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Trophic State Index Equations and Regional Predictive Equations For Wisconsin Lakes

By R. A. Lillie, S. Graham, and P. Rasmussen

Introduction

Numerous indices are available for evaluating the trophic state or nutrient condition of lakes. Among the more widely used is Carlson's Trophic State Index (TSI)(Carlson 1977). Carlson TSI values can be derived for a water body from any of 3 water quality parameters: water clarity (Secchi disk depth), chlorophyll-*a* concentration, and total phosphorus concentration. TSI values represent a continuum ranging from very clear, nutrient-poor water (low TSIs) to extremely productive, nutrient-rich water (high TSIs). The Carlson TSI was based on a logarithmic base of 2; each doubling of algal biomass results in halving the Secchi disk reading. Because the scale was multiplied by 10, each increase of 10 TSI units corresponds to a doubling in algal biomass. Carlson's TSI scale and equations have been widely accepted and applied throughout North America in evaluating and comparing trophic condition of lakes.

The TSI concept is used extensively by Wisconsin Department of Natural Resources (DNR) lake managers in discussions with the general public and volunteer lake monitors, to rank lakes for inclusion in the Nonpoint Source Priority Watershed Program and to serve as a check on assumptions about nutrient and light limitations. Wisconsin DNR lake managers also apply TSI equations for preparing the biennial Water Quality Assessment Report to Congress.

Because Carlson developed his TSI equations on the basis of associations existing among water clarity, chlorophyll-*a*, and total phosphorus values of a relatively small set of Minnesota lakes, there was some concern that his equations did not accurately represent these same associations in Wisconsin lakes. Consequently, in the late 1970s the DNR developed a set of TSI equations based on more extensive Wisconsin lake data. Unfortunately, 2 independent sets of TSI equations were developed and applied by DNR water resources staff to compute TSIs, resulting in TSI values that could not be directly compared with one another. In order to correct this problem and thereby permit valid comparisons of lake trophic status among Wisconsin lakes, one set of TSI equations needed to be developed.

In this article we provide TSI equations specific to Wisconsin lakes and guidance for their application by lake managers. In addition, we provide a set of modelling equations that express the relationships among the 3 primary TSI parameters for particular lake types and geographic locations. These equations may be used to predict the response of water clarity corresponding to a given chlorophyll-*a* or total phosphorus concentration or the response of chlorophyll-*a* to total phosphorus within a particular type of lake or lake region.

Methods

Data Set: Water clarity, chlorophyll-*a*, and total phosphorus data were obtained from a random data set of 661 lakes (stratified random subset of 25% of all lakes within each county) sampled by the DNR Bureau of Research's Water Resources Research Section during the summer of 1979 (Lillie and Mason 1983). This data set provides an unbiased view of all lakes and impoundments in Wisconsin > 5 ft deep and > 25 acres in size.

Statewide TSI Equations: The statewide TSI equations were developed from the linear regression relationships existing between water clarity and chlorophyll-*a* concentration and between water clarity and total phosphorus concentration in the Wisconsin data set (natural lakes and impoundments). The slopes and intercepts of these relationships were substituted into Carlson's TSI equations to generate the new Wisconsin TSI (WTSI) equations.

Regional Modelling or Predictive Equations: Equations representing the associations among TSI parameters were developed for specific geographic regions of the state and for specific lake types in order to provide the most accurate and reliable models for predicting responses in water clarity or chlorophyll-*a* concentration to changes in total phosphorus concentration. Each lake in the data set was located with respect to Omernik's lake phosphorus regions (21 regions in Wisconsin)(Omernik et al. 1989). Total phosphorus concentrations and the associations among TSI parameters within each of Omernik's lake phosphorus regions are believed to be influenced by a distinct combination of environmental factors (e.g., geology, land use, topography, and vegetation).

