2009

A Comparison and Validation of Four Aquatic Macrophyte-Based Lake Assessment Techniques

John Brittenham

A COMPARISON AND VALIDATION OF FOUR AQUATIC MACROPHYTE-BASED LAKE ASSESSMENT TECHNIQUES

by

JOHN BRITTENHAM

A thesis submitted in partial fulfillment
of the requirements for the degree
MASTER OF ENVIRONMENTAL SCIENCE

Taylor University
Department of Earth and Environmental Science
Upland, Indiana

______________________, 2009

Approved by:

____
Paul E. Rothrock, PhD
Committee Chair
Professor of Environmental Science
Taylor University

____
Robert T. Reber, MS
Committee Member
Assoc. Professor of Environmental Science
Taylor University

____
Mitchell S. Alix, PhD
Outside Committee Member
Assistant Professor of Biology
Purdue University North Central

____
Edwin R. Squiers, PhD
MES Director
Graduate Program Director
Taylor University

____
Connie D. Lightfoot, PhD.
Dean
School of Professional and Graduate Studies
Taylor University

Abstract

Lake macrophyte assemblages in northeast Indiana were examined to compare the ability of four aquatic macrophyte-based lake assessment techniques to detect lake quality using two independent measures of human disturbance and one measure of water quality. Study objectives were to test the relationship of the four lake assessment techniques to the three measures of human disturbance or water quality, test the relationship of the four lake assessment techniques to each other, and to determine which lake assessment technique was the most time and resource efficient. Lake vegetation was sampled using two techniques. The first was a rake-based, stratified, random sampling technique. The second was a modified relevé sampling approach with a modified Braun-Blanquet Cover Abundance Scale Method. The four aquatic macrophyte-based lake assessment indices investigated were the Aquatic Macrophyte Community Index (AMCI), the Plant Index of Biotic Integrity (PIBI), the Index of Aquatic Macrophyte Community Quality (IAMCQ), and the Floristic Quality Assessment (FQA). The two measures of human disturbance compared were the Lake Qualitative Habitat Evaluation Index (L-QHEI) and the Landscape Development Intensity Index (LDI). The measure of water quality was the Indiana Trophic State Index (ITSI). Additional investigations were made comparing the difference between FQA scores that included or excluded non-native species. The use of FQA scores weighted by species frequency or relative cover also was addressed. The two FQA scores, the Floristic Quality Index (FQI) and the Mean Coefficient of Conservatism (MC), were found to have the highest correlation to all three measures of human disturbance or water quality and were deemed best at assessing lake quality. AMCI and IAMCQ scores significantly correlated to L-QHEI and ITSI scores and were able to assess lake quality in northeast Indiana lakes. PIBI scores significantly correlated to L-QHEI and LDI scores, but were low enough to suggest recalibration of this index for lakes in northeast Indiana is needed. The use of non-native species in FQA calculations did not show a clear advantage over the use of only native species. Additionally, weighting MC and FQI scores by species frequency did not provide any advantages when using FQA scores based on AMCI sampling to assess lake quality. However, weighting MC and FQI scores by relative cover did improve correlations to the L-QHEI and ITSI when PIBI sampling was used. The PIBI sampling method was slightly faster than the AMCI method, but both were able to be done rapidly and resulted in similar assessments of lake quality.

Key words: Aquatic macrophyte, biological indicator, lake assessment, metrics, AMCI, FQA, IAMCQ, LDI, Lake QHEI, PIBI.

