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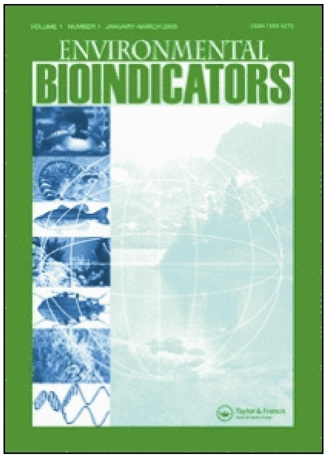

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A Diatom Quality Index from a Diatom-Based Total Phosphorus Inference Model

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A diatom quality index to assess diatom community impairment in the nearshore wetlands of the Laurentian Great Lakes was developed from a diatom-based total phosphorus (TP) weighted average inference model. The index is calculated with a weighted average equation using species optima standardized to a 1–10 scale and species tolerance standardized to a 1–3 scale. Multiple regression analysis revealed a moderate fit (R^2 = 0.63) between site scores of the selected index and GIS derived watershed characteristics (agriculture, soils, and industrial facilities). These index scores more closely fit watershed characteristics than the diatom inferred TP (R^2 = 0.59). In a regression tree analysis, soil permeability separated higher index scores from lower scores identifying this variable as an important interaction factor in the analysis. The diatom quality index can be a powerful tool for analyzing habitat quality in the Great Lakes and can communicate the link between quantifiable diatom assemblage response with watershed-level disturbance.

Keywords Diatoms, Great Lakes, water quality index

Introduction

The International Joint Commission (1989) mandates the protection of biologic integrity in aquatic habitats of the Great Lakes. Protecting biologic integrity in Great Lakes habitats requires the ability to measure changes in biological conditions such as taxonomic composition and to recognize biologic degradation and impairment. The protection mandate also involves the ability to interpret the causes of biological changes, to identify those that result from human activities and to link the changes in biological condition in Great Lakes coastal environments to stressors in the watersheds.

While it is important to protect fish and other economic commodities in the lakes, doing so requires that we fully protect biologic integrity and take an integrated ecological approach to habitat assessment (International Joint Commission 1989; Karr and Chu

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1999; Holling 1996). Thus, identifying links between stresses in an aquatic system to biological response at all trophic levels, including the primary producers such as diatoms, is necessary for effective management. It is also important to communicate the health of these systems clearly so that the public understands why management decisions are made.

Weighted average (WA) regression has emerged as an effective method of linking environmental stress with diatom assemblages in aquatic environments. Diatom based WA models have been used to successfully infer, for example, the effects of shoreline development (Garrison and Wakeman 2001), trophic status (Heiskary and Swain 2002), and logging impacts (Laird and Cumming 2001) by reconstructing historic water quality data such as pH, total phosphorus (TP), acid-neutralizing capacity, and chloride from sedimentary diatom assemblages. Although diatom-based models have been typically applied to fossil assemblages in paleolimnological studies, recently Reavie et al. (2006) developed a benthic diatom WA inference model for current habitat assessment calibrated to TP for the nearshore habitats of the Great Lakes. This model provides a robust reconstructive relationship, reflecting a strong response of the diatoms to TP and watershed disturbance determined from geographic information system (GIS) databases.

It would be appropriate, however, to convert this diatom-based WA inference model to a diatom quality index to clearly reflect and communicate diatom response rather than inferred TP. A diatom quality index has assigned indicator values for the species that are used to calculate a score for a site which represents the level of pollution sensitivity of the diatom assemblage. The emphasis of a diatom quality index is on diatom community response defined by the abundance of species sensitive to or tolerant of pollution in the diatom assemblage. A diatom quality index score derived from the WA TP inference model represents the diatom response to the sum of environmental impacts for which TP is a proxy in the nearshore habitats of the Great Lakes. We can, therefore, use the index to quantify and communicate diatom response to environmental conditions in the Great Lakes nearshore.

In this work, we describe a diatom quality index based on the WA TP inference model proposed by Reavie et al. (2006). We test the index by correlating index scores for sites with disturbance gradients derived from GIS data in watersheds associated with the sites and compare it with the WA model. We also explore the combined effects of watershed disturbance on index scores.

Methods

Weighted Average Model used for Index Development

The diatom-based TP model used for index development in this study was constructed and evaluated (Reavie et al. 2006) as part of the larger Great Lakes Environmental Indicators (GLEI) project designed to develop and test indicators of nearshore ecological condition for the Laurentian Great Lakes (Niemi et al. 2004; Danz et al. 2005). The training set for the diatom inference model was composed of 155 surface sediment (88%) and epilithic (12%) samples collected from Great Lakes coastal wetlands, embayments, and high-energy sites in 2002 and 2003 summer seasons. Four hundred diatom valves were counted for each sample and diatom taxa were identified to lowest possible taxonomic level. Variety and form designations were assigned within the study to taxa which did not fit established nomenclature. Three hundred and fifty-five taxa (or taxonomic complexes) were included in the model development (see Reavie et al. 2006) for full field work and analytical methods). Multivariate analysis revealed a strong relationship between diatom assemblages and measured TP and the final TP inference model provided a robust reconstructive relationship when diatom inferred TP was compared to measured TP ($r^2 = 0.75$; RMSE = 0.22 log (μg TP/L); $r^2_{\text{jackknife}} = 0.65$; RMSEP = 0.26 log (μg TP/L).

Assigning Optima and Tolerance Indicator Values to Species

A species optimum coefficient in the WA inference model (Reavie et al. 2006) is based on the maximum modeled relative abundance in a unimodal species response along the TP gradient, and thus represents the TP concentration at which that species is most abundant. A species tolerance coefficient represents the standardized range of TP concentrations around the optimum from sites in which the species is found. Optima and tolerance coefficients calculated for each species in the GLEI inference model were used along with species relative abundance to infer TP at a site.

We rescaled species optima coefficients from the inference model to assign as species indicator values for the diatom quality index. We simply rank ordered the species TP optima (derived for 402 diatom taxa) and assigned the first 10% interval (species 1–40), corresponding to lowest TP optima, an index value of 10. We assigned the next 10% interval (species 41–80) an index value of 9 and so forth. The last interval which was assigned an index value of 1 (containing the highest TP coefficients) contained 42 species. The ten scale was selected because Sgro and Johansen (1998) as well as exploratory work in this study indicated that sampling error for other similarly constructed diatom indices, the Lange-Bertalot Index (Lange-Bertalot 1979), and the Trophic Diatom Index (Kelly and Whitton 1995), tested in Great Lakes nearshore sites is approximately 10%. A ten scale could conveniently represent error as approximately within one point.

