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Characteristics of Minnesota's Cisco Lakes

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Abstract

Bathymetric and other limnological characteristics of 620 Minnesota cisco lakes have been analyzed and compared with the same characteristics in another Minnesota lakes database consisting of 3002 lakes. It has been found that, on average, Minnesota cisco lakes are deeper, more transparent and less trophic than other lakes. They are preferentially located in north central and northeastern Minnesota.

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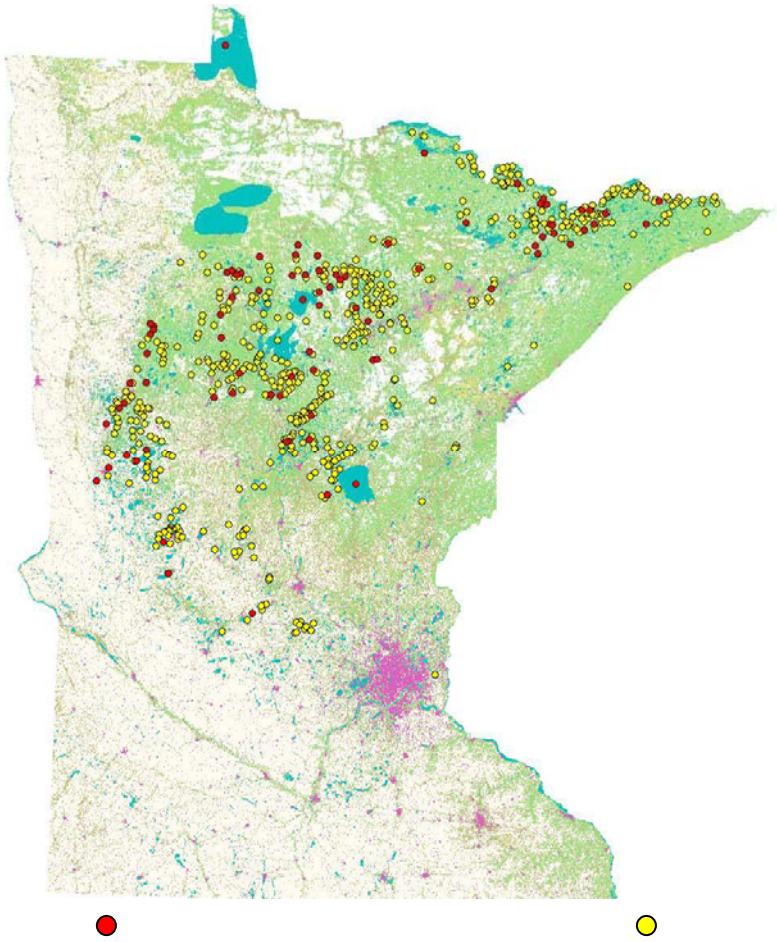
1. Objectives and Methods

Cisco (*Coregonus artedi*, lake herring, tullibee; Figure 1.1) is a coldwater fish that is commercially harvested in Lake Superior and also is foraged upon by walleyed pike and northern pike in many inland lakes. Cisco is the most common coldwater stenothermal fish in Minnesota lakes. Minnesota Department of Natural Resources (Mn DNR) netting assessments have sampled cisco (Coregonus artedi, lake herring, tullibee) from 648 lakes since 1946 (Minnesota DNR files). The lakes are scattered throughout much of the central and northern portions of the state (Figure 1.2) 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.

Figure 1.1. Cisco, *Coregonus artedi*, lake herring, tullibee (from Peter Jacobson Mn DNR).

A report on carbon dioxide and climate by the U.S. National Academy of Science (NAS) concluded that doubling ambient carbon dioxide concentrations could increase global mean air temperature by 1.5 to 4.5^{o}C in approximately the next half century. This 'green house effect' projection has been reinforced by the development of several general circulation models (GCM) of ocean atmosphere heat budgets and other analyses producing similar temperature change estimates (Bolin and Doos 1986). Such changes are occurring many times faster than the background rate and might have severe and unexpected consequences (Harrington 1987,

Schneider 1989, NAS 1988, Houghton et al., 1989). Climate warming has the potential to reduce coldwater fish habitat by direct warming in unstratified lakes and increased hypolimnetic oxygen depletion in stratified lakes from extended periods of stratification and thermocline deepening (Schindler et al. 1996; Stefan et al. 1996; Magnuson et al. 1997; Fang et al. 2004). With global climate warming cisco habitat may be threatened, for example, Figure 1.3 shows lakes that were reported with cisco mortalities in the summer of 2006.



- Red dots unstratified lakes, - Yellow dots stratified lakes

Figure 1.2. Geographic location of cisco lakes in Minnesota (from Peter Jacobson, Mn DNR)

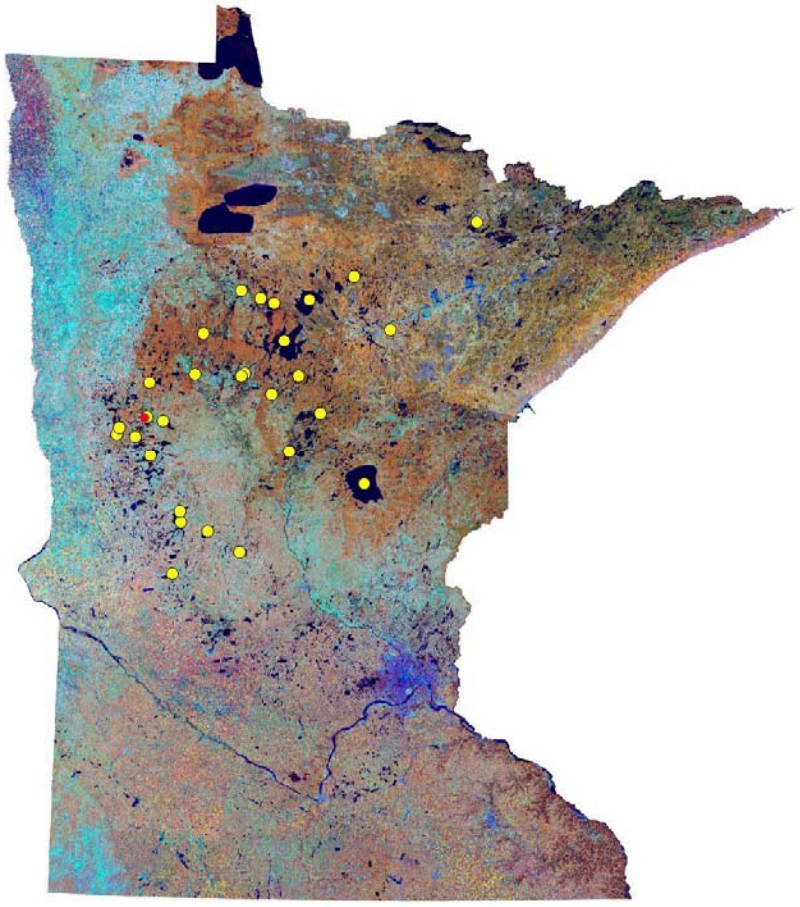


Figure 1.3. Lakes with reported cisco mortalities in the summer of 2006 (from Peter Jacobson, Mn DNR).

The characterization of Minnesota's cisco lakes is a necessary first step for our study. The Minnesota DNR (Peter Jacobson) has provided a database for 620 lakes with cisco present in Minnesota. Lake parameters in the database include lake name, surface area (A_S, ha), maximum depth (H_{MAX}, m), lake geometry ratio ($A_S^{0.25}/H_{MAX}$ $m^{-0.5}$), mean water temperature in July (^oC), mean summer epilimnetic total phosphorus concentration (TP, µg/L), number of TP measurements, mean summer epilimnetic chlorophyll-a concentration (Chl-a, µg/l), number of Chl-a measurements, mean Secchi Depth (SD, m), number of SD measurements, geographic coordinates, and DNR sentinel lakes long term monitoring region (ecoregions). To facilitate the interpretation of the cisco lake data, cumulative frequency distributions were developed for six selected lake parameters. Three of the selected parameters are bathymetric parameters (surface area, maximum depth, and geometry ratio) and the other three are related to lake trophic status (Secchi Depth, mean chlorophyll-a concentration, and TP concentration). Each parameter is ranked from the lowest to the highest values, and the corresponding cumulative frequency f =

m/(n+1) is computed using the Weibull index m/(n+1) where m is the rank and n is the total number of data values (Viessman and Lewis 2002). For the cisco data set we have n = 620 for three bathymetric parameters, but n could be less than 620 because not all lakes have measured Secchi Depth, mean chlorophyll-a concentration, and TP concentration.

In this brief study the cumulative frequency distributions will be used to determine (a) how Minnesota cisco lakes differ from Minnesota lakes in general, and (b) if the specific study lakes that will be selected for model calibration and validation, are representative of the 620 cisco lake data set.

2. Cumulative Frequency Distributions of Cisco Lake Characteristics

Cumulative frequency distributions for the six selected cisco lake parameters are shown in Figures 2.1 to 2.5. Tables 2.1 and 2.2 summarize three ranges of the six lake parameters from the cumulative frequency distribution curves: lower 30%, central 60%, and upper 10%. "Central 60%" gives the range of the parameter value with cumulative frequency distribution from 30% to 90%.

Cumulative frequency distributions for lake surface area, maximum lake depth, and Secchi Depth were previously developed in a study of potential global climate change impacts on water and fishery resources in Minnesota (Hondzo and Stefan 1993; Stefan et al. 1994a). The previous study focused on fish habitat for cold-, cool-, and warm-water fish species in small lakes. The database used was from Mr. Schupp in Mn DNR (1991) and comprised 3002 Minnesota lakes, but did not include very large lakes (over 40 km^2 surface area) and deep lakes (over 45 m maximum depth). Ranges of lake geometry parameters and Secchi Depth developed in previous study are given in Table 2.1 and representative lake classification values for lake geometry and trophic status from previous study are summarized in Table 3.1 for comparison and discussion given below. Figures 2.4, 2.5, and 2.6 also show these representative classification values (given in Table 3.1 derived from 3002 lakes) for lake geometry and trophic status as vertical lines.

Table 2.1. Characteristics of frequency distributions for maximum depth, surface area and Secchi Depth of cisco lakes in Minnesota, and comparison to typical Minnesota lakes.