Introduction

The Clean Water Act's principal goal of maintaining and restoring the physical, chemical, and biological integrity of the nation's surface waters and the Environmental Protection Agency's policy of no net loss of wetlands has created a need for efficient waterbody assessment techniques (Rothrock et al., 2008). Efficient waterbody assessment requires techniques that are rapid, cost-effective, precise, and repeatable (Herricks and Schaeffer, 1985). Prior to the late 1980's, most states used chemical measurements to assess surface waters (Karr and Chu, 1999). At the end of that decade, the Environmental Protection Agency recommended that states adopt biological criteria for the assessment of water resources because chemical measurements alone were failing to predict the quality of the aquatic habitat (Karr, 1981). Therefore, the focus of aquatic ecosystem assessment shifted to detecting the biotic integrity of the nation's surface waters. Karr and Dudley (1981) define biotic integrity as "…the capability of supporting and maintaining a balanced integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region." This current focus on biotic integrity provides a perfect opportunity to combine effective resource management with intelligent conservation efforts (Rothrock et al., 2008).

Many biological techniques have been developed to fulfill the monitoring requirements of the Clean Water Act, though most focus on rivers, streams, and non-lacustrine wetlands (Fore et al., 2007). These assessment methods have primarily used information from fish, macoinvertebrate, microalgae, and most recently aquatic macrophyte assemblages for assessment purposes (Ferreira et al., 2005). Only recently have biological monitoring approaches been developed for lakes. Many of these approaches utilize aquatic macrophytes for assessment purposes (Nichols, 1999; Nichols et al., 2000; Alix, 2006; Alix and Scribailo, 2006; Rothrock et al., 2008). Aquatic macrophytes are well-suited as indicators of ecological integrity for many reasons: 1) aquatic macrophytes are an ubiquitous and important ecological component of freshwater ecosystems (Adams and Sand-Jensen, 1991; Nichols et al., 2000; Cronk and Fennessy, 2001; Dodds, 2002), 2) communities of aquatic macrophytes have many attributes (percentage of exotic, sensitive, and tolerant species, total number of species, maximum depth of plant growth, etc.) that can be quantified to indicate ecological conditions (Miller et al., 2006), 3) aquatic macrophytes are immobile and integrate the effects of successive physical, chemical, and biological changes in the surrounding aquatic environment (Adams and Sand-Jensen, 1991; Nichols and Vennie, 1991; Nichols et al., 2000; Miller et al., 2006), 4) methods for sampling aquatic macrophytes are currently established (Jessen et al., 1962; Deppe and Lathrop, 1992; Nichols et al., 2000; Rothrock et al., 2008), 5) identification of most families of aquatic macrophytes requires minimal training (Nichols et al., 2000; Miller et al., 2006; Fore et al., 2007), and 6) aquatic macrophyte sampling can be accomplished with minimal costs in a relatively short period of time (Fore et al., 2007). Efforts to develop lake assessment techniques based on aquatic macrophytes are being conducted principally for regulatory purposes (Nichols et al., 2000). They also can be used for other reasons, such as: 1) identifying an aquatic resource's biotic potential, 2) preparing management plans and setting priorities for efforts to manage aquatic macrophytes, 3) reporting the results of management efforts, 4) educating and creating awareness among aquatic resource users, and 5) creating a means to study ecological trends, especially long-term changes a lake's littoral zone or aquatic macrophyte communities (Nichols et al., 2000).

Few lake assessment techniques have been developed using aquatic macrophytes, and they have been implemented in relatively limited geographic areas. Most of these lake assessment techniques have been developed using data collected from selected locations in the Great Lakes Region. Four indices currently being used for lake assessment purposes are: the Floristic Quality Assessment (Alix and Scribailo, 1998, 2006; Nichols, 1999; Alix, 2006), the Aquatic Macrophyte Community Index (Nichols et al., 2000), the Plant Index of Biotic Integrity (Rothrock et al., 2008), and the Index of Aquatic Macrophyte Community Quality (Alix, 2006).