A taxon with a broad tolerance to TP concentrations is considered less useful as an indicator of TP, so each species was assigned a tolerance indicator value from 1 to 3 based on how many optima index value intervals were spanned by the tolerance range of the species. A species was assigned a tolerance coefficient of 3 if its tolerance range spanned 1–3 optima intervals, a 2 if its tolerance range spanned 4–7 optima intervals, and one if the tolerance range spanned 8–10 optima intervals. For example, a species may have an optima in the top 10% of the rank ordered list giving it an index value of 10, but its tolerance range may span 5 optima index intervals giving it a tolerance index value of 2. This 3-point scale was selected because an index that gives less weight to tolerance may perform better than a 10-point scale which gives more weight to tolerance, since the original inference model performed less well with tolerance down-weighting (Reavie et al. 2006). However, an exploratory analysis was performed using a subset of 100 samples representative of the TP range from the original sample set (210 samples) described in Reavie et al. (2006). The samples for this analysis were selected by rank ordering the data set by TP concentration, splitting the list into ten groups and selecting ten samples from each group (stratified random sampling) to create ten subsets of ten samples that each represented the TP range of the original sample set. The ten representative subsets were each analyzed separately. The exploratory analysis revealed that the diatom quality index calculated with the three-point tolerance scale and the ten-point tolerance scale only performed slightly better than the index calculated without tolerance values (average $r^2 = 0.95$, 0.95, 0.93, $p < 0.0001$ for the ten groups calculated by the three methods respectively).

The diatom quality index we derived from the TP inference model is unit-less. The optimum indicator value is a number which quantifies the species sensitivity to pollution. The tolerance indicator value is a number which quantifies how well the species functions as an indicator. The optima and tolerance indicator values are used along with species abundance to assess diatom assemblage response to pollution at a site.

Index Calculation

We aimed to create a diatom index using optima and tolerance indicator values (as described above) that produces index scores closely related to model inferred TP for sites. We selected the following weighted average formula to calculate diatom quality index scores for sites:

$$S = \left(\sum_{i=1}^{n} o_i \times t_i \times ra_i\right) \div \left(\sum_{i=1}^{n} ra_i \times t_i\right), \tag{1}$$

where S is the diatom quality index score, o_i is the species optima indicator value for the i^{th} species, t_i is the species tolerance indicator value for the i^{th} species, and ra_i is the relative abundance for the i^{th} species.

Comparison of Index Scores and WA inferred TP concentrations with Watershed Disturbance Variables

Gradients of anthropogenic stress for coastal watersheds contributing to the wetland samples in the WA training dataset were described by Danz et al. (2005) and Reavie et al (2006). Briefly, spatially referenced variables related to human activities in contributing basins were summarized in a geographic information system (GIS) database for several primary categories. Principle components (PC) analysis was used to reduce the dimensionality within each category of human activity and soils and the resulting PCs within each category were interpreted as indicators of stress. The stressor categories included: agriculture, urban development, industrial development, atmospheric deposition, and soil properties. For example, the agricultural stressor gradient was the first principle component from an analysis of 26 variables related to pesticide use, herbicide application, runoff, and erosion. Although we used the soil variables as a potentially important source of environmental variation rather than a source of stress *per se*, the primary soils gradients were calculated with the same methods as the stress variables. For our analysis we used eight principle components from the five categories of environmental variables:

- AG 1 - increasing PC values reflect increasing overall agricultural activity in watersheds.
- ATM 1 - increasing PC values reflect increasing overall atmospheric deposition.
- ATM 2 - increasing PC values reflect increasing basicity (calcium, ammonium, magnesium cations) in atmospheric deposition.
- IND 1 - increasing PC values reflect increasing industrial facility density based on overall NPDES (regulated industrial discharge permits).
- IND 2 - increasing PC values reflect increasing density of NPDES industrial facilities that discharge PAHs or industrial facilities that physically disturb the environment.
- SOIL 1 - increasing PC values reflect a gradient of sandy permeable soils to clay impermeable soils.

- SOIL 2 - increasing PC values represent soils with higher water holding capacity, cation exchange capacity, and organic matter; lower values represent soils with higher bulk density.
- URBAN 1 - increasing PC values reflect increasing population density, road density, and urban land cover.

We used multiple linear regression to evaluate the relationship between the eight independent watershed variables and the index scores. A similar test was performed for the WA inferred TP concentrations (Reavie et al. 2006). Manual selection was used to select the smallest subset of watershed variables that had the best fit with index score data. Type II analysis of variance was used to test the significance of the models using R software package (R Development Core Team 2005). This analysis was performed on samples from the exploratory subset described above for which watershed variable data existed (53 samples).

Effects of Watershed Disturbance on Index Scores

We examined how watershed variables as interaction factors influence the index scores using regression tree analysis. The R software package (R Development Core Team 2005) was used with a contributed library (Ripley 2005). Regression trees partition the variables based on the amount of explained deviance determined for each branch. Deviance in a regression tree is defined in terms of corrected sum of squared deviations from the mean value in each branch of the tree, so the best tree minimizes the residual variance in the response variable (McCune and Grace 2002). We used a cost complexity approach to simplify the tree. This approach measures the increased deviance resulting from a simpler tree. We used 100 cross-validation folds in this analysis. Our analysis recursively partitioned the AG 1, IND 1, SOIL 1, and SOIL 2 PCA component scores from the 53 sites to identify nodes of index scores based on disturbance type. Stopping rules determined a minimum group size of five by default.

Results

Index scores were calculated for the 100-sample subset of Great Lakes nearshore sites using the WA equation with optima and tolerance indicator values derived from the TP inference model (Table 1). The scores for the 100-sample subset ranged from 2.21 to 9.66 with an average score of 6.2 and a standard deviation of 1.8 reflecting a normal frequency distribution (Fig. 1).

The best multiple-regression model for the index scores as well as for WA inferred TP concentrations included four explanatory variables (AG 1, IND 1, SOILS 1, and SOILS 2) of the eight tested. The AG 1 variable was most important in both models based on an examination of regression coefficients and Type II analysis of variance (ANOVA) sums of squares. The diatom quality index has a slightly better fit with the independent variables than the WA model (Table 2).