Parameter	Number of cisco lakes	Cumulative frequency distribution	Range for cisco lakes	Range for 3002* Minnesota lakes
Maximum Depth (m)	620	Lower 30%	3.0 - 12.2	1.0 - 5.0
		Central 60%	12.2 - 32.9	5.0 - 20.0
		Upper 10%	32.9 - 64.9	20.0 - 45.0
Surface Area (km^2)	620	Lower 30%	0.04 - 0.9	0.06 - 0.4
		Central 60%	0.9 - 10.0	0.4 - 5.0
		Upper 10%	10.0 - 3847.0	5.0 - 40.0
Secchi Depth (m)	561	Lower 30%	0.7 - 2.8	0.8 - 1.8
		Central 60%	2.8 - 5.0	1.9 - 4.5
		Upper 10%	5.0 - 9.5	4.6 - 7.0

* from Schupp's data base (Hondzo and Stefan 1993; Stefan et al. 1994a)

Table 2.2. Characteristics of frequency distributions for lake geometry ratio, mean total phosphorus, and mean chlorophyll-a concentrations of cisco lakes in Minnesota.

Parameter	Number of cisco lakes	Cumulative frequency distribution	Range for cisco lakes
Lake Geometry Ratio $A_s^{0.25}/H_{max}$ ($m^{-0.5}$)	620	Lower 30%	0.5 - 1.7
		Central 60%	1.7 - 4.4
		Upper 10%	4.4 - 22.7
Mean Total Phosphorus (µg/L)	386	Lower 30%	4.0 - 15.0
		Central 60%	15.0 - 36.7
		Upper 10%	36.7 – 200.1
Mean Chlorophyll-a (µg/L)	393	Lower 30%	1.0 - 3.9
		Central 60%	3.9 - 11.9
		Upper 10%	11.9 - 62.5

Figure 2.1 shows the cumulative frequency distribution of the maximum depth for the 620 Minnesota cisco lakes. 10% of the cisco lakes have maximum depth greater than 32.9 meters and only 30% have maximum depth less than 12.2 meters. This suggests that cisco lakes are often deeper lakes. According to Figure 2.1 there are only 14 cisco lakes (1.6% of 620 lakes) with maximum depth less than 5.0 m (shallow lakes), indicating that relative deep lakes (67.4% cisco lakes with H_{MAX} greater than 13.0 m, and 24.3% greater than 24 m) provide preferentially the cisco habitat in Minnesota lakes. Figure 2.2 and Table 3.1 show that cisco habitat does exist in lakes with surface areas from 0.04 to 3847 km^2 (47.6% of cisco lakes with A_S greater than 1.7 km^2, and 10.1% greater than 10 km^2).

Figure 2.3 and Table 3.1 show that cisco habitat exists preferentially in highly transparent lakes (81.0% of 620 cisco lakes with Secchi Depth SD greater than 2.5 m, and 18.7% greater than 4.5 m, only 2 lakes or 0.4% with SD < 1.2 m). Carlson's trophic state index (Carlson, 1977) is often used to estimate a lake's primary productivity. Carlson's index is based on chlorophyll (chl-a), Secchi Depth (SD) and total phosphorus (TP). Carlson's index specifies that eutrophic lakes have SD less than 2.0 m, and oligotrophic lakes have SD greater than 4.0 m. Accordingly, 28.2% and 61.9% of the 620 cisco lakes are oligotrophic and mesotrophic lakes, respectively (Figure 2.3).

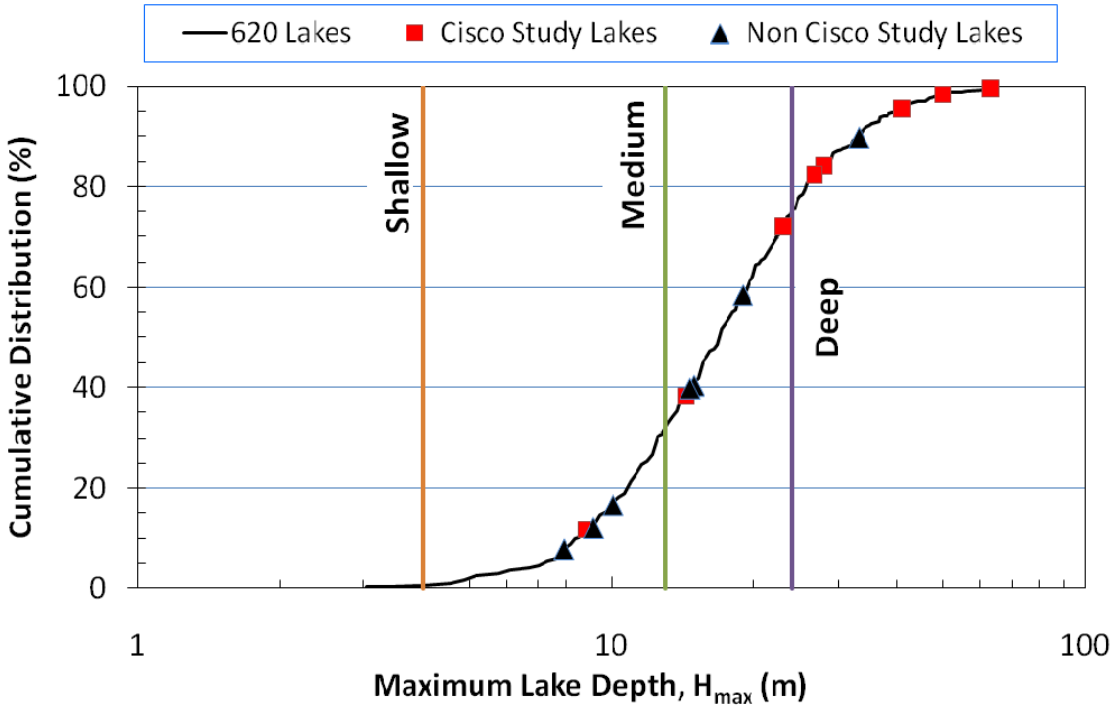


Figure 2.1. Cumulative frequency distribution (%) of the maximum depths of 620 cisco lakes in Minnesota (solid line), and distribution of the maximum depths of 15 study lakes (symbols).

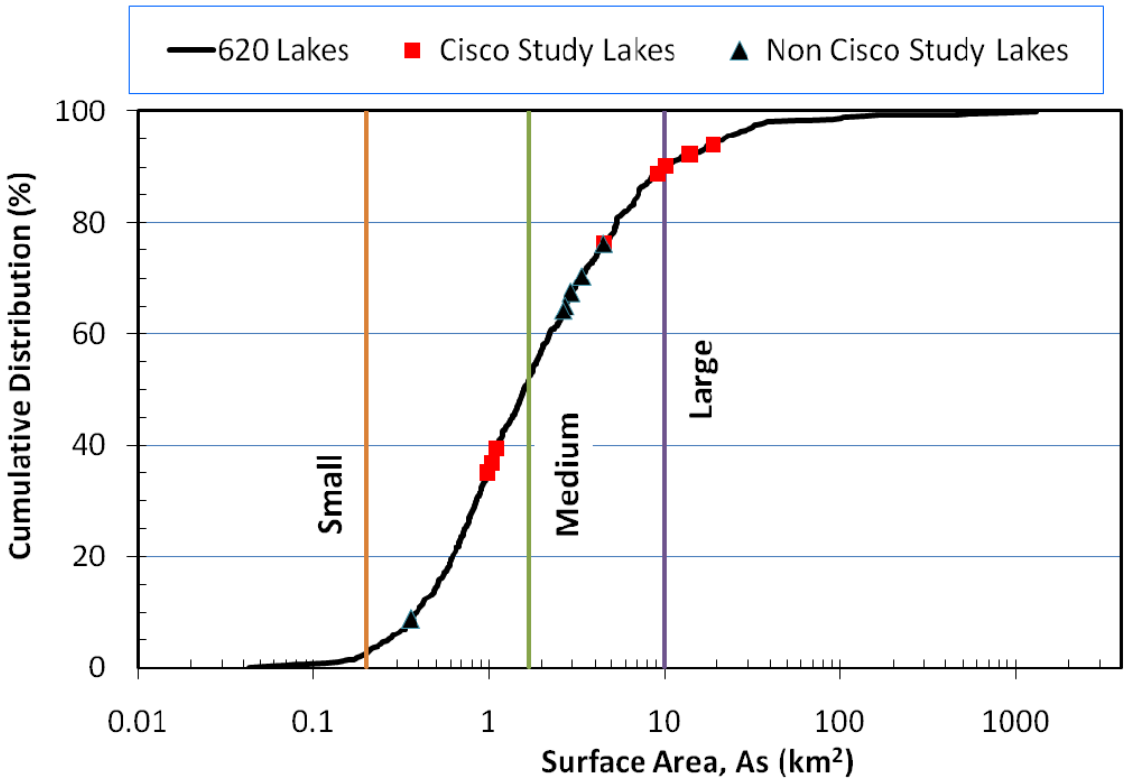


Figure 2.2. Cumulative frequency distribution (%) of the surface areas of 620 cisco lakes in Minnesota (solid line), and distribution of the surface areas of 15 study lakes (symbols).