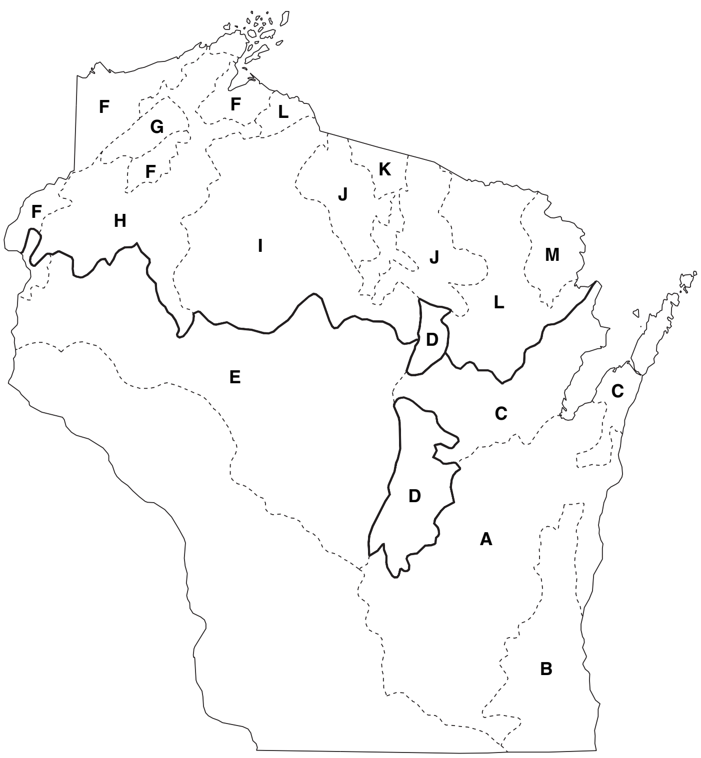

Figure 1. *Composited geographical regions (A-M) resulting from WTSI regional modelling. The solid line delineates the northern and southern tiers as well as region D, which was distinctly different from surrounding regions.*

A combination of methods, including frequency tables, box plots, histograms, normal probability plots, correlation, linear regression, and analysis of covariance (ANCOVA) were used to evaluate relationships among TSI variables (SAS 1988). ANCOVA was used to compare slopes and intercepts of regression models among regions and lake types (details in Lillie and Rasmussen 1991). As a consequence of the paucity of lakes within some phosphorus regions, we composited lakes from some adjoining phosphorus regions to make valid statistical comparisons. Compositing produced 13 geographical regions (Fig. 1). All natural lakes were categorized according to water source (seepage or drainage type) and thermal stratification condition (mixed or stratified). Impoundments were analyzed separately, leaving 578 natural lakes in the data set. Seepage lakes accounted for 60% of all natural lakes; 58% were thermally stratified. Preliminary analysis of the results indicated that associations among TSI parameters were not significantly different within the northern and southern tiers of regions, but the associations were significantly different between northern and southern regions. Region D was an exception, being distinctly different from surrounding northern and southern regions. Consequently, we combined lakes from adjoining northern and southern regions and recalculated the regressions.

Results:

Statewide TSIs: Wisconsin TSI formulae are provided in Table 1.

Table 1. *Wisconsin trophic state index (WTSI) equations in Natural Logarithm and Log_{10} format.**

Format	Equation	
Nat. Log	$WTSI_{SD}$	$= 60 - (14.4\ Log_n\ SD)$
Log_{10}		$= 60 - (33.2\ Log_{10}\ SD)$
Nat. Log	$WTSI_{CHL}$	$= 34.8 + (7.56\ Log_n\ Chla)$
Log_{10}		$= 60 - [33.2 \times (0.76 - 0.52\ Log_{10}\ Chla)]$
Nat. Log	$WTSI_{TP}$	$= 28.2 + (7.73\ Log_n\ TP)$
Log_{10}		$= 60 - [33.2 \times (0.96 - 0.54\ Log_{10}\ TP)]$

* SD = Secchi disk depth, CHL = chlorophyll-*a*, TP = total phosphorus. $WTSI_{CHL}$ and $WTSI_{TP}$ are based on the Bureau of Research's 1979 random survey data set (combined lakes and impoundments); N = 515 and 513, respectively. Where SD is in meters, Chl*a* is in µg/L, TP is in µg/L. Note that the $WTSI_{SD}$ equation is identical to Carlson's equation #11 (Carlson 1977:365); this equation never changes because water clarity is the basis for all TSI comparisons.

Predictive Equations: Associations among TSI parameters were influenced by both lake type and geographic location. Thermal stratification condition generally had a greater influence on the associations than either seepage-drainage type or geographic location. Geographic influence appeared to be primarily a function of north versus south, with the exception of region D, which was distinctly different from surrounding regions. Predictive equations for associations among TSI parameters, separated by lake type, are provided for these 3 regions in Table 2. An alternative set of statewide predictive equations is provided in Table 3 for all natural lakes and impoundments, separated according to thermal stratification condition. To apply these equations, simply select the equation corresponding to the type and location of a particular lake. Remember that although these

Table 2. *Regional linear regression equations expressing the relationships between water clarity and chlorophyll-*a*, water clarity and total phosphorus, and chlorophyll-*a *and total phosphorus for naturally occurring Wisconsin lakes of different drainage and mixing types.**