The two least important splits were arbitrarily pruned from the original seven node default regression tree (deviance = 18.62) after examining the results of the cross-validation analysis. This resulted in a five-node tree (deviance = 26.07) (Fig. 2). This regression tree demonstrated that soils, followed by agricultural activities, were the primary factors influencing index scores. The diatom quality index is scaled such that low scores indicate greater diatom assemblage impairment, whereas high scores reflect a less impaired diatom assemblage with regard to TP impact. The tree can be interpreted as follows:

Table 1

Diatom taxa with optima and tolerance values used for calculating the Great Lakes Environmental Indicators (GLEI) diatom quality index. Variety and form numbers were assigned within the study to taxa which did not fit established nomenclature

Genus	Species	Variety	Authority	Opt.	Tol.
Achnanthes	*conspicua*		Mayer	8	2
Achnanthes	*curtissima*		J.R.Carter	5	1
Achnanthes	*daui*		Foged	2	2
Achnanthes	*grana*		Hohn et Hellerm.	7	1
Achnanthes	*minuscula*		Hust.	7	1
Achnanthes	*ziegleri*		Lange-Bert.	8	2
Achnanthidium	*affine*		(Grun.) Czarn.	9	2
Achnanthidium	*biasolettianum*	*subatomus*	Lange-Bert.	7	1
Achnanthidium	*biasolettianum*	*thienemannii*	(Hust.) Lange-Bert.	7	1
Achnanthidium	*biasolettianum*	var. 1		7	1
Achnanthidium	*biasolettianum*		(Grun.) Bukht.	7	1
Achnanthidium	*exiguum*		(Grun.) Czarn.	5	1
Achnanthidium	*jackii*		Rabh.	7	1
Achnanthidium	*macrocephalum*		(Hust.) Round et Bukht.	7	2
Achnanthidium	*microcephalum*		Kütz.	9	2
Achnanthidium	*minutissimum*	fo. 1		7	1
Achnanthidium	*minutissimum*	fo. 2	(Kütz.) Czarn.	7	1
Achnanthidium	*minutissimum*	*gracillima*	(Meister) Bukht..	7	1
Achnanthidium	*minutissimum*	*scotica*	(Carter) (new authority unknown)	7	1
Achnanthidium	*minutissimum*	var. 1		7	1
Achnanthidium	*minutissimum*	var. 100		7	1
Achnanthidium	*minutissimum*	var. 4		7	1
Achnanthidium	*minutissimum*		(Kütz.) Czarn.	7	1
Achnanthidium	*saprophila*		(Kobay. et Mayama) Round et Bukht.	6	2
Actinocyclus	*normanii*		(Greg.) Hust.	2	2
Adlafia	*bryophila*		(Petersen) Moser, Lange-Bert., et Metzeltin	8	2
Adlafia	*minuscula*		(Grun.) Lange-Bert.	3	2
Amphora	*aequalis*		Krammer	7	2
Amphora	*coffeaeformis*		(Ag.) Kütz.	6	1
Amphora	*inariensis*		Krammer	7	1
Amphora	*libyca*		Ehrenb.	5	1
Amphora	*neglecta*		Stoermer et Yang	8	2
Amphora	*ovalis*	*affinis*	(Kütz.) Pero	3	2
Amphora	*ovalis*		(Kütz.) Kütz.	5	1
Amphora	*pediculus*		(Kütz.) Grun.	7	1
Amphora	*perpusilla*		(Grun.) Grun. in V.H.	7	1
Amphora	sp. 1			7	2
Amphora	*subcostulata*		Stoermer et Yang	8	1

(Continued)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Amphora	*thumensis*		(Mayer) Cleve-Euler	7	2
Amphora	*veneta*		Kütz.	6	1
Aneumastus	*minor*		Lange-Bert.	10	2
Asterionella	*formosa*		Hass.	9	2
Aulacoseira	*alpigena*		(Grun.) Krammer	3	1
Aulacoseira	*ambigua*		(Grun.) Simonsen	6	1
Aulacoseira	*granulata*		(Ehrenb.) Simonsen	7	1
Aulacoseira	*islandica*		(Müller) Simonsen	9	1
Aulacoseira	*italica*		(Ehrenb.) Simonsen	7	1
Aulacoseira	*subarctica*		(Müller) Haworth	9	2
Bacillaria	*paradoxa*		Müller	1	3
Belonastrum	*berolinensis*		(Lemm.) Round et Maidana	4	2
Brachysira	*brebissonii*		Ross in Hartley	8	2
Brachysira	*neoexilis*		Lange-Bert.	9	2
Brachysira	*vitrea*		(Grun.) R.Ross in B.Hartley	8	2
Caloneis	*bacillum*		(Grun.) Cleve	7	1
Cavinula	*cocconeiformis*		(W.Greg. ex Grev.) Mann et Stickle	8	2
Cavinula	*jaernefeltii*		(Hust.) Mann et Stickle	10	3
Cavinula	*scutelloides*		(W.Sm.) Lange-Bert.	4	1
Cavinula	*utermoehlii*		(unknown)	6	1
Cocconeis	*neodiminuta*		Krammer	8	2
Cocconeis	*neothumensis*		Krammer	6	1
Cocconeis	*pediculus*		Ehrenb.	6	1
Cocconeis	*placentula*	*euglypta*	Ehrenb.	5	1
Cocconeis	*placentula*	*lineata*	(Ehrenb.) V.H.	5	1
Cocconeis	*placentula*	*pseudolineata*	Geit.	4	1
Cocconeis	*placentula*		Ehrenb.	5	1
Cocconeis	*pseudothumensis*		Reich.	6	2
Craticula	*accomoda*		(Hust.) Mann	3	2
Craticula	*cuspidata*		(Kütz.) Mann	2	2
Craticula	sp. 1			7	2
Ctenophora	*pulchella*		(Ralfs ex Kütz.) D.M.Williams et Round	2	2
Cyclostephanos	*dubius*		(Fricke) Round	1	3
Cyclostephanos	*invisitatus*		(Hohn et Hellerm.) Theriot, Stoermer et Håk.	4	1
Cyclostephanos	*tholiformis*		Stoermer, Håk. et Theriot	4	1
Cyclotella	*aff. comta*	*unipunctata*	Hust.	10	1
Cyclotella	*atomus*	var. 1		1	2
Cyclotella	*atomus*		Hust.	3	1
Cyclotella	*bodanica*		Grun.	10	3