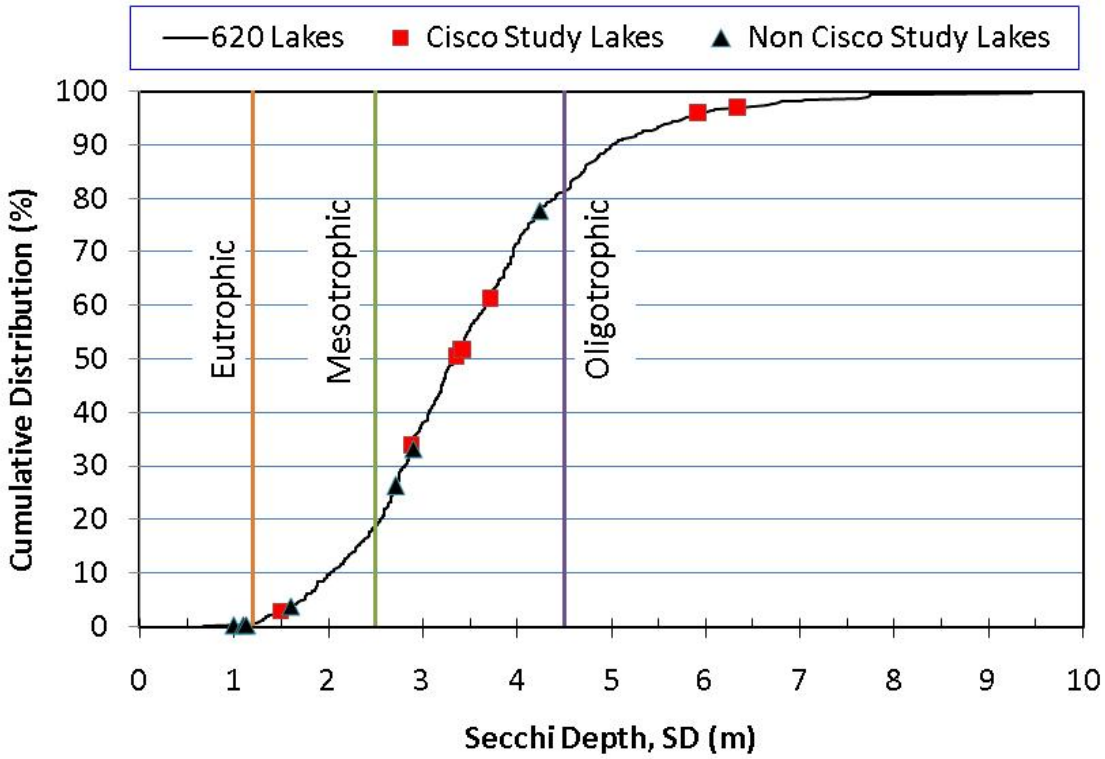


Figure 2.3. Cumulative frequency distribution (%) of the Secchi Depths of 620 cisco lakes in Minnesota (solid line), and distribution of the Secchi Depths of 15 study lakes (symbols).

The likelihood of a strong or weak stratification in a lake can be related to the lake geometry ratio $A_S^{0.25}/H_{MAX}$ (Gorham and Boyce 1989). The 620 cisco lakes have geometry ratios from 0.4 to 22.7 $m^{-0.5}$ (Figure 2.4). Strongly stratified (dimictic or monomictic) lakes have the lowest geometry ratios, while polymictic lakes have the highest. The transition occurs between 3 and 5 (Fang and Stefan, 1999). Figure 2.4 shows that 72.8% of the cisco lakes have geometry ratios less than 3.0, and only 6.3% have geometry ratios greater than 5.0. Most of Minnesota's cisco lakes are seasonally stratified lakes. However, 2 very large cisco lakes have geometry ratios greater than 10.0; they are Mille Lacs Lake (A_s = 536.5 km^2, H_{max} = 12.8 m) and Lake of the Woods (Minnesota portion: A_s = 1293.4 km^2), and cover - of the total surface area of all 620 cisco lakes (excluding Lake Superior). There is also one medium size and shallow cisco lake (A_s = 2.5 km^2, H_{max} = 4.0 m) in the northern forested lake eco-region with a lake geometry ratio greater than 10.

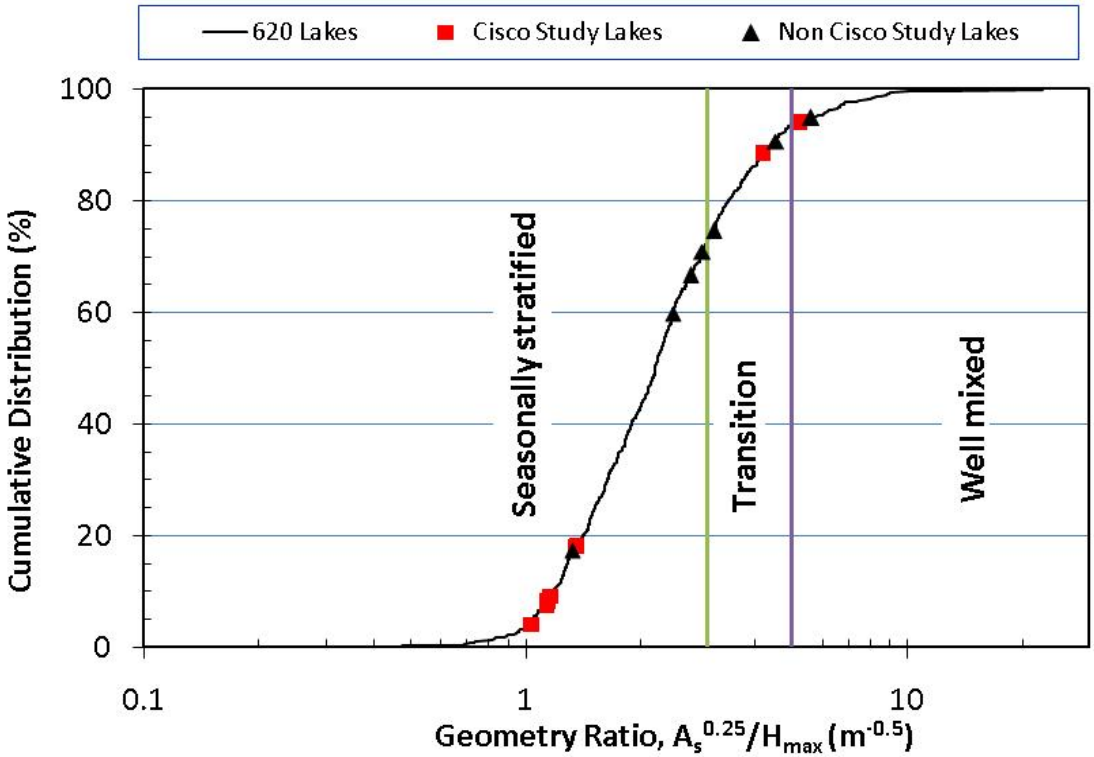


Figure 2.4. Cumulative frequency distribution (%) of the lake geometry ratios of 620 cisco lakes in Minnesota (solid line), and distribution of the lake geometry ratios of 15 study lakes (symbols).

Figure 2.5 shows the cumulative frequency distribution of summer mean total phosphorus (TP) for the 620 cisco lakes. According to Carlson's trophic index (Carlson 1977), oligotrophic lakes have TP less than 12 µg/L, and eutrophic lakes have TP greater than 24 µg/L. These two limits are also plotted on Fig. 2.5. Based on Carlson's index and Figure 2.5, 17.1% and 48.2% of the 620 cisco lakes are oligotrophic and mesotrophic lakes, respectively. Figure 2.5 also shows that 34.6% of the 620 cisco lakes are eutrophic lakes.

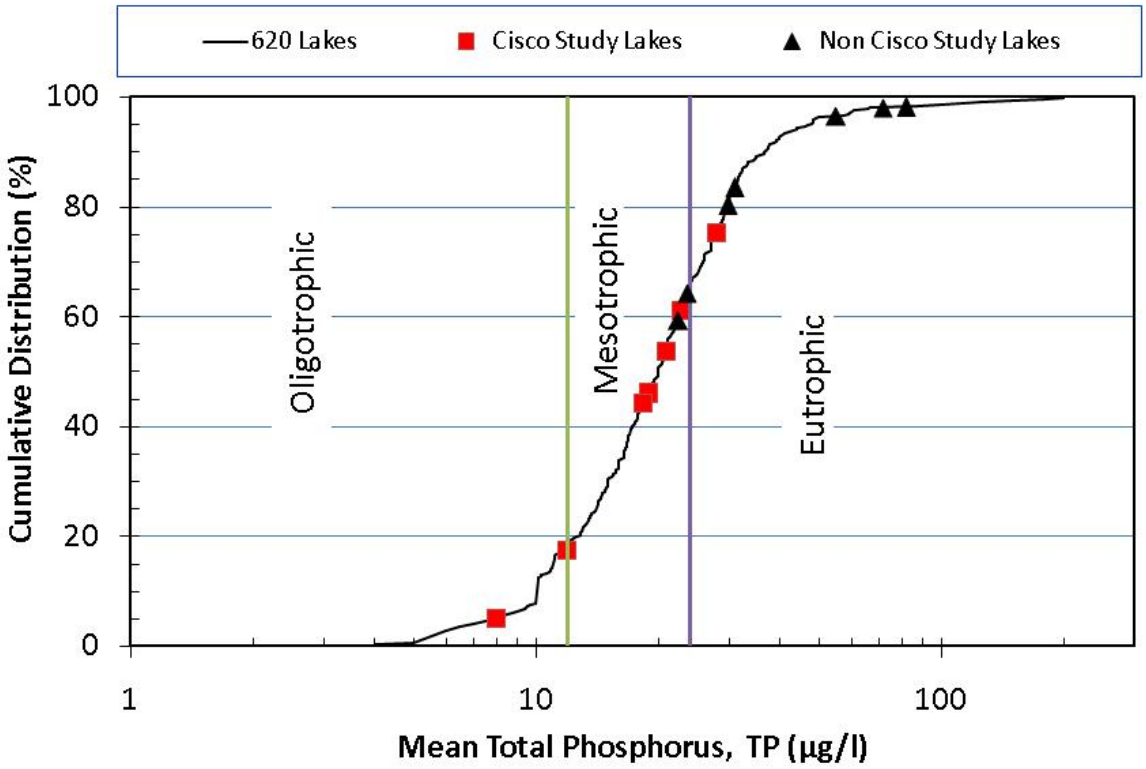


Figure 2.5. Cumulative frequency distribution (%) of the mean TP of 620 cisco lakes in Minnesota (solid line), and distribution of the mean TP of 15 study lakes (symbols).

Figure 2.6 gives cumulative frequency distribution of summer mean chlorophyll-a (Chl-a) for the 620 cisco lakes. According to Carlson's trophic index (Carlson 1977), oligotrophic lakes have Chl-a less than 2.6 µg/l, and eutrophic lakes have Chl-a greater than 7.3 µg/l, and these two limits are plotted on Fig. 2.6. Based on Carlson's index and Figure 2.6, 9.7% and 63.4% of the 620 cisco lakes are oligotrophic and mesotrophic, respectively. Figure 2.6 also shows that 27.0% of the 620 cisco lakes are eutrophic lakes. The National Academy Sciences (NAS and NAE 1973) specified that oligotrophic lakes have Chl-a less than 4.0 µg/l, and eutrophic lakes have Chl-a greater than 10.0 µg/l. Using the NAS and NAE standard, Figure 2.6 shows that 31.6% and 52.9% of the 620 cisco lakes are oligotrophic and mesotrophic, respectively, and 15.5% are eutrophic lakes.

