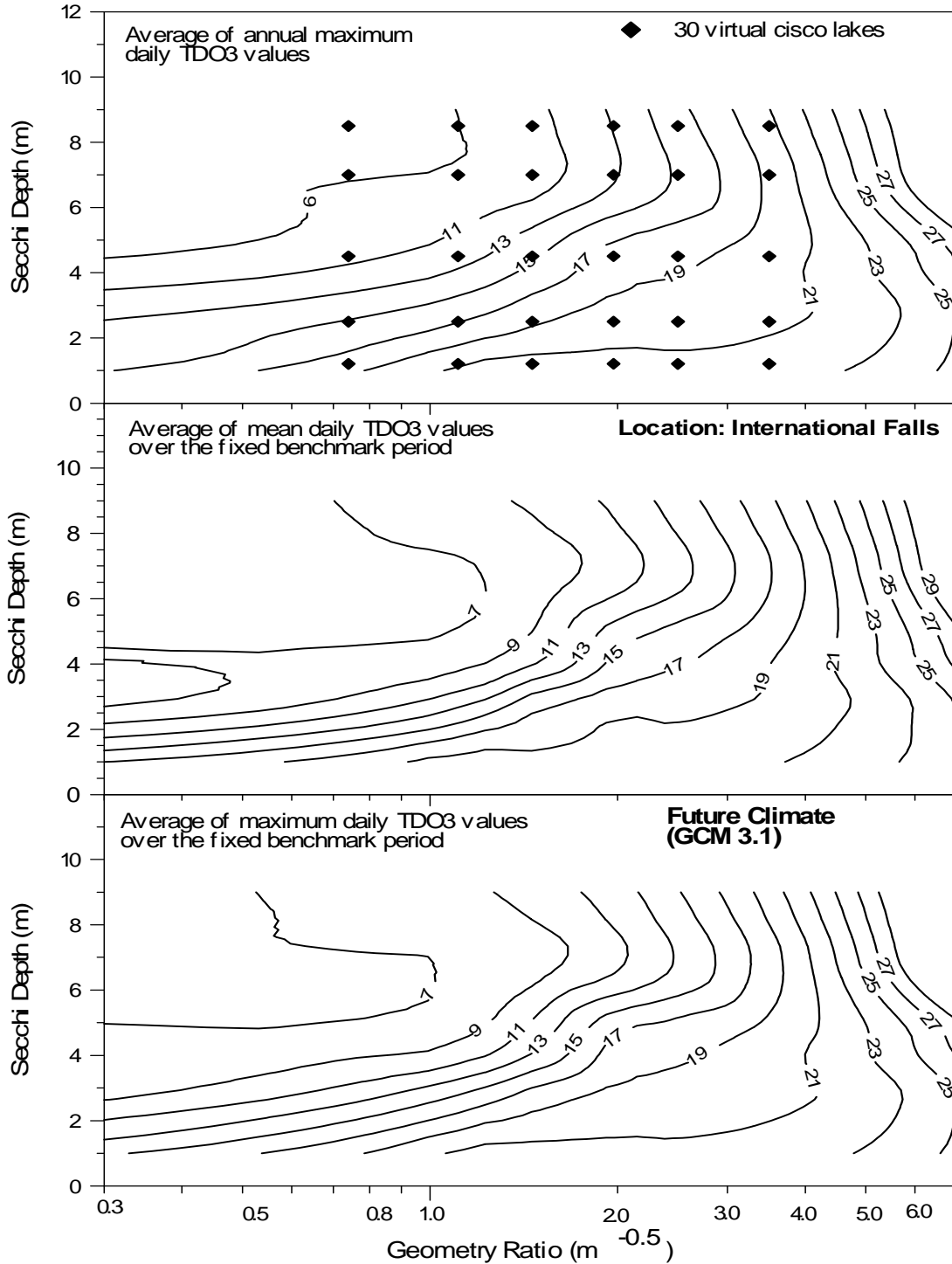


Figure C.9. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), and AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **CGCM 3.1 future climate scenario** using **International Falls** weather data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

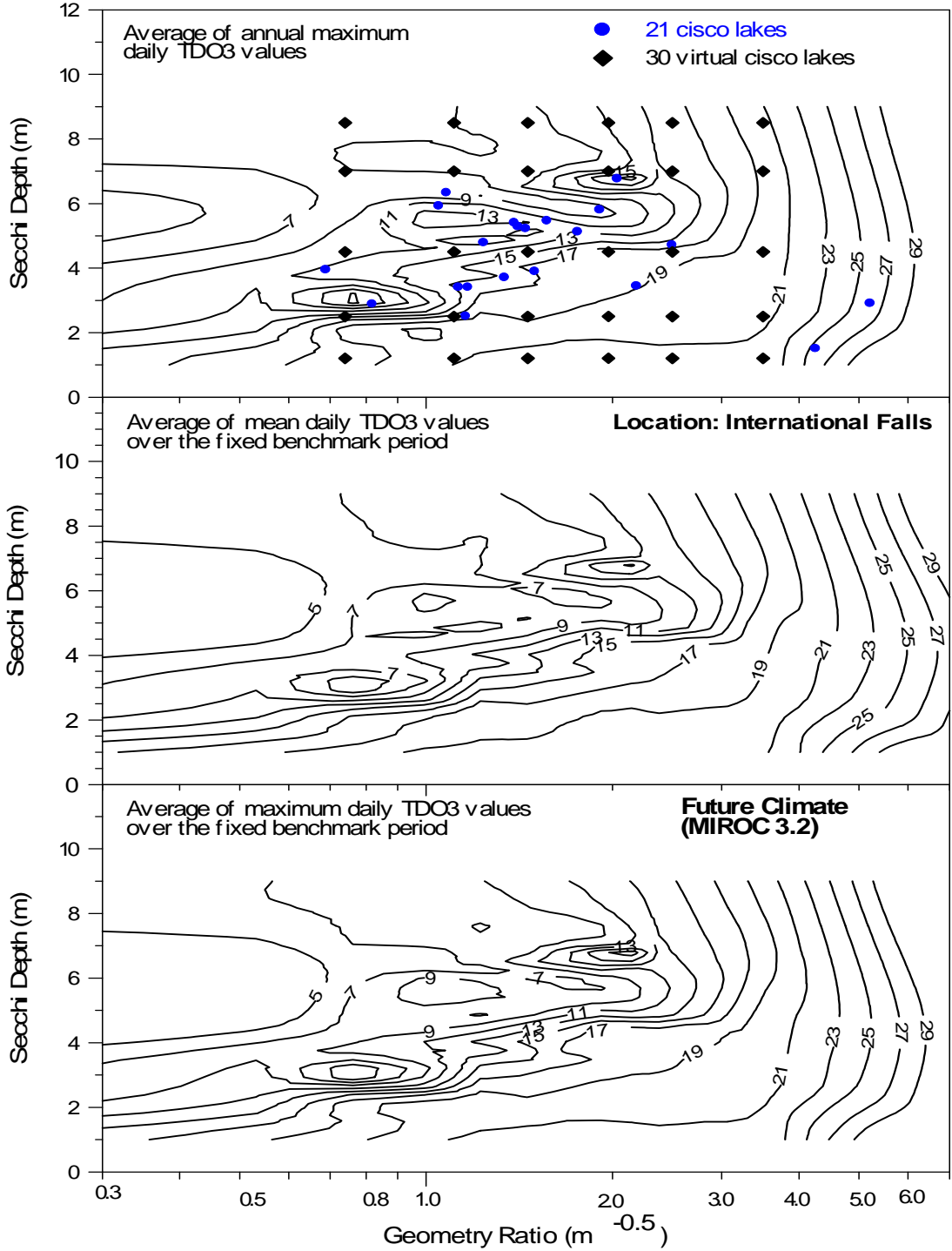


Figure C.10. Contour plots of  $AvgTDO3_{AM}$  (Table 3.1, line 3), and  $AvgATDO3_{FB}$  and  $AvgMTDO3_{FB}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **MIROC 3.2 future climate scenario** using **International Falls** weather data. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.

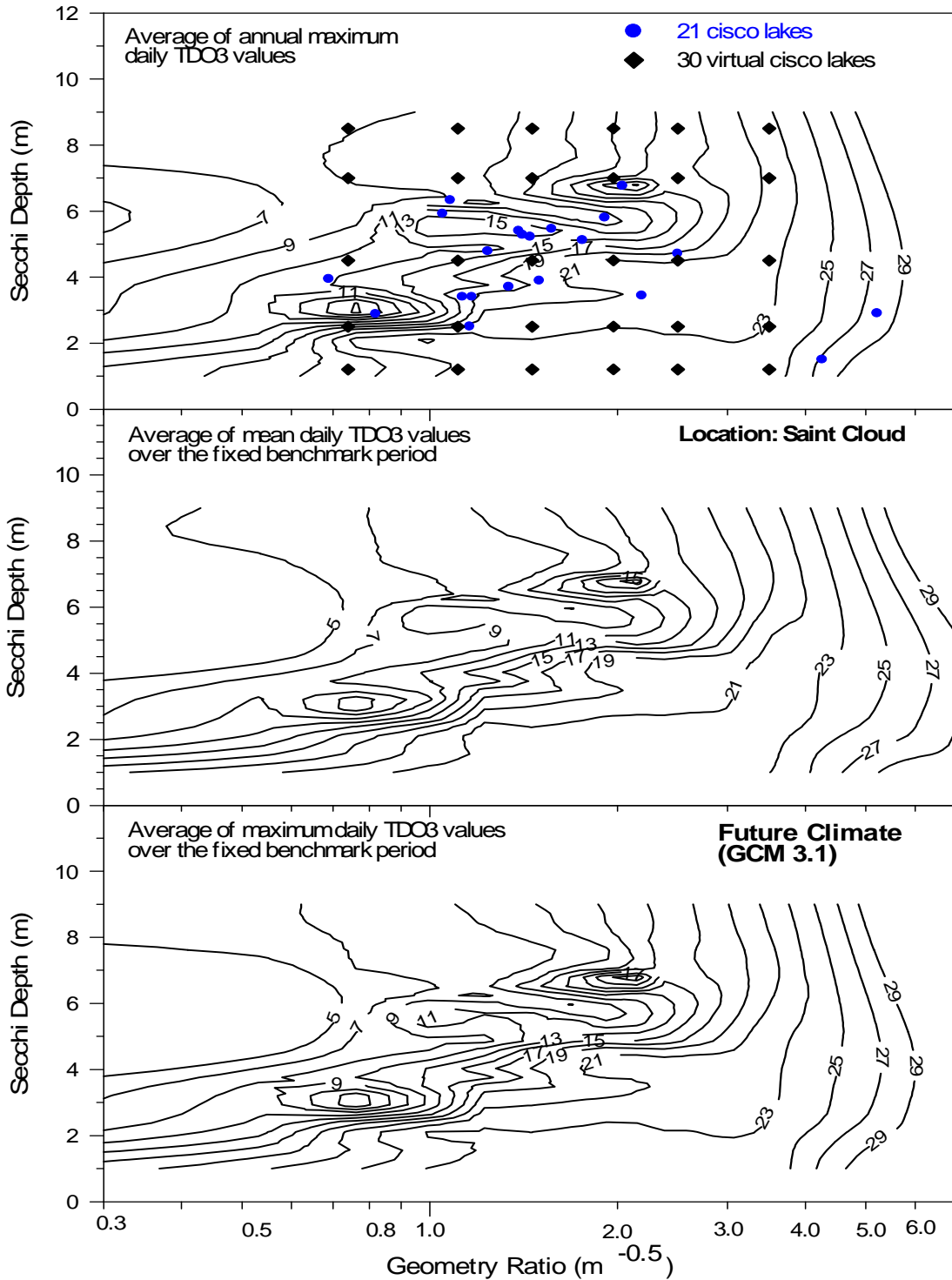


Figure C.11. Contour plots of AvgTDO3<sub>AM</sub> (Table 3.1, line 3), and AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub> (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **CGCM 3.1 future climate scenario** using **St. Cloud** weather data. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.

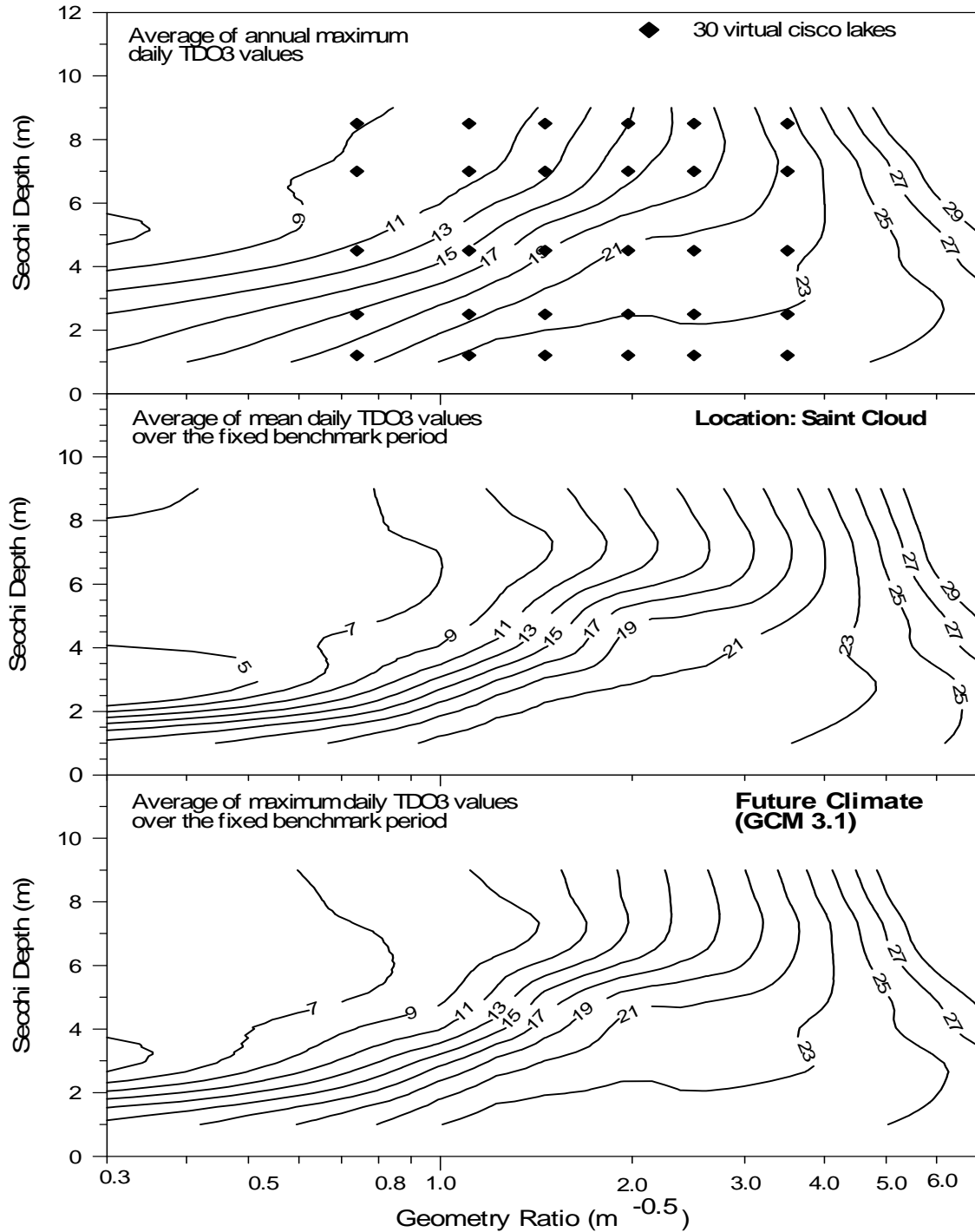


Figure C.12. Contour plots of  $AvgTDO3_{AM}$  (Table 3.1, line 3), and  $AvgATDO3_{FB}$  and  $AvgMTDO3_{FB}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **CGCM 3.1 future climate scenario** using **St. Cloud** weather data. Contours were derived by interpolation from simulated data points for **30 virtual cisco lakes only**.

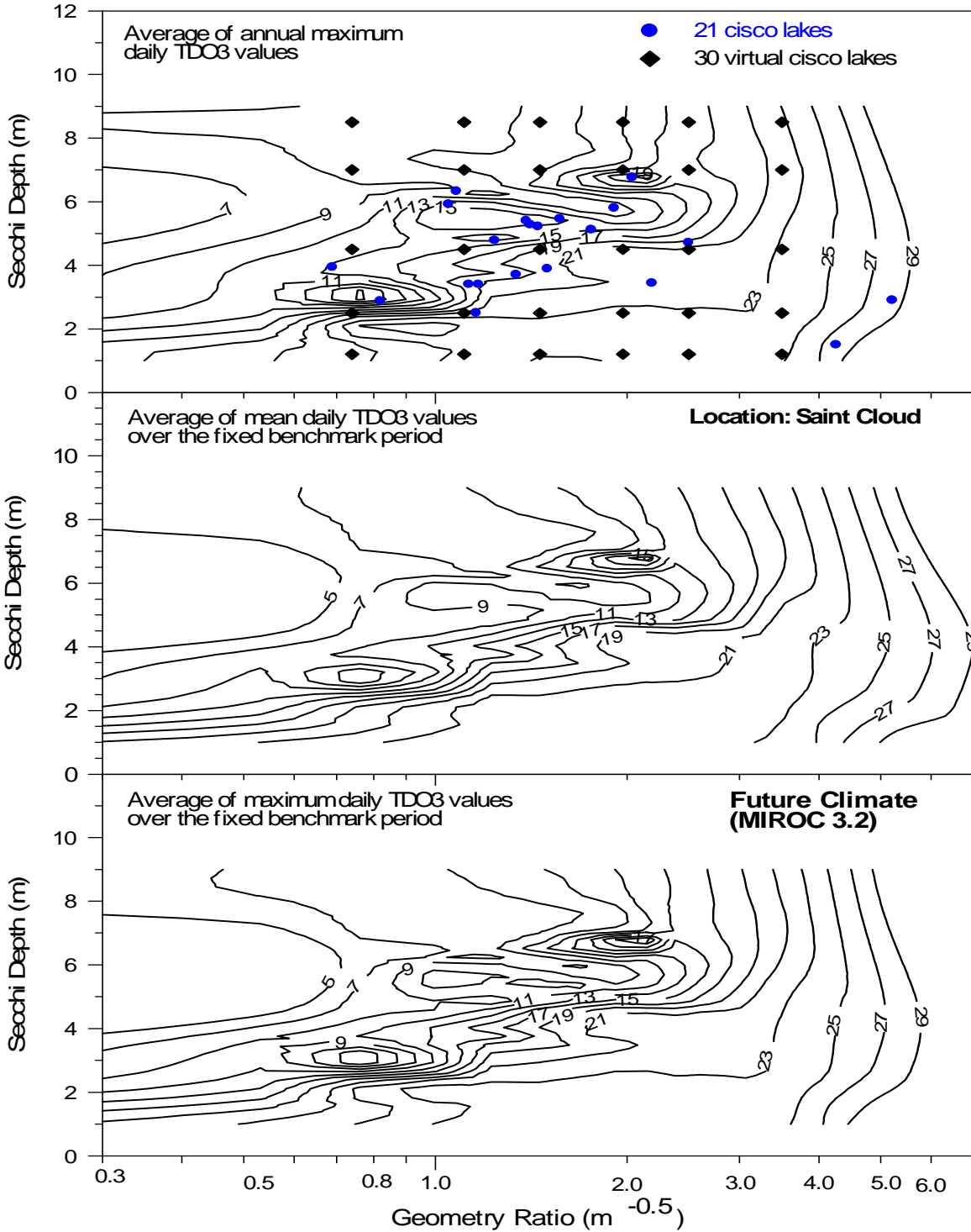


Figure C.13. Contour plots of  $\text{AvgTDO3}_{\text{AM}}$  (Table 3.1, line 3), and  $\text{AvgATDO3}_{\text{FB}}$  and  $\text{AvgMTDO3}_{\text{FB}}$  (Table 3.1, lines 6 and 9) for the fixed benchmark period (DOY 209 to DOY 239) in the 47-year simulation period. TDO3 values were simulated under the **MIROC 3.2 future climate scenario** using **St. Cloud** weather data. Contours were derived by interpolation from simulated data points for **21 cisco lakes** and **30 virtual cisco lakes**.



Table C.1 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period ( $AvgTDO3_{AM}$ ,  $AvgATDO3_{FB}$  and  $AvgMTDO3_{FB}$ , Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **CGCM 3.1** climate scenario, and **Duluth** weather data have been used in the simulations of **the 21 cisco study lakes**.

Lake Name	Geometry ratio $m^{-0.5}$ )	Secchi depth (m)	Past Climate			Future (CGCM 3.1)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Six	0.69	3.94	9.00	6.32	7.17	11.78	8.08	9.17
Grindstone	0.82	2.88	5.44	4.83	4.88	6.22	5.41	5.48
Ten Mile	1.05	5.92	10.12	8.24	8.78	12.88	9.56	10.13
Little Trout	1.08	6.33	6.08	5.45	5.53	7.29	6.00	6.16
Carlos	1.13	3.40	11.64	6.70	7.44	16.24	8.95	11.15
Elk	1.16	2.50	15.43	13.79	15.13	19.74	18.43	19.59
Cedar	1.17	3.40	13.70	10.61	12.44	18.32	15.63	17.62
Big Trout	1.24	4.78	8.75	6.57	6.95	12.14	8.39	9.18
Kabekona	1.34	3.70	11.95	8.05	9.42	15.90	11.64	13.92
Trout (Cook)	1.39	5.40	9.87	6.24	6.90	13.58	7.69	9.16
Snowbank	1.41	5.28	8.77	7.12	7.40	12.06	8.69	9.21
Little Sand	1.45	5.22	8.67	6.50	7.09	13.09	9.41	10.86
Siseebakwet	1.50	3.89	14.58	10.19	13.04	18.53	15.53	17.73
Greenwood	1.57	5.46	8.91	6.78	7.21	13.72	9.65	11.63
Mukooda	1.76	5.12	10.26	7.79	8.36	13.99	10.38	11.72
Burntside	1.91	5.80	7.92	6.80	7.00	9.39	7.78	7.96
Blue	2.04	6.76	15.49	12.86	14.66	20.27	17.83	19.84
Fish Hook	2.19	3.44	15.20	12.68	14.63	18.94	17.20	18.63
Trout (St. Louis)	2.50	4.71	11.49	9.41	9.94	15.84	12.10	14.44
White Iron	4.26	1.50	21.38	20.12	21.30	24.27	22.94	24.16
South Twin	5.22	2.90	22.26	19.94	21.97	25.17	22.79	24.83

Note: Annual maximum is average of annual maximum daily TDO3 values in the simulation period, and is  $AvgTDO3_{AM}$  defined in Table 3.1. Benchmark mean is average of mean daily TDO3 values over the fixed benchmark period, and is  $AvgATDO3_{FB}$  defined in Table 3.1. Benchmark maximum is average of maximum daily TDO3 values over the fixed benchmark period, and is  $MaxATDO3_{FB}$  defined in Table 3.1

Table C.2 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **CGCM 3.1** climate scenario, and **St. Cloud** weather data have been used in the simulations of **the 21 cisco study lakes**.

Lake Name	Geometry ratio (m <sup>-0.5</sup> )	Secchi depth (m)	Past Climate			Future (CGCM 3.1)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Six	0.69	3.94	10.44	7.29	8.20	12.94	8.49	9.65
Grindstone	0.82	2.88	5.53	4.68	4.72	6.30	5.33	5.41
Ten Mile	1.05	5.92	10.99	8.63	9.12	14.29	9.84	10.64
Little Trout	1.08	6.33	6.42	5.64	5.72	7.90	6.03	6.16
Carlos	1.13	3.40	14.33	7.41	9.19	18.06	10.76	15.32
Elk	1.16	2.50	17.32	15.65	17.00	21.40	20.14	21.29
Cedar	1.17	3.40	15.15	11.50	13.45	19.81	16.39	18.70
Big Trout	1.24	4.78	9.53	6.65	7.09	12.86	8.54	9.41
Kabekona	1.34	3.70	13.82	9.25	11.13	17.60	12.86	15.46
Trout (Cook)	1.39	5.40	12.45	7.35	8.62	15.79	8.69	10.57
Snowbank	1.41	5.28	9.23	7.03	7.37	13.31	8.71	9.46
Little Sand	1.45	5.22	9.79	7.00	7.67	14.64	10.04	11.64
Siseebakwet	1.50	3.89	16.74	12.81	15.22	20.57	17.32	19.76
Greenwood	1.57	5.46	10.30	7.24	7.87	15.44	10.51	12.90
Mukooda	1.76	5.12	11.37	7.98	8.75	15.01	10.64	12.05
Burntside	1.91	5.80	8.10	6.72	6.93	10.21	7.66	7.86
Blue	2.04	6.76	17.95	14.30	16.65	22.60	19.43	21.95
Fish Hook	2.19	3.44	17.63	15.14	17.08	21.27	19.55	20.94
Trout (St. Louis)	2.50	4.71	13.96	9.99	11.75	18.51	14.71	17.37
White Iron	4.26	1.50	24.40	22.69	24.11	27.23	25.32	26.85
South Twin	5.22	2.90	25.23	22.46	24.59	27.89	25.10	27.27

Table C.3 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **MIROC 3.2** climate scenario, and **International Falls** weather data have been used in the simulations of **the 21 cisco study lakes**.

Lake Name	Geometry ratio (m <sup>-0.5</sup> )	Secchi depth (m)	Past Climate			Future (MIROC 3.2)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Six	0.69	3.94	9.12	6.62	7.42	11.39	7.71	8.69
Grindstone	0.82	2.88 <sup>1</sup>	5.22	4.52	4.55	5.91	4.66	4.72
Ten Mile	1.05	5.92	9.78	8.01	8.54	11.99	8.85	9.38
Little Trout	1.08	6.33	5.72	5.42	5.49	6.50	5.65	5.72
Carlos	1.13	3.40	11.78	6.37	7.47	15.64	8.35	11.04
Elk	1.16	2.50 <sup>2</sup>	14.55	12.69	14.11	18.57	16.70	18.18
Cedar	1.17	3.40	12.52	9.24	10.78	16.43	12.44	14.52
Big Trout	1.24	4.78	8.00	5.94	6.30	10.29	6.79	7.34
Kabekona	1.34	3.70	11.55	7.67	9.04	14.95	10.08	12.14
Trout (Cook)	1.39	5.40	10.20	6.51	7.36	13.44	7.58	8.99
Snowbank	1.41	5.28	8.09	6.44	6.74	10.13	7.14	7.56
Little Sand	1.45	5.22	7.65	6.06	6.38	10.39	6.79	7.45
Siseebakwet	1.50	3.89	14.14	10.30	12.30	17.87	13.71	16.26
Greenwood	1.57	5.46	8.09	6.47	6.81	11.44	7.37	8.28
Mukooda	1.76	5.12	9.41	7.04	7.51	12.13	8.24	9.12
Burntside	1.91	5.80	7.41	6.30	6.52	8.36	6.84	7.04
Blue	2.04	6.76	14.93	11.88	13.64	19.19	14.91	17.67
Fish Hook	2.19	3.44	15.06	12.26	14.33	18.94	16.45	18.39
Trout (St. Louis)	2.50	4.71	11.23	8.91	9.51	15.47	10.38	13.38
White Iron	4.26	1.50	21.95	20.47	21.71	25.47	23.78	25.17
South Twin	5.22	2.90	22.95	20.31	22.23	26.17	23.66	25.57

Table C.4 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period ( $AvgTDO3_{AM}$ ,  $AvgATDO3_{FB}$  and  $AvgMTDO3_{FB}$ , Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **MIROC 3.2** climate scenario, and **Duluth** weather data have been used in the simulations of **the 21 cisco study lakes**.