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Cyclotella	*cf. atomus*			8	2
Cyclotella	*comensis*	var. 6		10	3
Cyclotella	*comensis*	*var. 1*		10	3
Cyclotella	*comensis*		Grun.	10	3
Cyclotella	*cryptica*		Reim., Lewin et Guillard	1	2
Cyclotella	*cyclopunctata*		Håk. et J.R.Carter	10	3
Cyclotella	*delicatula*		Hust.	10	3
Cyclotella	*distinguenda*	*unipunctata*	(Hust.) Håk.	9	2
Cyclotella	*distinguenda*		Hust.	9	2
Cyclotella	*dubia*		Hilse	1	2
Cyclotella	*kuetzingiana*		Thwaites	10	2
Cyclotella	*michiganiana*		Skvortzow	10	3
Cyclotella	*ocellata*	var. 6		10	2
Cyclotella	*ocellata*		Pant.	9	2
Cyclotella	*pseudostelligera*		Hust.	2	2
Cyclotella	sp. 1			10	3
Cyclotella	*stelligera*		(Cleve et Grun.) V.H.	8	1
Cyclotella	*stelligeroides*		Hust.	10	3
Cyclotella	*tripartita*		Håk.	10	3
Cymatopleura	*solea*		(Bréb.) W.Sm.	2	2
Cymbella	*affinis*		Kütz.	9	2
Cymbella	*amphicephala*		Näg. ex Kütz.	7	1
Cymbella	sp. 111			9	2
Delicata	*delicatula*		(Kütz.) Krammer	10	3
Denticula	*kuetzingii*		Grun.	9	2
Denticula	*tenuis*	*crassula*	(Näg.) W.West et G.S.West	10	3
Denticula	*tenuis*		Kütz.	9	2
Diatoma	*tenuis*	*elongatum*	Lyngb.	9	2
Diatoma	*tenuis*		Ag.	5	1
Diatoma	*vulgaris*		Bory	3	1
Distrionella	*asterionelloides*		Williams 1990	10	3
Encyonema	*caespitosum*		Kütz.	7	1
Encyonema	*evergladianum*		Krammer	10	3
Encyonema	*minutum*		(Hilse ex Rabh.) Mann	8	2
Encyonema	*reichardtii*		(Krammer) Mann	8	2
Encyonema	*silesiacum*		(Bleisch in Rabh.) Mann	7	1
Encyonema	*ventricosum*		Kütz.	9	2
Encyonopsis	*cesatii*		(Rabh.) Krammer	9	2
Encyonopsis	*krammeri*		Reich.	10	2
Encyonopsis	*microcephala*		(Grun.) Krammer	8	2
Encyonopsis	*minuta*		Krammer et Reich.	8	2

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Encyonopsis	sp. 1			8	2
Encyonopsis	*subminuta*		Krammer et Reich.	9	2
Encyonopsis	*vandamii*		Krammer et Lange-Bert.	10	3
Eolimna	*minima*		Grun.	5	1
Epithemia	*argus*		(Ehrenb.) Kütz.	2	2
Epithemia	*sorex*		Kütz.	4	2
Epithemia	*turgida*		(Ehrenb.) Kütz.	4	1
Eucocconeis	*flexella*	*alpestris*	(Brun) Hust.	9	2
Eucocconeis	*flexella*		(Kütz.) Meister	9	2
Eucocconeis	*laevis*		(Østrup) Lange-Bert.	10	2
Eunotia	*bilunaris*		(Ehrenb.) Mills	4	1
Eunotia	*formica*		Ehrenb.	4	2
Eunotia	*implicata*		Norpel, Alles, et Lange-Bert.	3	1
Eunotia	*incisa*		Smith ex Gregory	6	2
Eunotia	*pectinalis*	*minor*	(Kütz.) Rabh.	6	2
Eunotia	*praerupta*		Ehrenb.	3	1
Eunotia	*soleirolii*		(Kütz.) Rabh.	8	1
Fallacia	*pygmaea*		(Kütz.) Stickle et Mann	1	3
Fallacia	*sublucidula*		(Hust.) D.G. Mann in Round	9	2
Fallacia	*tenera*		(Hust.) Mann	1	3
Fragilaria	*capucina*	*gracilis*	(Øestrup) Hust.	6	1
Fragilaria	*capucina*	*mesolepta*	Rabh.	3	2
Fragilaria	*capucina*	*perminuta*	(Grun.) Lange-Bert.	5	1
Fragilaria	*capucina*	*rumpens*	(Kütz.) Lange-Bert.	8	2
Fragilaria	*capucina*		Desm.	5	2
Fragilaria	*crotonensis*		Kitton	10	2
Fragilaria	*delicatissima*	var. 1		10	3
Fragilaria	*delicatissima*		(W. Smith) Lange-Bert.	9	2
Fragilaria	*nanana*		Lange-Bert.	10	2
Fragilaria	*nitzschioides*		Grun.	1	3
Fragilaria	sp. 7			1	3
Fragilaria	*tenera*		(W. Smith) Lange-Bert.	7	1
Fragilaria	*vaucheriae*		(Kütz.) J.B.Petersen	6	1
Frankophila	*similioides*		Lange-Bert. et. Rumrich	5	1
Frustulia	*crassinervia*		(Breb.) Lange-Bert. et Krammer	8	3
Geissleria	*acceptata*		(Hust.) Lange-Bert. et Metzeltin	9	2
Geissleria	*arkensii*		(unknown)	1	2
Geissleria	*cummerowii*		(Kalbe) Lange-Bert.	6	1
Geissleria	*decussis*		(Østrup) Lange-Bert. et Metzeltin	5	1