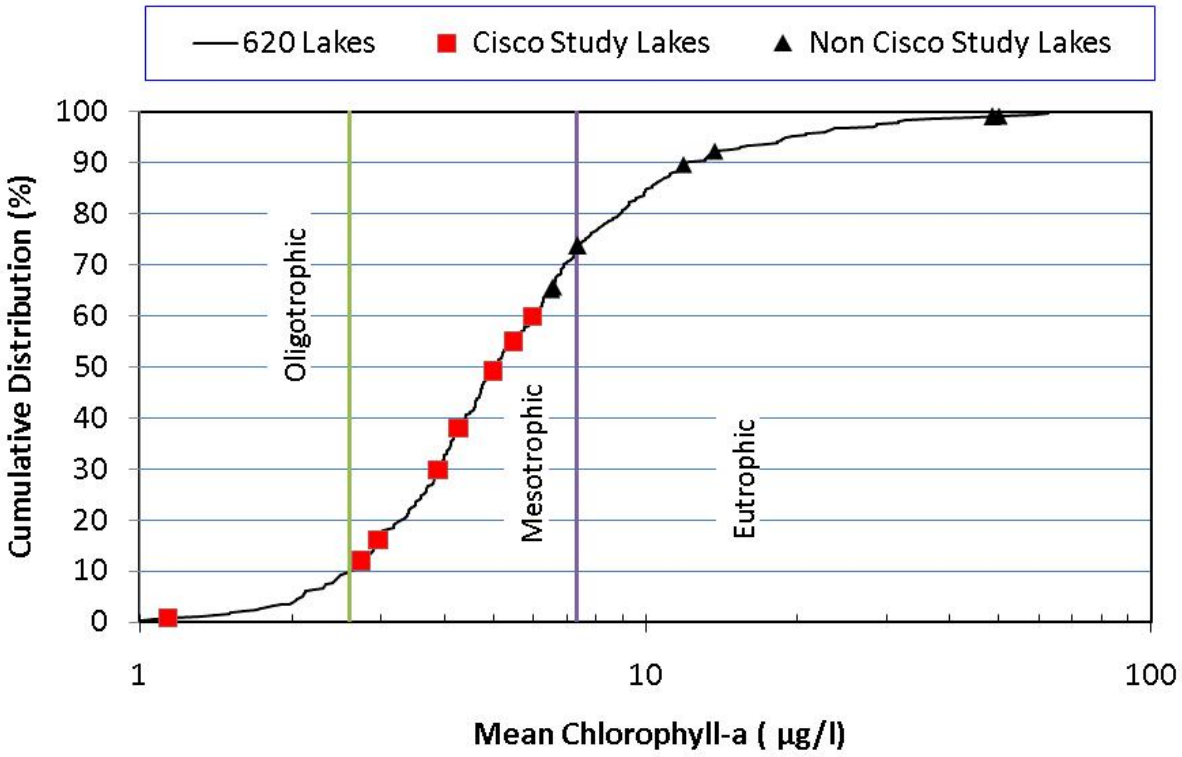


Figure 2.6. Cumulative frequency distribution (%) of the mean Chlorophyll-a of 620 cisco lakes in Minnesota (solid line), and distribution of the mean Chlorophyll-a of 15 study lakes (symbols).

3. Characteristics of Cisco Lakes Compared with other Minnesota Lakes

How do cisco lakes in Minnesota differ from lakes in Minnesota? The geographic distribution of the 3002 lakes (Schupp 1991) in Minnesota is shown in Figure 3.1, and the cumulative distribution functions for three lake parameters derived for the 3002 lakes are shown in Figure 3.2 from Stefan et al. (1994b).

The current 620 cisco lake database has surface areas ranging from 0.04 to 1293.4 km^2, maximum lake depths ranging from 3.0 To 64.9 m, and Secchi depths from 0.7 to 9.5 m (Table 2.1). The median values for lake surface area, maximum lake depth, and Secchi Depth for the 620 cisco lake database are 1.6 km^2, 17.0 m, and 3.4 m (Figs. 2.1 to 2.3), respectively. There are 18 lakes with maximum depth greater than 45 m, and 11 lakes with surface area greater than 40 km^2. Only 561 of the 620 cisco lakes have Secchi Depth measurements, only 386 lakes have total phosphorus measurements, and only 393 lakes have chlorophyll-a concentration measurements.

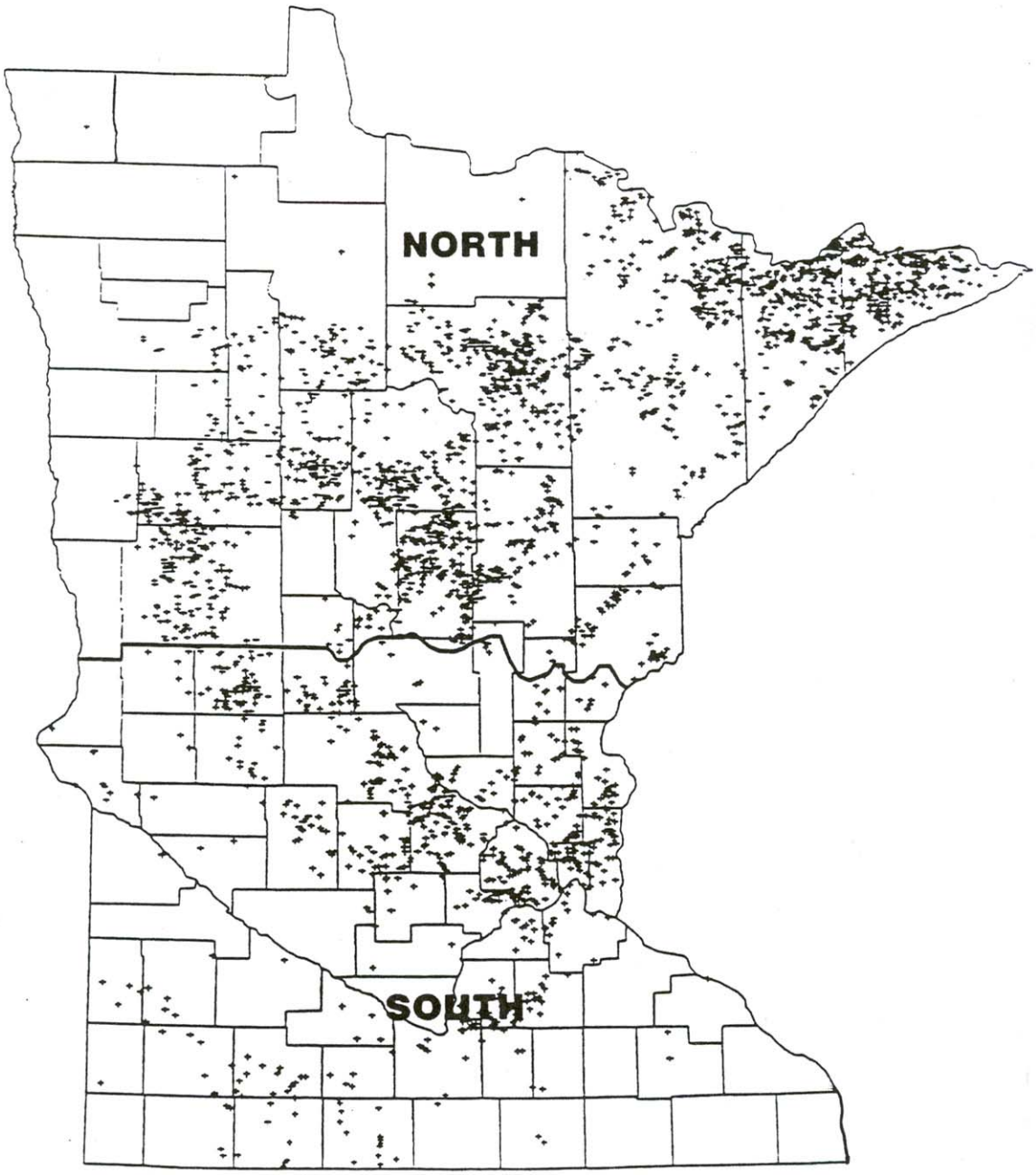


Figure 3.1. Geographic distribution of 3002 Minnesota lakes (Stefan et al. 1994b) in the MLFD database (Schupp 1991).