Lake Name	Geometry ratio ( $m^{-0.5}$ )	Secchi depth (m)	Past Climate			Future (MIROC 3.2)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Six	0.69	3.94	9.00	6.32	7.17	11.61	7.63	8.68
Grindstone	0.82	2.88	5.44	4.83	4.88	5.90	5.07	5.14
Ten Mile	1.05	5.92	10.12	8.24	8.78	12.54	9.14	9.67
Little Trout	1.08	6.33	6.08	5.45	5.53	6.91	5.68	5.80
Carlos	1.13	3.40	11.64	6.70	7.44	16.23	8.42	10.88
Elk	1.16	2.50	15.43	13.79	15.13	19.74	18.32	19.54
Cedar	1.17	3.40	13.70	10.61	12.44	18.04	14.80	17.03
Big Trout	1.24	4.78	8.75	6.57	6.95	11.41	7.59	8.21
Kabekona	1.34	3.70	11.95	8.05	9.42	15.68	10.79	13.10
Trout (Cook)	1.39	5.40	9.87	6.24	6.90	13.56	7.44	8.81
Snowbank	1.41	5.28	8.77	7.12	7.40	11.37	7.93	8.38
Little Sand	1.45	5.22	8.67	6.50	7.09	12.09	8.20	9.37
Siseebakwet	1.50	3.89	14.58	10.19	13.04	18.55	14.96	17.47
Greenwood	1.57	5.46	8.91	6.78	7.21	13.14	8.62	10.35
Mukooda	1.76	5.12	10.26	7.79	8.36	13.21	9.25	10.39
Burntside	1.91	5.80	7.92	6.80	7.00	8.95	7.33	7.51
Blue	2.04	6.76	15.49	12.86	14.66	20.26	17.05	19.49
Fish Hook	2.19	3.44	15.20	12.68	14.63	19.22	17.17	18.82
Trout (St. Louis)	2.50	4.71	11.49	9.41	9.94	15.85	11.52	14.15
White Iron	4.26	1.50	21.38	20.12	21.30	24.89	23.58	24.77
South Twin	5.22	2.90	22.26	19.94	21.97	25.81	23.49	25.46

Table C.5 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **MIROC 3.2** climate scenario, and **St. Cloud** weather data have been used in the simulations of **the 21 cisco study lakes**.

Lake Name	Geometry ratio (m <sup>-0.5</sup> )	Secchi depth (m)	Past Climate			Future (MIRO)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Six	0.69	3.94	10.44	7.29	8.20	13.29	8.59	9.78
Grindstone	0.82	2.88	5.53	4.68	4.72	6.34	5.09	5.16
Ten Mile	1.05	5.92	10.99	8.63	9.12	14.25	9.61	10.37
Little Trout	1.08	6.33	6.42	5.64	5.72	7.78	5.91	6.00
Carlos	1.13	3.40	14.33	7.41	9.19	18.24	10.70	15.30
Elk	1.16	2.50	17.32	15.65	17.00	21.56	19.97	21.29
Cedar	1.17	3.40	15.15	11.50	13.45	19.69	15.63	18.09
Big Trout	1.24	4.78	9.53	6.65	7.09	12.50	7.98	8.77
Kabekona	1.34	3.70	13.82	9.25	11.13	17.63	12.38	15.01
Trout (Cook)	1.39	5.40	12.45	7.35	8.62	16.52	9.06	11.06
Snowbank	1.41	5.28	9.23	7.03	7.37	12.95	8.18	8.88
Little Sand	1.45	5.22	9.79	7.00	7.67	14.03	8.94	10.45
Siseebakwet	1.50	3.89	16.74	12.81	15.22	20.80	17.01	19.72
Greenwood	1.57	5.46	10.30	7.24	7.87	15.10	9.61	11.78
Mukooda	1.76	5.12	11.37	7.98	8.75	14.70	9.95	11.28
Burntside	1.91	5.80	8.10	6.72	6.93	10.02	7.35	7.58
Blue	2.04	6.76	17.95	14.30	16.65	23.22	19.50	22.43
Fish Hook	2.19	3.44	17.63	15.14	17.08	21.73	19.76	21.36
Trout (St. Louis)	2.50	4.71	13.96	9.99	11.75	18.85	14.03	17.52
White Iron	4.26	1.50	24.40	22.69	24.11	27.89	25.95	27.52
South Twin	5.22	2.90	25.23	22.46	24.59	28.42	25.76	27.88

Table C.6 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **CGCM 3.1** climate scenario, and **Duluth** weather data have been used in the simulation of the **30 virtual cisco lakes**.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	Past Climate			Future (CGCM 3.1)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
LakeC01	0.74	1.25	15.56	13.88	15.34	18.33	17.23	18.24
LakeC02	0.74	2.50	12.01	8.61	10.29	14.96	9.45	11.88
LakeC03	0.74	4.50	8.80	6.14	6.72	10.34	6.59	7.29
LakeC04	0.74	7.00	7.83	6.15	6.42	8.60	6.28	6.57
LakeC05	0.74	8.50	7.88	6.34	6.82	8.37	6.75	7.17
LakeC06	1.11	1.25	17.16	15.26	17.03	21.58	19.42	21.49
LakeC07	1.11	2.50	13.39	10.26	12.53	18.01	15.20	17.43
LakeC08	1.11	4.50	9.93	6.54	7.40	13.52	8.46	9.95
LakeC09	1.11	7.00	7.86	6.38	6.62	9.65	7.14	7.41
LakeC10	1.11	8.50	8.35	7.41	7.69	9.27	8.22	8.47
LakeC11	1.46	1.25	17.10	15.59	16.99	21.15	19.29	21.02
LakeC12	1.46	2.50	15.00	12.83	14.62	19.70	18.23	19.54
LakeC13	1.46	4.50	11.93	8.19	9.83	16.73	12.62	15.25
LakeC14	1.46	7.00	8.89	7.45	7.72	11.71	8.61	9.02
LakeC15	1.46	8.50	9.71	8.44	8.79	11.08	9.62	9.97
LakeC16	1.97	1.25	17.53	16.27	17.45	21.42	19.87	21.29
LakeC17	1.97	2.50	15.93	14.53	15.76	20.27	19.03	20.17
LakeC18	1.97	4.50	14.28	11.49	13.51	19.03	17.07	18.69
LakeC19	1.97	7.00	11.53	9.63	10.06	15.15	11.72	12.77
LakeC20	1.97	8.50	12.52	10.62	11.16	14.54	12.52	13.06
LakeC21	2.50	1.25	17.57	16.47	17.50	21.35	20.00	21.23
LakeC22	2.50	2.50	15.99	14.75	15.81	20.05	18.98	19.95
LakeC23	2.50	4.50	15.00	12.75	14.48	19.30	17.74	19.05
LakeC24	2.50	7.00	13.86	11.77	12.44	16.89	14.09	15.30
LakeC25	2.50	8.50	15.00	12.82	13.63	17.35	15.06	15.87
LakeC26	3.50	1.25	18.13	17.18	18.03	21.70	20.57	21.59
LakeC27	3.50	2.50	17.01	15.90	16.81	20.60	19.68	20.50
LakeC28	3.50	4.50	16.81	15.03	16.31	20.24	19.02	20.03
LakeC29	3.50	7.00	17.61	15.57	16.72	20.13	17.96	19.09
LakeC30	3.50	8.50	18.47	16.61	17.85	21.06	19.07	20.31

Table C.7 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **CGCM 3.1** climate scenario, and **St. Cloud** weather data have been used in the simulation of **the 30 virtual cisco lakes**.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	Past Climate			Future (CGCM 3.1)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
LakeC01	0.74	1.25	17.54	16.32	17.43	20.09	18.98	19.96
LakeC02	0.74	2.50	14.45	10.56	12.65	17.35	11.10	14.05
LakeC03	0.74	4.50	10.15	6.91	7.60	11.52	7.14	7.90
LakeC04	0.74	7.00	8.70	6.56	6.89	9.31	6.56	6.90
LakeC05	0.74	8.50	8.50	6.60	7.36	8.94	6.72	7.38
LakeC06	1.11	1.25	19.88	18.28	19.75	23.47	21.70	23.34
LakeC07	1.11	2.50	15.98	12.81	15.12	20.57	17.67	20.02
LakeC08	1.11	4.50	11.65	7.40	8.49	15.16	9.10	10.76
LakeC09	1.11	7.00	9.07	6.90	7.19	10.47	7.30	7.64
LakeC10	1.11	8.50	8.99	7.95	8.22	9.71	8.44	8.70
LakeC11	1.46	1.25	20.16	18.15	20.04	24.41	21.89	24.09
LakeC12	1.46	2.50	17.27	15.30	16.95	22.22	20.62	22.07
LakeC13	1.46	4.50	13.58	8.90	10.83	18.99	13.77	17.01
LakeC14	1.46	7.00	9.74	7.75	8.04	12.68	8.82	9.29
LakeC15	1.46	8.50	10.33	8.90	9.26	11.63	9.92	10.28
LakeC16	1.97	1.25	20.31	18.60	20.11	24.18	22.08	23.82
LakeC17	1.97	2.50	18.59	17.21	18.46	22.97	21.47	22.87
LakeC18	1.97	4.50	16.24	12.65	15.18	21.32	19.16	20.98
LakeC19	1.97	7.00	12.16	9.76	10.22	16.50	11.96	13.17
LakeC20	1.97	8.50	12.93	10.89	11.45	15.00	12.76	13.33
LakeC21	2.50	1.25	20.18	18.78	20.05	23.95	22.22	23.74
LakeC22	2.50	2.50	18.51	17.29	18.38	22.72	21.40	22.61
LakeC23	2.50	4.50	17.10	14.35	16.48	21.59	19.99	21.36
LakeC24	2.50	7.00	14.50	11.90	12.61	18.39	14.41	16.12
LakeC25	2.50	8.50	15.70	13.16	14.00	17.95	15.27	16.10
LakeC26	3.50	1.25	20.76	19.60	20.64	24.27	22.84	24.10
LakeC27	3.50	2.50	19.40	18.39	19.28	23.11	22.00	22.99
LakeC28	3.50	4.50	18.91	17.11	18.59	22.62	21.42	22.46
LakeC29	3.50	7.00	18.90	16.32	17.57	21.41	18.75	20.33
LakeC30	3.50	8.50	19.99	17.61	18.98	22.41	19.90	21.26

Table C.8 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **MIROC 3.2** climate scenario, and **International Falls** weather data have been used in the simulation of the **30 virtual cisco lakes**.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	Past Climate			Future (MIROC 3.2)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
LakeC01	0.74	1.25	15.60	14.33	15.44	18.05	17.07	17.93
LakeC02	0.74	2.50	12.51	9.66	11.31	15.13	10.76	13.08
LakeC03	0.74	4.50	9.10	6.50	7.12	10.53	7.05	7.77
LakeC04	0.74	7.00	8.01	6.29	6.58	8.92	6.58	6.93
LakeC05	0.74	8.50	7.92	6.35	7.10	8.65	6.98	7.37
LakeC06	1.11	1.25	16.72	15.12	16.64	20.87	19.24	20.79
LakeC07	1.11	2.50	13.30	10.62	12.55	16.90	13.60	16.07
LakeC08	1.11	4.50	9.73	6.50	7.32	12.20	7.57	8.75
LakeC09	1.11	7.00	7.99	6.41	6.68	9.16	6.83	7.12
LakeC10	1.11	8.50	8.29	7.40	7.68	8.91	7.90	8.16
LakeC11	1.46	1.25	16.97	15.40	16.88	21.68	19.25	21.35
LakeC12	1.46	2.50	14.37	12.02	13.88	18.73	16.98	18.47
LakeC13	1.46	4.50	11.03	7.35	8.63	14.73	9.71	12.06
LakeC14	1.46	7.00	8.46	7.16	7.43	10.05	7.84	8.12
LakeC15	1.46	8.50	9.36	8.12	8.48	10.34	8.95	9.30
LakeC16	1.97	1.25	17.22	15.87	17.13	21.71	19.73	21.41
LakeC17	1.97	2.50	15.24	13.67	15.00	20.04	18.69	19.96
LakeC18	1.97	4.50	13.06	9.53	11.56	17.73	14.56	17.06
LakeC19	1.97	7.00	10.52	8.84	9.27	12.82	9.93	10.48
LakeC20	1.97	8.50	11.64	9.81	10.35	13.08	11.00	11.56
LakeC21	2.50	1.25	17.16	16.02	17.08	21.52	19.91	21.28
LakeC22	2.50	2.50	15.35	13.91	15.14	19.87	18.67	19.78
LakeC23	2.50	4.50	14.03	11.04	13.01	18.54	16.25	18.15
LakeC24	2.50	7.00	12.98	10.82	11.48	15.28	12.38	13.20
LakeC25	2.50	8.50	14.16	11.89	12.69	16.13	13.55	14.38
LakeC26	3.50	1.25	17.97	16.96	17.88	21.98	20.65	21.82
LakeC27	3.50	2.50	16.63	15.37	16.40	20.61	19.59	20.52
LakeC28	3.50	4.50	16.30	14.05	15.65	20.04	18.57	19.80
LakeC29	3.50	7.00	17.07	14.71	15.93	19.47	16.87	18.14
LakeC30	3.50	8.50	18.02	15.84	17.16	20.55	18.13	19.49



Table C.9 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **MIROC 3.2** climate scenario, and **Duluth** weather data have been used in the simulation of the **30 virtual cisco lakes**.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	Past Climate			Future (MIROC 3.2)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
LakeC01	0.74	1.25	15.56	13.88	15.34	18.62	17.59	18.51
LakeC02	0.74	2.50	12.01	8.61	10.29	15.77	10.30	12.86
LakeC03	0.74	4.50	8.80	6.14	6.72	10.84	6.83	7.54
LakeC04	0.74	7.00	7.83	6.15	6.42	9.04	6.43	6.74
LakeC05	0.74	8.50	7.88	6.34	6.82	8.70	6.95	7.43
LakeC06	1.11	1.25	17.16	15.26	17.03	21.87	20.05	21.82
LakeC07	1.11	2.50	13.39	10.26	12.53	18.24	15.02	17.51
LakeC08	1.11	4.50	9.93	6.54	7.40	13.43	8.06	9.47
LakeC09	1.11	7.00	7.86	6.38	6.62	9.76	7.01	7.29
LakeC10	1.11	8.50	8.35	7.41	7.69	9.29	8.11	8.37
LakeC11	1.46	1.25	17.10	15.59	16.99	21.84	19.88	21.69
LakeC12	1.46	2.50	15.00	12.83	14.62	19.99	18.36	19.77
LakeC13	1.46	4.50	11.93	8.19	9.83	16.50	11.58	14.34
LakeC14	1.46	7.00	8.89	7.45	7.72	11.27	8.17	8.49
LakeC15	1.46	8.50	9.71	8.44	8.79	10.88	9.25	9.60
LakeC16	1.97	1.25	17.53	16.27	17.45	21.96	20.27	21.78
LakeC17	1.97	2.50	15.93	14.53	15.76	20.79	19.38	20.68
LakeC18	1.97	4.50	14.28	11.49	13.51	19.23	16.87	18.80
LakeC19	1.97	7.00	11.53	9.63	10.06	14.73	10.96	11.91
LakeC20	1.97	8.50	12.52	10.62	11.16	14.16	11.90	12.46
LakeC21	2.50	1.25	17.57	16.47	17.50	21.83	20.38	21.71
LakeC22	2.50	2.50	15.99	14.75	15.81	20.51	19.33	20.41
LakeC23	2.50	4.50	15.00	12.75	14.48	19.58	17.77	19.28
LakeC24	2.50	7.00	13.86	11.77	12.44	16.78	13.51	14.73
LakeC25	2.50	8.50	15.00	12.82	13.63	17.20	14.57	15.39
LakeC26	3.50	1.25	18.13	17.18	18.03	22.21	21.03	22.11
LakeC27	3.50	2.50	17.01	15.90	16.81	21.08	20.07	20.96
LakeC28	3.50	4.50	16.81	15.03	16.31	20.68	19.32	20.46
LakeC29	3.50	7.00	17.61	15.57	16.72	20.24	17.74	19.00
LakeC30	3.50	8.50	18.47	16.61	17.85	21.26	18.96	20.25

Table C.10 Values of GR, SD and averages of annual maximum daily TDO3, mean and maximum daily TDO3 in the fixed benchmark period (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively). Past climate conditions (1962-2008) and the **MIROC 3.2** climate scenario, and **St. Cloud** weather data have been used in the simulation of **the 30 virtual cisco lakes**.

Lake Name	GR (m <sup>-0.5</sup> )	SD (m)	Past Climate			Future (MIROC 3.2)		
			Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
LakeC01	0.74	1.25	17.54	16.32	17.43	20.56	19.41	20.41
LakeC02	0.74	2.50	14.45	10.56	12.65	18.43	11.99	15.24
LakeC03	0.74	4.50	10.15	6.91	7.60	12.39	7.52	8.32
LakeC04	0.74	7.00	8.70	6.56	6.89	10.00	6.90	7.29
LakeC05	0.74	8.50	8.50	6.60	7.36	9.52	7.39	7.79
LakeC06	1.11	1.25	19.88	18.28	19.75	23.51	22.04	23.36
LakeC07	1.11	2.50	15.98	12.81	15.12	21.05	17.91	20.50
LakeC08	1.11	4.50	11.65	7.40	8.49	15.57	9.11	10.78
LakeC09	1.11	7.00	9.07	6.90	7.19	11.12	7.49	7.89
LakeC10	1.11	8.50	8.99	7.95	8.22	10.15	8.59	8.85
LakeC11	1.46	1.25	20.16	18.15	20.04	24.92	22.50	24.76
LakeC12	1.46	2.50	17.27	15.30	16.95	22.61	20.93	22.45
LakeC13	1.46	4.50	13.58	8.90	10.83	19.21	13.20	16.67
LakeC14	1.46	7.00	9.74	7.75	8.04	12.66	8.62	9.03
LakeC15	1.46	8.50	10.33	8.90	9.26	11.65	9.80	10.16
LakeC16	1.97	1.25	20.31	18.60	20.11	24.71	22.57	24.37
LakeC17	1.97	2.50	18.59	17.21	18.46	23.47	21.97	23.34
LakeC18	1.97	4.50	16.24	12.65	15.18	21.69	19.05	21.22
LakeC19	1.97	7.00	12.16	9.76	10.22	16.34	11.46	12.56
LakeC20	1.97	8.50	12.93	10.89	11.45	14.96	12.35	12.92
LakeC21	2.50	1.25	20.18	18.78	20.05	24.38	22.62	24.13
LakeC22	2.50	2.50	18.51	17.29	18.38	23.16	21.79	23.03
LakeC23	2.50	4.50	17.10	14.35	16.48	22.03	20.17	21.74
LakeC24	2.50	7.00	14.50	11.90	12.61	18.54	14.09	15.70
LakeC25	2.50	8.50	15.70	13.16	14.00	18.02	15.06	15.91
LakeC26	3.50	1.25	20.76	19.60	20.64	24.75	23.29	24.55
LakeC27	3.50	2.50	19.40	18.39	19.28	23.61	22.45	23.49
LakeC28	3.50	4.50	18.91	17.11	18.59	23.18	21.87	22.99
LakeC29	3.50	7.00	18.90	16.32	17.57	21.80	18.79	20.62
LakeC30	3.50	8.50	19.99	17.61	18.98	22.71	19.93	21.32

Table C.11 Statistical differences of three TDO3 parameters (AvgTDO3<sub>AM</sub>, AvgATDO3<sub>FB</sub> and AvgMTDO3<sub>FB</sub>, Table 3.1, lines 3, 6 and 9, respectively) between **Duluth** and **International Falls** weather station under the **CGCM 3.1** future climate scenario.

Lakes	21 cisco study lakes			30 virtual cisco lakes		
Statistical parameters	Annual maximum	Benchmark mean	Benchmark maximum	Annual maximum	Benchmark mean	Benchmark maximum
Maximum	3.02	3.19	3.31	2.33	2.91	3.19
Minimum	-1.05	-0.52	-0.77	-0.53	-1.31	-1.20
Mean	1.14	1.24	1.29	0.60	0.69	0.64
Standard Deviation	0.97	1.00	1.13	0.77	0.91	0.94

## Appendix D List of 620 Cisco Lakes Divided into Refuge Lake Tiers

Table D.1 List of 620 cisco lakes and lake parameters. Refuge lakes were selected using contour lines of averages of mean daily TDO3 for **fixed and variable** benchmark periods (**AvgATDO3<sub>FB</sub>**, **AvgATDO3<sub>VB</sub>**, Table 3.1, lines 6 and 12). Simulations were made for the MIROC 3.2 future climate scenario using Duluth weather data for all 620 cisco lakes. Lakes are sorted by tier (using the fixed benchmark period) and then by lake name (in alphabetical order). Tier 1 = most suitable refuge lake (TDO3 < 11°C) after climate change; Tier 2 = suitable refuge lake (11°C < TDO3 < 17°C) after climate change; Tier 3 = non-refuge lake (TDO3 > 17°C) after climate change. “After climate change” means under the MIROC 3.2 climate change scenario.

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
31034900	Antler	1.24	27.43	1.22	4.57	1	2
11046900	Anway	0.09	13.72	1.26	3.96	1	2
38050200	Ashigan	0.77	17.98	1.64	7.62	1	2
03008500	Bad Medicine	3.23	25.60	1.66	7.05	1	2
01004600	Ball Bluff	0.64	23.77	1.19	3.98	1	2
18003000	Barbour	0.21	16.46	1.30	4.72	1	2
29004800	Benedict	1.78	27.74	1.32	4.11	1	2
11027700	Big Deep	1.96	32.61	1.15	4.15	1	2
29018500	Big Sand	6.72	41.15	1.24	5.46	1	2
31079300	Big Too Much	0.94	28.95	1.08	3.96	1	2
18031500	Big Trout	5.43	39.01	1.24	4.70	1	2
29018400	Blue	1.31	25.60	1.32	4.52	1	2
18021100	Blue	0.39	13.72	1.83	7.74	1	2
31039500	Bluewater	1.47	36.57	0.95	5.50	1	1
04029700	Buzzle	0.77	25.30	1.17	5.79	1	2
77012000	Charlotte	0.60	25.60	1.09	4.57	1	2
31074900	Chase	0.85	28.95	1.05	7.73	1	1
38016600	Cherry	0.60	27.43	1.01	5.87	1	1
16013900	Clearwater	5.36	39.62	1.21	9.46	1	1
31054000	Clubhouse	0.85	31.39	0.97	4.69	1	2
15009000	Deep	0.19	23.16	0.90	4.72	1	1
11023700	Deep Portage	0.50	32.00	0.83	3.96	1	2
16023200	Duncan	1.95	39.62	0.94	5.70	1	1
11046600	Fifth	0.18	18.29	1.13	4.95	1	2
16014700	Flour	1.36	22.86	1.49	5.53	1	2
38037200	Fraser	3.28	32.00	1.33	4.41	1	2
16031900	Gaskin	1.40	24.99	1.38	4.42	1	2
16058000	Granite	0.08	13.72	1.23	4.25	1	2
04021700	Grant	0.84	28.04	1.08	4.07	1	2
58012300	Grindstone	2.13	46.63	0.82	3.93	1	2
69048700	Gun	0.64	41.15	0.69	5.64	1	1
16035600	Gunflint	17.04	60.96	1.05	3.96	1	2

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
31045200	Gunn	0.36	22.86	1.07	3.93	1	2
31091100	Hamrey	0.18	18.29	1.12	4.27	1	2
38020600	Hanson	1.15	30.48	1.07	4.80	1	2
18026900	Island-Loon	0.71	23.16	1.25	4.39	1	2
11040000	Jack	0.81	33.53	0.90	5.01	1	1
18036100	Kimball	0.77	23.47	1.26	5.04	1	2
38040400	Knife	21.27	54.56	1.24	6.80	1	1
29030900	LaSalle	0.89	64.92	0.47	3.20	1	2
21010600	Latoka	3.14	32.92	1.28	4.02	1	2
38022900	Little Knife	2.63	56.08	0.72	6.71	1	1
56032800	Little McDonald	4.75	33.22	1.41	5.91	1	2
29015000	Little Sand	1.56	24.38	1.45	6.77	1	1
31077800	Little Too Much	0.27	18.29	1.25	4.27	1	2
31039400	Little Trout	0.30	24.38	0.96	5.73	1	1
69068200	Little Trout	0.97	28.95	1.08	6.26	1	1
01008900	Long	1.68	35.36	1.02	3.41	1	2
31078100	Long	0.38	21.94	1.13	3.81	1	2
16044800	Loon	4.15	61.57	0.73	5.01	1	1
29018000	Lower Bottle	2.64	33.53	1.20	5.30	1	2
31023900	Lower Hanson	0.33	22.86	1.05	3.96	1	2
16046300	Magnetic	1.74	27.43	1.32	5.79	1	2
03037100	Meadow	0.28	21.94	1.05	3.96	1	2
21010800	Mina	1.72	37.49	0.97	3.28	1	2
77002200	Mons	0.35	24.38	1.00	4.18	1	2
16004300	Moose	4.07	34.44	1.30	5.64	1	2
16023400	Moss	1.03	26.21	1.21	5.79	1	2
29023700	Newman	0.16	19.20	1.04	4.88	1	2
16033100	North	10.91	38.10	1.51	8.08	1	1
38064000	Ojibway	1.50	35.05	1.00	5.65	1	1
31021900	O'Reilly	0.82	24.08	1.25	4.27	1	2
38021100	Ottertrack	4.64	35.36	1.31	7.01	1	1
16004100	Pine	9.14	34.44	1.60	6.04	1	2
11047600	Portage	1.13	25.60	1.27	6.71	1	1
31042200	Ruby	0.98	26.82	1.17	7.71	1	1
56035800	Scalp	0.98	27.43	1.15	6.01	1	1
38071400	Section Twelve	0.17	15.85	1.29	5.49	1	2
31021800	Shamrock	0.24	16.76	1.32	4.57	1	2
56036900	Six	0.76	42.67	0.69	5.57	1	1
38052900	Snowbank	17.30	45.72	1.41	5.87	1	2
16024400	South	4.82	42.67	1.10	7.62	1	1
29023900	Spearhead	0.70	24.69	1.17	3.80	1	2
38038800	Spoon	0.90	25.91	1.19	4.19	1	2