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Geissleria	*paludosa*		(Hust.) Lange-Bert. et Metzeltin	4	2
Geissleria	*schoenfeldii*		(Hust.) Lange-Bert. et Metzeltin	4	1
Geissleria	*similis*		(Krasske) Lange-Bert. et Metzeltin	7	1
Gomphonema	*acuminatum*		Ehrenb.	5	1
Gomphonema	*angustatum*		(Kütz.) Rabh.	7	1
Gomphonema	*angustatum*	var. 1		2	2
Gomphonema	*angustum*		Ag.	8	2
Gomphonema	*cf. bavaricum*			9	2
Gomphonema	*cf. pumilum*			7	2
Gomphonema	*clavatum*		Ehrenb.	2	2
Gomphonema	*gracile*		Ehrenb.	2	2
Gomphonema	*minutum*		(Ag.) Ag.	6	1
Gomphonema	*olivaceum*	*olivaceoides*	(Hust.) Lange-Bert.	10	3
Gomphonema	*olivaceum*		(Hornem.) Kütz.	4	1
Gomphonema	*parvulum*		Kütz.	3	2
Gomphonema	*pumilum*	*elegans*	Reich. et Lange-Bert.	4	1
Gomphonema	*pumilum*		(Grun.) Reich. et Lange-Bert.	8	2
Gomphonema	*sarcophagus*	var. 1		9	2
Gomphonema	*utae*		Lange-Bert. et Reich.	1	3
Gyrosigma	*attenuatum*		(Kütz.) Rabh.	2	1
Gyrosigma	*spencerii*		(Baily ex Quek.) Griff. et Henfr.	1	3
Hippodonta	*capitata*		(Grun.) Lange-Bert., Metzeltin et Witkowski	2	2
Hippodonta	*costulata*		(Grun.) Lange-Bert., Metzeltin et Witkowski	5	1
Hippodonta	*hungarica*		(Grun.) Lange-Bert., Metzeltin et Witk.	3	2
Hippodonta	*neglecta*		Lange-Bert., Metzeltin et Witk.	10	3
Hippodonta	*subcostulata*		(Hust.) Lange-Bert., Metzeltin et Witkowski	10	3
Karayevia	*clevei*	*bottnica*	(Grun.) Round et Bukht. (?)	10	3
Karayevia	*clevei*	*rostratum*	(Hust.) Kingston	9	2
Karayevia	*clevei*		(Grun.) Round et Bukht.	8	2
Karayevia	*laterostrata*		(Hust.) Kingston	9	2
Kolbesia	*amoena*		(Hust.) Kingston	10	3
Kolbesia	*ploenensis*		(Hust.) Kingston	5	2

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Kolbesia	*suchlandtii*		(Hust.) Kingston	10	3
Lemnicola	*hungarica*		(Grun.) Round et P.W.Basson	1	3
Luticola	*mutica*		(Kütz.) Mann	9	1
Martyana	*martyi*			7	1
Martyana	sp. 2			7	2
Martyana	sp. 3			4	2
Martyana	sp. 4			5	2
Martyana	sp. 5			3	1
Martyana	sp. 6			3	1
Martyana	sp. 7			3	1
Martyana	sp. 8			4	1
Martyana	sp. 9			4	1
Mayamaea	*agrestis*		(Hust.) Lange-Bert.	7	2
Mayamaea	*atomus*		(Kütz.) Lange-Bert.	1	2
Melosira	*varians*		Ag.	1	2
Navicula	*angusta*		Grun.	4	1
Navicula	*antonii*		Lange-Beralot in Rumrich et al	4	1
Navicula	*bourrellyivera*		Lange-Bert., Witk. et Stach.	1	3
Navicula	*capitatoradiata*		Germain	2	2
Navicula	*cari*		Ehrenb.	6	1
Navicula	*caterva*		Hohn et Hellerm.	2	2
Navicula	*cf. novaesiberica*			7	2
Navicula	*cf. viridula*			2	2
Navicula	*cryptocephala*		Kütz.	4	1
Navicula	*cryptotenella*		Lange-Bert.	6	1
Navicula	*cryptotenelloides*		Lange-Bert.	8	1
Navicula	*erifuga*		Lange-Bert.	1	3
Navicula	*germainii*		Wallace	1	3
Navicula	*gregaria*		Donkin	2	2
Navicula	*kotschyi*		Grun.	7	2
Navicula	*lanceolata*		(Ag.) Kütz.	2	2
Navicula	*libonensis*		Schoemann	2	2
Navicula	*menisculus*		Schum.	3	2
Navicula	*meniscus*		Schum.	2	2
Navicula	*moskalii*		Metzeltin, Witkowski et Lange-Bert.	4	1
Navicula	*novaesiberica*		Lange-Bert.	3	2
Navicula	*phyllepta*		Kütz.	1	2
Navicula	*pseudoventralis*		Hust.	7	1
Navicula	*radiosa*		Kütz.	5	1

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Navicula	*reichardtiana*		Lange-Bert.	4	1
Navicula	*reinhardtii*		Grun.	3	2
Navicula	*rhynchocephala*		Kütz.	3	1
Navicula	*salinarum*		Grun.	1	3
Navicula	*schadei*		Krasske	6	2
Navicula	*slesvicensis*		Grun.	2	2
Navicula	sp. 132			7	2
Navicula	sp. 49			1	3
Navicula	*stroemii*		Hust.	10	2
Navicula	*subminuscula*		Manguin	4	1
Navicula	*subrotunda*		Hust.	6	1
Navicula	*subrotundata*		Hust.	6	1
Navicula	*tantula*		Hust.	3	1
Navicula	*tripunctata*		(Müll.) Bory	5	1
Navicula	*trivialis*		Lange-Bert.	2	2
Navicula	*upsaliensis*		Grun.	4	1
Navicula	*vandamii*		Schoemann et Archibald	1	2
Navicula	*veneta*		Kütz.	2	2
Navicula	*viridula*	*rostellata*	(Kütz.) Cleve	1	3
Navicula	*viridula*		(Kütz.) Ehrenb.	2	2
Navicula	*vitiosa*		Schimanski	8	2
Navicula	*wildii*		Lange-Bert.	9	3
Neidium	*ampliatum*		(Ehrenb.) Krammer	7	2
Nitzschia	*acicularioides*	var. 1		2	2
Nitzschia	*acicularis*		(Kütz.) W.Sm.	1	2
Nitzschia	*acidoclinata*		Lange-Bert.	3	2
Nitzschia	*agnita*		Hust.	6	1
Nitzschia	*amphibia*		Grun.	3	1
Nitzschia	*angustata*		(W.Sm.) Grun.	4	1
Nitzschia	*angustatula*		Lange-Bert.	8	1
Nitzschia	*apiculata*		(Greg.) Grun.	1	3
Nitzschia	*bacillum*		Hust.	8	1
Nitzschia	*calida*		Grun.	1	1
Nitzschia	*denticula*		Grun.	2	2
Nitzschia	*dissipata*	*media*	(Hantzsch) Grun.	9	2
Nitzschia	*dissipata*		(Hantzsch) Grun.	4	1
Nitzschia	*fonticola*		Grun.	6	1
Nitzschia	*frustulum*		(Kütz.) Grun.	3	2
Nitzschia	*gracilis*		Hantzsch	6	1
Nitzschia	*heufleriana*		Grun.	2	1
Nitzschia	*hungarica*		Grun.	1	3
Nitzschia	*incognita*		Krasske	3	1
Nitzschia	*inconspicua*		Grun.	3	2