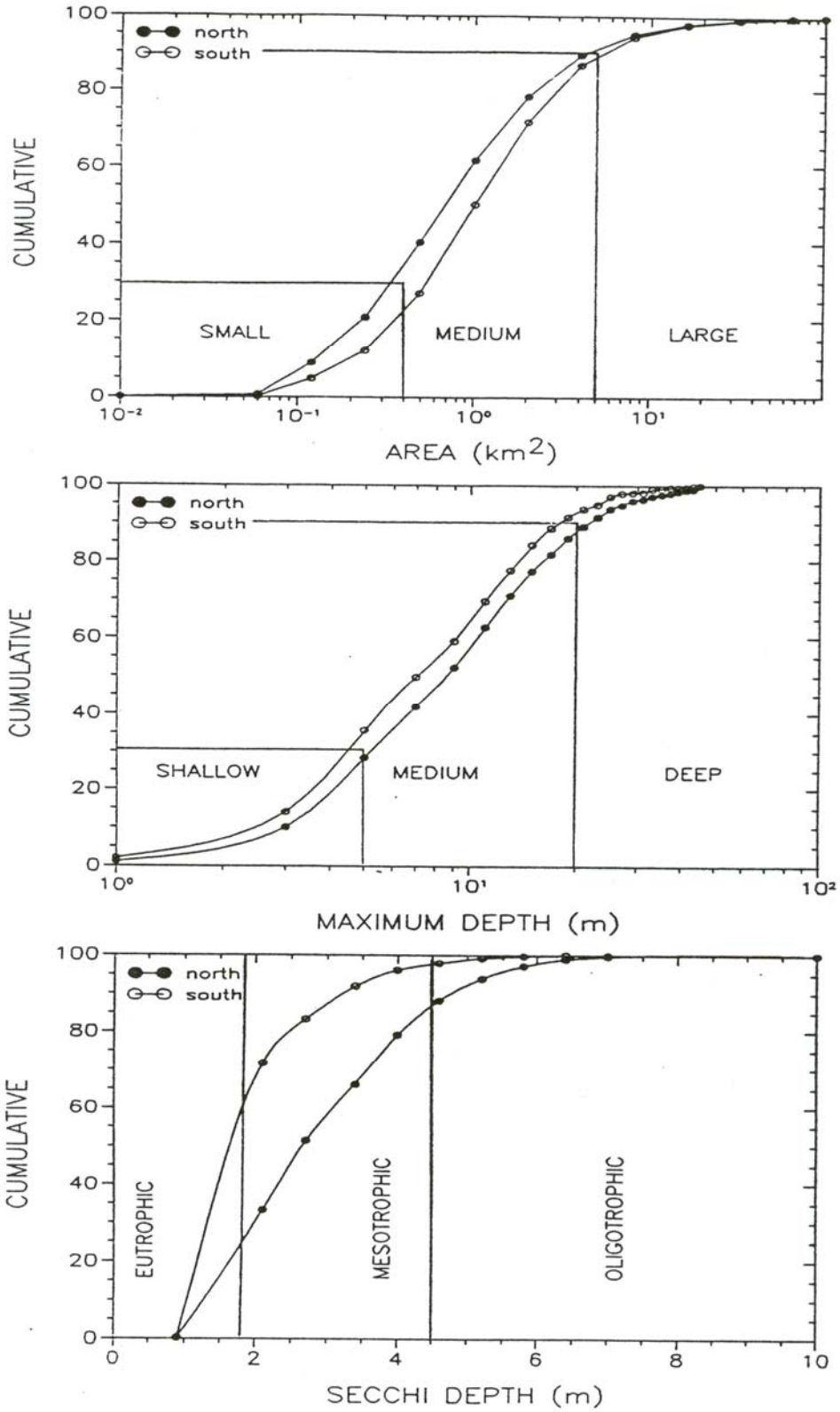


Figure 3.2. Cumulative frequency distributions of three key parameters for 3002 lakes (Stefan et al. 1994b) in the MLFD database (Schupp 1991).

Ranges (lower 30%, central 60% and upper 10%) on the cumulative frequency distributions of maximum lake depths, lake surface areas, and Secchi depths are given in Table 2.1 for both the 620 cisco lakes and the previous 3002 lakes. The comparison shows that cisco lakes are generally more transparent. Lake size and maximum depth cannot be compared because the 3002 lakes were severely truncated.

In the previous study "representative values" for lake maximum depth, surface area and Secchi depth were developed. They are used to designate 27 regional lake classifications for previous study (Stefan et al. 1994a) and are summarized in Table 3.1. A somewhat ambiguous comparison with "representative values" from the 620 cisco lakes database is also provided in Table 3.1.

Table 3.1. Representative values for maximum lake depth, lake surface area, and Secchi depth for 3002 Minnesota lakes (Stefan et al. 1994a) and comparison with the cisco lakes

Parameter	Regional classification for 3002 MN lakes	Represent. value for 3002 MN lakes	Represent. value for 620 cisco lakes [1]	Number of cisco lakes [2]	Number of cisco study lakes
Maximum Depth (m)	Shallow	4	11	33 (< 5 m)	0 (< 5 m)
	Medium	13	20	99 (< 20 m)[3]	8 (< 20 m) [3]
	Deep	24	40	488 (> 20 m)	7 (> 20 m)
Surf. Area (km^2)	Small	0.2	0.6	66 (< 0.4 km^2)	2 (< 0.4 km^2)
	Medium	1.7	2.2	417 (< 5.0 km^2)[4]	8 (< 5.0 km^2) [4]
	Large	10.0	20.0	137 (> 5.0 km^2)	5 (> 5.0 km^2)
Secchi Depth (m)	Eutrophic	1.2	2.6	34 (< 1.8 m)	5 (< 1.8 m)
	Mesotrophic	2.5	3.7	422 (< 4.5 m) [5]	8 (< 4.5 m) [5]
	Oligotrophic	4.5	5.8	164 (> 4.5 m)	2 (> 4.5 m)

[1] these representative values for 620 cisco lakes do not correspond with the regional lake classification.

[2] out of 620 lakes using limits specified in bracket.

[3] 5 m < H_{max} < 20 m.

[4] 0.4 km^2 < A_s < 5.0 km^2.

[5] 1.8 m < SD < 4.5 m.

These "representative values" are really not representative, and correspond to cumulative distributions of about 20%, 60% and 95%. It can be noticed also that these "representative values" in the fourth column of Table 3.1 do not correspond to the regional lake classifications developed from the 3002 Minnesota lake database. For example, a lake having 11 m maximum depth does not have the same mixing characteristics as a 4 m shallow lake studied before. Table

3.1 also gives the number of cisco lakes in the 620 lake database that fit into the previous regional classification. According to Table 3.1, there are 33 lakes with maximum depth less than 5.0 m (this is the limit for 3002 Minnesota lakes, see Table 2.1), 99 lakes with 5.0 m < H_{max} < 20 m, and 488 lakes (78.7% of 620 lakes) with H_{max} > 20 m. Only a small fraction of cisco lakes has a Secchi depth < 1.8 m.

4. Selection and Representativeness of 15 Study Lakes

To calibrate and validate the MINLAKE08 model, fifteen study lakes have been suggested by the Minnesota DNR. Figure 4.1 shows their locations in Minnesota. Measured profiles of temperature and dissolved oxygen (DO) such as shown in Figure 4.2 are available for these lakes. Most of them belong to the sentinel lakes selected for long-term monitoring by the Minnesota DNR.

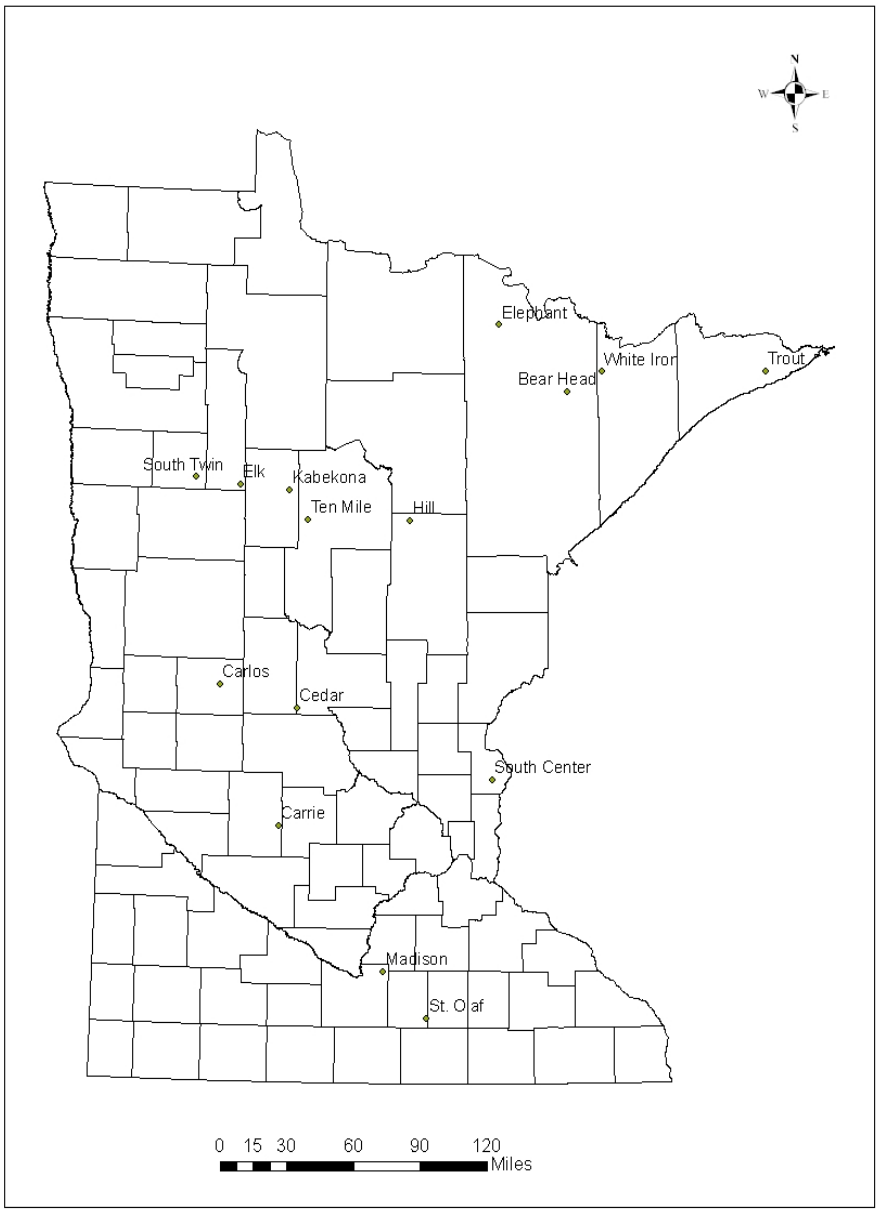


Figure 4.1. Geographic location of 15 study lakes used for model calibration and validation.

Table 4.1 summarizes the lake characteristics of the fifteen study lakes. The fifteen lakes are divided into a group of eight lakes that have cisco populations and a group of seven lakes without cisco. In Table 4.1, each group of lakes is sorted by the lake geometry ratio. The seasonal lake stratification is stronger when the geometry ratio is lower. To identify the representativeness of the fifteen lakes for model calibration and validation, the fifteen study lakes are marked on all cumulative frequency distribution curves in Figures 2.1 to 2.6. Lakes with cisco habitat are represented by red squares, and those without cisco habitat by black triangles.