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
18035900	Star	0.51	25.30	1.06	4.82	1	2
69036900	Takumich	1.32	45.72	0.74	5.49	1	1
11086600	Tamarack	0.04	13.11	1.10	3.81	1	2
01010900	Taylor	0.21	25.60	0.84	3.81	1	2
11041300	Ten Mile	18.90	63.40	1.04	5.92	1	1
38072400	Tofte	0.63	22.25	1.27	6.49	1	1
38017200	Topaz	0.53	21.33	1.26	5.08	1	2
31041000	Trout	7.10	47.85	1.08	4.99	1	2
16004900	Trout	1.04	23.47	1.36	6.34	1	2
31072500	Turtle	8.31	41.76	1.29	4.86	1	2
86027900	West Lake Sylvia	3.53	29.56	1.47	5.19	1	2
16008600	West Pike	2.89	36.57	1.13	6.10	1	1
16035400	Winchell	3.34	48.77	0.88	4.25	1	2
03025800	Acorn	0.51	16.76	1.59	3.24	2	3
18020800	Allen	0.20	14.02	1.51	4.11	2	2
56024100	Annie Battle	1.35	15.54	2.19	4.93	2	3
86028400	Augusta	0.72	24.99	1.16	2.60	2	3
31027800	Barwise	0.37	15.24	1.62	5.79	2	2
77002400	Bass	0.46	24.99	1.04	3.12	2	2
11006900	Bass	0.86	16.76	1.82	5.33	2	2
18035800	Bass	0.47	14.32	1.83	5.06	2	2
31070400	Batson	0.45	15.24	1.70	3.55	2	3
69048000	Beartrack	0.68	16.76	1.71	4.02	2	3
38050300	Boot	0.85	25.30	1.20	3.00	2	2
69011800	Burntside	28.90	38.40	1.91	6.09	2	2
21005700	Carlos	10.21	49.70	1.14	3.27	2	2
49014000	Cedar	1.02	26.82	1.19	3.24	2	2
21014500	Chippewa	4.80	28.95	1.62	3.97	2	3
18036400	Clear	0.89	19.20	1.60	4.65	2	2
11016300	Cooper	0.60	21.33	1.30	3.50	2	2
18004100	Crooked	1.79	21.94	1.67	3.81	2	3
31071900	Deer	16.59	36.88	1.73	4.72	2	3
16061600	Devils Elbow	0.36	15.24	1.61	3.96	2	3
69006400	Dry	0.33	13.41	1.79	3.86	2	3
31046000	East	0.65	19.81	1.43	3.05	2	3
18029800	East Fox	0.97	19.81	1.58	5.08	2	2
86028900	East Lake Sylvia	2.64	23.77	1.70	5.28	2	2
56052300	East Loon	4.24	32.00	1.42	3.41	2	3
18039600	Edna	0.62	19.20	1.46	4.75	2	2
56051400	Elbow	0.34	25.91	0.93	2.26	2	2
29003600	7th Crow Wing	3.20	24.38	1.73	4.57	2	3
15001000	Elk	1.10	28.35	1.14	3.36	2	2

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
69066000	Ely	2.72	21.33	1.90	4.41	2	3
29018600	Emma	0.31	15.24	1.55	3.29	2	3
69047300	Eugene	0.67	19.51	1.47	3.35	2	3
18039700	Fawn	0.24	12.19	1.82	3.91	2	3
69034800	Finger	1.16	18.29	1.80	3.96	2	3
56076800	Fish	1.06	21.03	1.52	3.45	2	3
31046300	Fox	1.13	22.86	1.43	3.66	2	2
11017400	Girl	1.64	24.69	1.45	4.12	2	2
16061700	Gneiss	0.97	21.33	1.47	4.57	2	2
38071800	Greenstone	1.40	21.94	1.57	3.86	2	3
16007700	Greenwood	8.18	34.14	1.57	4.69	2	2
31037300	Hale	0.57	18.29	1.51	4.77	2	2
11024200	Hand	1.09	17.37	1.86	4.22	2	3
31034400	Hanson	0.30	20.12	1.16	2.74	2	2
31077100	Hatch	0.98	26.82	1.17	2.97	2	2
31046600	Horseshoe	0.51	18.29	1.46	4.27	2	2
69034300	Hustler	1.10	22.55	1.44	3.44	2	3
03015600	Ice Cracking	1.34	22.25	1.53	4.15	2	2
38040000	Ima	3.13	35.36	1.19	3.11	2	2
38051100	Jordan	0.55	20.12	1.35	3.58	2	2
29007500	Kabekona	9.12	40.54	1.36	3.72	2	2
18001900	Kenney	0.40	16.76	1.50	3.54	2	3
11026200	Kid	0.68	15.85	1.81	4.08	2	3
11005300	Lawrence	0.84	21.33	1.42	2.88	2	3
31073900	Leighton	0.93	19.20	1.62	3.81	2	3
01005700	Little Ball Bluff	0.14	14.93	1.29	3.66	2	2
31057500	Little Bass	0.63	18.90	1.49	4.77	2	2
03023400	Little Bemidji	1.11	17.68	1.84	4.42	2	3
09003500	Little Hanging Horn	0.47	21.33	1.23	3.45	2	2
31056600	Little Jay Gould	0.61	17.07	1.64	3.66	2	3
69006600	Little Long	1.19	13.72	2.41	5.56	2	3
31066500	Little North Star	0.22	13.11	1.65	3.64	2	3
01017600	Little Pine	0.89	13.41	2.29	4.99	2	3
18036000	Little Star	0.20	9.14	2.32	5.11	2	3
77003400	Little Swan	0.60	20.42	1.36	3.20	2	3
11006100	Little Thunder	0.28	14.32	1.61	3.66	2	3
31039900	Little Wabana	0.42	17.37	1.47	4.71	2	2
29016100	Long	7.99	41.15	1.29	3.25	2	2
11048000	Long	1.10	24.38	1.33	3.52	2	2
31057100	Loon	0.95	21.03	1.49	4.18	2	2
18037800	Lower Hay	2.77	30.48	1.34	4.10	2	2
69038300	Lynx	1.19	25.91	1.28	2.74	2	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
11028200	Mann	1.80	28.35	1.29	3.72	2	2
11048200	May	0.50	17.98	1.48	3.96	2	2
16002700	McFarland	1.55	14.93	2.36	5.26	2	3
73012800	Middle Spunk	0.96	24.69	1.27	2.94	2	3
18029400	Mitchell	1.78	23.77	1.54	3.45	2	3
56030300	Molly Stark	0.62	14.63	1.92	4.47	2	3
11004700	Mule	0.25	13.72	1.63	4.57	2	2
31019200	Nashwauk	0.58	16.15	1.71	3.35	2	3
29002500	Ninth Crow Wing	0.92	19.81	1.56	3.77	2	3
31065300	North Star	4.29	27.43	1.66	4.51	2	2
31077500	No-ta-she-bun	0.96	13.72	2.28	6.65	2	2
18035200	Ossawinnamakee	2.61	19.20	2.09	4.88	2	3
69033000	Oyster	2.89	39.62	1.04	2.72	2	2
56082900	Pebble	0.68	18.90	1.52	4.31	2	2
31033900	Pickereel	1.19	21.33	1.55	3.10	2	3
56047500	Pickereel	3.36	23.77	1.80	3.75	2	3
18035400	Pig	0.77	17.07	1.74	4.03	2	3
11038300	Pleasant	4.20	21.94	2.06	5.04	2	3
31053200	Pokegama	26.77	34.14	2.11	4.99	2	3
31019600	Poplar	0.39	15.24	1.64	3.96	2	3
16023900	Poplar	2.95	22.25	1.86	3.88	2	3
38052400	Portage	0.28	13.72	1.68	4.27	2	3
04003400	Rabideau	2.34	34.14	1.15	3.21	2	2
11028500	Rat	0.41	10.67	2.38	5.18	2	3
16079300	Red Rock	1.43	19.51	1.77	3.73	2	3
11004300	Roosevelt	6.42	39.32	1.28	3.38	2	2
56036000	Rose	4.82	41.76	1.12	3.42	2	2
16023000	Rose	5.32	27.43	1.75	5.77	2	2
01020400	Round	3.11	38.10	1.10	3.03	2	2
18031100	Rush-Hen	3.61	32.00	1.36	4.19	2	2
16062900	Sea Gull	16.32	44.19	1.44	4.65	2	2
31008400	Shallow	2.15	25.91	1.48	4.62	2	2
31055400	Siseebakwet	5.29	32.00	1.50	3.89	2	2
69018100	Slim	1.20	14.93	2.22	4.88	2	3
69011100	Smith	0.73	15.54	1.88	4.22	2	3
31025500	Snaptail	0.59	21.33	1.30	3.48	2	2
29011700	Spider	2.20	29.26	1.32	3.75	2	2
69076100	Spring	0.79	18.29	1.63	4.57	2	2
73018300	St. Anna	0.48	32.61	0.81	2.45	2	2
56043700	Stalker	5.18	28.95	1.65	3.45	2	3
21010100	Stony	0.35	17.68	1.38	3.54	2	2
04008500	Swenson	1.57	23.16	1.53	5.33	2	2



DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
56038700	Sybil	2.86	22.55	1.82	5.21	2	2
73024900	Sylvia	0.33	17.07	1.40	2.86	2	3
56034800	Tenter	0.34	19.20	1.25	2.44	2	3
38035100	Thomas	5.96	33.53	1.47	4.91	2	2
69033700	Thumb	0.21	16.76	1.28	3.35	2	2
11006200	Thunder	5.38	28.95	1.66	5.11	2	2
69021300	Toe	0.67	17.37	1.65	4.57	2	2
38071500	Triangle	1.25	13.11	2.55	5.42	2	3
29014800	Upper Bottle	1.88	16.76	2.21	4.94	2	3
11010500	Upper Trelipe	1.66	21.03	1.71	3.78	2	3
38049100	Vera	0.99	16.76	1.88	5.26	2	2
16026700	Vernon	0.94	30.78	1.01	3.00	2	2
31039200	Wabana	8.97	35.05	1.56	4.85	2	2
11005900	Washburn	6.29	33.83	1.48	3.74	2	2
31028100	Wasson	1.68	20.42	1.76	3.93	2	3
03032800	White Earth	8.42	36.57	1.47	3.86	2	2
18031000	Whitefish	29.84	42.06	1.76	3.44	2	3
56035500	Wimer	1.11	17.68	1.84	3.93	2	3
11025000	Ada	3.94	18.29	2.44	4.11	3	3
69022300	Agnes	3.98	9.14	4.89	3.35	3	3
01004000	Aitkin	1.97	10.67	3.51	2.08	3	3
49007900	Alexander	11.19	19.51	2.96	4.71	3	3
38033000	Alice	6.34	16.15	3.11	2.90	3	3
16075900	Alpine	3.40	19.81	2.17	4.57	3	3
16062200	Alton	4.21	21.94	2.06	4.11	3	3
38040100	Alworth	0.82	10.06	2.99	2.59	3	3
38033600	Amber	0.55	8.23	3.30	3.00	3	3
38022700	Amoeber	1.56	33.53	1.05	1.52	3	3
21008500	Andrew	3.83	25.30	1.75	2.85	3	3
04003800	Andrusia	6.11	18.29	2.72	3.05	3	3
38021000	Ashdick	0.40	15.24	1.66	3.05	3	3
31069000	Aspen	0.39	7.92	3.15	2.44	3	3
11028300	Baby	2.85	21.03	1.95	3.75	3	3
29020800	Bad Axe	1.10	11.89	2.72	4.72	3	3
38063700	Bald Eagle	5.01	10.97	4.31	2.59	3	3
31081200	Ball Club	15.94	25.91	2.44	3.64	3	3
31025900	Balsam	2.87	11.28	3.65	3.25	3	3
01007300	Bass	0.23	17.68	1.24	1.34	3	3
31057600	Bass	9.74	23.16	2.41	3.93	3	3
69055300	Bass	0.60	10.67	2.61	3.96	3	3
38064500	Basswood	91.99	33.83	2.89	2.98	3	3
31019700	Battle	0.81	4.57	6.55	2.91	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
18003400	Bay	9.68	22.55	2.47	4.18	3	3
09003400	Bear	0.37	9.45	2.61	2.70	3	3
69011500	Bear Island	9.52	18.90	2.94	2.33	3	3
69008900	Bear Trap	0.49	11.58	2.29	2.59	3	3
31072600	Bello	2.00	17.68	2.13	3.28	3	3
04013500	Beltrami	2.20	15.24	2.53	3.90	3	3
18035500	Bertha	1.35	19.51	1.75	3.12	3	3
04004900	Big	14.30	10.67	5.77	3.86	3	3
77008400	Big Birch	8.53	24.69	2.19	2.30	3	3
15000100	Big LaSalle	0.89	14.63	2.10	2.44	3	3
56013000	Big Pine	19.15	23.16	2.86	2.01	3	3
04003100	Big Rice	2.50	3.96	10.04	2.53	3	3
01006200	Big Sandy	26.42	25.60	2.80	1.24	3	3
73011700	Big Spunk	1.78	11.58	3.15	2.72	3	3
77002300	Big Swan	3.72	13.72	3.20	2.32	3	3
11041200	Birch	5.20	13.72	3.48	4.04	3	3
38053200	Birch	2.88	10.36	3.97	3.93	3	3
69000300	Birch	22.79	7.62	9.07	1.33	3	3
31083400	Bird's Eye	0.33	15.24	1.58	3.05	3	3
04015700	Black	1.00	12.80	2.47	3.23	3	3
18014000	Black Bear	0.89	14.63	2.10	3.66	3	3
04006900	Blackduck	10.51	8.53	6.67	2.67	3	3
31056100	Blackwater	2.73	21.94	1.85	2.86	3	3
11027400	Blackwater	2.92	20.42	2.02	3.86	3	3
56024000	Blanche	5.13	19.51	2.44	3.59	3	3
56021200	Boedigheimer	0.71	7.92	3.67	3.13	3	3
69010000	Boot	1.27	8.23	4.08	1.88	3	3
04021100	Bootleg	1.08	9.14	3.53	2.59	3	3
18002000	Borden	3.87	25.60	1.73	2.70	3	3
11035000	Bowen	0.71	7.62	3.81	2.13	3	3
31081300	Bowstring	37.33	9.75	8.01	1.83	3	3
11014300	Boy	12.90	13.72	4.37	3.10	3	3
31014700	Bray	0.79	13.41	2.23	1.58	3	3
21010200	Brophy	1.17	13.41	2.45	3.02	3	3
16034800	Brule	18.69	23.77	2.77	4.80	3	3
04004200	Buck	1.10	12.19	2.65	4.88	3	3
03035000	Buffalo	1.52	11.58	3.03	2.91	3	3
21004900	Burgen	0.74	13.11	2.24	3.79	3	3
31053000	Busties	0.96	13.41	2.33	2.29	3	3
38047700	Cache	0.17	4.57	4.44	1.22	3	3
04019600	Campbell	1.92	7.62	4.89	2.58	3	3
86028100	Caroline	0.51	13.72	1.95	1.46	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
04014100	Carr	0.12	9.14	2.02	2.90	3	3
04003000	Cass	63.14	36.57	2.44	4.02	3	3
86022700	Cedar	3.39	32.92	1.30	2.49	3	3
01020900	Cedar	7.16	32.00	1.62	2.92	3	3
31082900	Cedar	0.68	13.72	2.09	3.60	3	3
11028900	Cedar	0.57	12.80	2.15	3.75	3	3
38081000	Cedar	1.88	13.72	2.70	3.35	3	3
11026300	Child	1.28	8.84	3.81	3.66	3	3
18035600	Clamshell	0.77	13.41	2.21	2.56	3	3
04034300	Clearwater	4.08	19.81	2.27	3.06	3	3
18003800	Clearwater	3.56	16.46	2.64	3.77	3	3
18013100	Clinker	0.34	10.67	2.26	3.51	3	3
56023800	Clitherall	10.09	21.03	2.68	4.07	3	3
03028600	Cotton	6.96	8.53	6.02	3.23	3	3
21010300	Cowdrey	0.96	15.85	1.98	3.58	3	3
69022000	Crab	2.19	17.37	2.21	3.40	3	3
16035700	Crab	0.32	5.18	4.59	4.34	3	3
69061600	Crane	12.50	24.38	2.44	1.77	3	3
38081700	Crooked	32.15	50.29	1.50	2.74	3	3
11049400	Crooked	2.14	22.55	1.70	2.29	3	3
31019300	Crooked	1.69	18.29	1.97	1.86	3	3
18031200	Cross Lake Reservoir	7.09	25.60	2.02	3.66	3	3
56074900	Crystal	5.33	16.76	2.87	2.90	3	3
69032500	Cummings	4.54	12.50	3.69	2.74	3	3
31085700	Cut Foot Sioux	11.21	23.77	2.43	3.72	3	3
31042900	Cutaway	1.04	16.76	1.91	3.22	3	3
18027100	Daggett	0.91	7.01	4.41	2.58	3	3
01009600	Dam	2.60	14.63	2.74	3.19	3	3
21008000	Darling	3.86	18.90	2.35	3.08	3	3
56038300	Dead	31.99	19.81	3.80	2.39	3	3
04023000	Deer	1.06	12.80	2.51	3.54	3	3
31033400	Deer	7.08	15.24	3.38	2.90	3	3
56029800	Deer	1.85	7.92	4.65	3.39	3	3
03038100	Detroit	12.48	27.13	2.19	2.97	3	3
69091200	Dewey	0.79	12.19	2.45	3.54	3	3
38048800	Disappointment	3.51	16.46	2.63	3.45	3	3
31092100	Dixon	2.49	8.84	4.50	1.76	3	3
31088200	Dora	1.81	5.49	6.69	2.91	3	3
31090400	Dunbar	1.03	9.14	3.48	1.88	3	3
16063400	Dyers	0.27	7.01	3.26	2.37	3	3
29025600	Eagle	1.66	23.47	1.53	2.91	3	3
18029600	Eagle	1.45	10.97	3.16	3.05	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
56013800	East Battle	7.89	26.52	2.00	3.88	3	3
56037800	East Lost	2.03	10.97	3.44	2.91	3	3
16004200	East Pike	2.01	12.19	3.09	4.22	3	3
18030500	Edward	8.23	22.86	2.34	4.32	3	3
29007200	Eighth Crow Wing	1.99	9.14	4.11	2.85	3	3
03015900	Elbow	4.05	23.16	1.94	3.51	3	3
69074400	Elbow	6.72	18.29	2.78	1.88	3	3
31049000	Elizabeth	0.78	12.80	2.32	3.10	3	3
69049600	Embarrass	1.79	5.79	6.32	1.18	3	3
38049800	Ensign	5.70	9.14	5.34	2.84	3	3
69056500	Esquagama	1.48	27.43	1.27	2.22	3	3
03050300	Eunice	1.32	9.14	3.70	4.22	3	3
77015400	Fairy	1.20	11.28	2.94	3.60	3	3
38081100	Fall	8.80	9.75	5.58	2.03	3	3
38077900	Farm	5.38	17.07	2.82	2.09	3	3
01015900	Farm Island	8.32	17.07	3.15	3.76	3	3
31060900	Fawn	0.68	11.28	2.54	3.66	3	3
69008500	Fenske	0.43	13.11	1.95	4.27	3	3
29009200	Fifth Crow Wing	1.59	10.67	3.33	2.86	3	3
29008600	First Crow Wing	2.13	4.57	8.36	1.53	3	3
56024700	Fischer (Carroll)	0.27	10.06	2.26	2.44	3	3
29024200	Fish Hook	6.61	23.16	2.19	3.28	3	3
49013700	Fish Trap	5.28	12.80	3.74	3.69	3	3
31018300	Five Island	0.71	10.06	2.88	3.86	3	3
11035100	Five Point	0.89	11.28	2.72	4.36	3	3
03038700	Floyd	4.91	10.36	4.54	4.55	3	3
38052800	Four	2.65	7.62	5.30	2.06	3	3
38081300	Fourtown	7.70	7.62	6.91	2.35	3	3
04016200	Fox	0.60	5.79	4.80	4.02	3	3
56075900	Franklin	5.41	14.63	3.30	3.21	3	3
29024100	Frontenac	0.83	4.88	6.18	1.98	3	3
38070100	Gabbro	3.63	15.24	2.86	1.80	3	3
38078200	Garden	2.71	16.76	2.42	1.72	3	3
69035000	Ge-Be-On-Equat	2.46	16.76	2.36	3.05	3	3
21005200	Geneva	2.55	19.20	2.08	3.14	3	3
29021600	George	3.23	8.84	4.80	2.99	3	3
38050800	Gibson	0.14	7.31	2.63	4.05	3	3
04002400	Gilstad	1.19	16.76	1.97	2.70	3	3
38072600	Good	0.72	15.54	1.87	3.20	3	3
56036800	Graham	0.85	10.36	2.93	2.52	3	3
31062400	Grave	2.02	11.89	3.17	3.86	3	3
34007900	Green	21.89	33.53	2.04	3.07	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
16063200	Gull	0.74	12.19	2.41	3.61	3	3
11030500	Gull	38.13	24.38	3.22	3.22	3	3
31048000	Gunn	1.38	11.89	2.89	3.12	3	3
09003800	Hanging Horn	1.65	24.38	1.47	2.25	3	3
01017000	Hanging Kettle	1.22	10.67	3.12	2.16	3	3
18004400	Hanks	0.65	13.72	2.07	4.40	3	3
31002000	Hart	1.32	16.76	2.02	3.24	3	3
31015400	Hartley	1.14	14.93	2.19	2.94	3	3
38036900	Hatchet	0.51	12.19	2.19	1.50	3	3
29030000	Hattie	1.05	11.89	2.69	2.67	3	3
11023200	Hattie	1.96	9.14	4.09	2.86	3	3
11019900	Hay	1.42	17.07	2.02	3.23	3	3
09001000	Hay	0.87	4.88	6.26	2.44	3	3
69046900	Heritage	0.74	13.11	2.24	2.90	3	3
01017900	Hickory	0.80	9.75	3.06	3.47	3	3
31048100	Highland	0.41	11.58	2.19	3.50	3	3
29024900	Hinds	1.19	10.97	3.01	4.22	3	3
56078200	Hoot	0.63	6.10	4.62	2.70	3	3
38079200	Horse	2.76	7.62	5.35	2.90	3	3
73015700	Horseshoe	2.23	17.37	2.22	1.27	3	3
11047200	Howard	1.48	18.29	1.91	3.97	3	3
18037500	Hubert	5.24	25.30	1.89	3.72	3	3
21012300	Ida	17.36	32.31	2.00	4.04	3	3
38039700	Insula	11.97	19.20	3.06	2.69	3	3
21007600	Irene	2.55	13.41	2.98	2.46	3	3
69012100	Iron	7.49	18.29	2.86	4.19	3	3
04014000	Irving	2.48	5.79	6.85	1.46	3	3
29025400	Island	2.20	19.81	1.94	2.74	3	3
31021700	Island	0.25	10.67	2.09	2.21	3	3
31091300	Island	12.50	10.67	5.57	2.90	3	3
69037200	Island Lake Reservoir	32.84	28.65	2.64	1.77	3	3
15001600	Itasca	4.36	12.19	3.75	1.96	3	3
31065700	Jack the Horse	1.55	13.72	2.57	3.81	3	3
31056500	Jay Gould	1.72	10.06	3.60	3.43	3	3
21005500	Jessie	0.43	7.92	3.22	1.99	3	3
31078600	Jessie	7.10	12.80	4.03	2.56	3	3
56087700	Jewett	2.98	22.86	1.82	3.13	3	3
69069100	Johnson	6.78	26.82	1.90	3.16	3	3
31068700	Johnson	1.23	15.54	2.14	3.37	3	3
69084500	Kabetogama	104.29	24.38	4.14	2.59	3	3
04000700	Kitchi	7.23	15.24	3.40	2.95	3	3
69074800	Kjostad	1.61	15.24	2.34	1.87	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
69022400	Lac la Croix	137.94	51.20	2.12	3.63	3	3
39000200	Lake of the Woods	3847.77	10.97	22.70	1.03	3	3
31023100	Lawrence	1.60	9.75	3.65	1.60	3	3
21005600	Le Homme Dieu	7.06	25.91	1.99	3.19	3	3
69079600	Leander	1.00	13.72	2.31	4.37	3	3
11003700	Leavitt	0.53	18.29	1.47	2.65	3	3
11020300	Leech	451.53	45.72	3.19	2.74	3	3
11036700	Lind	1.53	8.23	4.27	2.69	3	3
61003700	Linka	0.80	15.24	1.96	4.05	3	3
77008900	Little Birch	3.39	27.13	1.58	2.66	3	3
31075800	Little Bowstring	1.29	10.06	3.35	2.47	3	3
11016700	Little Boy	5.55	22.55	2.15	3.15	3	3
31085200	Little Cut Foot Sioux	2.67	6.10	6.63	1.50	3	3
69104000	Little Dry	0.05	8.23	1.84	3.15	3	3
03038600	Little Floyd	0.83	10.36	2.91	2.83	3	3
38070300	Little Gabbro	0.62	7.92	3.55	1.30	3	3
31078400	Little Jessie	2.58	15.24	2.63	4.84	3	3
31061000	Little Moose	1.10	7.01	4.62	2.81	3	3
56076100	Little Pelican	1.40	7.62	4.51	2.47	3	3
56014200	Little Pine	7.97	19.20	2.77	2.38	3	3
18026600	Little Pine	1.57	10.97	3.22	2.53	3	3
18013900	Little Rabbit	0.69	9.14	3.15	2.74	3	3
31071600	Little Rice	0.66	9.75	2.92	2.13	3	3
31085300	Little Sand	1.46	5.79	6.00	2.40	3	3
69008600	Little Sletten	0.07	9.75	1.66	2.74	3	3
31034100	Little Split Hand	0.90	7.62	4.05	1.94	3	3
31079700	Little Spring	0.54	3.05	8.89	2.19	3	3
69129000	Little Sturgeon	1.08	6.71	4.80	1.62	3	3
69045500	Little Trout	2.18	11.28	3.41	2.74	3	3
31077900	Little Turtle	1.92	8.84	4.21	1.66	3	3
04015500	Little Turtle	1.88	7.62	4.86	2.16	3	3
69060800	Little Vermillion	5.39	15.85	3.04	1.76	3	3
11003000	Little Vermillion	0.54	16.76	1.62	2.74	3	3
31085000	Little Winnibigoshish	3.80	8.53	5.17	2.64	3	3
21014400	Lobster	5.30	19.81	2.42	2.29	3	3
69093600	Locator	0.57	15.85	1.73	2.17	3	3
77002700	Long	1.51	19.20	1.82	3.19	3	3
03038300	Long	1.45	18.59	1.86	3.55	3	3
56078400	Long	3.06	22.25	1.88	3.26	3	3
69085900	Long	1.08	10.97	2.94	1.88	3	3
73013900	Long	1.86	10.67	3.46	1.30	3	3
18000200	Long / Tame Fish	0.45	17.68	1.46	2.74	3	3
31057900	Loon	0.23	12.19	1.80	1.68	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
69047000	Loon	12.55	21.33	2.79	2.51	3	3
21010500	Lottie	0.20	9.45	2.23	3.58	3	3
21009400	Louise	0.89	10.06	3.05	3.16	3	3
31024700	Lower Balsam	1.15	8.84	3.70	2.74	3	3
18040300	Lower Cullen	2.07	11.89	3.19	4.06	3	3
18024300	Lower Mission	2.83	8.23	4.98	2.68	3	3
73012300	Lower Spunk	1.13	8.38	3.89	2.75	3	3
11031300	Lower Sucker	2.37	10.67	3.68	1.95	3	3
11012900	Lower Trelipe	2.44	9.75	4.05	2.64	3	3
80003000	Lower Twin	1.58	7.92	4.48	1.89	3	3
31070500	Lundeen	0.31	9.14	2.58	2.59	3	3
38009000	Malberg	1.64	11.28	3.17	2.44	3	3
29015100	Mantrap	6.30	20.73	2.42	4.11	3	3
03015800	Many Point	7.03	28.04	1.84	3.40	3	3
31077300	Maple	0.92	11.89	2.61	3.05	3	3
11022200	Margaret	0.90	7.92	3.89	1.55	3	3
56024300	Marion	6.74	18.90	2.70	3.39	3	3
04014200	Marquette	2.04	15.54	2.43	2.77	3	3
21009200	Mary	9.60	12.19	4.57	2.18	3	3
03050000	Maud	2.21	9.75	3.96	3.94	3	3
44008000	McCraney	1.09	13.11	2.46	3.43	3	3
11026100	McKeown	0.60	11.28	2.46	4.60	3	3
03047500	Melissa	7.41	11.28	4.63	2.76	3	3
18037700	Middle Cullen	1.55	14.63	2.41	3.93	3	3
31039600	Middle Hanson	0.26	9.75	2.32	3.20	3	3
21018000	Mill	1.87	12.19	3.03	2.16	3	3
48000200	Mille Lacs	536.50	12.80	11.89	3.33	3	3
18013300	Miller	0.43	10.67	2.40	3.35	3	3
21008300	Miltona	23.64	32.00	2.18	3.37	3	3
61013000	Minnewaska	28.79	9.75	7.51	2.66	3	3
38064400	Moose	4.90	19.81	2.38	3.84	3	3
31072200	Moose	5.12	18.59	2.56	4.29	3	3
38081600	Moosecamp	0.77	4.88	6.07	2.90	3	3
04015200	Movil	3.74	15.24	2.89	3.74	3	3
69027500	Mud	0.58	8.23	3.35	3.96	3	3
69007800	Mudro	0.38	23.16	1.08	1.52	3	3
69068400	Mukooda	3.05	23.77	1.76	3.31	3	3
11020000	Mule	1.85	14.32	2.57	4.83	3	3
56022900	Murphy	1.26	9.14	3.66	1.37	3	3
69069300	Namakan	101.74	45.72	2.20	2.85	3	3
38061900	Newfound	2.45	13.72	2.88	3.51	3	3
38078400	Newton	2.02	14.32	2.63	1.98	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
18039900	Nisswa	0.84	7.01	4.32	4.11	3	3
18010400	Nokay	2.67	12.80	3.16	2.60	3	3
18037200	North Long	24.28	29.56	2.37	4.28	3	3
31019000	North Twin	1.01	12.80	2.48	3.35	3	3
44002300	North Twin	3.65	4.88	8.96	2.67	3	3
21009500	North Union	0.47	12.80	2.05	3.10	3	3
38060500	One	3.55	17.37	2.50	2.34	3	3
69006100	One Pine	1.47	3.96	8.79	1.37	3	3
77021500	Osakis	25.38	22.25	3.19	2.37	3	3
73001500	Otter	0.39	15.54	1.61	2.78	3	3
56024200	Otter Tail	55.57	36.57	2.36	3.47	3	3
31010600	Ox Hide	0.49	12.19	2.17	4.19	3	3
38052600	Parent	1.32	15.24	2.22	4.30	3	3
18030800	Pelican	33.41	31.70	2.40	4.67	3	3
56078600	Pelican	16.14	16.76	3.78	3.65	3	3
38022000	Perent	7.29	8.53	6.09	1.52	3	3
11041500	Pike Bay	19.27	28.95	2.29	4.59	3	3
11032000	Pillager	0.83	11.89	2.54	3.35	3	3
04003200	Pimushe	5.13	12.19	3.90	3.00	3	3
11041100	Pine Mountain	6.34	24.38	2.06	2.71	3	3
29015600	Plantagenet	10.24	19.81	2.86	2.77	3	3
18008800	Platte	7.07	7.01	7.36	1.81	3	3
86025100	Pleasant	2.06	22.55	1.68	2.42	3	3
31082400	Portage	0.28	18.29	1.26	2.29	3	3
18006900	Portage	0.49	17.37	1.52	2.71	3	3
11049000	Portage	1.44	19.81	1.75	3.25	3	3
18005000	Portage	1.11	11.28	2.88	3.63	3	3
11020400	Portage	6.02	16.76	2.96	3.00	3	3
29024300	Potato	8.50	26.52	2.04	3.19	3	3
69084800	Prairie	3.43	14.32	3.00	1.72	3	3
31038400	Prairie	4.31	9.45	4.82	1.67	3	3
56091500	Prairie	4.11	6.71	6.72	2.54	3	3
18020900	Pug Hole	0.19	9.14	2.30	4.42	3	3
21016000	Rachel	2.01	19.81	1.90	2.98	3	3
69069400	Rainy	893.93	49.07	3.52	2.64	3	3
11022000	Ray	0.55	8.23	3.31	2.97	3	3
31071700	Rice	3.47	20.73	2.08	4.40	3	3
73019600	Rice	6.64	12.50	4.06	1.89	3	3
01014600	Ripple	2.25	11.89	3.26	1.85	3	3
01007000	Round	0.75	15.85	1.86	2.59	3	3
03015500	Round	4.40	21.03	2.18	3.90	3	3
49001900	Round	0.49	8.84	3.00	2.59	3	3



DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
18037300	Round	6.66	15.54	3.27	3.05	3	3
31089600	Round	11.45	7.31	7.95	2.05	3	3
18039800	Roy	1.10	7.92	4.08	3.49	3	3
56014100	Rush	21.61	20.73	3.29	2.12	3	3
31083200	Rush Island	1.20	9.75	3.39	2.68	3	3
38022500	Sagus	0.70	11.28	2.56	3.20	3	3
03035900	Sallie	5.04	15.24	3.11	2.39	3	3
31082600	Sand	17.52	21.33	3.03	2.86	3	3
69061700	Sand Point	35.91	56.08	1.38	2.28	3	3
44010800	Sargent	0.52	4.57	5.87	2.13	3	3
31034500	Scraper	0.62	8.53	3.29	2.79	3	3
29008500	Second Crow Wing	0.73	10.67	2.74	1.89	3	3
18009000	Serpent	4.28	19.81	2.30	4.55	3	3
29009100	Seventh Crow Wing	1.03	12.80	2.49	2.17	3	3
69006900	Shagawa	9.60	14.63	3.80	2.77	3	3
31091000	Shallow Pond	0.71	4.27	6.81	1.75	3	3
69092500	Shannon	0.55	3.35	8.11	1.83	3	3
38037300	Shepo	0.21	5.18	4.13	1.83	3	3
29004300	Shingobee	0.65	12.19	2.33	4.04	3	3
69093300	Side	1.51	9.75	3.59	3.72	3	3
56018000	Siverson	0.55	12.50	2.18	3.51	3	3
11014600	Six Mile	5.21	20.73	2.31	2.64	3	3
29009300	Sixth Crow Wing	1.30	12.19	2.77	2.81	3	3
31050200	Slauson	0.43	12.19	2.10	4.27	3	3
18002800	Smith	1.79	16.46	2.22	3.10	3	3
44004500	Snider	2.56	8.84	4.52	3.25	3	3
38077800	South Farm	2.50	9.14	4.35	1.63	3	3
18013600	South Long	5.32	14.32	3.35	2.74	3	3
31000300	South Sturgeon	0.78	13.11	2.27	1.31	3	3
31055500	South Sugar	0.36	10.97	2.23	4.45	3	3
16045700	South Temperance	0.83	7.31	4.12	3.35	3	3
31019100	South Twin	0.72	12.19	2.39	3.73	3	3
44001400	South Twin	4.05	8.84	5.07	2.86	3	3
01017800	Spirit	2.15	14.93	2.56	3.99	3	3
38053100	Splash	0.39	5.49	4.56	3.51	3	3
31035300	Split Hand	5.75	10.36	4.73	1.75	3	3
31078900	Spring	0.51	10.97	2.44	2.90	3	3
69065100	St. Mary's	0.87	13.41	2.28	4.58	3	3
56038500	Star	19.11	28.65	2.31	3.96	3	3
11050400	Steamboat	7.19	28.35	1.83	3.47	3	3
69047500	Steep	0.35	12.19	1.99	2.87	3	3
03001000	Straight	1.71	19.20	1.88	2.83	3	3

DOW number	Lake Name	Surface area (km <sup>2</sup> )	Maximum depth (m)	Geometry ratio (m <sup>-0.5</sup> )	SD (m)	Refuge lake Tier	
						Fixed	Variable
03032300	Strawberry	6.16	12.19	4.09	4.95	3	3
56019100	Stuart	2.83	14.93	2.75	4.37	3	3
69020500	Stuart	3.04	12.19	3.43	1.98	3	3
38078100	Stub	0.36	6.10	4.03	2.13	3	3
38053000	Sucker	1.55	9.45	3.73	3.81	3	3
86023300	Sugar	4.11	21.03	2.14	2.98	3	3
49001600	Sullivan	4.94	17.37	2.71	2.55	3	3
31006700	Swan	10.01	19.81	2.84	2.84	3	3
11013300	Swift	1.43	15.85	2.18	2.83	3	3
29004500	Tenth Crow Wing	0.70	12.19	2.37	3.40	3	3
29007700	Third Crow Wing	2.60	10.67	3.77	2.02	3	3
38060000	Three	3.57	11.28	3.85	2.90	3	3
04013400	Three Island	2.74	7.62	5.34	3.26	3	3
29000500	Tripp	0.59	19.81	1.40	2.74	3	3
69049800	Trout	30.94	29.87	2.50	4.94	3	3
44000300	Tulaby	3.13	13.11	3.21	3.08	3	3
77008800	Turtle	0.42	11.89	2.14	2.97	3	3
04015900	Turtle	5.81	13.72	3.58	3.20	3	3
38060800	Two	1.95	10.67	3.50	2.49	3	3
03001700	Two Inlets	2.34	18.29	2.14	2.74	3	3
18037600	Upper Cullen	1.76	12.19	2.99	2.86	3	3
11021800	Upper Gull	1.50	16.46	2.13	2.53	3	3
18024200	Upper Mission	3.31	10.97	3.89	3.17	3	3
18009600	Upper South Long	3.25	14.32	2.96	2.22	3	3
69037800	Vermilion	164.20	23.16	4.89	2.68	3	3
21005400	Victoria	1.70	18.29	1.97	2.83	3	3
11017100	Wabedo	4.80	28.95	1.62	2.62	3	3
56031000	Walker	2.19	8.84	4.35	2.21	3	3
69093700	War Club	0.37	12.19	2.02	3.54	3	3
11049300	Welch	0.76	17.98	1.64	2.27	3	3
56023900	West Battle	22.77	32.92	2.10	3.86	3	3
18029700	West Fox	1.91	16.76	2.22	4.72	3	3
56011400	West Leaf	2.77	16.76	2.43	3.22	3	3
56048100	West Lost	2.93	4.88	8.48	2.46	3	3
69000400	White Iron	13.88	14.32	4.26	1.49	3	3
18000100	Whitefish	2.82	18.90	2.17	3.67	3	3
31084300	Whitefish	2.28	15.54	2.50	2.06	3	3
69069000	Winchester	1.46	15.24	2.28	2.66	3	3
04007900	Wolf	4.43	17.37	2.64	3.07	3	3
11020100	Woman	19.36	16.46	4.03	2.73	3	3
73008900	Zumwalde	0.43	7.01	3.65	0.68	3	3

## Appendix E Names and Geographic Locations of Tier 1 plus Tier 2 Refuge Cisco Lakes in Minnesota

Table E.1 Names and geographic locations of Tier 1 plus Tier 2 cisco refuge lakes in Minnesota ranked by the number of times (max = 5; min = 0) that they were identified as refuge lakes by five different lake and weather station pairings. Simulations were made for two future climate scenarios (MIROC 3.2 and CGCM 3.1) for fixed and variable benchmark periods (AvgATDO3<sub>FB</sub>, AvgATDO3<sub>VB</sub>, Table 3.1, lines 6 and 12).

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
18020800	Allen	424014.0	5182910.0	5	5	4	4
31034900	Antler	466207.0	5275090.0	5	5	5	5
11046900	Anway	376737.0	5211040.0	5	5	3	3
38050200	Ashigan	624749.0	5320500.0	5	5	5	5
03008500	Bad Medicine	317655.0	5221710.0	5	5	5	5
01004600	Ball Bluff	478651.0	5197700.0	5	5	5	5
18003000	Barbour	432303.0	5123450.0	5	5	5	5
31027800	Barwise	468711.0	5267270.0	5	5	5	5
11006900	Bass	427017.0	5195460.0	5	5	4	4
18035800	Bass	409240.0	5167800.0	5	5	3	3
77002400	Bass	366498.0	5085360.0	5	5	2	2
29004800	Benedict	371657.0	5221980.0	5	5	3	3
11027700	Big Deep	394595.0	5196110.0	5	5	5	5
29018500	Big Sand	350361.0	5207040.0	5	5	5	5
31079300	Big Too Much	440872.0	5277200.0	5	5	5	5
18031500	Big Trout	411532.0	5174230.0	5	5	5	5
18021100	Blue	423977.0	5180350.0	5	5	5	5
29018400	Blue	347677.0	5209100.0	5	5	5	5
31039500	Bluewater	458235.0	5252040.0	5	5	5	5
38050300	Boot	622470.0	5319150.0	5	5	4	4
69011800	Burntside	581302.0	5310720.0	5	5	5	5
04029700	Buzzle	339646.0	5276030.0	5	5	5	5
21005700	Carlos	316947.0	5091130.0	5	5	2	2
49014000	Cedar	372840.0	5074700.0	5	5	2	2
77012000	Charlotte	355635.0	5090450.0	5	5	5	5
31074900	Chase	444194.0	5246180.0	5	5	5	5
38016600	Cherry	641319.0	5333210.0	5	5	5	5
21014500	Chippewa	303158.0	5096880.0	5	5	1	1
18036400	Clear	405698.0	5166480.0	5	5	3	3
16013900	Clearwater	697251.0	5328720.0	5	5	5	5
31054000	Clubhouse	457155.0	5272470.0	5	5	5	5
11016300	Cooper	408898.0	5201950.0	5	5	4	4
15009000	Deep	320013.0	5283860.0	5	5	5	5

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
11023700	Deep Portage	393944.0	5191690.0	5	5	5	5
31071900	Deer	449898.0	5247700.0	5	5	1	1
16061600	Devils Elbow	661998.0	5338700.0	5	5	2	2
16023200	Duncan	688691.0	5328360.0	5	5	5	5
18029800	East Fox	417710.0	5177450.0	5	5	3	3
86028900	East Lake Sylvia	406210.0	5011660.0	5	5	2	2
18039600	Edna	399225.0	5154230.0	5	5	3	3
56051400	Elbow	283903.0	5160430.0	5	5	3	3
29003600	Eleventh Crow Wing	369070.0	5208250.0	5	5	1	1
15001000	Elk	331973.0	5228580.0	5	5	4	4
11046600	Fifth	376618.0	5212610.0	5	5	5	5
16014700	Flour	693783.0	5325350.0	5	5	5	5
31046300	Fox	458903.0	5272300.0	5	5	4	4
38037200	Fraser	634053.0	5318890.0	5	5	5	5
16031900	Gaskin	682846.0	5319510.0	5	5	4	4
11017400	Girl	405649.0	5204090.0	5	5	4	4
16061700	Gneiss	662965.0	5338100.0	5	5	4	4
16058000	Granite	666146.0	5335850.0	5	5	5	5
04021700	Grant	348931.0	5261900.0	5	5	5	5
38071800	Greenstone	603736.0	5309460.0	5	5	2	2
16007700	Greenwood	710490.0	5320110.0	5	5	4	4
58012300	Grindstone	499427.0	5107650.0	5	5	5	5
69048700	Gun	559422.0	5352420.0	5	5	5	5
16035600	Gunflint	672943.0	5329800.0	5	5	5	5
31045200	Gunn	459357.0	5265500.0	5	5	5	5
31037300	Hale	458520.0	5232670.0	5	5	4	4
31091100	Hamrey	406242.0	5285940.0	5	5	5	5
38020600	Hanson	642735.0	5333610.0	5	5	5	5
31077100	Hatch	443582.0	5278860.0	5	5	4	4
31046600	Horseshoe	461830.0	5272270.0	5	5	4	4
03015600	Ice Cracking	306412.0	5209340.0	5	5	3	3
38040000	Ima	628408.0	5319480.0	5	5	4	4
18026900	Island-Loon	413256.0	5173460.0	5	5	5	5
11040000	Jack	390145.0	5213090.0	5	5	5	5
38051100	Jordan	626367.0	5318710.0	5	5	4	4
29007500	Kabekona	366808.0	5225200.0	5	5	4	4
18036100	Kimball	408024.0	5167390.0	5	5	5	5
38040400	Knife	634276.0	5328310.0	5	5	5	5
29030900	LaSalle	335945.0	5244920.0	5	5	5	5
21010600	Latoka	310959.0	5082980.0	5	5	2	2
31073900	Leighton	442924.0	5227310.0	5	4	1	1
01005700	Little Ball Bluff	479174.0	5198320.0	5	5	4	4
31057500	Little Bass	454599.0	5237110.0	5	5	4	4

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
09003500	Little Hanging Horn	524719.0	5147700.0	5	5	4	4
38022900	Little Knife	636926.0	5333150.0	5	5	5	5
56032800	Little McDonald	292892.0	5165460.0	5	5	5	5
29015000	Little Sand	353063.0	5205920.0	5	5	5	5
31077800	Little Too Much	441738.0	5274880.0	5	5	5	5
31039400	Little Trout	458897.0	5254040.0	5	5	5	5
69068200	Little Trout	535431.0	5360490.0	5	5	5	5
31039900	Little Wabana	462902.0	5249760.0	5	5	4	4
01008900	Long	462404.0	5148280.0	5	5	5	5
11048000	Long	378329.0	5214670.0	5	5	3	3
29016100	Long	347647.0	5194460.0	5	5	3	3
31078100	Long	441433.0	5280740.0	5	5	5	5
16044800	Loon	671907.0	5327530.0	5	5	5	5
31057100	Loon	451222.0	5231220.0	5	5	4	4
29018000	Lower Bottle	352030.0	5210180.0	5	5	5	5
31023900	Lower Hanson	466217.0	5250430.0	5	5	5	5
18037800	Lower Hay	401812.0	5169230.0	5	5	3	3
16046300	Magnetic	665952.0	5330660.0	5	5	5	5
11028200	Mann	397848.0	5203010.0	5	5	3	3
11048200	May	379050.0	5216490.0	5	5	3	3
03037100	Meadow	280699.0	5181750.0	5	5	5	5
21010800	Mina	307985.0	5085170.0	5	5	5	5
77002200	Mons	367464.0	5087210.0	5	5	5	5
16004300	Moose	716878.0	5331470.0	5	5	5	5
16023400	Moss	687734.0	5326820.0	5	5	5	5
11004700	Mule	424154.0	5188480.0	5	5	4	4
29023700	Newman	351221.0	5250800.0	5	5	5	5
29002500	Ninth Crow Wing	365366.0	5204220.0	5	5	1	1
16033100	North	681002.0	5331430.0	5	5	5	5
31065300	North Star	449897.0	5266910.0	5	5	4	4
31077500	No-ta-she-bun	441437.0	5222430.0	5	5	4	4
38064000	Ojibway	608799.0	5311710.0	5	5	5	5
31021900	O'Reilly	467570.0	5245500.0	5	5	5	5
38021100	Ottertrack	641140.0	5336920.0	5	5	5	5
69033000	Oyster	566301.0	5341780.0	5	5	4	4
56082900	Pebble	265969.0	5126590.0	5	5	3	3
16004100	Pine	707341.0	5327100.0	5	5	5	5
31019600	Poplar	474206.0	5299830.0	5	5	3	3
11047600	Portage	381932.0	5207450.0	5	5	5	5
38052400	Portage	626152.0	5325270.0	5	5	2	2
04003400	Rabideau	386622.0	5277240.0	5	5	4	4
11004300	Roosevelt	427545.0	5185290.0	5	5	4	4
16023000	Rose	690083.0	5330660.0	5	5	5	5

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
56036000	Rose	290565.0	5172740.0	5	5	3	3
01020400	Round	438137.0	5131450.0	5	5	3	3
31042200	Ruby	458339.0	5262900.0	5	5	5	5
18031100	Rush-Hen	413972.0	5171730.0	5	5	3	3
56035800	Scalp	287474.0	5174890.0	5	5	5	5
16062900	Sea Gull	654464.0	5333260.0	5	5	4	4
38071400	Section Twelve	608813.0	5312520.0	5	5	5	5
31008400	Shallow	477729.0	5219260.0	5	5	4	4
31021800	Shamrock	468692.0	5245840.0	5	5	5	5
31055400	Siseebakwet	449178.0	5222790.0	5	5	4	4
56036900	Six	287670.0	5176620.0	5	5	5	5
31025500	Snaptail	471657.0	5257370.0	5	5	4	4
38052900	Snowbank	617945.0	5315770.0	5	5	5	5
16024400	South	682582.0	5329800.0	5	5	5	5
29023900	Spearhead	352132.0	5248390.0	5	5	4	5
29011700	Spider	358726.0	5206440.0	5	5	3	3
38038800	Spoon	633501.0	5326830.0	5	5	5	5
69076100	Spring	527395.0	5357650.0	5	5	4	4
73018300	St. Anna	374291.0	5066760.0	5	5	2	3
18035900	Star	410022.0	5167710.0	5	5	5	5
21010100	Stony	311791.0	5086600.0	5	5	2	2
04008500	Swenson	373092.0	5258540.0	5	5	5	5
56038700	Sybil	286904.0	5167120.0	5	5	3	3
69036900	Takucmich	562210.0	5353350.0	5	5	5	5
01010900	Taylor	460999.0	5204520.0	5	5	5	5
11041300	Ten Mile	380379.0	5203110.0	5	5	5	5
38035100	Thomas	631603.0	5316590.0	5	5	4	4
69033700	Thumb	560384.0	5339160.0	5	5	4	4
11006200	Thunder	426712.0	5199860.0	5	5	4	4
69021300	Toe	570681.0	5347990.0	5	5	4	4
38072400	Tofte	606653.0	5313510.0	5	5	5	5
38017200	Topaz	639601.0	5332420.0	5	5	5	5
16004900	Trout	711435.0	5305720.0	5	5	5	5
31041000	Trout	458192.0	5256660.0	5	5	5	5
31072500	Turtle	448327.0	5275130.0	5	5	5	5
11086600	Tamarack	401048.0	5202160.0	5	5	5	5
38049100	Vera	625682.0	5323900.0	5	5	4	4
16026700	Vernon	680957.0	5312910.0	5	5	4	4
31039200	Wabana	460476.0	5252590.0	5	5	4	4
11005900	Washburn	424057.0	5191210.0	5	5	4	1
86027900	West Lake Sylvia	404790.0	5011290.0	5	5	5	5
16008600	West Pike	708128.0	5329680.0	5	5	5	5
03032800	White Earth	291148.0	5223110.0	5	5	3	3

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
16035400	Winchell	679256.0	5318140.0	5	5	5	5
31070400	Batson	453828.0	5276980.0	4	4	0	2
69048000	Beartrack	559248.0	5350060.0	4	4	3	3
69006400	Dry	584290.0	5312420.0	4	4	0	2
31046000	East	458611.0	5274550.0	4	4	2	2
69066000	Ely	538977.0	5255380.0	4	4	1	1
69047300	Eugene	557783.0	5350470.0	4	4	3	3
69034800	Finger	561761.0	5349220.0	4	4	3	3
31034400	Hanson	466003.0	5251850.0	4	4	4	4
69034300	Hustler	562755.0	5342200.0	4	4	3	3
11005300	Lawrence	428769.0	5185650.0	4	1	0	1
31056600	Little Jay Gould	453693.0	5232280.0	4	4	1	1
69006600	Little Long	582688.0	5310080.0	4	4	2	2
31066500	Little North Star	449862.0	5269730.0	4	4	2	2
11006100	Little Thunder	428199.0	5201610.0	4	4	1	1
69038300	Lynx	559875.0	5340870.0	4	4	3	3
16002700	McFarland	718479.0	5326390.0	4	4	2	2
31019200	Nashwauk	475804.0	5253040.0	4	4	0	0
31033900	Pickerel	473175.0	5296930.0	4	3	0	3
31053200	Pokegama	456223.0	5226050.0	4	4	1	1
16023900	Poplar	685622.0	5324510.0	4	2	0	0
16079300	Red Rock	650916.0	5335990.0	4	4	0	2
69018100	Slim	576841.0	5318000.0	4	3	0	3
69011100	Smith	582159.0	5222660.0	4	4	0	1
38071500	Triangle	608174.0	5310360.0	4	4	2	2
11010500	Upper Trelipe	421271.0	5203000.0	4	4	1	1
31028100	Wasson	474042.0	5274860.0	4	4	2	2
03025800	Acorn	289344.0	5180770.0	3	3	0	1
56024100	Annie Battle	295211.0	5133880.0	3	3	0	1
18004100	Crooked	430110.0	5135770.0	3	3	1	1
38081700	Crooked	596254.0	5334950.0	3	3	0	0
56052300	East Loon	283037.0	5167780.0	3	3	1	1
29018600	Emma	352025.0	5208940.0	3	3	1	1
18039700	Fawn	398593.0	5154490.0	3	3	0	1
69008500	Fenske	581985.0	5315950.0	3	3	0	3
56076800	Fish	269761.0	5173690.0	3	3	1	1
11024200	Hand	399957.0	5189740.0	3	3	1	1
18001900	Kenney	434643.0	5130380.0	3	3	1	1
11026200	Kid	394668.0	5200920.0	3	3	1	1
69022400	Lac la Croix	566478.0	5353810.0	3	3	0	0
03023400	Little Bemidji	304998.0	5218800.0	3	3	1	1
01017600	Little Pine	442658.0	5143540.0	3	3	0	1
18036000	Little Star	410596.0	5167570.0	3	3	1	1