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Nitzschia	*intermedia*		Hantzsch	2	2
Nitzschia	*liebetruthii*		Rabh.	5	1
Nitzschia	*linearis*		(Ag.) W.Sm.	3	1
Nitzschia	*microcephala*		Grun.	3	1
Nitzschia	*minuta*		Bleisch	1	2
Nitzschia	*palea*	*debilis*	(Kütz.) Grun.	3	2
Nitzschia	*palea*	*tenuirostris*	Grun.	2	2
Nitzschia	*palea*		(Kütz.) W.Sm.	4	1
Nitzschia	*paleacea*		Grun.	4	1
Nitzschia	*perminuta*		(Grun.) M.Perag.	3	1
Nitzschia	*radicula*		Hust.	4	2
Nitzschia	*recta*		Hantzsch ex. Rabh.	6	1
Nitzschia	*siliqua*		Archibald	1	3
Nitzschia	*solita*		Hust.	2	2
Nitzschia	*subacicularis*		Hust.	3	2
Nitzschia	*supralitorea*		Lange-Bert.	3	2
Placoneis	*clementis*		(Grun.) Cox	4	1
Placoneis	*exigua*		(Greg.) Mersechk.	2	2
Placoneis	*gastrum*		(Ehrenb.) Mersechk.	4	2
Placoneis	*pseudanglica*		(Lange-Bert.) Cox	3	2
Planothidium	*biporomum*		Hohn and Hellerm.	6	2
Planothidium	*delicatulum*		(Kütz.) Round et Bukht.	2	1
Planothidium	*dubium*		(Grun.) Round et Bukht.	4	1
Planothidium	*engelbrechtii*		(Choln.) Round et Bukht.	3	2
Planothidium	*frequentissimum*		(Lange-Bert.) Round et Bukht.	4	1
Planothidium	*hauckianum*		(Grun.) Round et Bukht.	5	1
Planothidium	*joursacense*		(Hérib.) Lange-Bert.	8	2
Planothidium	*lanceolatum*	*minutissima*		10	2
Planothidium	*lanceolatum*		(Breb.) Round et Bukht.	3	1
Planothidium	*oestrupii*		(Cleve) Round et Bukht.	10	3
Planothidium	*peragalli*	*parvulum*	(Patrick) Andresen, Stoermer et Kreis	5	2
Planothidium	*peragalli*		(Brun et Hérib. in Hérib.) Round et Bukht.	5	1
Planothidium	*robustum*	*abbreviata*	(Hust.) Lange-Bert. (?)	5	1
Planothidium	*rostratum*	var. 1		8	2
Psammothidium	*bioretii*		(Germain) Bukht. et Round	6	1
Psammothidium	*daonense*		(Lange-Bert.) Lange-Bert.	8	2
Psammothidium	*helveticum*		(Hust.) Bukht. et Round 1996	5	1
Psammothidium	*lacus-vulcani*		(Lange-Bert.) Bukht.	8	1

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Psammothidium	*lauenburgianum*		(Hust.) Bukht. et Round	9	2
Psammothidium	*levanderi*		(Hust.) Bukht. et Round	9	2
Psammothidium	*pseudoswazi*		(J.R.Carter) Bukht. et Round	8	1
Psammothidium	*rosenstockii*		(Lange-Bert.) Bukht.	8	2
Psammothidium	*sacculum*		(J.R.Carter) Bukht.	7	1
Psammothidium	*subatomoides*		(Hust.) Bukht. et Round	6	2
Psammothidium	*ventralis*		(Krasske) Bukht. et Round	8	2
Pseudostaurosira	*brevistriata*	*binodis*	(Pantocsek) Andresen, Stoermer et Kreis	5	1
Pseudostaurosira	*brevistriata*	*inflata*	(Pant.) Edlund	5	1
Pseudostaurosira	*brevistriata*	*lopsided*		6	1
Pseudostaurosira	*brevistriata*	var. 1		4	2
Pseudostaurosira	*brevistriata*		(Grun. in V.H.) Williams et Round	5	1
Pseudostaurosira	*microstriata*		(Marciniak) Flower	9	2
Pseudostaurosira	*polonica*		sensu Morales and Edlund	2	1
Pseudostaurosira	sp. 1			2	3
Pseudostaurosira	sp. 2			6	2
Pseudostaurosira	*zeilleri*		(Hérib.) D.M.Williams et Round	3	1
Punctastriata	sp. 1			6	1
Reimeria	*sinuata*		(Greg.) Kociolek et Stoermer	8	2
Rhoicosphenia	*abbreviata*		(Ag.) Lange-Bert.	4	1
Rhopalodia	*gibba*		(Ehrenb.) Müll.	1	3
Rossithidium	*linearis*	fo. *curta*	(W.Sm.) Round et Bukht. (?)	6	2
Rossithidium	*linearis*		(W.Sm.) Round et Bukht.	6	2
Rossithidium	*petersennii*		(Hust.) Round et Bukht.	7	1
Rossithidium	*pusillum*		(Grun.) Round et Bukht.	8	2
Sellaphora	*cf. pupula*			4	1
Sellaphora	*laevissima*		(Kütz.) Mann	2	2
Sellaphora	*mutata*		(Krasske) Lange-Bert.	6	1
Sellaphora	*nyassensis*	fo. *minor*	(Müller) Andresen, Stoermer et Kreis	10	3
Sellaphora	*pupula*		(Kütz.) Mereschk.	3	1
Sellaphora	*seminuloides*		(Grun.) Mann	7	1
Sellaphora	*seminulum*	*hustedtii*	(Patrick) Mann	4	1
Sellaphora	*seminulum*		(Grun.) Mann	6	2
Sellaphora	sp. 1			5	2