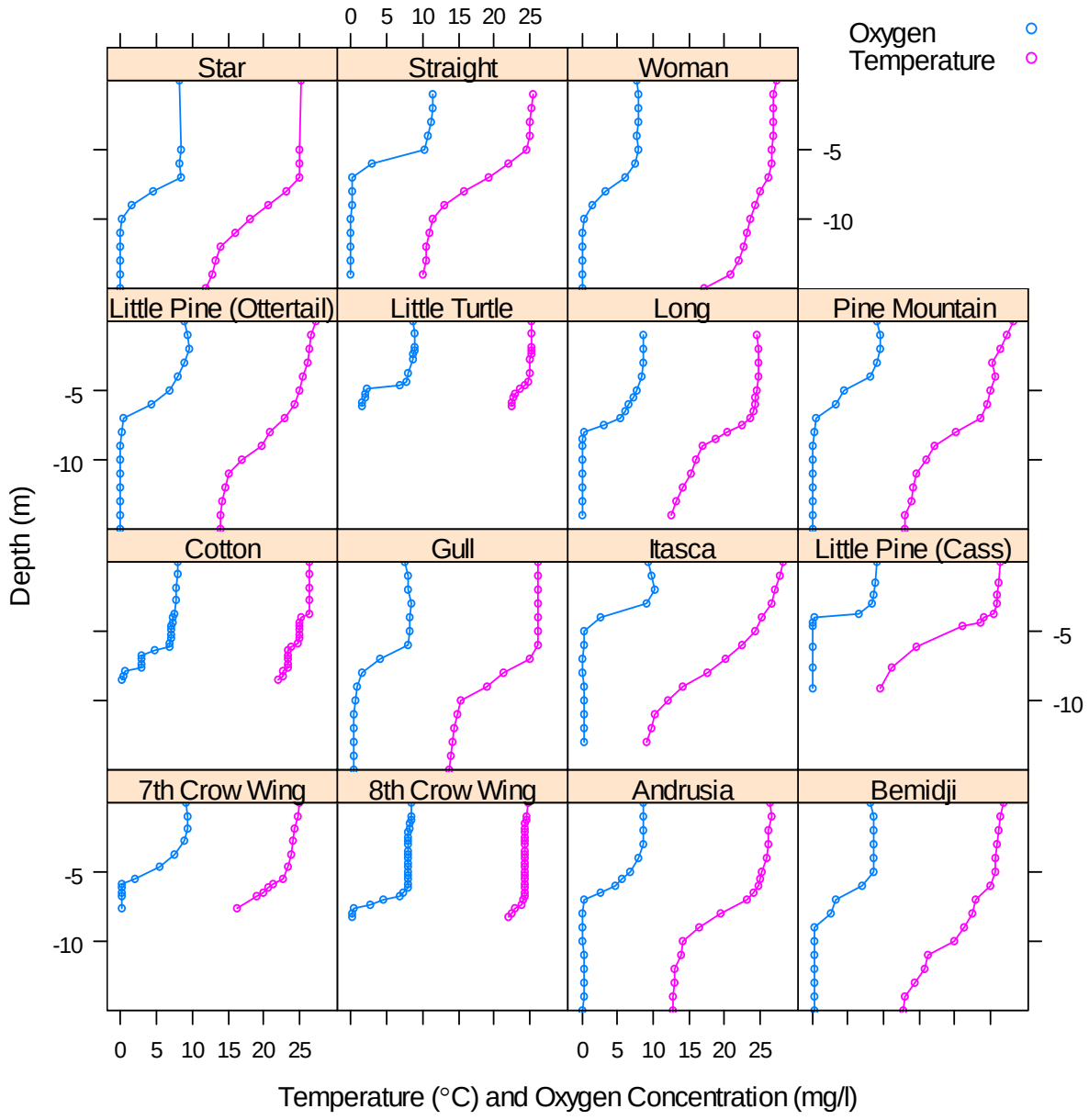


Figure 4.2. Temperature and DO profiles in Minnesota lakes. All profiles represent lethal conditions for cisco (from Peter Jacobson, Mn DNR).

Figures 2.5 and 2.6 show that the seven non-cisco study lakes have higher mean TP and chlorophyll-a concentrations than the eight cisco-habitat study lakes. Six cisco study lakes are strongly stratified and two are weakly stratified (Table 4.1 and Figure 2.4).

Figures 2.1 to 2.6 indicate that the 15 study lakes cover the range of lake parameters that is also covered by the 620 cisco lakes. It should be mentioned that in Lake Carlos cisco is known

to be present but was not sampled with DNR assessments, and all seven lakes without cisco are, of course, not in the 620 cisco lake database.

How do the eight cisco lakes in the 15 study lakes sample compare to all 620 cisco lakes in Minnesota? To make the comparison, the average values of six lake parameters computed for each group are compared at the bottom of Table 4.1. The averages for lake surface area and maximum lake depth are significantly greater for the study lakes with cisco, but the averages of the other four important lake parameters (geometry ratio, mean TP, mean Chl-a and mean Secchi depth) are almost the same. Since the effect of lake bathymetry is captured in the lake geometry ratio, the eight lakes can be considered as representative of the 620 Minnesota cisco lakes.

Table 4.1. Characteristics of 15 study lakes selected for model calibration and validation.

Lake Name	Surface Area (km^2)	Max. Depth (m)	Geometry Ratio $As^{0.25}/H_{max}$ ($m^{-0.5}$)	Mean TP (µg/L)	Mean Chl-a (µg/L)	Mean Secchi Depth (m)	Cisco Habitat Y or N
Ten Mile	18.9	63.0	1.0	19	2.8	5.9	Y
Carlos	10.2	50.0	1.1	23	3.9	3.4	Y
Elk	1.1	28.0	1.2	21	6	3.4	Y
Cedar	0.98	26.8	1.2	8	5	3.4	Y
Kabekona	9.12	41.0	1.3	8	1.1	6.3	Y
Trout	1.04	23.0	1.4	12	3	3.7	Y
White Iron	13.88	14.3	4.3	28	5.5	1.5	Y
South Twin	4.52	8.8	5.2	18.4	4.3	2.9	Y
South Center	3.38	33.2	1.3	55	48.5	1.1	N
St. Olaf	0.37	10.1	2.4	31	13.7	1.6	N
Madison	4.5	18.9	2.6	82	50	1	N
Hill	2.66	14.6	2.8	22.4	7.4	2.9	N
Bear Head	2.73	14.9	2.9	29.8	6.6	1.1	N
Carrie	0.37	7.9	3.1	23.6	6.5	2.7	N
Elephant	2.93	9.1	4.5	72	11.9	4.2	N
Ave. (8 cisco lakes, Y)	7.47	31.9	2.1	17.2	4	3.8	Y
Average (15 study lakes)	5.11	24.1	2.4	30.2	11.7	3.3	Y&N
Ave. (7 no-cisco lakes, N)	2.42	15.3	2.8	45.1	19.7	2.1	N
Ave. 620 Mn cisco lakes	14.05	18.9	2.6	23.4	7.06	3.5	Y
Max. 620 Mn cisco lakes	3847.77	64.9	22.7	200.2	62.5	9.5	Y
Min. 620 Mn cisco lakes	0.04	3.0	0.5	4.0	1.0	0.7	Y

The last column in Table 3.1 shows how many of the 15 study lakes selected for model calibration and validation fall within the lake classifications used in the previous study of Minnesota lakes (Hondzo and Stefan 1993; Stefan et al. 1994a). Table 3.1 shows that the 15 study lakes are representative of lakes in Minnesota in general.

5. Cumulative Frequency Distributions by Ecoregions of Minnesota

Cumulative frequency distributions for the selected six lake parameters were also determined after dividing the 620 cisco lakes into major ecoregions. Minnesota cisco lakes are located in three of Minnesota's major ecoregions (Figure 5.1). The 620 cisco lake database was divided among three eco-regions by the DNR: Border Lakes (146 lakes), Northern Forested Lakes (358 lakes), and Transition Lakes (113 lakes); three lakes in the 620 lake database are not classified by any ecoregions. Frequency distributions for each lake parameter by major ecoregion and for all 620 cisco lakes are plotted on the same graphs for comparison in Figures 5.2 to 5.7. The frequency distributions of maximum depth, surface area, and lake geometry ratio are fairly independent of ecoregion (Figures 5.2, 5.3 and 5.5). There are more substantial differences in the cumulative frequency distributions of Secchi depth, mean total phosphorus and chlorophyll-a concentrations (Figures 5.4, 5.6 and 5.7, and Table 5.1). For example, 30% of the border lakes have Secchi depths greater than 4.6 meters and 30% of the lakes in the northern forested area have Secchi depths greater than 4.0 meters (Figure 5.4), indicating that they are very transparent lakes,. The maximum Secchi depth is 6.0 meters for transition lakes, and 9.5 meters for border lakes. Border lakes have relatively low total phosphorus and chlorophyll-a concentrations, whereas transition lakes have relative high total phosphorus and chlorophyll-a concentration (Figures 5.6 and 5.7). Cumulative frequency distributions for lake maximum depth, surface area, and Secchi depth previously developed from the 3002 Minnesota lake database (Schupp 1991) are plotted on Figures 5.2 to 5.4, respectively, for comparison. Figures 5.2 and 5.4 show quite different distributions of lake maximum depths and Secchi depths for cisco lakes and the 3002 Minnesota lakes used for previous study (Stefan et al. 1994a, 1994b). Cisco habitat obviously exists in more depth transparent (mesotrophic or oligotrophic) lakes.

Table 5.1. Characteristics for Secchi depth, mean total phosphorus and mean chlorophyll-a concentrations of cisco lakes in Minnesota by ecoregion.