Equation Format	Region	Stratified Seepage	Stratified Drainage	Mixed Seepage	Mixed Drainage
LnSD = a + b (LnChl*a*) To predict Secchi given Chl*a*	South	1.46 - 0.42 LnChl*a* (P=.0222; r^2=0.34)	1.62 - 0.48 LnChl*a* (P=.0003; r^2=0.72)	0.49 - 0.25 LnChl*a* (P= n.s.; r^2=0.27)	0.88 - 0.38 LnChl*a* (P=.0041; r^2=0.39)
	Central	1.55 - 0.30 LnChl*a* (P= n.s.; r^2=0.17)	2.00 - 0.58 LnChl*a* (P=.0511; r^2=0.90)	2.91 - 1.12 LnChl*a* (P=.0003; r^2=0.94)	No Data
	North	1.70 - 0.39 LnChl*a* (P=.0001; r^2=0.35)	1.84 - 0.53 LnChl*a* (P=.0001; r^2=0.56)	1.62 - 0.45 LnChl*a* (P=.0001; r^2=0.43)	0.80 - 0.21 LnChl*a* (P=.0585; r^2=0.10)
LnSD = a + b (LnTP) To predict Secchi given TP	South	1.90 - 0.40 LnTP (P=.0800; r^2=0.22)	2.27 - 0.58 LnTP (P=.0019; r^2=0.60)	1.17 - 0.41 LnTP (P= n.s.; r^2=0.62)	0.70 - 0.27 LnTP (P=.0747; r^2=0.18)
	Central	1.24 - 0.06 LnTP (P= n.s.; r^2=0.01)	3.10 - 0.96 LnTP (P= n.s.; r^2=0.43)	2.66 - 0.76 LnTP (P=.0069; r^2=0.80)	No Data
	North	1.64 - 0.25 LnTP (P=.0022; r^2=0.08)	2.57 - 0.60 LnTP (P=.0001; r^2=0.30)	1.84 - 0.41 LnTP (P=.0001; r^2=0.29)	1.68 - 0.44 LnTP (P=.0050; r^2=0.20)
LnChl*a* = a + b (LnTP) To predict Chl*a* given TP	South	-0.01 + 0.64 LnTP (P=.0275; r^2=0.30)	-1.29 + 1.20 LnTP (P=.0001; r^2=0.81)	-0.21 + 0.78 LnTP (P=.0404; r^2=0.36)	-0.29 + 0.86 LnTP (P=.0005; r^2=0.48)
	Central	0.06 + 0.60 LnTP (P= n.s.; r^2=0.20)	-1.53 + 1.49 LnTP (P= n.s.; r^2=0.40)	0.34 + 0.64 LnTP (P=.0311; r^2=0.46)	No Data
	North	1.38 + 0.17 LnTP (P= n.s.; r^2=0.02)	-0.41 + 0.80 LnTP (P=.0001; r^2=0.26)	0.54 + 0.53 LnTP (P=.0001; r^2=0.23)	1.87 + 0.15 LnTP (P= n.s.; r^2=0.02)

* In each equation, the first value represents the intercept (a) and the second value represents the slope (b). Probabilities (P) > 0.10 are indicated as nonsignificant (n.s.); r^2 values indicate the strength of the linear regression (i.e., the percent of the variability in the y-parameter explained by the regression). The higher the r^2 value, the better the model.

Table 3. *Statewide linear regression equations for natural lakes and impoundments separated according to thermal stratification type.*

	Natural Lakes		Impoundments	
Equation Format	**Stratified**	**Mixed**	**Stratified**	**Mixed**
LnSD = a + b (LnChl*a*) To predict Secchi given Chl*a*	1.77 - 0.47 LnChl*a* (P=.0001; r^2=0.47)	1.61 - 0.51 LnChl*a* (P=.0001; r^2=0.49)	1.30 - 0.32 LnChl*a* (P= n.s.; r^2=0.31)	1.07 - 0.37 Ln Chl*a* (P=.0001; r^2=0.58)
LnSD = a + b (LnTP) To predict Secchi given TP	2.10 - 0.44 LnTP (P=.0001; r^2=0.22)	2.15 - 0.57 LnTP (P=.0001; r^2=0.49)	2.08 - 0.51 LnTP (P=.0183; r^2=0.48)	1.14 - 0.30 LnTP (P=.0001; r^2=0.42)
LnChl*a* = a + b (LnTP) To predict Chl*a* given TP	0.39 + 0.54 LnTP (P=.0001; r^2=0.16)	0.27 + 0.65 LnTP (P=.0001; r^2=0.35)	-0.72 + 1.02 LnTP (P=.0039; r^2=0.62)	0.14 + 0.70 LnTP (P=.0001; r^2=0.52)

equations are fairly accurate at predicting average Secchi depth or chlorophyll-*a* of all lakes matching the type and location selected, the equations provide only a rough prediction of clarity or chlorophyll of individual lakes.

Recommendations

The statewide WTSI equations provided in this article should be used exclusively for reporting the trophic status of lakes throughout Wisconsin. Reported WTSI values should reference which equation was used to derive the value. The predictive regression equations should be applied cautiously for purposes of estimating general associations among water quality parameters in a particular type of lake or group of lakes. Due to the great amount of natural variability within lakes, these equations should not be used alone in making management decisions on individual lakes.

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About the Authors

Richard Lillie is a research biologist with the DNR Bureau of Research, Research Center, 1350 Femrite Drive, Monona, WI 53716: phone (608)-221-6338.

Susan Graham is a lake assessment specialist with the DNR Bureau of Water Resources Management, P.O. Box 7921, Madison, WI 53707: phone (608)-266-3599.

Paul Rasmussen is a biostatistician with the DNR Bureau of Research, Research Center, 1350 Femrite Drive, Monona, WI 53716: phone (608)-221-6323.

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