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Sellaphora	*vitabunda*		(Hust.) Mann	7	1
Skeletonema	*potamos*		(Weber) Hasle	2	2
Staurosira	*construens*	*binodis*	(Ehrenb.) Hamilton	3	1
Staurosira	*construens*	*binodis* fo. 1		1	2
Staurosira	*construens*	*pumila*	(Grun.) Kingston	2	2
Staurosira	*construens*	*subsalina*	(Hust.) Andresen, Stoermer et Kreis	1	2
Staurosira	*construens*	var. 1		5	1
Staurosira	*construens*	var. 2		5	2
Staurosira	*construens*	var. 7		7	1
Staurosira	*construens*	*venter*	(Ehrenb.) Hamilton	6	1
Staurosira	*construens*	*venter* fo. 4		6	2
Staurosira	*construens*		(Ehrenb.) Williams et Round	5	1
Staurosira	*elliptica*		(Schum.) Williams et Round	9	1
Staurosira	*pseudoconstruens*		(Marciniak) Williams et Round	5	1
Staurosira	sp. 108			1	3
Staurosirella	*leptostauron*		(Ehrenb.) Williams et Round	8	2
Staurosirella	*minuta*		Morales et M. B. Edlund	5	1
Staurosirella	*pinnata*	*acuminata*	Mayer	3	2
Staurosirella	*pinnata*	fo. *parallela*		6	1
Staurosirella	*pinnata*	*intercedens*	(Grun.) Hamilton	8	2
Staurosirella	*pinnata*	*intercedens* fo. 1		6	1
Staurosirella	*pinnata*	*lancettula*	(Schum.) Haworth et Kelly	6	1
Staurosirella	*pinnata*	*lancettula* fo. 1		6	1
Staurosirella	*pinnata*	*rostrata*		6	1
Staurosirella	*pinnata*	var. 1		6	1
Staurosirella	*pinnata*	var. 10		6	1
Staurosirella	*pinnata*	var. 100		6	1
Staurosirella	*pinnata*	var. 103		6	1
Staurosirella	*pinnata*	var. 12		6	1
Staurosirella	*pinnata*	var. 14		6	1
Staurosirella	*pinnata*	var. 2		6	1
Staurosirella	*pinnata*	var. 3		6	1
Staurosirella	*pinnata*	var. 4		6	1
Staurosirella	*pinnata*	var. 5		6	1

(*Continued*)

Table 1
(*Continued*)

Genus	Species	Variety	Authority	Opt.	Tol.
Staurosirella	*pinnata*		(Ehrenb.) Williams et Round	6	1
Staurosirella	sp. 1			6	2
Staurosirella	sp. 2			9	2
Stephanocyclus	*meneghiniana*	*plana*	(Kütz.) Skabitschevsky (?)	1	3
Stephanocyclus	*meneghiniana*		(Kütz.) Skabitschevsky	1	2
Stephanodiscus	*agassizensis*		Håk. et Kling	9	1
Stephanodiscus	*alpinus*		Hust.	9	1
Stephanodiscus	*hantzschii*	fo. *tenuis*	(Hust.) Håk. et Stoermer	2	2
Stephanodiscus	*hantzschii*		Grun.	7	1
Stephanodiscus	*medius*		Håk.	10	3
Stephanodiscus	*minutulus*		(Kütz.) Cleve et J.D.Möll.	9	2
Stephanodiscus	*niagarae*		Ehrenb.	8	1
Stephanodiscus	*oregonicus*		(Ehrenb.) Håk.	10	3
Stephanodiscus	*parvus*		Stoermer et Håk.	9	1
Stephanodiscus	sp. 1			10	3
Stephanodiscus	*transylvanicus*		Pant.	10	3
Surirella	*brebissonii*	*kuetzingii*	Krammer et Lange-Bert.	1	3
Surirella	*minuta*		Breb.	1	2
Synedra	*amphicephala*	*austraica*	(Grun.) Hust.	7	2
Synedra	*radians*		Kütz.	10	3
Synedra	*ulna*		(Nitzsch.) Ehrenb.	4	1
Synedrella	*parasitica*		(W. Smith) Round et Maidana	5	1
Tabellaria	*quadriseptata*		Knuds.	9	3
Tabularia	*fasciculata*		(Ag.) Williams et Round	2	2
Thalassiosira	*pseudonana*		Hasle et Heim.	1	2

- Soil type, followed by agricultural impact and finally industrial density produce the strongest threshold responses in index scores.
- The left branch of the tree, representing more permeable soils, was secondarily split on an agriculture threshold. The sites on the right branch of this split with greater agricultural impact have the lowest (poorest quality) average index scores overall (2.8) of all terminal nodes in the tree. The sites with less agriculture, but with permeable soils (left branch of the split) have moderately low index scores (4.7).
- The right branch of the main tree, representing less permeable soils, has generally higher scores than the left branch. It is similarly split by agriculture with lower agricultural activity sites to the left and higher agricultural activity sites to the right. The sites with highest index scores are to the left of the split and reflect those sites

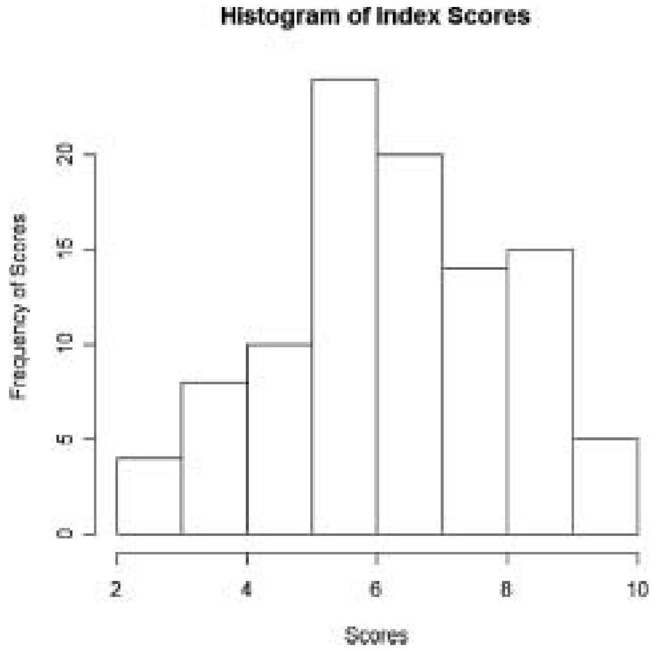

Figure 1. Frequency histogram of index scores calculated for one hundred near shore Great Lakes samples. The histogram forms eight intervals ranging from a lower limit of 2 to an upper limit of 10. The number of index scores in each interval is indicated on the left scale bar.

Table 2

Model 1 and model 2 represent the two best multiple linear regression models of weighted average (WA)-inferred total phosphorus (TP), and diatom quality index scores against watershed PC gradients resulting from manual selection. The coefficients in this type II regression indicate the relative importance of each of the variables in the models

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Inferred TP

Model 1 = 1.47 + 0.063(IND 1) – 0.087(SOIL 1) + 0.118(AG 1) + 0.064(SOIL 2)
$R^2 = 58.95$, $p < .0001$
Model 2 = 1.458 + 0.096(AG 1) = 0.096(IND 1) – 0.096(SOIL 1) – 0.084(URBAN)
$R^2 = 58.64$, $p < .0001$

Diatom Quality Index

Model 1 = 5.362 – 0.562(AG 1) – 0.438(IND 1) + 0.385(SOIL 1) – 0.371(SOIL 2)
$R^2 = 63.15$ $p < .0001$
Model 2 = 5.301 – 0.417(AG 1) – 0.556(ATM 1) – 0.508(IND 1) – 0.424(SOIL 2)
$R^2_{adj} = 62.56$, $p < .0001$

in the study with impermeable soils and less agriculture. These sites with the lowest agricultural usage scores have the highest average index score (6.3).