Parameter	Cumulative Frequency Distribution	Border Lakes	Northern Forested Lakes	Transition Lakes
Secchi Depth (m)	Lower 30%	1.2 – 2.7	1.2 - 2.8	0.7 – 2.7
	Central 60%	2.7 – 6.1	2.8 - 4.8	2.7 – 4.5
	Upper 10%	6.1 - 9.5	4.8 – 7.7	4.5 - 6.0
Mean Total Phosphorus (µg/L)	Lower 30%	5.0 - 10.0	4.0 -14.8	5.0 – 18.0
	Central 60%	10.0 – 29.0	14.8 – 34.4	18.0 - 57.3
	Upper 10%	29.0 – 33.0	34.4 – 200.1	57.3 – 179.1
Mean Chlorophyll-a (µg/L)	Lower 30%	1.1 – 2.7	1.0 – 3.7	2.0 – 5.0
	Central 60%	2.7 – 9.3	3.7 -11.3	5.0 – 18.7
	Upper 10%	9.3 – 15.9	11.3 - 44.4	18.7 – 62.5

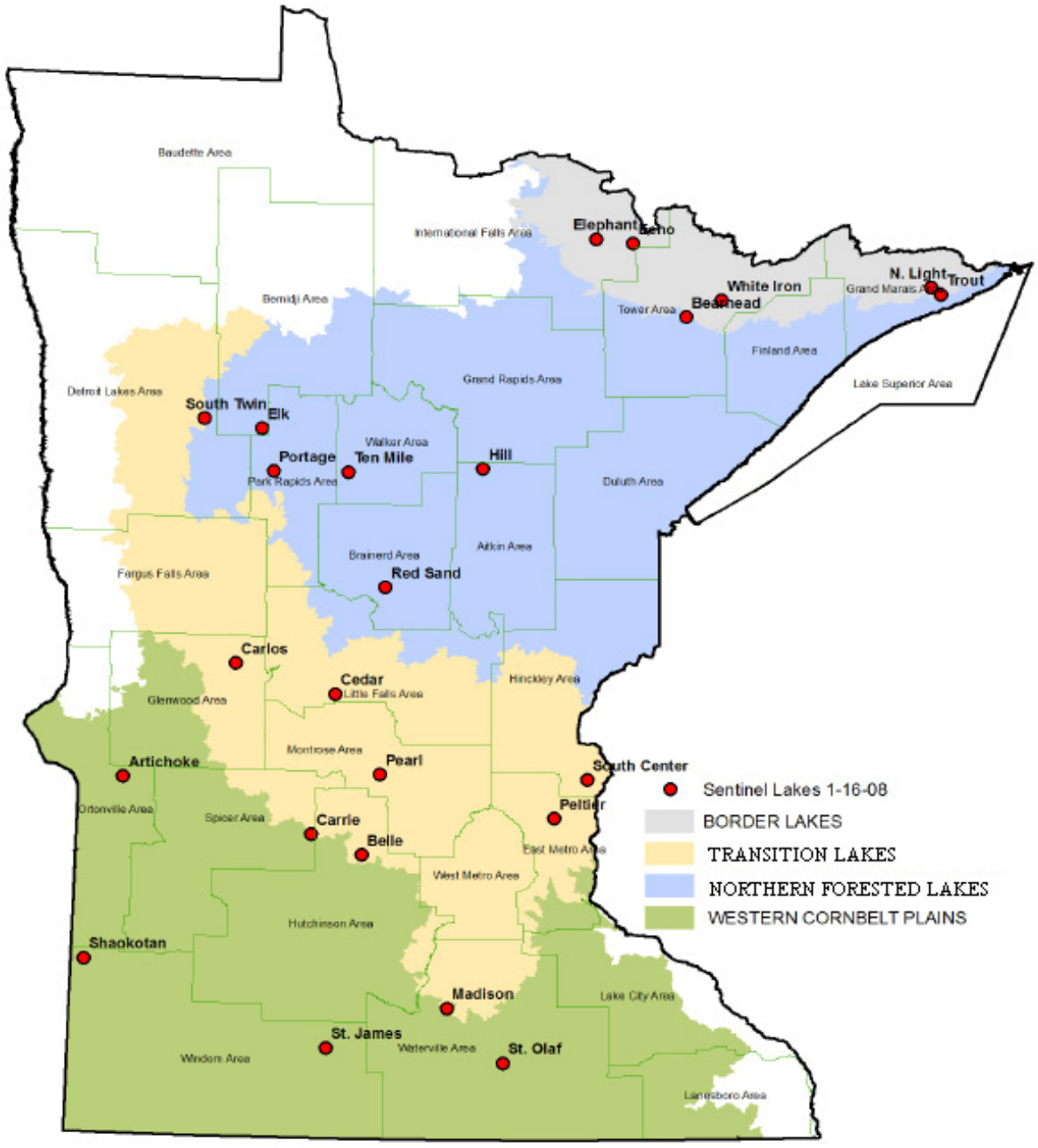
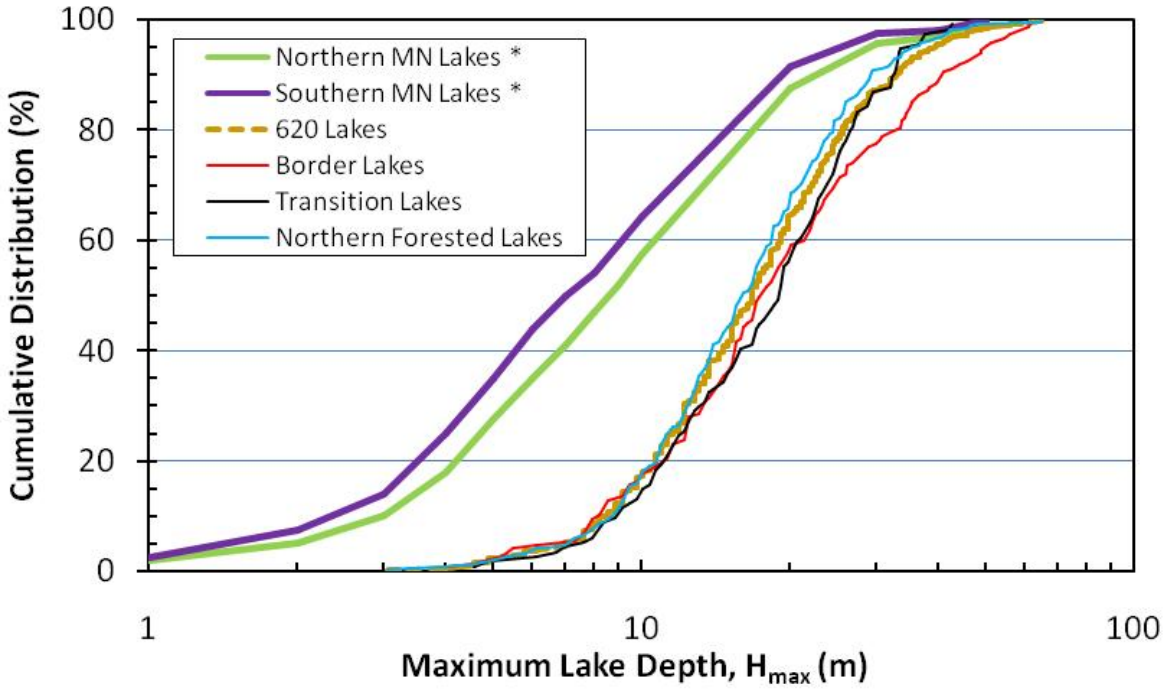
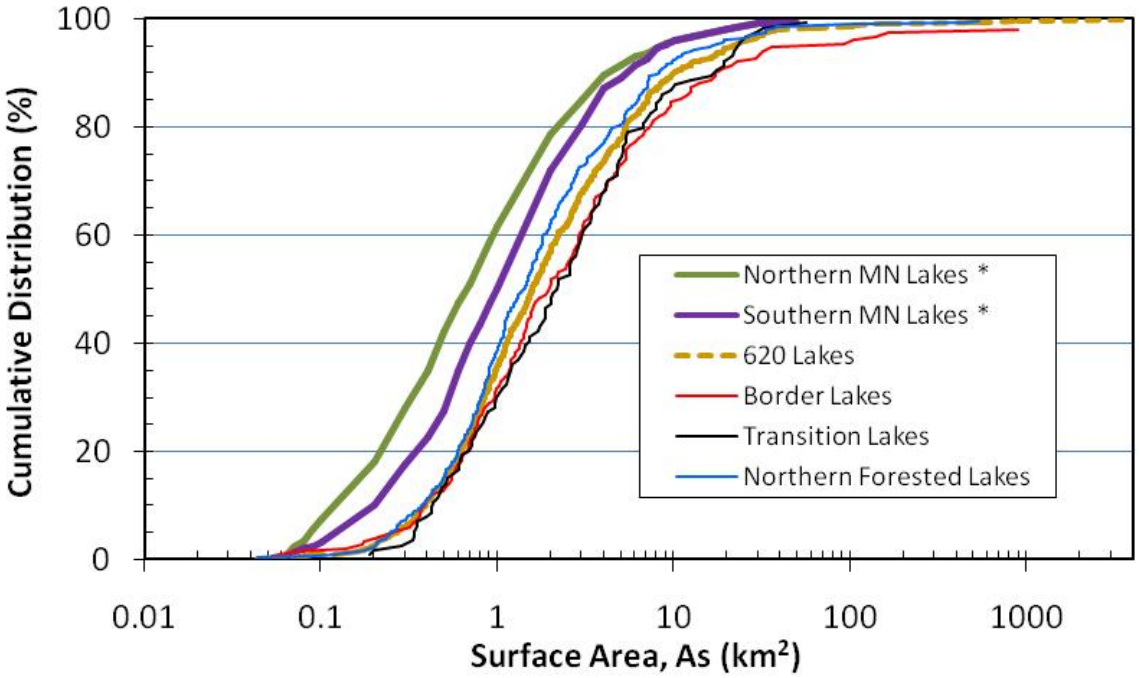


Figure 5.1. DNR sentinel lakes long term monitoring ecoregions in Minnesota (from Peter Jacobson, Mn DNR).



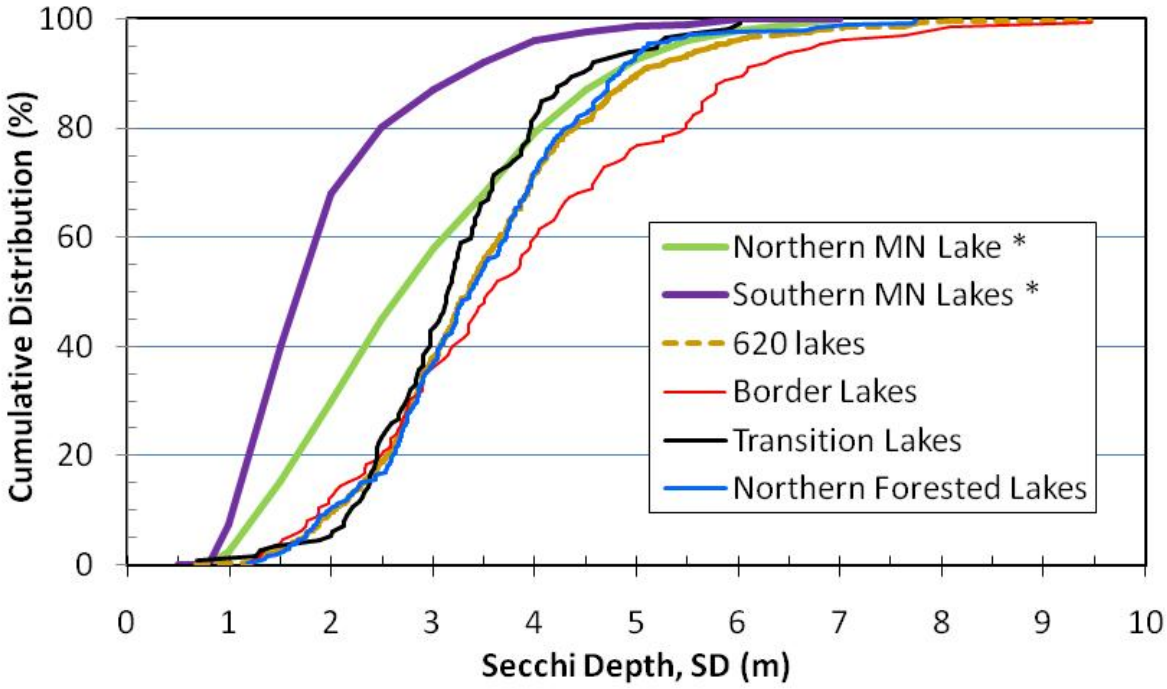
* developed from 3002 Minnesota lake database.