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
18029400	Mitchell	420024.0	5180970.0	3	3	1	1
56030300	Molly Stark	294326.0	5132590.0	3	3	1	1
69068400	Mukooda	537894.0	5353770.0	3	3	0	0
18035200	Ossawinnamakee	406569.0	5165330.0	3	3	1	1
56047500	Pickerel	284417.0	5145370.0	3	3	0	1
18035400	Pig	409429.0	5169810.0	3	3	1	1
11038300	Pleasant	387711.0	5196590.0	3	3	1	1
11028500	Rat	395025.0	5211180.0	3	3	1	1
69061700	Sand Point	537243.0	5357680.0	3	3	0	0
56043700	Stalker	281806.0	5121140.0	3	3	1	1
56034800	Tenter	289919.0	5159880.0	3	3	0	1
69049800	Trout	550807.0	5313550.0	3	3	0	0
29014800	Upper Bottle	353585.0	5211680.0	3	3	0	1
69093700	War_Club	501476.0	5375960.0	3	3	0	0
18031000	Whitefish	407170.0	5171640.0	3	1	0	0
56035500	Wimer	291886.0	5175210.0	3	3	0	1
16075900	Alpine	649531.0	5332970.0	2	2	0	0
16062200	Alton	656349.0	5304070.0	2	2	0	0
38021000	Ashdick	644603.0	5337730.0	2	2	0	0
86028400	Augusta	408408.0	5017250.0	2	2	1	1
31083400	Bird's Eye	426217.0	5273040.0	2	2	0	0
16034800	Brule	673870.0	5312050.0	2	2	0	0
04004200	Buck	382628.0	5257840.0	2	2	0	0
04003000	Cass	384633.0	5253390.0	2	2	0	0
31082900	Cedar	426789.0	5276770.0	2	2	0	0
38072600	Good	603396.0	5317820.0	2	2	0	0
69104000	Little Dry	583873.0	5311920.0	2	2	0	0
31078400	Little Jessie	438271.0	5267430.0	2	2	0	0
77003400	Little Swan	368729.0	5087740.0	2	2	1	1
73012800	Middle Spunk	385747.0	5051410.0	2	2	1	1
38064400	Moose	611711.0	5316830.0	2	2	0	0
38052600	Parent	619730.0	5313550.0	2	2	0	0
11041500	Pike Bay	381520.0	5245770.0	2	2	0	0
11049000	Portage	378945.0	5237320.0	2	2	0	0
31082400	Portage	426992.0	5270380.0	2	2	0	0
31050200	Slauson	457810.0	5275710.0	2	2	0	0
11050400	Steamboat	374321.0	5235860.0	2	2	0	0
73024900	Sylvia	360998.0	5067970.0	2	2	0	1
11025000	Ada	397259.0	5187120.0	1	1	0	0
11028300	Baby	396245.0	5201980.0	1	1	0	0
29020800	Bad Axe	351943.0	5216320.0	1	1	0	0
31057600	Bass	451320.0	5240140.0	1	1	0	0
18003400	Bay	434578.0	5137110.0	1	1	0	0



DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
18035500	Bertha	404168.0	5168510.0	1	1	0	0
18014000	Black Bear	418692.0	5151050.0	1	1	0	0
11027400	Blackwater	400655.0	5195900.0	1	1	0	0
21004900	Burgen	318043.0	5079910.0	1	1	0	0
01020900	Cedar	438607.0	5149860.0	1	1	0	0
11028900	Cedar	399266.0	5209590.0	1	1	0	0
86022700	Cedar	416685.0	5013020.0	1	1	0	1
21010300	Cowdrey	312512.0	5085750.0	1	1	0	0
18031200	Cross Lake Reservoir	413290.0	5168890.0	1	1	0	0
31042900	Cutaway	465628.0	5260360.0	1	1	0	0
29025600	Eagle	340353.0	5210560.0	1	1	0	0
56013800	East Battle	304690.0	5130610.0	1	1	0	0
18030500	Edward	411042.0	5151200.0	1	1	0	0
03015900	Elbow	305655.0	5222160.0	1	1	0	0
69056500	Esquagama	548740.0	5257340.0	1	1	0	0
11035100	Five Point	389591.0	5192770.0	1	1	0	0
18004400	Hanks	430553.0	5134130.0	1	1	0	0
11047200	Howard	374365.0	5205910.0	1	1	0	0
18037500	Hubert	402596.0	5148950.0	1	1	0	0
21012300	Ida	312492.0	5095580.0	1	1	0	0
56087700	Jewett	265556.0	5144260.0	1	1	0	0
69079600	Leander	518479.0	5280400.0	1	1	0	0
11003700	Leavitt	431340.0	5187180.0	1	1	0	0
61003700	Linka	315208.0	5040130.0	1	1	0	0
03038300	Long	279360.0	5188960.0	1	1	0	0
56078400	Long	265281.0	5146400.0	1	1	0	0
77002700	Long	366300.0	5082940.0	1	1	0	0
18000200	Long/Tame Fish	437054.0	5139390.0	1	1	0	0
29015100	Mantrap	354367.0	5215070.0	1	1	0	0
03015800	Many Point	307284.0	5216900.0	1	1	0	0
11026100	McKeown	398442.0	5201700.0	1	1	0	0
18037700	Middle Cullen	402964.0	5156350.0	1	1	0	0
31072200	Moose	447808.0	5249510.0	1	1	0	0
11020000	Mule	403154.0	5196140.0	1	1	0	0
18037200	North Long	404694.0	5143610.0	1	1	0	0
73001500	Otter	409189.0	5019660.0	1	1	0	0
31010600	Ox Hide	484038.0	5243150.0	1	1	0	0
18030800	Pelican	409953.0	5158500.0	1	1	0	0
18006900	Portage	431876.0	5144380.0	1	1	0	0
18020900	Pug Hole	423222.0	5181970.0	1	1	0	0
31071700	Rice	448307.0	5229370.0	1	1	0	0
03015500	Round	306933.0	5212470.0	1	1	0	0
18009000	Serpent	428743.0	5147870.0	1	1	0	0

DOW Number	Lake Name	UTM Easting	UTM Northing	Fixed Benchmark		Variable Benchmark	
				MIROC	CGCM	MIROC	CGCM
29004300	Shingobee	371667.0	5207000.0	1	1	0	0
31055500	South Sugar	448301.0	5221560.0	1	1	0	0
69065100	St. Mary's	536725.0	5252780.0	1	1	0	0
56038500	Star	284385.0	5155620.0	1	1	0	0
29000500	Tripp	365429.0	5190210.0	1	1	0	1
56023900	West Battle	295607.0	5130070.0	1	1	0	0
18029700	West Fox	416471.0	5177400.0	1	1	0	0
18000100	Whitefish	437041.0	5116960.0	1	1	0	0

## Appendix F Names and Geographic Locations of Cisco Lakes in Minnesota Ranked by 2°C TDO3 Increment Values

Table F.1 Names and geographic locations of cisco lakes in Minnesota ranked by 2°C TDO3 increment values. Simulations of the 30 virtual cisco lakes (Table 1.2) were used to construct TDO3 the contour lines that served as the basis for this table. Simulations were made for the MIROC 3.2 future climate scenario with Duluth weather data to obtain TDO3 (°C) values for fixed and variable (sliding) benchmark periods (**AvgATDO3<sub>FB</sub>**, **AvgATDO3<sub>VB</sub>**, Table 3.1, lines 6 and 12).

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
31039500	Bluewater	458235.0	5252040.0	5 - 7	9 - 11
38016600	Cherry	641319.0	5333210.0	5 - 7	9 - 11
15009000	Deep	320013.0	5283860.0	5 - 7	9 - 11
16023200	Duncan	688691.0	5328360.0	5 - 7	9 - 11
69048700	Gun	559422.0	5352420.0	5 - 7	< 9
11040000	Jack	390145.0	5213090.0	5 - 7	9 - 11
29030900	LaSalle	335945.0	5244920.0	5 - 7	11 - 13
38022900	Little Knife	636926.0	5333150.0	5 - 7	< 9
31039400	Little Trout	458897.0	5254040.0	5 - 7	9 - 11
69068200	Little Trout	535431.0	5360490.0	5 - 7	9 - 11
16044800	Loon	671907.0	5327530.0	5 - 7	9 - 11
38064000	Ojibway	608799.0	5311710.0	5 - 7	9 - 11
56036900	Six	287670.0	5176620.0	5 - 7	< 9
69036900	Takucmich	562210.0	5353350.0	5 - 7	9 - 11
11041300	Ten Mile	380379.0	5203110.0	5 - 7	9 - 11
31034900	Antler	466207.0	5275090.0	7 - 9	13 - 15
29018500	Big Sand	350361.0	5207040.0	7 - 9	11 - 13
31079300	Big Too Much	440872.0	5277200.0	7 - 9	13 - 15
18031500	Big Trout	411532.0	5174230.0	7 - 9	13 - 15
04029700	Buzzle	339646.0	5276030.0	7 - 9	11 - 13
77012000	Charlotte	355635.0	5090450.0	7 - 9	11 - 13
31074900	Chase	444194.0	5246180.0	7 - 9	9 - 11
31054000	Clubhouse	457155.0	5272470.0	7 - 9	11 - 13
11023700	Deep Portage	393944.0	5191690.0	7 - 9	11 - 13
11046600	Fifth	376618.0	5212610.0	7 - 9	11 - 13
04021700	Grant	348931.0	5261900.0	7 - 9	13 - 15
58012300	Grindstone	499427.0	5107650.0	7 - 9	11 - 13
16035600	Gunflint	672943.0	5329800.0	7 - 9	13 - 15
31045200	Gunn	459357.0	5265500.0	7 - 9	13 - 15
31091100	Hamrey	406242.0	5285940.0	7 - 9	13 - 15
38020600	Hanson	642735.0	5333610.0	7 - 9	11 - 13
18036100	Kimball	408024.0	5167390.0	7 - 9	11 - 13
38040400	Knife	634276.0	5328310.0	7 - 9	9 - 11

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
56032800	Little McDonald	292892.0	5165460.0	7 - 9	11 - 13
29015000	Little Sand	353063.0	5205920.0	7 - 9	9 - 11
29018000	Lower Bottle	352030.0	5210180.0	7 - 9	11 - 13
31023900	Lower Hanson	466217.0	5250430.0	7 - 9	13 - 15
16046300	Magnetic	665952.0	5330660.0	7 - 9	11 - 13
03037100	Meadow	280699.0	5181750.0	7 - 9	13 - 15
77002200	Mons	367464.0	5087210.0	7 - 9	11 - 13
16004300	Moose	716878.0	5331470.0	7 - 9	11 - 13
16023400	Moss	687734.0	5326820.0	7 - 9	11 - 13
29023700	Newman	351221.0	5250800.0	7 - 9	11 - 13
38021100	Ottertrack	641140.0	5336920.0	7 - 9	9 - 11
11047600	Portage	381932.0	5207450.0	7 - 9	9 - 11
31042200	Ruby	458339.0	5262900.0	7 - 9	9 - 11
56035800	Scalp	287474.0	5174890.0	7 - 9	9 - 11
38071400	Section Twelve	608813.0	5312520.0	7 - 9	11 - 13
16024400	South	682582.0	5329800.0	7 - 9	9 - 11
18035900	Star	410022.0	5167710.0	7 - 9	11 - 13
01010900	Taylor	460999.0	5204520.0	7 - 9	11 - 13
38072400	Tofte	606653.0	5313510.0	7 - 9	9 - 11
38017200	Topaz	639601.0	5332420.0	7 - 9	11 - 13
16004900	Trout	711435.0	5305720.0	7 - 9	11 - 13
31041000	Trout	458192.0	5256660.0	7 - 9	11 - 13
16008600	West Pike	708128.0	5329680.0	7 - 9	9 - 11
16035400	Winchell	679256.0	5318140.0	7 - 9	11 - 13
11046900	Anway	376737.0	5211040.0	9 - 11	13 - 15
38050200	Ashigan	624749.0	5320500.0	9 - 11	11 - 13
03008500	Bad Medicine	317655.0	5221710.0	9 - 11	11 - 13
01004600	Ball Bluff	478651.0	5197700.0	9 - 11	13 - 15
18003000	Barbour	432303.0	5123450.0	9 - 11	13 - 15
29004800	Benedict	371657.0	5221980.0	9 - 11	15 - 17
11027700	Big Deep	394595.0	5196110.0	9 - 11	13 - 15
18021100	Blue	423977.0	5180350.0	9 - 11	13 - 15
29018400	Blue	347677.0	5209100.0	9 - 11	13 - 15
16013900	Clearwater	697251.0	5328720.0	9 - 11	9 - 11
16014700	Flour	693783.0	5325350.0	9 - 11	13 - 15
38037200	Fraser	634053.0	5318890.0	9 - 11	13 - 15
16031900	Gaskin	682846.0	5319510.0	9 - 11	15 - 17
16058000	Granite	666146.0	5335850.0	9 - 11	13 - 15
18026900	Island-Loon	413256.0	5173460.0	9 - 11	13 - 15
21010600	Latoka	310959.0	5082980.0	9 - 11	13 - 15
31077800	Little Too Much	441738.0	5274880.0	9 - 11	13 - 15
01008900	Long	462404.0	5148280.0	9 - 11	13 - 15

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
31078100	Long	441433.0	5280740.0	9 - 11	13 - 15
21010800	Mina	307985.0	5085170.0	9 - 11	13 - 15
16033100	North	681002.0	5331430.0	9 - 11	9 - 11
31021900	O'Reilly	467570.0	5245500.0	9 - 11	13 - 15
16004100	Pine	707341.0	5327100.0	9 - 11	13 - 15
31021800	Shamrock	468692.0	5245840.0	9 - 11	13 - 15
38052900	Snowbank	617945.0	5315770.0	9 - 11	11 - 13
29023900	Spearhead	352132.0	5248390.0	9 - 11	13 - 15
38038800	Spoon	633501.0	5326830.0	9 - 11	13 - 15
31072500	Turtle	448327.0	5275130.0	9 - 11	13 - 15
11086600	Tamarack	401048.0	5202160.0	9 - 11	13 - 15
86027900	West Lake Sylvia	404790.0	5011290.0	9 - 11	13 - 15
18020800	Allen	424014.0	5182910.0	11 - 13	15 - 17
31027800	Barwise	468711.0	5267270.0	11 - 13	13 - 15
77002400	Bass	366498.0	5085360.0	11 - 13	15 - 17
69011800	Burntside	581302.0	5310720.0	11 - 13	15 - 17
21005700	Carlos	316947.0	5091130.0	11 - 13	15 - 17
49014000	Cedar	372840.0	5074700.0	11 - 13	15 - 17
11016300	Cooper	408898.0	5201950.0	11 - 13	15 - 17
18029800	East Fox	417710.0	5177450.0	11 - 13	15 - 17
18039600	Edna	399225.0	5154230.0	11 - 13	15 - 17
15001000	Elk	331973.0	5228580.0	11 - 13	15 - 17
11017400	Girl	405649.0	5204090.0	11 - 13	15 - 17
16061700	Gneiss	662965.0	5338100.0	11 - 13	15 - 17
16007700	Greenwood	710490.0	5320110.0	11 - 13	15 - 17
31037300	Hale	458520.0	5232670.0	11 - 13	15 - 17
31046600	Horseshoe	461830.0	5272270.0	11 - 13	15 - 17
29007500	Kabekona	366808.0	5225200.0	11 - 13	15 - 17
01005700	Little Ball Bluff	479174.0	5198320.0	11 - 13	15 - 17
31057500	Little Bass	454599.0	5237110.0	11 - 13	15 - 17
09003500	Little Hanging Horn	524719.0	5147700.0	11 - 13	15 - 17
31039900	Little Wabana	462902.0	5249760.0	11 - 13	15 - 17
31057100	Loon	451222.0	5231220.0	11 - 13	15 - 17
18037800	Lower Hay	401812.0	5169230.0	11 - 13	15 - 17
11028200	Mann	397848.0	5203010.0	11 - 13	15 - 17
31077500	No-ta-she-bun	441437.0	5222430.0	11 - 13	15 - 17
56082900	Pebble	265969.0	5126590.0	11 - 13	15 - 17
04003400	Rabideau	386622.0	5277240.0	11 - 13	15 - 17
16023000	Rose	690083.0	5330660.0	11 - 13	13 - 15
56036000	Rose	290565.0	5172740.0	11 - 13	15 - 17
01020400	Round	438137.0	5131450.0	11 - 13	15 - 17
18031100	Rush-Hen	413972.0	5171730.0	11 - 13	15 - 17

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
16062900	Sea Gull	654464.0	5333260.0	11 - 13	15 - 17
31008400	Shallow	477729.0	5219260.0	11 - 13	15 - 17
31025500	Snaptail	471657.0	5257370.0	11 - 13	15 - 17
29011700	Spider	358726.0	5206440.0	11 - 13	15 - 17
73018300	St. Anna	374291.0	5066760.0	11 - 13	15 - 17
04008500	Swenson	373092.0	5258540.0	11 - 13	13 - 15
38035100	Thomas	631603.0	5316590.0	11 - 13	15 - 17
16026700	Vernon	680957.0	5312910.0	11 - 13	15 - 17
31039200	Wabana	460476.0	5252590.0	11 - 13	15 - 17
11006900	Bass	427017.0	5195460.0	13 - 15	15 - 17
18035800	Bass	409240.0	5167800.0	13 - 15	15 - 17
38050300	Boot	622470.0	5319150.0	13 - 15	15 - 17
21014500	Chippewa	303158.0	5096880.0	13 - 15	17 - 19
18036400	Clear	405698.0	5166480.0	13 - 15	15 - 17
31071900	Deer	449898.0	5247700.0	13 - 15	15 - 17
16061600	Devils Elbow	661998.0	5338700.0	13 - 15	17 - 19
86028900	East Lake Sylvia	406210.0	5011660.0	13 - 15	15 - 17
56052300	East Loon	283037.0	5167780.0	13 - 15	17 - 19
56051400	Elbow	283903.0	5160430.0	13 - 15	15 - 17
29003600	Eleventh Crow Wing	369070.0	5208250.0	13 - 15	17 - 19
31046300	Fox	458903.0	5272300.0	13 - 15	15 - 17
38071800	Greenstone	603736.0	5309460.0	13 - 15	17 - 19
31034400	Hanson	466003.0	5251850.0	13 - 15	15 - 17
31077100	Hatch	443582.0	5278860.0	13 - 15	15 - 17
69034300	Hustler	562755.0	5342200.0	13 - 15	17 - 19
03015600	Ice Cracking	306412.0	5209340.0	13 - 15	15 - 17
38040000	Ima	628408.0	5319480.0	13 - 15	15 - 17
38051100	Jordan	626367.0	5318710.0	13 - 15	15 - 17
18001900	Kenney	434643.0	5130380.0	13 - 15	17 - 19
31073900	Leighton	442924.0	5227310.0	13 - 15	17 - 19
11048000	Long	378329.0	5214670.0	13 - 15	15 - 17
29016100	Long	347647.0	5194460.0	13 - 15	15 - 17
11048200	May	379050.0	5216490.0	13 - 15	15 - 17
11004700	Mule	424154.0	5188480.0	13 - 15	15 - 17
29002500	Ninth Crow Wing	365366.0	5204220.0	13 - 15	17 - 19
31065300	North Star	449897.0	5266910.0	13 - 15	15 - 17
69033000	Oyster	566301.0	5341780.0	13 - 15	15 - 17
31019600	Poplar	474206.0	5299830.0	13 - 15	17 - 19
38052400	Portage	626152.0	5325270.0	13 - 15	17 - 19
11004300	Roosevelt	427545.0	5185290.0	13 - 15	15 - 17
31055400	Siseebakwet	449178.0	5222790.0	13 - 15	15 - 17
69076100	Spring	527395.0	5357650.0	13 - 15	15 - 17

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
21010100	Stony	311791.0	5086600.0	13 - 15	15 - 17
56038700	Sybil	286904.0	5167120.0	13 - 15	15 - 17
69033700	Thumb	560384.0	5339160.0	13 - 15	15 - 17
11006200	Thunder	426712.0	5199860.0	13 - 15	15 - 17
69021300	Toe	570681.0	5347990.0	13 - 15	15 - 17
38049100	Vera	625682.0	5323900.0	13 - 15	15 - 17
11005900	Washburn	424057.0	5191210.0	13 - 15	15 - 17
03032800	White Earth	291148.0	5223110.0	13 - 15	15 - 17
03025800	Acorn	289344.0	5180770.0	15 - 17	17 - 19
56024100	Annie Battle	295211.0	5133880.0	15 - 17	17 - 19
86028400	Augusta	408408.0	5017250.0	15 - 17	17 - 19
31070400	Batson	453828.0	5276980.0	15 - 17	17 - 19
69048000	Beartrack	559248.0	5350060.0	15 - 17	17 - 19
18004100	Crooked	430110.0	5135770.0	15 - 17	17 - 19
69006400	Dry	584290.0	5312420.0	15 - 17	17 - 19
31046000	East	458611.0	5274550.0	15 - 17	17 - 19
69066000	Ely	538977.0	5255380.0	15 - 17	17 - 19
29018600	Emma	352025.0	5208940.0	15 - 17	17 - 19
69047300	Eugene	557783.0	5350470.0	15 - 17	17 - 19
18039700	Fawn	398593.0	5154490.0	15 - 17	17 - 19
69034800	Finger	561761.0	5349220.0	15 - 17	17 - 19
56076800	Fish	269761.0	5173690.0	15 - 17	17 - 19
11024200	Hand	399957.0	5189740.0	15 - 17	17 - 19
11026200	Kid	394668.0	5200920.0	15 - 17	17 - 19
03023400	Little Bemidji	304998.0	5218800.0	15 - 17	17 - 19
31056600	Little Jay Gould	453693.0	5232280.0	15 - 17	17 - 19
69006600	Little Long	582688.0	5310080.0	15 - 17	17 - 19
31066500	Little North Star	449862.0	5269730.0	15 - 17	17 - 19
01017600	Little Pine	442658.0	5143540.0	15 - 17	17 - 19
18036000	Little Star	410596.0	5167570.0	15 - 17	17 - 19
77003400	Little Swan	368729.0	5087740.0	15 - 17	17 - 19
11006100	Little Thunder	428199.0	5201610.0	15 - 17	17 - 19
69038300	Lynx	559875.0	5340870.0	15 - 17	17 - 19
16002700	McFarland	718479.0	5326390.0	15 - 17	17 - 19
73012800	Middle Spunk	385747.0	5051410.0	15 - 17	17 - 19
18029400	Mitchell	420024.0	5180970.0	15 - 17	17 - 19
56030300	Molly Stark	294326.0	5132590.0	15 - 17	17 - 19
31019200	Nashwauk	475804.0	5253040.0	15 - 17	17 - 19
18035200	Ossawinnamakee	406569.0	5165330.0	15 - 17	17 - 19
31033900	Pickerel	473175.0	5296930.0	15 - 17	17 - 19
56047500	Pickerel	284417.0	5145370.0	15 - 17	17 - 19
18035400	Pig	409429.0	5169810.0	15 - 17	17 - 19

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
11038300	Pleasant	387711.0	5196590.0	15 - 17	17 - 19
31053200	Pokegama	456223.0	5226050.0	15 - 17	17 - 19
16023900	Poplar	685622.0	5324510.0	15 - 17	17 - 19
11028500	Rat	395025.0	5211180.0	15 - 17	17 - 19
16079300	Red Rock	650916.0	5335990.0	15 - 17	17 - 19
69018100	Slim	576841.0	5318000.0	15 - 17	17 - 19
69011100	Smith	582159.0	5222660.0	15 - 17	17 - 19
56043700	Stalker	281806.0	5121140.0	15 - 17	17 - 19
73024900	Sylvia	360998.0	5067970.0	15 - 17	17 - 19
56034800	Tenter	289919.0	5159880.0	15 - 17	17 - 19
38071500	Triangle	608174.0	5310360.0	15 - 17	17 - 19
29014800	Upper Bottle	353585.0	5211680.0	15 - 17	17 - 19
11010500	Upper Trelipe	421271.0	5203000.0	15 - 17	17 - 19
31028100	Wasson	474042.0	5274860.0	15 - 17	17 - 19
18031000	Whitefish	407170.0	5171640.0	15 - 17	17 - 19
56035500	Wimer	291886.0	5175210.0	15 - 17	17 - 19
11025000	Ada	397259.0	5187120.0	17 - 19	19 - 21
49007900	Alexander	380926.0	5118380.0	17 - 19	19 - 21
16075900	Alpine	649531.0	5332970.0	17 - 19	17 - 19
16062200	Alton	656349.0	5304070.0	17 - 19	17 - 19
38022700	Amoeber	637882.0	5331760.0	17 - 19	19 - 21
21008500	Andrew	312104.0	5076890.0	17 - 19	19 - 21
38021000	Ashdick	644603.0	5337730.0	17 - 19	17 - 19
11028300	Baby	396245.0	5201980.0	17 - 19	17 - 19
29020800	Bad Axe	351943.0	5216320.0	17 - 19	17 - 19
31081200	Ball Club	428770.0	5245550.0	17 - 19	19 - 21
31057600	Bass	451320.0	5240140.0	17 - 19	19 - 21
69055300	Bass	550467.0	5255250.0	17 - 19	19 - 21
18003400	Bay	434578.0	5137110.0	17 - 19	19 - 21
31072600	Bello	446882.0	5279540.0	17 - 19	19 - 21
04013500	Beltrami	363587.0	5272810.0	17 - 19	19 - 21
18035500	Bertha	404168.0	5168510.0	17 - 19	17 - 19
31083400	Bird's Eye	426217.0	5273040.0	17 - 19	17 - 19
04015700	Black	363357.0	5277150.0	17 - 19	19 - 21
18014000	Black Bear	418692.0	5151050.0	17 - 19	19 - 21
11027400	Blackwater	400655.0	5195900.0	17 - 19	17 - 19
31056100	Blackwater	448650.0	5233590.0	17 - 19	19 - 21
56024000	Blanche	295430.0	5136060.0	17 - 19	19 - 21
18002000	Borden	434470.0	5127900.0	17 - 19	19 - 21
21010200	Brophy	310581.0	5086380.0	17 - 19	19 - 21
16034800	Brule	673870.0	5312050.0	17 - 19	17 - 19
04004200	Buck	382628.0	5257840.0	17 - 19	17 - 19



DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
21004900	Burgen	318043.0	5079910.0	17 - 19	19 - 21
04014100	Carr	357384.0	5255950.0	17 - 19	19 - 21
04003000	Cass	384633.0	5253390.0	17 - 19	19 - 21
01020900	Cedar	438607.0	5149860.0	17 - 19	17 - 19
11028900	Cedar	399266.0	5209590.0	17 - 19	19 - 21
31082900	Cedar	426789.0	5276770.0	17 - 19	19 - 21
38081000	Cedar	590177.0	5312220.0	17 - 19	19 - 21
86022700	Cedar	416685.0	5013020.0	17 - 19	17 - 19
04034300	Clearwater	336043.0	5288920.0	17 - 19	19 - 21
18003800	Clearwater	429708.0	5138390.0	17 - 19	19 - 21
18013100	Clinker	427010.0	5152160.0	17 - 19	19 - 21
56023800	Clitherall	294394.0	5125000.0	17 - 19	19 - 21
21010300	Cowdrey	312512.0	5085750.0	17 - 19	19 - 21
69022000	Crab	570365.0	5310570.0	17 - 19	19 - 21
38081700	Crooked	596254.0	5334950.0	17 - 19	17 - 19
18031200	Cross Lake Reservoir	413290.0	5168890.0	17 - 19	19 - 21
31085700	Cut Foot Sioux	421050.0	5261090.0	17 - 19	19 - 21
31042900	Cutaway	465628.0	5260360.0	17 - 19	19 - 21
21008000	Darling	314177.0	5087870.0	17 - 19	19 - 21
04023000	Deer	348027.0	5280280.0	17 - 19	19 - 21
03038100	Detroit	283672.0	5185560.0	17 - 19	19 - 21
69091200	Dewey	504222.0	5270940.0	17 - 19	19 - 21
38048800	Disappointment	622356.0	5315860.0	17 - 19	19 - 21
29025600	Eagle	340353.0	5210560.0	17 - 19	17 - 19
56013800	East Battle	304690.0	5130610.0	17 - 19	17 - 19
16004200	East Pike	715762.0	5329140.0	17 - 19	19 - 21
18030500	Edward	411042.0	5151200.0	17 - 19	17 - 19
03015900	Elbow	305655.0	5222160.0	17 - 19	17 - 19
31049000	Elizabeth	461746.0	5266960.0	17 - 19	19 - 21
69056500	Esquagama	548740.0	5257340.0	17 - 19	17 - 19
31060900	Fawn	447940.0	5251690.0	17 - 19	19 - 21
69008500	Fenske	581985.0	5315950.0	17 - 19	17 - 19
29024200	Fish Hook	342946.0	5202390.0	17 - 19	19 - 21
31018300	Five Island	477935.0	5298610.0	17 - 19	19 - 21
11035100	Five Point	389591.0	5192770.0	17 - 19	19 - 21
69035000	Ge-Be-On-Equat	565472.0	5347990.0	17 - 19	19 - 21
21005200	Geneva	319386.0	5085640.0	17 - 19	19 - 21
38050800	Gibson	624839.0	5319500.0	17 - 19	19 - 21
38072600	Good	603396.0	5317820.0	17 - 19	17 - 19
34007900	Green	350567.0	5012690.0	17 - 19	19 - 21
16063200	Gull	656853.0	5336480.0	17 - 19	19 - 21
09003800	Hanging Horn	523502.0	5147210.0	17 - 19	19 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
18004400	Hanks	430553.0	5134130.0	17 - 19	17 - 19
31002000	Hart	488322.0	5233580.0	17 - 19	19 - 21
31015400	Hartley	476810.0	5267220.0	17 - 19	19 - 21
11019900	Hay	402344.0	5191510.0	17 - 19	19 - 21
69046900	Heritage	558482.0	5341940.0	17 - 19	19 - 21
31048100	Highland	460943.0	5268450.0	17 - 19	19 - 21
29024900	Hinds	343557.0	5188760.0	17 - 19	19 - 21
11047200	Howard	374365.0	5205910.0	17 - 19	17 - 19
18037500	Hubert	402596.0	5148950.0	17 - 19	17 - 19
21012300	Ida	312492.0	5095580.0	17 - 19	17 - 19
69012100	Iron	579878.0	5342140.0	17 - 19	19 - 21
29025400	Island	340058.0	5212750.0	17 - 19	19 - 21
31065700	Jack the Horse	452194.0	5273850.0	17 - 19	19 - 21
56087700	Jewett	265556.0	5144260.0	17 - 19	17 - 19
31068700	Johnson	450773.0	5275000.0	17 - 19	19 - 21
69069100	Johnson	528994.0	5354220.0	17 - 19	19 - 21
69022400	Lac la Croix	566478.0	5353810.0	17 - 19	19 - 21
11005300	Lawrence	428769.0	5185650.0	17 - 19	17 - 19
21005600	Le Homme Dieu	317574.0	5088720.0	17 - 19	19 - 21
69079600	Leander	518479.0	5280400.0	17 - 19	17 - 19
11003700	Leavitt	431340.0	5187180.0	17 - 19	17 - 19
61003700	Linka	315208.0	5040130.0	17 - 19	17 - 19
77008900	Little Birch	359878.0	5070750.0	17 - 19	17 - 19
11016700	Little Boy	409479.0	5199310.0	17 - 19	19 - 21
69104000	Little Dry	583873.0	5311920.0	17 - 19	17 - 19
31078400	Little Jessie	438271.0	5267430.0	17 - 19	17 - 19
69008600	Little Sletten	582979.0	5315530.0	17 - 19	19 - 21
11003000	Little Vermillion	436520.0	5226360.0	17 - 19	17 - 19
03038300	Long	279360.0	5188960.0	17 - 19	17 - 19
56078400	Long	265281.0	5146400.0	17 - 19	17 - 19
77002700	Long	366300.0	5082940.0	17 - 19	17 - 19
18000200	Long /Tame Fish	437054.0	5139390.0	17 - 19	17 - 19
21010500	Lottie	311575.0	5085870.0	17 - 19	19 - 21
29015100	Mantrap	354367.0	5215070.0	17 - 19	19 - 21
03015800	Many Point	307284.0	5216900.0	17 - 19	17 - 19
56024300	Marion	297221.0	5156330.0	17 - 19	19 - 21
44008000	McCraney	295625.0	5227690.0	17 - 19	19 - 21
11026100	McKeown	398442.0	5201700.0	17 - 19	17 - 19
18037700	Middle Cullen	402964.0	5156350.0	17 - 19	19 - 21
31039600	Middle Hanson	465872.0	5253550.0	17 - 19	19 - 21
18013300	Miller	419043.0	5152230.0	17 - 19	19 - 21
21008300	Miltona	316217.0	5101020.0	17 - 19	19 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
31072200	Moose	447808.0	5249510.0	17 - 19	19 - 21
38064400	Moose	611711.0	5316830.0	17 - 19	19 - 21
04015200	Movil	360165.0	5272390.0	17 - 19	19 - 21
69007800	Mudro	588640.0	5321030.0	17 - 19	19 - 21
69068400	Mukooda	537894.0	5353770.0	17 - 19	17 - 19
11020000	Mule	403154.0	5196140.0	17 - 19	17 - 19
18037200	North Long	404694.0	5143610.0	17 - 19	17 - 19
31019000	North Twin	475945.0	5239320.0	17 - 19	19 - 21
21009500	North Union	311759.0	5087670.0	17 - 19	19 - 21
73001500	Otter	409189.0	5019660.0	17 - 19	17 - 19
56024200	Otter Tail	295279.0	5142030.0	17 - 19	19 - 21
31010600	Ox Hide	484038.0	5243150.0	17 - 19	17 - 19
38052600	Parent	619730.0	5313550.0	17 - 19	17 - 19
18030800	Pelican	409953.0	5158500.0	17 - 19	17 - 19
11041500	Pike Bay	381520.0	5245770.0	17 - 19	17 - 19
11032000	Pillager	386358.0	5136020.0	17 - 19	19 - 21
11049000	Portage	378945.0	5237320.0	17 - 19	17 - 19
18005000	Portage	429496.0	5133530.0	17 - 19	19 - 21
18006900	Portage	431876.0	5144380.0	17 - 19	17 - 19
31082400	Portage	426992.0	5270380.0	17 - 19	17 - 19
29024300	Potato	344157.0	5207100.0	17 - 19	19 - 21
18020900	Pug Hole	423222.0	5181970.0	17 - 19	17 - 19
21016000	Rachel	301463.0	5074820.0	17 - 19	19 - 21
31071700	Rice	448307.0	5229370.0	17 - 19	17 - 19
03015500	Round	306933.0	5212470.0	17 - 19	19 - 21
38022500	Sagus	637256.0	5319710.0	17 - 19	19 - 21
69061700	Sand Point	537243.0	5357680.0	17 - 19	17 - 19
18009000	Serpent	428743.0	5147870.0	17 - 19	17 - 19
29004300	Shingobee	371667.0	5207000.0	17 - 19	19 - 21
56018000	Siverson	301237.0	5123450.0	17 - 19	19 - 21
31050200	Slauson	457810.0	5275710.0	17 - 19	17 - 19
18002800	Smith	434158.0	5123550.0	17 - 19	19 - 21
31055500	South Sugar	448301.0	5221560.0	17 - 19	17 - 19
31019100	South Twin	475632.0	5238400.0	17 - 19	19 - 21
01017800	Spirit	445916.0	5143450.0	17 - 19	19 - 21
69065100	St. Mary's	536725.0	5252780.0	17 - 19	17 - 19
56038500	Star	284385.0	5155620.0	17 - 19	19 - 21
11050400	Steamboat	374321.0	5235860.0	17 - 19	17 - 19
69047500	Steep	556556.0	5350670.0	17 - 19	19 - 21
03001000	Straight	327455.0	5201350.0	17 - 19	19 - 21
56019100	Stuart	301096.0	5127880.0	17 - 19	19 - 21
86023300	Sugar	418656.0	5018770.0	17 - 19	19 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
29004500	Tenth Crow Wing	366600.0	5205450.0	17 - 19	19 - 21
29000500	Tripp	365429.0	5190210.0	17 - 19	17 - 19
69049800	Trout	550807.0	5313550.0	17 - 19	17 - 19
77008800	Turtle	363416.0	5116960.0	17 - 19	19 - 21
21005400	Victoria	318174.0	5082590.0	17 - 19	19 - 21
11017100	Wabedo	407120.0	5195650.0	17 - 19	19 - 21
69093700	War Club	501476.0	5375960.0	17 - 19	19 - 21
56023900	West Battle	295607.0	5130070.0	17 - 19	19 - 21
18029700	West Fox	416471.0	5177400.0	17 - 19	17 - 19
56011400	West Leaf	308473.0	5142670.0	17 - 19	19 - 21
18000100	Whitefish	437041.0	5116960.0	17 - 19	19 - 21
01004000	Aitkin	477881.0	5183130.0	19 - 21	19 - 21
38033000	Alice	633333.0	5311930.0	19 - 21	19 - 21
38040100	Alworth	628130.0	5317880.0	19 - 21	19 - 21
38033600	Amber	635689.0	5312670.0	19 - 21	19 - 21
04003800	Andrusia	375346.0	5257210.0	19 - 21	19 - 21
31069000	Aspen	450394.0	5285140.0	19 - 21	19 - 21
38063700	Bald Eagle	609523.0	5296760.0	19 - 21	21 - 23
31025900	Balsam	468931.0	5264210.0	19 - 21	19 - 21
01007300	Bass	471710.0	5163170.0	19 - 21	19 - 21
38064500	Basswood	604141.0	5323330.0	19 - 21	19 - 21
09003400	Bear	524867.0	5149430.0	19 - 21	19 - 21
69011500	Bear Island	577437.0	5291940.0	19 - 21	19 - 21
69008900	Bear Trap	584072.0	5332440.0	19 - 21	19 - 21
77008400	Big Birch	363766.0	5071140.0	19 - 21	19 - 21
15000100	Big LaSalle	335749.0	5240070.0	19 - 21	19 - 21
56013000	Big Pine	309661.0	5164940.0	19 - 21	19 - 21
01006200	Big Sandy	480893.0	5178490.0	19 - 21	19 - 21
73011700	Big Spunk	385246.0	5049910.0	19 - 21	19 - 21
77002300	Big Swan	363787.0	5082180.0	19 - 21	19 - 21
11041200	Birch	382126.0	5199300.0	19 - 21	19 - 21
38053200	Birch	620584.0	5324060.0	19 - 21	19 - 21
56021200	Boedigheimer	301187.0	5154540.0	19 - 21	19 - 21
69010000	Boot	587357.0	5326780.0	19 - 21	21 - 23
04021100	Bootleg	349047.0	5257240.0	19 - 21	19 - 21
11035000	Bowen	386229.0	5185130.0	19 - 21	19 - 21
11014300	Boy	415630.0	5218280.0	19 - 21	21 - 23
31014700	Bray	478607.0	5256750.0	19 - 21	19 - 21
03035000	Buffalo	287611.0	5205620.0	19 - 21	19 - 21
31053000	Busties	462756.0	5300700.0	19 - 21	19 - 21
86028100	Caroline	406232.0	5018940.0	19 - 21	19 - 21
11026300	Child	397850.0	5200080.0	19 - 21	19 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
18035600	Clamshell	405902.0	5169020.0	19 - 21	19 - 21
69061600	Crane	537602.0	5350630.0	19 - 21	19 - 21
11049400	Crooked	381350.0	5233310.0	19 - 21	19 - 21
31019300	Crooked	475920.0	5255100.0	19 - 21	19 - 21
56074900	Crystal	274000.0	5166590.0	19 - 21	19 - 21
69032500	Cummings	566275.0	5315930.0	19 - 21	19 - 21
18027100	Daggett	416603.0	5171270.0	19 - 21	21 - 23
01009600	Dam	464371.0	5150860.0	19 - 21	19 - 21
56038300	Dead	288869.0	5151050.0	19 - 21	19 - 21
31033400	Deer	471615.0	5298330.0	19 - 21	19 - 21
31090400	Dunbar	406944.0	5277220.0	19 - 21	19 - 21
16063400	Dyers	652006.0	5265890.0	19 - 21	19 - 21
18029600	Eagle	419933.0	5178560.0	19 - 21	19 - 21
56037800	East Lost	285988.0	5137710.0	19 - 21	19 - 21
29007200	Eighth Crow Wing	363682.0	5202230.0	19 - 21	19 - 21
69074400	Elbow	527672.0	5317960.0	19 - 21	19 - 21
03050300	Eunice	273201.0	5180430.0	19 - 21	19 - 21
77015400	Fairy	345596.0	5072650.0	19 - 21	19 - 21
38077900	Farm	594981.0	5305880.0	19 - 21	19 - 21
01015900	Farm Island	440567.0	5141320.0	19 - 21	19 - 21
29009200	Fifth Crow Wing	355740.0	5197660.0	19 - 21	19 - 21
56024700	Fischer (Carroll)	295593.0	5177030.0	19 - 21	19 - 21
49013700	Fish Trap	375266.0	5118690.0	19 - 21	19 - 21
56075900	Franklin	272328.0	5169680.0	19 - 21	19 - 21
38070100	Gabbro	605407.0	5301180.0	19 - 21	19 - 21
38078200	Garden	593602.0	5308500.0	19 - 21	19 - 21
04002400	Gilstad	385070.0	5280690.0	19 - 21	19 - 21
56036800	Graham	291516.0	5176770.0	19 - 21	19 - 21
31062400	Grave	449973.0	5261460.0	19 - 21	19 - 21
11030500	Gull	395764.0	5144720.0	19 - 21	19 - 21
31048000	Gunn	459752.0	5269430.0	19 - 21	19 - 21
01017000	Hanging Kettle	446216.0	5147470.0	19 - 21	19 - 21
38036900	Hatchet	630329.0	5319380.0	19 - 21	19 - 21
11023200	Hattie	393768.0	5185750.0	19 - 21	19 - 21
29030000	Hattie	344604.0	5237240.0	19 - 21	19 - 21
01017900	Hickory	443744.0	5143130.0	19 - 21	19 - 21
73015700	Horseshoe	380075.0	5031490.0	19 - 21	19 - 21
38039700	Insula	627827.0	5308350.0	19 - 21	19 - 21
21007600	Irene	321549.0	5103410.0	19 - 21	19 - 21
31021700	Island	468665.0	5245300.0	19 - 21	19 - 21
69037200	Island Lake Reservoir	562931.0	5206960.0	19 - 21	19 - 21
15001600	Itasca	333335.0	5231540.0	19 - 21	19 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
31056500	Jay Gould	452692.0	5232580.0	19 - 21	19 - 21
21005500	Jessie	320839.0	5081410.0	19 - 21	19 - 21
31078600	Jessie	438449.0	5270650.0	19 - 21	19 - 21
69084500	Kabetogama	501151.0	5363800.0	19 - 21	19 - 21
04000700	Kitchi	385900.0	5261530.0	19 - 21	19 - 21
69074800	Kjostad	529495.0	5328680.0	19 - 21	19 - 21
31023100	Lawrence	471617.0	5253760.0	19 - 21	21 - 23
11020300	Leech	392202.0	5226300.0	19 - 21	19 - 21
11036700	Lind	387364.0	5186280.0	19 - 21	19 - 21
31075800	Little Bowstring	445248.0	5260210.0	19 - 21	19 - 21
03038600	Little Floyd	284096.0	5195150.0	19 - 21	19 - 21
18026600	Little Pine	418477.0	5172770.0	19 - 21	19 - 21
56014200	Little Pine	304356.0	5167610.0	19 - 21	19 - 21
18013900	Little Rabbit	419231.0	5146690.0	19 - 21	19 - 21
31071600	Little Rice	446677.0	5231510.0	19 - 21	19 - 21
31034100	Little Split Hand	465958.0	5212580.0	19 - 21	21 - 23
69045500	Little Trout	553631.0	5316290.0	19 - 21	19 - 21
69060800	Little Vermilion	543659.0	5347600.0	19 - 21	19 - 21
21014400	Lobster	303874.0	5083620.0	19 - 21	19 - 21
69093600	Locator	500228.0	5376200.0	19 - 21	19 - 21
69085900	Long	506622.0	5271520.0	19 - 21	19 - 21
73013900	Long	380649.0	5028330.0	19 - 21	21 - 23
31057900	Loon	450034.0	5244000.0	19 - 21	19 - 21
69047000	Loon	553513.0	5343390.0	19 - 21	19 - 21
21009400	Louise	312439.0	5088940.0	19 - 21	19 - 21
31024700	Lower Balsam	473343.0	5261010.0	19 - 21	19 - 21
18040300	Lower Cullen	400998.0	5154730.0	19 - 21	19 - 21
73012300	Lower Spunk	386219.0	5052620.0	19 - 21	19 - 21
11031300	Lower Sucker	392208.0	5242810.0	19 - 21	19 - 21
11012900	Lower Trelipe	418621.0	5204710.0	19 - 21	19 - 21
31070500	Lundeen	450527.0	5277240.0	19 - 21	19 - 21
38009000	Malberg	640725.0	5312800.0	19 - 21	19 - 21
31077300	Maple	445848.0	5277410.0	19 - 21	19 - 21
04014200	Marquette	356146.0	5254630.0	19 - 21	19 - 21
03050000	Maud	272152.0	5181630.0	19 - 21	19 - 21
21018000	Mill	303411.0	5080710.0	19 - 21	19 - 21
69027500	Mud	566527.0	5303620.0	19 - 21	19 - 21
69069300	Namakan	524538.0	5367940.0	19 - 21	19 - 21
38061900	Newfound	614900.0	5320150.0	19 - 21	19 - 21
38078400	Newton	595843.0	5315350.0	19 - 21	19 - 21
18039900	Nisswa	400447.0	5152570.0	19 - 21	21 - 23
18010400	Nokay	425925.0	5136540.0	19 - 21	19 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
38060500	One	613393.0	5309270.0	19 - 21	19 - 21
77021500	Osakis	336615.0	5086080.0	19 - 21	19 - 21
56078600	Pelican	269128.0	5176090.0	19 - 21	19 - 21
04003200	Pimushe	384671.0	5270540.0	19 - 21	19 - 21
11041100	Pine Mountain	383041.0	5186700.0	19 - 21	19 - 21
29015600	Plantagenet	354892.0	5248830.0	19 - 21	19 - 21
86025100	Pleasant	411744.0	5014100.0	19 - 21	19 - 21
11020400	Portage	400900.0	5244140.0	19 - 21	19 - 21
69084800	Prairie	507340.0	5182010.0	19 - 21	19 - 21
69069400	Rainy	492109.0	5379040.0	19 - 21	19 - 21
11022000	Ray	397903.0	5152930.0	19 - 21	19 - 21
73019600	Rice	373478.0	5025900.0	19 - 21	21 - 23
01014600	Ripple	448612.0	5145780.0	19 - 21	19 - 21
01007000	Round	470998.0	5166210.0	19 - 21	19 - 21
18037300	Round	401596.0	5145720.0	19 - 21	19 - 21
49001900	Round	424958.0	5111690.0	19 - 21	19 - 21
18039800	Roy	398633.0	5152050.0	19 - 21	19 - 21
56014100	Rush	305734.0	5152370.0	19 - 21	19 - 21
31083200	Rush Island	427922.0	5275010.0	19 - 21	19 - 21
03035900	Sallie	278875.0	5183880.0	19 - 21	19 - 21
31082600	Sand	424288.0	5274410.0	19 - 21	19 - 21
31034500	Scrapper	466412.0	5262640.0	19 - 21	19 - 21
29008500	Second Crow Wing	357214.0	5188850.0	19 - 21	19 - 21
29009100	Seventh Crow Wing	360801.0	5200540.0	19 - 21	19 - 21
69006900	Shagawa	583837.0	5307140.0	19 - 21	19 - 21
69093300	Side	498486.0	5280090.0	19 - 21	19 - 21
11014600	Six Mile	413380.0	5240420.0	19 - 21	19 - 21
29009300	Sixth Crow Wing	358126.0	5198890.0	19 - 21	19 - 21
18013600	South Long	416333.0	5125670.0	19 - 21	19 - 21
31000300	South Sturgeon	495203.0	5275970.0	19 - 21	19 - 21
16045700	South Temperance	666008.0	5311350.0	19 - 21	19 - 21
31078900	Spring	434870.0	5277810.0	19 - 21	19 - 21
03032300	Strawberry	295036.0	5216570.0	19 - 21	19 - 21
69020500	Stuart	573633.0	5337720.0	19 - 21	19 - 21
38078100	Stub	596606.0	5311100.0	19 - 21	21 - 23
38053000	Sucker	617944.0	5322320.0	19 - 21	19 - 21
49001600	Sullivan	427068.0	5110000.0	19 - 21	19 - 21
31006700	Swan	486007.0	5238930.0	19 - 21	19 - 21
11013300	Swift	417857.0	5216400.0	19 - 21	19 - 21
29007700	Third Crow Wing	358407.0	5191530.0	19 - 21	19 - 21
38060000	Three	616125.0	5305190.0	19 - 21	19 - 21
44000300	Tulaby	302422.0	5225200.0	19 - 21	19 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
04015900	Turtle	359754.0	5275580.0	19 - 21	19 - 21
38060800	Two	614725.0	5307640.0	19 - 21	19 - 21
03001700	Two Inlets	333395.0	5210660.0	19 - 21	19 - 21
18037600	Upper Cullen	403727.0	5157740.0	19 - 21	19 - 21
11021800	Upper Gull	396854.0	5153810.0	19 - 21	19 - 21
18024200	Upper Mission	417755.0	5156050.0	19 - 21	19 - 21
18009600	Upper South Long	419996.0	5129080.0	19 - 21	19 - 21
11049300	Welch	381947.0	5234770.0	19 - 21	19 - 21
31084300	Whitefish	427625.0	5281600.0	19 - 21	19 - 21
69069000	Winchester	532896.0	5320630.0	19 - 21	19 - 21
04007900	Wolf	372425.0	5254000.0	19 - 21	19 - 21
11020100	Woman	402376.0	5200070.0	19 - 21	19 - 21
69022300	Agnes	570272.0	5340920.0	21 - 23	21 - 23
38047700	Cache	627470.0	5311360.0	21 - 23	21 - 23
04019600	Campbell	354193.0	5276400.0	21 - 23	21 - 23
16035700	Crab	675980.0	5328250.0	21 - 23	21 - 23
56029800	Deer	287024.0	5137590.0	21 - 23	21 - 23
31092100	Dixon	402826.0	5274150.0	21 - 23	21 - 23
38049800	Ensign	624504.0	5321860.0	21 - 23	21 - 23
38081100	Fall	594312.0	5311410.0	21 - 23	21 - 23
03038700	Floyd	282346.0	5194890.0	21 - 23	21 - 23
38052800	Four	619984.0	5307320.0	21 - 23	21 - 23
04016200	Fox	361550.0	5274530.0	21 - 23	21 - 23
29021600	George	350237.0	5228390.0	21 - 23	21 - 23
56078200	Hoot	266603.0	5132450.0	21 - 23	21 - 23
38079200	Horse	592218.0	5325910.0	21 - 23	21 - 23
31091300	Island	407447.0	5296370.0	21 - 23	21 - 23
38070300	Little Gabbro	603158.0	5301310.0	21 - 23	21 - 23
31061000	Little Moose	450018.0	5250470.0	21 - 23	21 - 23
56076100	Little Pelican	274643.0	5176880.0	21 - 23	21 - 23
31085300	Little Sand	422850.0	5277710.0	21 - 23	21 - 23
69129000	Little Sturgeon	496683.0	5278430.0	21 - 23	21 - 23
04015500	Little Turtle	358002.0	5277780.0	21 - 23	21 - 23
31077900	Little Turtle	442618.0	5273200.0	21 - 23	21 - 23
31085000	Little Winnibigoshish	422704.0	5252020.0	21 - 23	21 - 23
18024300	Lower Mission	415412.0	5153640.0	21 - 23	21 - 23
80003000	Lower Twin	344479.0	5184790.0	21 - 23	21 - 23
11022200	Margaret	395254.0	5149820.0	21 - 23	21 - 23
21009200	Mary	307127.0	5078040.0	21 - 23	21 - 23
03047500	Melissa	278087.0	5180240.0	21 - 23	21 - 23
38081600	Moosecamp	589993.0	5330370.0	21 - 23	> 23
56022900	Murphy	296961.0	5176470.0	21 - 23	21 - 23



DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
31038400	Prairie	459083.0	5240550.0	21 - 23	21 - 23
44010800	Sargent	297136.0	5238590.0	21 - 23	21 - 23
38037300	Shepo	635850.0	5319260.0	21 - 23	21 - 23
44004500	Snider	297678.0	5230750.0	21 - 23	21 - 23
38077800	South Farm	597772.0	5305050.0	21 - 23	21 - 23
44001400	South Twin	299810.0	5234400.0	21 - 23	21 - 23
38053100	Splash	618439.0	5321490.0	21 - 23	21 - 23
31035300	Split Hand	463144.0	5211910.0	21 - 23	21 - 23
04013400	Three Island	365025.0	5275860.0	21 - 23	21 - 23
69037800	Vermilion	531870.0	5312660.0	21 - 23	21 - 23
56031000	Walker	294361.0	5146000.0	21 - 23	21 - 23
69000400	White Iron	588920.0	5302340.0	21 - 23	21 - 23
73008900	Zumwalde	383780.0	5032510.0	21 - 23	21 - 23
31019700	Battle	474438.0	5297350.0	> 23	> 23
04004900	Big	377794.0	5262870.0	> 23	> 23
04003100	Big Rice	382917.0	5265030.0	> 23	> 23
69000300	Birch	585710.0	5289410.0	> 23	> 23
04006900	Blackduck	378752.0	5287780.0	> 23	> 23
31081300	Bowstring	431043.0	5265140.0	> 23	> 23
03028600	Cotton	294457.0	5195630.0	> 23	> 23
31088200	Dora	421576.0	5288130.0	> 23	> 23
69049600	Embarrass	551050.0	5264130.0	> 23	> 23
29008600	First Crow Wing	358592.0	5187860.0	> 23	> 23
38081300	Fourtown	590513.0	5325490.0	> 23	> 23
29024100	Frontenac	349695.0	5245530.0	> 23	> 23
09001000	Hay	541085.0	5160800.0	> 23	> 23
04014000	Irving	358007.0	5258040.0	> 23	> 23
39000200	Lake of the Woods	353219.3	5442359.6	> 23	> 23
31085200	Little Cut Foot Sioux	422866.0	5261800.0	> 23	> 23
31079700	Little Spring	435703.0	5274750.0	> 23	> 23
48000200	Mille Lacs	450391.0	5120690.0	> 23	> 23
61013000	Minnewaska	310731.0	5055100.0	> 23	> 23
44002300	North Twin	299958.0	5237020.0	> 23	> 23
69006100	One Pine	583868.0	5295850.0	> 23	> 23
38022000	Perent	639373.0	5295630.0	> 23	> 23
18008800	Platte	428767.0	5112690.0	> 23	> 23
56091500	Prairie	264845.0	5165400.0	> 23	> 23
31089600	Round	412845.0	5274580.0	> 23	> 23
31091000	Shallow Pond	405568.0	5289250.0	> 23	> 23
69092500	Shannon	502171.0	5275510.0	> 23	> 23
56048100	West Lost	279653.0	5141400.0	> 23	> 23

## Appendix G Names and Geographic Locations of Cisco Lakes in Minnesota Ranked by 1°C TDO3 Increment Values

Table G.1 Names and geographic locations of cisco lakes in Minnesota ranked by 1°C TDO3 increment values. Simulations of the 30 virtual cisco lakes (Table 1.2) were used to construct TDO3 the contour lines that served as the basis for this table. Simulations were made for the MIROC 3.2 future climate scenario with Duluth weather data to obtain TDO3 (°C) values for fixed and variable (sliding) benchmark periods (**AvgATDO3<sub>FB</sub>**, **AvgATDO3<sub>VB</sub>**, Table 3.1, lines 6 and 12).

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
29030900	LaSalle	335945.0	5244920.0	5 - 6	11 - 12
31039500	Bluewater	458235.0	5252040.0	6 - 7	10 - 11
38016600	Cherry	641319.0	5333210.0	6 - 7	9 - 10
16023200	Duncan	688691.0	5328360.0	6 - 7	9 - 10
69048700	Gun	559422.0	5352420.0	6 - 7	8 - 9
11040000	Jack	390145.0	5213090.0	6 - 7	10 - 11
38022900	Little Knife	636926.0	5333150.0	6 - 7	8 - 9
31039400	Little Trout	458897.0	5254040.0	6 - 7	9 - 10
69068200	Little Trout	535431.0	5360490.0	6 - 7	9 - 10
16044800	Loon	671907.0	5327530.0	6 - 7	9 - 10
38064000	Ojibway	608799.0	5311710.0	6 - 7	10 - 11
56036900	Six	287670.0	5176620.0	6 - 7	8 - 9
69036900	Takucmich	562210.0	5353350.0	6 - 7	9 - 10
11041300	Ten Mile	380379.0	5203110.0	6 - 7	10 - 11
04029700	Buzzle	339646.0	5276030.0	7 - 8	10 - 11
77012000	Charlotte	355635.0	5090450.0	7 - 8	12 - 13
31074900	Chase	444194.0	5246180.0	7 - 8	9 - 10
31054000	Clubhouse	457155.0	5272470.0	7 - 8	11 - 12
15009000	Deep	320013.0	5283860.0	7 - 8	10 - 11
11023700	Deep Portage	393944.0	5191690.0	7 - 8	11 - 12
11046600	Fifth	376618.0	5212610.0	7 - 8	12 - 13
58012300	Grindstone	499427.0	5107650.0	7 - 8	11 - 12
38020600	Hanson	642735.0	5333610.0	7 - 8	11 - 12
38040400	Knife	634276.0	5328310.0	7 - 8	10 - 11
16023400	Moss	687734.0	5326820.0	7 - 8	11 - 12
29023700	Newman	351221.0	5250800.0	7 - 8	11 - 12
38021100	Ottertrack	641140.0	5336920.0	7 - 8	10 - 11
11047600	Portage	381932.0	5207450.0	7 - 8	10 - 11
31042200	Ruby	458339.0	5262900.0	7 - 8	9 - 10
56035800	Scalp	287474.0	5174890.0	7 - 8	10 - 11
16024400	South	682582.0	5329800.0	7 - 8	9 - 10
18035900	Star	410022.0	5167710.0	7 - 8	11 - 12
01010900	Taylor	460999.0	5204520.0	7 - 8	12 - 13

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
38072400	Tofte	606653.0	5313510.0	7 - 8	10 - 11
31041000	Trout	458192.0	5256660.0	7 - 8	11 - 12
16008600	West Pike	708128.0	5329680.0	7 - 8	10 - 11
16035400	Winchell	679256.0	5318140.0	7 - 8	11 - 12
29018500	Big Sand	350361.0	5207040.0	8 - 9	11 - 12
04021700	Grant	348931.0	5261900.0	8 - 9	13 - 14
16035600	Gunflint	672943.0	5329800.0	8 - 9	13 - 14
31091100	Hamrey	406242.0	5285940.0	8 - 9	13 - 14
18036100	Kimball	408024.0	5167390.0	8 - 9	12 - 13
56032800	Little McDonald	292892.0	5165460.0	8 - 9	12 - 13
29015000	Little Sand	353063.0	5205920.0	8 - 9	10 - 11
29018000	Lower Bottle	352030.0	5210180.0	8 - 9	11 - 12
31023900	Lower Hanson	466217.0	5250430.0	8 - 9	13 - 14
16046300	Magnetic	665952.0	5330660.0	8 - 9	11 - 12
03037100	Meadow	280699.0	5181750.0	8 - 9	13 - 14
77002200	Mons	367464.0	5087210.0	8 - 9	12 - 13
16004300	Moose	716878.0	5331470.0	8 - 9	12 - 13
38071400	Section Twelve	608813.0	5312520.0	8 - 9	12 - 13
38052900	Snowbank	617945.0	5315770.0	8 - 9	12 - 13
38017200	Topaz	639601.0	5332420.0	8 - 9	12 - 13
16004900	Trout	711435.0	5305720.0	8 - 9	11 - 12
31034900	Antler	466207.0	5275090.0	9 - 10	13 - 14
38050200	Ashigan	624749.0	5320500.0	9 - 10	11 - 12
03008500	Bad Medicine	317655.0	5221710.0	9 - 10	12 - 13
18003000	Barbour	432303.0	5123450.0	9 - 10	13 - 14
11027700	Big Deep	394595.0	5196110.0	9 - 10	13 - 14
31079300	Big Too Much	440872.0	5277200.0	9 - 10	13 - 14
18031500	Big Trout	411532.0	5174230.0	9 - 10	13 - 14
16013900	Clearwater	697251.0	5328720.0	9 - 10	9 - 10
16058000	Granite	666146.0	5335850.0	9 - 10	14 - 15
31045200	Gunn	459357.0	5265500.0	9 - 10	13 - 14
18026900	Island-Loon	413256.0	5173460.0	9 - 10	13 - 14
31077800	Little Too Much	441738.0	5274880.0	9 - 10	14 - 15
31078100	Long	441433.0	5280740.0	9 - 10	14 - 15
16033100	North	681002.0	5331430.0	9 - 10	10 - 11
31021900	O'Reilly	467570.0	5245500.0	9 - 10	14 - 15
38038800	Spoon	633501.0	5326830.0	9 - 10	13 - 14
31072500	Turtle	448327.0	5275130.0	9 - 10	13 - 14
11086600	Tamarack	401048.0	5202160.0	9 - 10	14 - 15
11046900	Anway	376737.0	5211040.0	10 - 11	14 - 15
01004600	Ball Bluff	478651.0	5197700.0	10 - 11	14 - 15
31027800	Barwise	468711.0	5267270.0	10 - 11	13 - 14

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
29004800	Benedict	371657.0	5221980.0	10 - 11	14 - 15
18021100	Blue	423977.0	5180350.0	10 - 11	13 - 14
29018400	Blue	347677.0	5209100.0	10 - 11	14 - 15
16014700	Flour	693783.0	5325350.0	10 - 11	13 - 14
38037200	Fraser	634053.0	5318890.0	10 - 11	14 - 15
16031900	Gaskin	682846.0	5319510.0	10 - 11	14 - 15
21010600	Latoka	310959.0	5082980.0	10 - 11	14 - 15
01008900	Long	462404.0	5148280.0	10 - 11	14 - 15
21010800	Mina	307985.0	5085170.0	10 - 11	14 - 15
16004100	Pine	707341.0	5327100.0	10 - 11	13 - 14
31021800	Shamrock	468692.0	5245840.0	10 - 11	14 - 15
29023900	Spearhead	352132.0	5248390.0	10 - 11	14 - 15
04008500	Swenson	373092.0	5258540.0	10 - 11	14 - 15
38035100	Thomas	631603.0	5316590.0	10 - 11	15 - 16
86027900	West Lake Sylvia	404790.0	5011290.0	10 - 11	14 - 15
77002400	Bass	366498.0	5085360.0	11 - 12	15 - 16
18029800	East Fox	417710.0	5177450.0	11 - 12	15 - 16
18039600	Edna	399225.0	5154230.0	11 - 12	15 - 16
15001000	Elk	331973.0	5228580.0	11 - 12	15 - 16
16061700	Gneiss	662965.0	5338100.0	11 - 12	15 - 16
31037300	Hale	458520.0	5232670.0	11 - 12	15 - 16
31057500	Little Bass	454599.0	5237110.0	11 - 12	15 - 16
31039900	Little Wabana	462902.0	5249760.0	11 - 12	15 - 16
18037800	Lower Hay	401812.0	5169230.0	11 - 12	15 - 16
11028200	Mann	397848.0	5203010.0	11 - 12	15 - 16
16023000	Rose	690083.0	5330660.0	11 - 12	14 - 15
56036000	Rose	290565.0	5172740.0	11 - 12	15 - 16
18031100	Rush-Hen	413972.0	5171730.0	11 - 12	15 - 16
16062900	Sea Gull	654464.0	5333260.0	11 - 12	15 - 16
31008400	Shallow	477729.0	5219260.0	11 - 12	15 - 16
73018300	St. Anna	374291.0	5066760.0	11 - 12	15 - 16
16026700	Vernon	680957.0	5312910.0	11 - 12	15 - 16
31039200	Wabana	460476.0	5252590.0	11 - 12	15 - 16
18020800	Allen	424014.0	5182910.0	12 - 13	16 - 17
69011800	Burntside	581302.0	5310720.0	12 - 13	15 - 16
21005700	Carlos	316947.0	5091130.0	12 - 13	15 - 16
49014000	Cedar	372840.0	5074700.0	12 - 13	15 - 16
18036400	Clear	405698.0	5166480.0	12 - 13	16 - 17
11016300	Cooper	408898.0	5201950.0	12 - 13	16 - 17
86028900	East Lake Sylvia	406210.0	5011660.0	12 - 13	15 - 16
11017400	Girl	405649.0	5204090.0	12 - 13	16 - 17
16007700	Greenwood	710490.0	5320110.0	12 - 13	15 - 16

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
31046600	Horseshoe	461830.0	5272270.0	12 - 13	15 - 16
03015600	Ice Cracking	306412.0	5209340.0	12 - 13	16 - 17
29007500	Kabekona	366808.0	5225200.0	12 - 13	16 - 17
01005700	Little Ball Bluff	479174.0	5198320.0	12 - 13	15 - 16
09003500	Little Hanging Horn	524719.0	5147700.0	12 - 13	15 - 16
31057100	Loon	451222.0	5231220.0	12 - 13	16 - 17
11048200	May	379050.0	5216490.0	12 - 13	16 - 17
31077500	No-ta-she-bun	441437.0	5222430.0	12 - 13	15 - 16
56082900	Pebble	265969.0	5126590.0	12 - 13	16 - 17
04003400	Rabideau	386622.0	5277240.0	12 - 13	15 - 16
01020400	Round	438137.0	5131450.0	12 - 13	15 - 16
31025500	Snaptail	471657.0	5257370.0	12 - 13	16 - 17
29011700	Spider	358726.0	5206440.0	12 - 13	15 - 16
11006200	Thunder	426712.0	5199860.0	12 - 13	15 - 16
11006900	Bass	427017.0	5195460.0	13 - 14	16 - 17
38050300	Boot	622470.0	5319150.0	13 - 14	16 - 17
56051400	Elbow	283903.0	5160430.0	13 - 14	16 - 17
31046300	Fox	458903.0	5272300.0	13 - 14	16 - 17
31077100	Hatch	443582.0	5278860.0	13 - 14	16 - 17
38040000	Ima	628408.0	5319480.0	13 - 14	16 - 17
38051100	Jordan	626367.0	5318710.0	13 - 14	16 - 17
11048000	Long	378329.0	5214670.0	13 - 14	16 - 17
29016100	Long	347647.0	5194460.0	13 - 14	16 - 17
11004700	Mule	424154.0	5188480.0	13 - 14	16 - 17
31065300	North Star	449897.0	5266910.0	13 - 14	16 - 17
69033000	Oyster	566301.0	5341780.0	13 - 14	16 - 17
11004300	Roosevelt	427545.0	5185290.0	13 - 14	16 - 17
31055400	Siseebakwet	449178.0	5222790.0	13 - 14	16 - 17
69076100	Spring	527395.0	5357650.0	13 - 14	16 - 17
21010100	Stony	311791.0	5086600.0	13 - 14	16 - 17
69033700	Thumb	560384.0	5339160.0	13 - 14	16 - 17
69021300	Toe	570681.0	5347990.0	13 - 14	16 - 17
11005900	Washburn	424057.0	5191210.0	13 - 14	16 - 17
03032800	White Earth	291148.0	5223110.0	13 - 14	16 - 17
18035800	Bass	409240.0	5167800.0	14 - 15	16 - 17
21014500	Chippewa	303158.0	5096880.0	14 - 15	17 - 18
31071900	Deer	449898.0	5247700.0	14 - 15	16 - 17
16061600	Devils Elbow	661998.0	5338700.0	14 - 15	17 - 18
56052300	East Loon	283037.0	5167780.0	14 - 15	17 - 18
29003600	Eleventh Crow Wing	369070.0	5208250.0	14 - 15	17 - 18
38071800	Greenstone	603736.0	5309460.0	14 - 15	17 - 18
31034400	Hanson	466003.0	5251850.0	14 - 15	16 - 17

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
69034300	Hustler	562755.0	5342200.0	14 - 15	17 - 18
18001900	Kenney	434643.0	5130380.0	14 - 15	17 - 18
31073900	Leighton	442924.0	5227310.0	14 - 15	17 - 18
77003400	Little Swan	368729.0	5087740.0	14 - 15	17 - 18
73012800	Middle Spunk	385747.0	5051410.0	14 - 15	17 - 18
29002500	Ninth Crow Wing	365366.0	5204220.0	14 - 15	17 - 18
31019600	Poplar	474206.0	5299830.0	14 - 15	17 - 18
38052400	Portage	626152.0	5325270.0	14 - 15	17 - 18
56038700	Sybil	286904.0	5167120.0	14 - 15	16 - 17
38049100	Vera	625682.0	5323900.0	14 - 15	16 - 17
86028400	Augusta	408408.0	5017250.0	15 - 16	17 - 18
69048000	Beartrack	559248.0	5350060.0	15 - 16	17 - 18
18004100	Crooked	430110.0	5135770.0	15 - 16	17 - 18
69047300	Eugene	557783.0	5350470.0	15 - 16	17 - 18
56076800	Fish	269761.0	5173690.0	15 - 16	17 - 18
03023400	Little Bemidji	304998.0	5218800.0	15 - 16	17 - 18
31056600	Little Jay Gould	453693.0	5232280.0	15 - 16	17 - 18
69006600	Little Long	582688.0	5310080.0	15 - 16	17 - 18
31066500	Little North Star	449862.0	5269730.0	15 - 16	17 - 18
11006100	Little Thunder	428199.0	5201610.0	15 - 16	17 - 18
69038300	Lynx	559875.0	5340870.0	15 - 16	17 - 18
18029400	Mitchell	420024.0	5180970.0	15 - 16	17 - 18
18035400	Pig	409429.0	5169810.0	15 - 16	17 - 18
11038300	Pleasant	387711.0	5196590.0	15 - 16	17 - 18
11010500	Upper Trelipe	421271.0	5203000.0	15 - 16	17 - 18
31028100	Wasson	474042.0	5274860.0	15 - 16	18 - 19
03025800	Acorn	289344.0	5180770.0	16 - 17	18 - 19
56024100	Annie Battle	295211.0	5133880.0	16 - 17	18 - 19
31070400	Batson	453828.0	5276980.0	16 - 17	18 - 19
86022700	Cedar	416685.0	5013020.0	16 - 17	18 - 19
69006400	Dry	584290.0	5312420.0	16 - 17	18 - 19
31046000	East	458611.0	5274550.0	16 - 17	17 - 18
69066000	Ely	538977.0	5255380.0	16 - 17	18 - 19
29018600	Emma	352025.0	5208940.0	16 - 17	17 - 18
18039700	Fawn	398593.0	5154490.0	16 - 17	18 - 19
69008500	Fenske	581985.0	5315950.0	16 - 17	18 - 19
69034800	Finger	561761.0	5349220.0	16 - 17	18 - 19
11024200	Hand	399957.0	5189740.0	16 - 17	18 - 19
11026200	Kid	394668.0	5200920.0	16 - 17	18 - 19
11005300	Lawrence	428769.0	5185650.0	16 - 17	18 - 19
01017600	Little Pine	442658.0	5143540.0	16 - 17	18 - 19
18036000	Little Star	410596.0	5167570.0	16 - 17	18 - 19

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
16002700	McFarland	718479.0	5326390.0	16 - 17	17 - 18
56030300	Molly Stark	294326.0	5132590.0	16 - 17	18 - 19
31019200	Nashwauk	475804.0	5253040.0	16 - 17	18 - 19
18035200	Ossawinnamakee	406569.0	5165330.0	16 - 17	17 - 18
31033900	Pickerel	473175.0	5296930.0	16 - 17	18 - 19
56047500	Pickerel	284417.0	5145370.0	16 - 17	18 - 19
31053200	Pokegama	456223.0	5226050.0	16 - 17	17 - 18
16023900	Poplar	685622.0	5324510.0	16 - 17	18 - 19
11028500	Rat	395025.0	5211180.0	16 - 17	18 - 19
16079300	Red Rock	650916.0	5335990.0	16 - 17	18 - 19
69018100	Slim	576841.0	5318000.0	16 - 17	18 - 19
69011100	Smith	582159.0	5222660.0	16 - 17	18 - 19
56043700	Stalker	281806.0	5121140.0	16 - 17	18 - 19
73024900	Sylvia	360998.0	5067970.0	16 - 17	17 - 18
56034800	Tenter	289919.0	5159880.0	16 - 17	17 - 18
38071500	Triangle	608174.0	5310360.0	16 - 17	17 - 18
29000500	Tripp	365429.0	5190210.0	16 - 17	18 - 19
29014800	Upper Bottle	353585.0	5211680.0	16 - 17	18 - 19
18031000	Whitefish	407170.0	5171640.0	16 - 17	18 - 19
56035500	Wimer	291886.0	5175210.0	16 - 17	18 - 19
16075900	Alpine	649531.0	5332970.0	17 - 18	18 - 19
16062200	Alton	656349.0	5304070.0	17 - 18	18 - 19
38021000	Ashdick	644603.0	5337730.0	17 - 18	18 - 19
11028300	Baby	396245.0	5201980.0	17 - 18	18 - 19
29020800	Bad Axe	351943.0	5216320.0	17 - 18	18 - 19
18035500	Bertha	404168.0	5168510.0	17 - 18	18 - 19
31083400	Bird's Eye	426217.0	5273040.0	17 - 18	18 - 19
11027400	Blackwater	400655.0	5195900.0	17 - 18	18 - 19
16034800	Brule	673870.0	5312050.0	17 - 18	18 - 19
04004200	Buck	382628.0	5257840.0	17 - 18	18 - 19
01020900	Cedar	438607.0	5149860.0	17 - 18	18 - 19
21010300	Cowdrey	312512.0	5085750.0	17 - 18	18 - 19
38081700	Crooked	596254.0	5334950.0	17 - 18	18 - 19
18031200	Cross Lake Reservoir	413290.0	5168890.0	17 - 18	18 - 19
29025600	Eagle	340353.0	5210560.0	17 - 18	18 - 19
56013800	East Battle	304690.0	5130610.0	17 - 18	18 - 19
18030500	Edward	411042.0	5151200.0	17 - 18	18 - 19
03015900	Elbow	305655.0	5222160.0	17 - 18	18 - 19
69056500	Esquagama	548740.0	5257340.0	17 - 18	18 - 19
18004400	Hanks	430553.0	5134130.0	17 - 18	18 - 19
11047200	Howard	374365.0	5205910.0	17 - 18	18 - 19
18037500	Hubert	402596.0	5148950.0	17 - 18	18 - 19

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
21012300	Ida	312492.0	5095580.0	17 - 18	18 - 19
56087700	Jewett	265556.0	5144260.0	17 - 18	18 - 19
69079600	Leander	518479.0	5280400.0	17 - 18	18 - 19
11003700	Leavitt	431340.0	5187180.0	17 - 18	18 - 19
61003700	Linka	315208.0	5040130.0	17 - 18	18 - 19
31078400	Little Jessie	438271.0	5267430.0	17 - 18	18 - 19
03038300	Long	279360.0	5188960.0	17 - 18	18 - 19
56078400	Long	265281.0	5146400.0	17 - 18	18 - 19
77002700	Long	366300.0	5082940.0	17 - 18	18 - 19
18000200	Long/Tame Fish	437054.0	5139390.0	17 - 18	18 - 19
03015800	Many Point	307284.0	5216900.0	17 - 18	18 - 19
11026100	McKeown	398442.0	5201700.0	17 - 18	18 - 19
69068400	Mukooda	537894.0	5353770.0	17 - 18	18 - 19
11020000	Mule	403154.0	5196140.0	17 - 18	18 - 19
18037200	North Long	404694.0	5143610.0	17 - 18	18 - 19
31010600	Ox Hide	484038.0	5243150.0	17 - 18	18 - 19
38052600	Parent	619730.0	5313550.0	17 - 18	18 - 19
18030800	Pelican	409953.0	5158500.0	17 - 18	18 - 19
11041500	Pike Bay	381520.0	5245770.0	17 - 18	18 - 19
11049000	Portage	378945.0	5237320.0	17 - 18	18 - 19
31082400	Portage	426992.0	5270380.0	17 - 18	18 - 19
18020900	Pug Hole	423222.0	5181970.0	17 - 18	18 - 19
31071700	Rice	448307.0	5229370.0	17 - 18	18 - 19
69061700	Sand Point	537243.0	5357680.0	17 - 18	18 - 19
18009000	Serpent	428743.0	5147870.0	17 - 18	18 - 19
31050200	Slauson	457810.0	5275710.0	17 - 18	18 - 19
31055500	South Sugar	448301.0	5221560.0	17 - 18	18 - 19
69065100	St. Mary's	536725.0	5252780.0	17 - 18	18 - 19
11050400	Steamboat	374321.0	5235860.0	17 - 18	18 - 19
69049800	Trout	550807.0	5313550.0	17 - 18	18 - 19
56023900	West Battle	295607.0	5130070.0	17 - 18	18 - 19
18029700	West Fox	416471.0	5177400.0	17 - 18	18 - 19
11025000	Ada	397259.0	5187120.0	18 - 19	19 - 20
49007900	Alexander	380926.0	5118380.0	18 - 19	19 - 20
38022700	Amoeber	637882.0	5331760.0	18 - 19	19 - 20
21008500	Andrew	312104.0	5076890.0	18 - 19	19 - 20
31081200	Ball Club	428770.0	5245550.0	18 - 19	19 - 20
31057600	Bass	451320.0	5240140.0	18 - 19	19 - 20
69055300	Bass	550467.0	5255250.0	18 - 19	19 - 20
18003400	Bay	434578.0	5137110.0	18 - 19	19 - 20
31072600	Bello	446882.0	5279540.0	18 - 19	19 - 20
04013500	Beltrami	363587.0	5272810.0	18 - 19	19 - 20



DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
04015700	Black	363357.0	5277150.0	18 - 19	19 - 20
18014000	Black Bear	418692.0	5151050.0	18 - 19	19 - 20
31056100	Blackwater	448650.0	5233590.0	18 - 19	19 - 20
56024000	Blanche	295430.0	5136060.0	18 - 19	19 - 20
18002000	Borden	434470.0	5127900.0	18 - 19	19 - 20
21010200	Brophy	310581.0	5086380.0	18 - 19	19 - 20
21004900	Burgen	318043.0	5079910.0	18 - 19	19 - 20
04014100	Carr	357384.0	5255950.0	18 - 19	19 - 20
04003000	Cass	384633.0	5253390.0	18 - 19	19 - 20
11028900	Cedar	399266.0	5209590.0	18 - 19	19 - 20
31082900	Cedar	426789.0	5276770.0	18 - 19	19 - 20
38081000	Cedar	590177.0	5312220.0	18 - 19	19 - 20
04034300	Clearwater	336043.0	5288920.0	18 - 19	19 - 20
18003800	Clearwater	429708.0	5138390.0	18 - 19	19 - 20
18013100	Clinker	427010.0	5152160.0	18 - 19	19 - 20
56023800	Clitherall	294394.0	5125000.0	18 - 19	19 - 20
69022000	Crab	570365.0	5310570.0	18 - 19	19 - 20
31085700	Cut Foot Sioux	421050.0	5261090.0	18 - 19	19 - 20
31042900	Cutaway	465628.0	5260360.0	18 - 19	19 - 20
21008000	Darling	314177.0	5087870.0	18 - 19	19 - 20
04023000	Deer	348027.0	5280280.0	18 - 19	19 - 20
03038100	Detroit	283672.0	5185560.0	18 - 19	19 - 20
69091200	Dewey	504222.0	5270940.0	18 - 19	19 - 20
38048800	Disappointment	622356.0	5315860.0	18 - 19	19 - 20
16004200	East Pike	715762.0	5329140.0	18 - 19	19 - 20
31049000	Elizabeth	461746.0	5266960.0	18 - 19	19 - 20
31060900	Fawn	447940.0	5251690.0	18 - 19	19 - 20
29024200	Fish Hook	342946.0	5202390.0	18 - 19	19 - 20
31018300	Five Island	477935.0	5298610.0	18 - 19	19 - 20
11035100	Five Point	389591.0	5192770.0	18 - 19	19 - 20
69035000	Ge-Be-On-Equat	565472.0	5347990.0	18 - 19	19 - 20
21005200	Geneva	319386.0	5085640.0	18 - 19	19 - 20
38050800	Gibson	624839.0	5319500.0	18 - 19	19 - 20
38072600	Good	603396.0	5317820.0	18 - 19	18 - 19
34007900	Green	350567.0	5012690.0	18 - 19	19 - 20
16063200	Gull	656853.0	5336480.0	18 - 19	19 - 20
09003800	Hanging Horn	523502.0	5147210.0	18 - 19	19 - 20
31002000	Hart	488322.0	5233580.0	18 - 19	19 - 20
31015400	Hartley	476810.0	5267220.0	18 - 19	19 - 20
11019900	Hay	402344.0	5191510.0	18 - 19	19 - 20
69046900	Heritage	558482.0	5341940.0	18 - 19	19 - 20
31048100	Highland	460943.0	5268450.0	18 - 19	19 - 20

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
29024900	Hinds	343557.0	5188760.0	18 - 19	19 - 20
69012100	Iron	579878.0	5342140.0	18 - 19	19 - 20
29025400	Island	340058.0	5212750.0	18 - 19	19 - 20
31065700	Jack the Horse	452194.0	5273850.0	18 - 19	19 - 20
31068700	Johnson	450773.0	5275000.0	18 - 19	19 - 20
69069100	Johnson	528994.0	5354220.0	18 - 19	19 - 20
69022400	Lac la Croix	566478.0	5353810.0	18 - 19	19 - 20
21005600	Le Homme Dieu	317574.0	5088720.0	18 - 19	19 - 20
77008900	Little Birch	359878.0	5070750.0	18 - 19	18 - 19
11016700	Little Boy	409479.0	5199310.0	18 - 19	19 - 20
69104000	Little Dry	583873.0	5311920.0	18 - 19	18 - 19
69008600	Little Sletten	582979.0	5315530.0	18 - 19	18 - 19
11003000	Little Vermillion	436520.0	5226360.0	18 - 19	18 - 19
21010500	Lottie	311575.0	5085870.0	18 - 19	19 - 20
29015100	Mantrap	354367.0	5215070.0	18 - 19	19 - 20
56024300	Marion	297221.0	5156330.0	18 - 19	19 - 20
44008000	McCraney	295625.0	5227690.0	18 - 19	19 - 20
18037700	Middle Cullen	402964.0	5156350.0	18 - 19	19 - 20
31039600	Middle Hanson	465872.0	5253550.0	18 - 19	19 - 20
18013300	Miller	419043.0	5152230.0	18 - 19	19 - 20
21008300	Miltona	316217.0	5101020.0	18 - 19	19 - 20
31072200	Moose	447808.0	5249510.0	18 - 19	19 - 20
38064400	Moose	611711.0	5316830.0	18 - 19	19 - 20
04015200	Movil	360165.0	5272390.0	18 - 19	19 - 20
69007800	Mudro	588640.0	5321030.0	18 - 19	19 - 20
69069300	Namakan	524538.0	5367940.0	18 - 19	19 - 20
31019000	North Twin	475945.0	5239320.0	18 - 19	19 - 20
21009500	North Union	311759.0	5087670.0	18 - 19	19 - 20
73001500	Otter	409189.0	5019660.0	18 - 19	18 - 19
56024200	Otter Tail	295279.0	5142030.0	18 - 19	19 - 20
11032000	Pillager	386358.0	5136020.0	18 - 19	19 - 20
18006900	Portage	431876.0	5144380.0	18 - 19	18 - 19
18005000	Portage	429496.0	5133530.0	18 - 19	19 - 20
29024300	Potato	344157.0	5207100.0	18 - 19	19 - 20
21016000	Rachel	301463.0	5074820.0	18 - 19	19 - 20
03015500	Round	306933.0	5212470.0	18 - 19	19 - 20
38022500	Sagus	637256.0	5319710.0	18 - 19	19 - 20
29004300	Shingobee	371667.0	5207000.0	18 - 19	19 - 20
56018000	Siverson	301237.0	5123450.0	18 - 19	19 - 20
18002800	Smith	434158.0	5123550.0	18 - 19	19 - 20
31019100	South Twin	475632.0	5238400.0	18 - 19	19 - 20
01017800	Spirit	445916.0	5143450.0	18 - 19	19 - 20

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
56038500	Star	284385.0	5155620.0	18 - 19	19 - 20
69047500	Steep	556556.0	5350670.0	18 - 19	19 - 20
03001000	Straight	327455.0	5201350.0	18 - 19	19 - 20
56019100	Stuart	301096.0	5127880.0	18 - 19	19 - 20
86023300	Sugar	418656.0	5018770.0	18 - 19	19 - 20
11013300	Swift	417857.0	5216400.0	18 - 19	19 - 20
29004500	Tenth Crow Wing	366600.0	5205450.0	18 - 19	19 - 20
77008800	Turtle	363416.0	5116960.0	18 - 19	19 - 20
21005400	Victoria	318174.0	5082590.0	18 - 19	19 - 20
11017100	Wabedo	407120.0	5195650.0	18 - 19	19 - 20
69093700	War Club	501476.0	5375960.0	18 - 19	19 - 20
56011400	West Leaf	308473.0	5142670.0	18 - 19	19 - 20
18000100	Whitefish	437041.0	5116960.0	18 - 19	19 - 20
38033000	Alice	633333.0	5311930.0	19 - 20	19 - 20
38040100	Alworth	628130.0	5317880.0	19 - 20	19 - 20
38033600	Amber	635689.0	5312670.0	19 - 20	20 - 21
04003800	Andrusia	375346.0	5257210.0	19 - 20	19 - 20
31069000	Aspen	450394.0	5285140.0	19 - 20	20 - 21
31025900	Balsam	468931.0	5264210.0	19 - 20	20 - 21
01007300	Bass	471710.0	5163170.0	19 - 20	20 - 21
38064500	Basswood	604141.0	5323330.0	19 - 20	19 - 20
09003400	Bear	524867.0	5149430.0	19 - 20	19 - 20
69011500	Bear Island	577437.0	5291940.0	19 - 20	20 - 21
69008900	Bear Trap	584072.0	5332440.0	19 - 20	19 - 20
77008400	Big Birch	363766.0	5071140.0	19 - 20	19 - 20
15000100	Big LaSalle	335749.0	5240070.0	19 - 20	19 - 20
56013000	Big Pine	309661.0	5164940.0	19 - 20	20 - 21
73011700	Big Spunk	385246.0	5049910.0	19 - 20	19 - 20
77002300	Big Swan	363787.0	5082180.0	19 - 20	20 - 21
11041200	Birch	382126.0	5199300.0	19 - 20	20 - 21
56021200	Boedigheimer	301187.0	5154540.0	19 - 20	20 - 21
03035000	Buffalo	287611.0	5205620.0	19 - 20	19 - 20
31053000	Busties	462756.0	5300700.0	19 - 20	19 - 20
18035600	Clamshell	405902.0	5169020.0	19 - 20	19 - 20
11049400	Crooked	381350.0	5233310.0	19 - 20	19 - 20
31019300	Crooked	475920.0	5255100.0	19 - 20	20 - 21
56074900	Crystal	274000.0	5166590.0	19 - 20	19 - 20
01009600	Dam	464371.0	5150860.0	19 - 20	19 - 20
31033400	Deer	471615.0	5298330.0	19 - 20	20 - 21
16063400	Dyers	652006.0	5265890.0	19 - 20	20 - 21
18029600	Eagle	419933.0	5178560.0	19 - 20	19 - 20
56037800	East Lost	285988.0	5137710.0	19 - 20	20 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
69074400	Elbow	527672.0	5317960.0	19 - 20	20 - 21
03050300	Eunice	273201.0	5180430.0	19 - 20	20 - 21
77015400	Fairy	345596.0	5072650.0	19 - 20	19 - 20
38077900	Farm	594981.0	5305880.0	19 - 20	20 - 21
01015900	Farm Island	440567.0	5141320.0	19 - 20	19 - 20
29009200	Fifth Crow Wing	355740.0	5197660.0	19 - 20	20 - 21
56024700	Fischer (Carroll)	295593.0	5177030.0	19 - 20	19 - 20
56075900	Franklin	272328.0	5169680.0	19 - 20	19 - 20
04002400	Gilstad	385070.0	5280690.0	19 - 20	19 - 20
56036800	Graham	291516.0	5176770.0	19 - 20	19 - 20
31062400	Grave	449973.0	5261460.0	19 - 20	19 - 20
11030500	Gull	395764.0	5144720.0	19 - 20	19 - 20
31048000	Gunn	459752.0	5269430.0	19 - 20	19 - 20
29030000	Hattie	344604.0	5237240.0	19 - 20	19 - 20
01017900	Hickory	443744.0	5143130.0	19 - 20	19 - 20
38039700	Insula	627827.0	5308350.0	19 - 20	19 - 20
21007600	Irene	321549.0	5103410.0	19 - 20	19 - 20
31021700	Island	468665.0	5245300.0	19 - 20	19 - 20
31056500	Jay Gould	452692.0	5232580.0	19 - 20	20 - 21
04000700	Kitchi	385900.0	5261530.0	19 - 20	20 - 21
69074800	Kjostad	529495.0	5328680.0	19 - 20	20 - 21
11020300	Leech	392202.0	5226300.0	19 - 20	20 - 21
31075800	Little Bowstring	445248.0	5260210.0	19 - 20	20 - 21
03038600	Little Floyd	284096.0	5195150.0	19 - 20	19 - 20
56014200	Little Pine	304356.0	5167610.0	19 - 20	19 - 20
18026600	Little Pine	418477.0	5172770.0	19 - 20	20 - 21
18013900	Little Rabbit	419231.0	5146690.0	19 - 20	19 - 20
31071600	Little Rice	446677.0	5231510.0	19 - 20	20 - 21
69045500	Little Trout	553631.0	5316290.0	19 - 20	20 - 21
21014400	Lobster	303874.0	5083620.0	19 - 20	19 - 20
69093600	Locator	500228.0	5376200.0	19 - 20	19 - 20
69047000	Loon	553513.0	5343390.0	19 - 20	19 - 20
31057900	Loon	450034.0	5244000.0	19 - 20	20 - 21
21009400	Louise	312439.0	5088940.0	19 - 20	19 - 20
18040300	Lower Cullen	400998.0	5154730.0	19 - 20	19 - 20
31070500	Lundeen	450527.0	5277240.0	19 - 20	19 - 20
38009000	Malberg	640725.0	5312800.0	19 - 20	20 - 21
31077300	Maple	445848.0	5277410.0	19 - 20	19 - 20
04014200	Marquette	356146.0	5254630.0	19 - 20	19 - 20
21018000	Mill	303411.0	5080710.0	19 - 20	20 - 21
69027500	Mud	566527.0	5303620.0	19 - 20	20 - 21
38061900	Newfound	614900.0	5320150.0	19 - 20	19 - 20

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
38078400	Newton	595843.0	5315350.0	19 - 20	20 - 21
18010400	Nokay	425925.0	5136540.0	19 - 20	20 - 21
38060500	One	613393.0	5309270.0	19 - 20	19 - 20
77021500	Osakis	336615.0	5086080.0	19 - 20	20 - 21
11041100	Pine Mountain	383041.0	5186700.0	19 - 20	19 - 20
29015600	Plantagenet	354892.0	5248830.0	19 - 20	19 - 20
86025100	Pleasant	411744.0	5014100.0	19 - 20	19 - 20
11020400	Portage	400900.0	5244140.0	19 - 20	19 - 20
69069400	Rainy	492109.0	5379040.0	19 - 20	20 - 21
11022000	Ray	397903.0	5152930.0	19 - 20	20 - 21
01007000	Round	470998.0	5166210.0	19 - 20	19 - 20
18037300	Round	401596.0	5145720.0	19 - 20	19 - 20
49001900	Round	424958.0	5111690.0	19 - 20	19 - 20
31083200	Rush Island	427922.0	5275010.0	19 - 20	20 - 21
03035900	Sallie	278875.0	5183880.0	19 - 20	20 - 21
31082600	Sand	424288.0	5274410.0	19 - 20	19 - 20
31034500	Scrapper	466412.0	5262640.0	19 - 20	20 - 21
29008500	Second Crow Wing	357214.0	5188850.0	19 - 20	20 - 21
29009100	Seventh Crow Wing	360801.0	5200540.0	19 - 20	19 - 20
69093300	Side	498486.0	5280090.0	19 - 20	20 - 21
11014600	Six Mile	413380.0	5240420.0	19 - 20	19 - 20
29009300	Sixth Crow Wing	358126.0	5198890.0	19 - 20	19 - 20
18013600	South Long	416333.0	5125670.0	19 - 20	20 - 21
31078900	Spring	434870.0	5277810.0	19 - 20	19 - 20
49001600	Sullivan	427068.0	5110000.0	19 - 20	19 - 20
31006700	Swan	486007.0	5238930.0	19 - 20	19 - 20
44000300	Tulaby	302422.0	5225200.0	19 - 20	19 - 20
04015900	Turtle	359754.0	5275580.0	19 - 20	20 - 21
03001700	Two Inlets	333395.0	5210660.0	19 - 20	19 - 20
18037600	Upper Cullen	403727.0	5157740.0	19 - 20	19 - 20
11021800	Upper Gull	396854.0	5153810.0	19 - 20	19 - 20
18009600	Upper South Long	419996.0	5129080.0	19 - 20	20 - 21
11049300	Welch	381947.0	5234770.0	19 - 20	19 - 20
31084300	Whitefish	427625.0	5281600.0	19 - 20	20 - 21
69069000	Winchester	532896.0	5320630.0	19 - 20	19 - 20
04007900	Wolf	372425.0	5254000.0	19 - 20	19 - 20
01004000	Aitkin	477881.0	5183130.0	20 - 21	20 - 21
38063700	Bald Eagle	609523.0	5296760.0	20 - 21	21 - 22
01006200	Big Sandy	480893.0	5178490.0	20 - 21	20 - 21
38053200	Birch	620584.0	5324060.0	20 - 21	20 - 21
69010000	Boot	587357.0	5326780.0	20 - 21	21 - 22
04021100	Bootleg	349047.0	5257240.0	20 - 21	20 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
11035000	Bowen	386229.0	5185130.0	20 - 21	20 - 21
11014300	Boy	415630.0	5218280.0	20 - 21	21 - 22
31014700	Bray	478607.0	5256750.0	20 - 21	20 - 21
86028100	Caroline	406232.0	5018940.0	20 - 21	20 - 21
11026300	Child	397850.0	5200080.0	20 - 21	20 - 21
69061600	Crane	537602.0	5350630.0	20 - 21	20 - 21
69032500	Cummings	566275.0	5315930.0	20 - 21	20 - 21
18027100	Daggett	416603.0	5171270.0	20 - 21	21 - 22
56038300	Dead	288869.0	5151050.0	20 - 21	20 - 21
31090400	Dunbar	406944.0	5277220.0	20 - 21	20 - 21
29007200	Eighth Crow Wing	363682.0	5202230.0	20 - 21	20 - 21
49013700	Fish Trap	375266.0	5118690.0	20 - 21	20 - 21
38070100	Gabbro	605407.0	5301180.0	20 - 21	20 - 21
38078200	Garden	593602.0	5308500.0	20 - 21	20 - 21
01017000	Hanging Kettle	446216.0	5147470.0	20 - 21	20 - 21
38036900	Hatchet	630329.0	5319380.0	20 - 21	20 - 21
11023200	Hattie	393768.0	5185750.0	20 - 21	20 - 21
73015700	Horseshoe	380075.0	5031490.0	20 - 21	20 - 21
69037200	Island Lake Reservoir	562931.0	5206960.0	20 - 21	20 - 21
15001600	Itasca	333335.0	5231540.0	20 - 21	20 - 21
21005500	Jessie	320839.0	5081410.0	20 - 21	20 - 21
31078600	Jessie	438449.0	5270650.0	20 - 21	20 - 21
69084500	Kabetogama	501151.0	5363800.0	20 - 21	20 - 21
31023100	Lawrence	471617.0	5253760.0	20 - 21	21 - 22
11036700	Lind	387364.0	5186280.0	20 - 21	20 - 21
38070300	Little Gabbro	603158.0	5301310.0	20 - 21	21 - 22
31034100	Little Split Hand	465958.0	5212580.0	20 - 21	21 - 22
69060800	Little Vermilion	543659.0	5347600.0	20 - 21	20 - 21
69085900	Long	506622.0	5271520.0	20 - 21	20 - 21
73013900	Long	380649.0	5028330.0	20 - 21	21 - 22
31024700	Lower Balsam	473343.0	5261010.0	20 - 21	20 - 21
73012300	Lower Spunk	386219.0	5052620.0	20 - 21	20 - 21
11031300	Lower Sucker	392208.0	5242810.0	20 - 21	20 - 21
11012900	Lower Trelipe	418621.0	5204710.0	20 - 21	20 - 21
03050000	Maud	272152.0	5181630.0	20 - 21	20 - 21
56022900	Murphy	296961.0	5176470.0	20 - 21	21 - 22
18039900	Nisswa	400447.0	5152570.0	20 - 21	21 - 22
56078600	Pelican	269128.0	5176090.0	20 - 21	20 - 21
04003200	Pimushe	384671.0	5270540.0	20 - 21	20 - 21
69084800	Prairie	507340.0	5182010.0	20 - 21	20 - 21
73019600	Rice	373478.0	5025900.0	20 - 21	21 - 22
01014600	Ripple	448612.0	5145780.0	20 - 21	20 - 21

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
18039800	Roy	398633.0	5152050.0	20 - 21	20 - 21
56014100	Rush	305734.0	5152370.0	20 - 21	20 - 21
69006900	Shagawa	583837.0	5307140.0	20 - 21	20 - 21
44004500	Snider	297678.0	5230750.0	20 - 21	21 - 22
31000300	South Sturgeon	495203.0	5275970.0	20 - 21	20 - 21
16045700	South Temperance	666008.0	5311350.0	20 - 21	20 - 21
03032300	Strawberry	295036.0	5216570.0	20 - 21	20 - 21
69020500	Stuart	573633.0	5337720.0	20 - 21	20 - 21
38078100	Stub	596606.0	5311100.0	20 - 21	21 - 22
38053000	Sucker	617944.0	5322320.0	20 - 21	20 - 21
29007700	Third Crow Wing	358407.0	5191530.0	20 - 21	20 - 21
38060000	Three	616125.0	5305190.0	20 - 21	20 - 21
38060800	Two	614725.0	5307640.0	20 - 21	20 - 21
18024200	Upper Mission	417755.0	5156050.0	20 - 21	20 - 21
56031000	Walker	294361.0	5146000.0	20 - 21	21 - 22
11020100	Woman	402376.0	5200070.0	20 - 21	20 - 21
69022300	Agnes	570272.0	5340920.0	21 - 22	21 - 22
38047700	Cache	627470.0	5311360.0	21 - 22	21 - 22
04019600	Campbell	354193.0	5276400.0	21 - 22	21 - 22
16035700	Crab	675980.0	5328250.0	21 - 22	21 - 22
56029800	Deer	287024.0	5137590.0	21 - 22	21 - 22
31092100	Dixon	402826.0	5274150.0	21 - 22	21 - 22
38049800	Ensign	624504.0	5321860.0	21 - 22	22 - 23
03038700	Floyd	282346.0	5194890.0	21 - 22	21 - 22
04016200	Fox	361550.0	5274530.0	21 - 22	21 - 22
29021600	George	350237.0	5228390.0	21 - 22	21 - 22
56078200	Hoot	266603.0	5132450.0	21 - 22	21 - 22
38079200	Horse	592218.0	5325910.0	21 - 22	22 - 23
31061000	Little Moose	450018.0	5250470.0	21 - 22	21 - 22
56076100	Little Pelican	274643.0	5176880.0	21 - 22	21 - 22
69129000	Little Sturgeon	496683.0	5278430.0	21 - 22	22 - 23
04015500	Little Turtle	358002.0	5277780.0	21 - 22	21 - 22
31077900	Little Turtle	442618.0	5273200.0	21 - 22	21 - 22
31085000	Little Winnibigoshish	422704.0	5252020.0	21 - 22	21 - 22
18024300	Lower Mission	415412.0	5153640.0	21 - 22	21 - 22
80003000	Lower Twin	344479.0	5184790.0	21 - 22	21 - 22
11022200	Margaret	395254.0	5149820.0	21 - 22	21 - 22
21009200	Mary	307127.0	5078040.0	21 - 22	21 - 22
03047500	Melissa	278087.0	5180240.0	21 - 22	21 - 22
31038400	Prairie	459083.0	5240550.0	21 - 22	21 - 22
38037300	Shepo	635850.0	5319260.0	21 - 22	21 - 22
38077800	South Farm	597772.0	5305050.0	21 - 22	21 - 22

DOW Number	Lake Name	UTM Easting	UTM Northing	TDO3 Value Range (°C)	
				Fixed Benchmark	Variable Benchmark
44001400	South Twin	299810.0	5234400.0	21 - 22	21 - 22
38053100	Splash	618439.0	5321490.0	21 - 22	21 - 22
31035300	Split Hand	463144.0	5211910.0	21 - 22	21 - 22
69037800	Vermilion	531870.0	5312660.0	21 - 22	21 - 22
69000400	White Iron	588920.0	5302340.0	21 - 22	21 - 22
73008900	Zumwalde	383780.0	5032510.0	21 - 22	21 - 22
38081100	Fall	594312.0	5311410.0	22 - 23	22 - 23
38052800	Four	619984.0	5307320.0	22 - 23	22 - 23
31091300	Island	407447.0	5296370.0	22 - 23	22 - 23
31085300	Little Sand	422850.0	5277710.0	22 - 23	22 - 23
38081600	Moosecamp	589993.0	5330370.0	22 - 23	23 - 24
44010800	Sargent	297136.0	5238590.0	22 - 23	22 - 23
04013400	Three Island	365025.0	5275860.0	22 - 23	22 - 23
31019700	Battle	474438.0	5297350.0	23 - 24	23 - 24
04004900	Big	377794.0	5262870.0	23 - 24	23 - 24
04006900	Blackduck	378752.0	5287780.0	23 - 24	23 - 24
03028600	Cotton	294457.0	5195630.0	23 - 24	23 - 24
31088200	Dora	421576.0	5288130.0	23 - 24	23 - 24
69049600	Embarrass	551050.0	5264130.0	23 - 24	23 - 24
29024100	Frontenac	349695.0	5245530.0	23 - 24	23 - 24
09001000	Hay	541085.0	5160800.0	23 - 24	23 - 24
31085200	Little Cut Foot Sioux	422866.0	5261800.0	23 - 24	23 - 24
38022000	Perent	639373.0	5295630.0	23 - 24	23 - 24
56091500	Prairie	264845.0	5165400.0	23 - 24	23 - 24
31091000	Shallow Pond	405568.0	5289250.0	23 - 24	> 24
04003100	Big_Rice	382917.0	5265030.0	> 24	> 24
69000300	Birch	585710.0	5289410.0	> 24	> 24
31081300	Bowstring	431043.0	5265140.0	> 24	> 24
29008600	First Crow Wing	358592.0	5187860.0	> 24	> 24
38081300	Fourtown	590513.0	5325490.0	> 24	> 24
04014000	Irving	358007.0	5258040.0	> 24	> 24
39000200	Lake of the Woods	353219.3	5442359.6	> 24	> 24
31079700	Little Spring	435703.0	5274750.0	> 24	> 24
48000200	Mille Lacs	450391.0	5120690.0	> 24	> 24
61013000	Minnewaska	310731.0	5055100.0	> 24	> 24
44002300	North Twin	299958.0	5237020.0	> 24	> 24
69006100	One Pine	583868.0	5295850.0	> 24	> 24
18008800	Platte	428767.0	5112690.0	> 24	> 24
31089600	Round	412845.0	5274580.0	> 24	> 24
69092500	Shannon	502171.0	5275510.0	> 24	> 24
56048100	West Lost	279653.0	5141400.0	> 24	> 24