- Following the low permeability/high agriculture branch to the right, the next split is due to industrial density, with greater industrial density equating with lower scores (4.3). The less industrial sites had higher index scores than the more industrial sites (5.7).

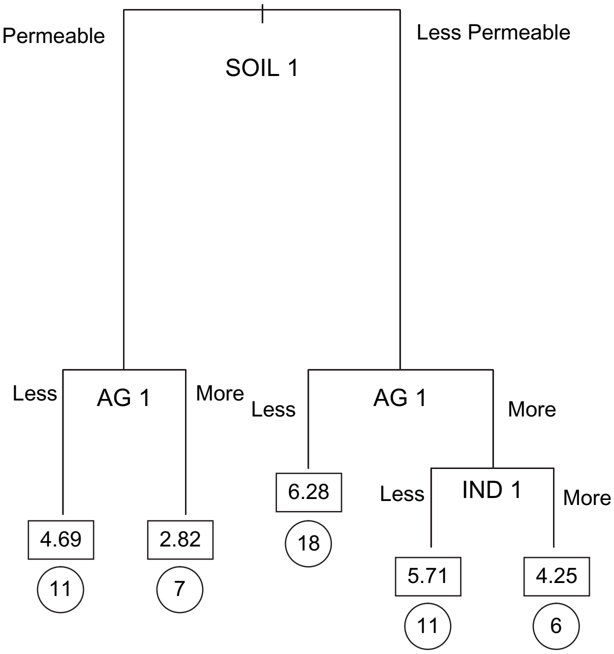

Figure 2. Regression tree analysis of diatom index scores and their relationship to watershed characteristics. The tree depicts thresholds of watershed disturbance gradients (SOIL 1 = soil permeability, AG 1 = agricultural density, IND 1 = industrial point source density). Split criteria are based on ordination scores for the synthetic disturbance gradients (Danz et al., 2005). Index score averages for each terminal node are shown in boxes at the bottom of each terminal node. The number of samples in each terminal node is shown in circles. Total deviance for the tree is 26.07. The deviance for each of the five terminal nodes from left to right is: 5.84, 2.82, 6.28, 5.71, 4.25.

Discussion

The diatom quality index presented here applies a subtle shift in calculation to the WA inference model of Reavie et al. (2006) to obtain an important conceptual shift. The WA inference model infers TP based on diatom composition, while the diatom quality index effectively quantifies the response of the diatom flora based on the temporally integrated impacts represented by concentration of TP. The diatom quality index facilitates the communication of habitat quality in terms of biologic attributes defined by Karr and Chu (1999) and biologic integrity defined by Karr and Dudley (1981).

Changing the WA optima coefficients to index values and including a tolerance index value in the diatom performance index slightly improves the fit of the index scores with watershed disturbance variables over the WA inferred TP in the multiple regression model. Both methods show a moderately good fit with watershed level variables, with agriculture being the most significant predictor. Yet, the concepts of biologic integrity and biologic attributes do not accommodate a measure of TP. A measurable biological attribute describes the predictable response of an organism to specific changes in the environment (Karr and Chu 1999) and this is not directly communicated by the WA model. Estimates of biologic integrity should encompass environmental impacts presumably not measured by water chemistry parameters alone. Though the diatom performance index is calibrated to TP, it expresses impairment due to impacts for which TP serves as a proxy (i.e. variables correlated with TP) and more clearly embraces the idea of a biologic attribute.

Furthermore, like the inference model, the diatom performance index may more accurately reflect conditions at those sites which lack a strict congruence between the diatom assemblage and measured TP concentrations. Conditions at such sites are best estimated by the diatoms which integrate impacts of TP and conditions for which TP serves as a proxy over time rather than a snapshot TP water sample measurement that does not capture spatially and temporally integrated conditions.

The response of the diatom assemblage to agricultural impacts as measured by the index may be influenced by other interaction factors present in the watershed, most notably the soil type. In this study, in areas of highly permeable soils the index appears to be primarily a measure of agricultural impact, but in areas of less permeable soils the index scores are confounded by soils, agriculture, and industry. Sites in areas of permeable soils do not achieve index scores as high as agricultural sites in areas of less permeable soil, but we need to be cautious with this interpretation. More permeable soils in the Great Lakes region are found mainly along Lake Erie and Lake Ontario, areas of higher concentrations of land use disturbance generally. Yet, the index scores in areas of high soil permeability in this analysis are most influenced by agricultural activity. In areas of less soil permeability the index will be affected by industrial activity as it becomes increasingly dense.

If indeed soil permeability has the dominant effect on index scores, we can use this information to guide management strategy. This study suggests that in areas of more permeable soil, management efforts should focus on farming practices, but in areas with less permeable soil, management efforts should focus on industrial practices. Coupling GIS watershed information with diatom index scores as done in this study can be a powerful tool for discovering the links between the watershed and the near-shore waters, separating the anthropogenic from non-anthropogenic stressors, and guiding appropriate management decisions.

This diatom index is closely linked to the TP inference model upon which it is based; therefore, in practice all the methodological considerations described in Reavie et al. (2006) also apply to this index. Specifically, the index has been developed primarily from surface sediment samples collected at approximately one meter depth. The index has not been tested on samples collected on different substrates or samples collected from different depths.

Interpretation of the index should be guided by local considerations. Regulatory agencies might base diatom index criteria on similarity to local reference conditions. The diatom index used conjointly with other bioindicators such as fish and macroinvertabrates will enable a more comprehensive assessment of the Great Lakes coastal ecosystems.

This diatom index, like the WA inference model from which it is derived, is shown to have good interpretive and assessment power. The site scores calculated with the index relate well with watershed characteristics, demonstrating that this diatom index is sensitive to watershed disturbance. The index scores are easily calculated on a spreadsheet and can be used in parametric analyses. The diatom performance index scores can be easier to communicate than results of mathematical models or narrative summaries of species assemblages. It can more appropriately describe biologic impairment and quantify biologic response than inferred TP estimates. The diatom performance index can be a powerful tool for analyzing habitat quality in the Great Lakes and can communicate quantifiable diatom assemblage response to site and watershed-level disturbance.

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