Figure 5.2. Cumulative frequency distributions (%) of maximum lake depths in Minnesota. Distributions are given (a) for northern and southern Minnesota lakes in the 3002 Minnesota lake database, (b) for 620 cisco lakes, and (c) for cisco lakes in three major eco-regions of Minnesota.



* developed from 3002 Minnesota lake database.

Figure 5.3. Cumulative frequency distributions (%) of maximum lake surface areas in Minnesota. Distributions are given (a) for northern and southern Minnesota lakes in the 3002 Minnesota lake database, (b) for 620 cisco lakes, and (c) for cisco lakes in three major eco-regions of Minnesota.



* developed from 3002 Minnesota lake database.

Figure 5.4. Cumulative frequency distributions (%) of mean Secchi depths in Minnesota. Distributions are given (a) for northern and southern Minnesota lakes in the 3002 Minnesota lake database, (b) for 620 cisco lakes, and (c) for cisco lakes in three major eco-regions of Minnesota.

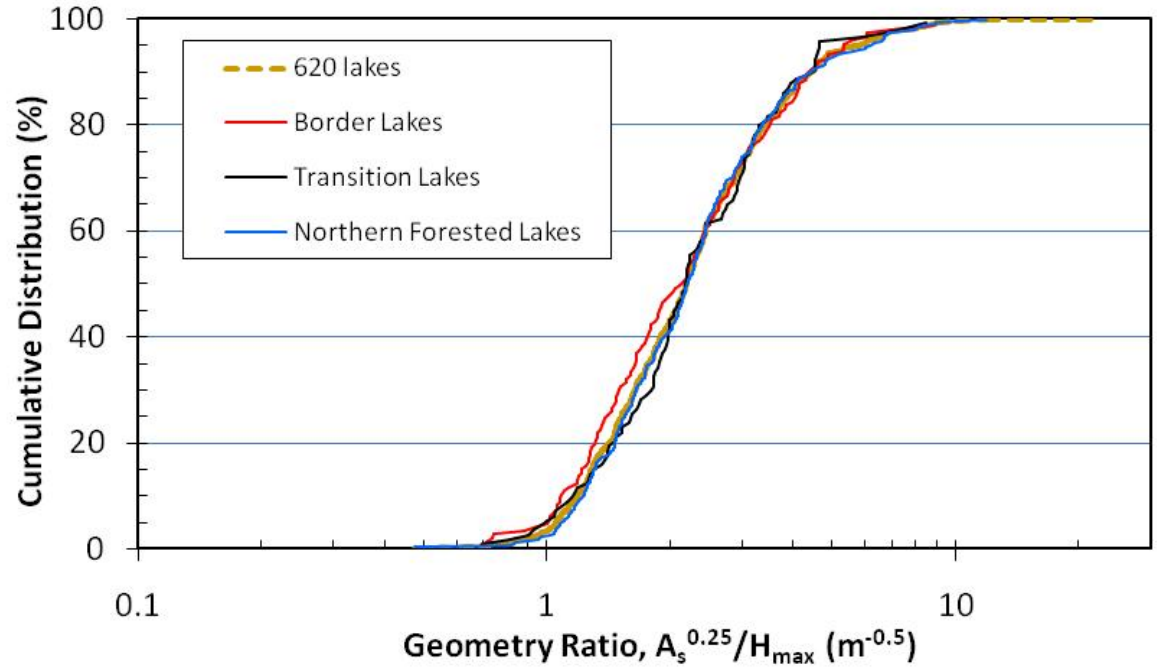


Figure 5.5. Cumulative frequency distributions (%) of lake geometry ratios in Minnesota cisco lakes by eco-regions.

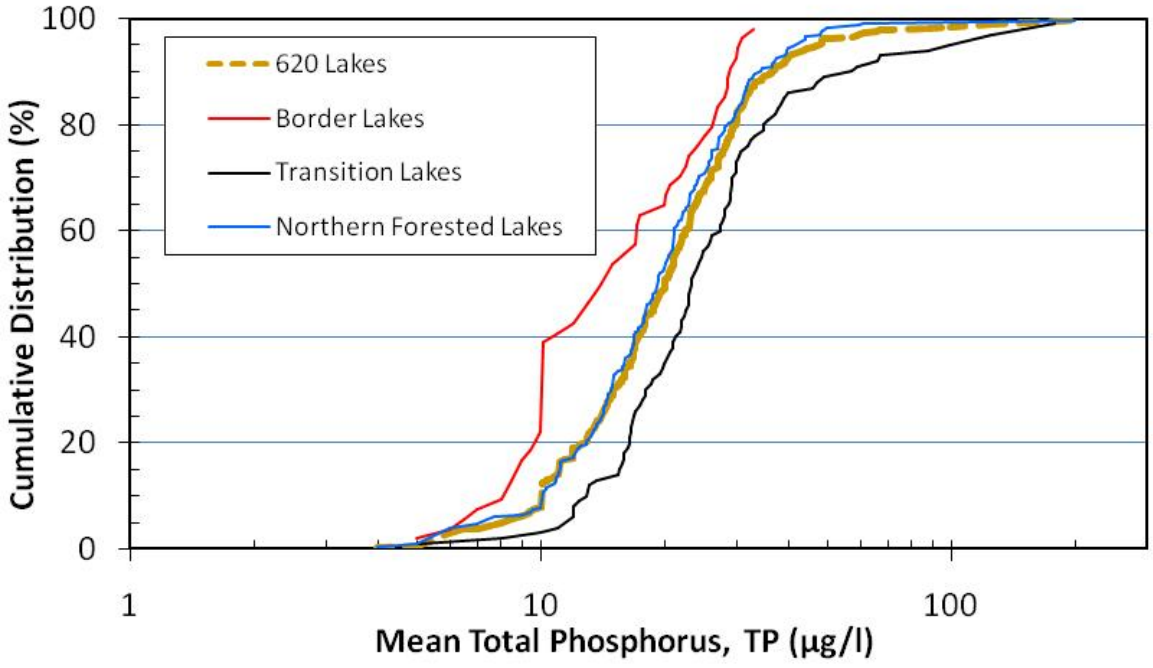


Figure 5.6. Cumulative frequency distributions (%) of mean total phosphorus in Minnesota cisco lakes by eco-region.

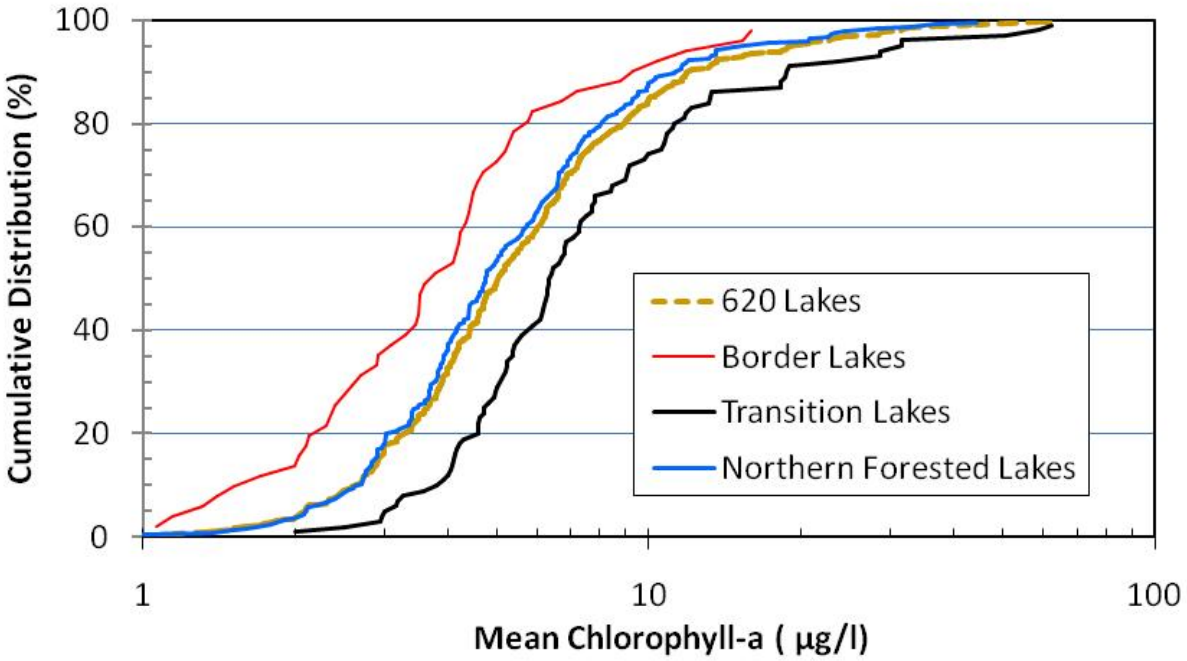


Figure 5.7. Cumulative frequency distributions (%) of mean chlorophyll-a concentrations in Minnesota cisco lakes by eco-regions.

6. Conclusions

Bathymetric and other limnological characteristics of 620 Minnesota cisco lakes have been analyzed and compared with a the same characteristics in another Minnesota lakes database consisting of 3002 lakes. It has been found that on average Minnesota cisco lakes are deeper, more transparent and less trophic than other lakes. They are preferentially located in north central and northeastern Minnesota.

Acknowledgment

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