The Floristic Quality Assessment (FQA) is the oldest of the four indices and has been recently adapted to lake settings (Alix and Scribailo, 1998, 2006; Nichols, 1999; Alix, 2006). Originally designed to assess the biotic quality of plant communities in the Chicago region of Illinois, the FQA is a rapid assessment technique that assigns each plant species a coefficient of conservatism (C value). C values indicate the likelihood that a plant species will be found in an area that is undisturbed by human actions (Swink and Wilhelm, 1994; Nichols, 1999; Rothrock, 2004). Swink and Wilhelm (1979, 1994) employed only native species in the development of the FQA; however, recent workers have implemented non-native species in FQA calculations (Taft et al., 1997; Alix and Scribailo, 1998; 2006, Fennessy et al., 1998; Rothrock, 2004; Rothrock and Homoya, 2005; Alix, 2006; Bourdaghs et al., 2006a). Despite this current trend, little work has been done to evaluate what effects the inclusion of non-native species will have on FQA calculations for lake assessment purposes (Alix and Scribailo, 2006).

Another lake assessment technique that utilizes aquatic macrophytes is the Aquatic Macrophyte Community Index (AMCI). This rapid lake assessment method was developed by Nichols et al. (2000) and was used to determine the biological quality of aquatic macrophyte communities in Wisconsin lakes. An estimated 365 lake surveys conducted over several years throughout Wisconsin were used to calibrate this index. While the AMCI worked well to quantify plant community quality throughout the state of Wisconsin, the effectiveness of this approach in other states has yet to be evaluated.

A more recent utilization of aquatic macrophytes in rapid lake quality assessment is the Plant Index of Biotic Integrity (PIBI) which was developed to assess the biotic integrity of lacustrine wetlands in northwest Indiana (Rothrock et al., 2008) and is a modified version of a previous PIBI used to assess riverine and palustrine wetlands along the southern end of Lake Michigan (Simon et al., 2001; Rothrock and Simon, 2006). Both PIBIs were modeled after the original index of biotic integrity (IBI) created by Karr (1981) to assess stream quality using fish communities. By analyzing eleven different metrics of a lake's plant community, the lacustrine PIBI evaluates important ecological attributes of plant assemblages (Rothrock et al., 2008). Sixty-five natural lakes in northwest Indiana were used to calibrate the lacustrine PIBI.

The fourth aquatic macrophyte-based lake assessment technique is the Index of Aquatic Macrophyte Community Quality (IAMCQ). This multimetric index was developed by Alix (2006) to assess the quality of aquatic macrophyte communities within natural lakes of Indiana. The IAMCQ was a modification and combination of the best metrics from both the AMCI (Nichols et al., 2000) and the PIBI (Simon et al., 2001). Twenty lakes spread across the northern portion of Indiana were used in the calibration of this technique. The objectives of the IAMCQ are: 1) to provide land managers, ecologists, and stewards with an additional tool to track long-term changes in littoral zone habitats, 2) to aid in the planning and monitoring of aquatic plant management practices, and 3) to evaluate efforts in lake restoration (Alix, 2006). Unlike the previously mentioned indices, the IAMCQ was not designed to be a rapid assessment method. This index uses intensive in-lake sampling based on SCUBA or snorkeling equipment to sample aquatic macrophytes. Additionally, Alix (2006) assigned C values to all species of the Characeae family of macrophytic algae found within Indiana and used individual species of the Characeae family in metric calculations. In comparison, the PIBI and AMCI identified members of the Characeae family to the genus level and all members of a genus were combined and recorded as a single taxon in metric calculations.

The FQA, AMCI, PIBI, and IAMCQ were created for states within the Great Lakes Region. These indices were calibrated for specific areas and have not been calibrated to assess lake quality in other parts of the Midwest. The purpose of this study was to test the ability of the four lake assessment techniques to assess lake quality in northeast Indiana lakes. To accomplish this, the four techniques were compared to two independent measures of human disturbance, the Lake Qualitative Habitat Evaluation Index (L-QHEI) and the Landscape Development Intensity Index (LDI), and one measure of lake water quality, the Indiana Trophic State Index (ITSI). Additionally, the similarity between the results of the lake assessment methods was compared and the technique that was most time and resource-efficient was determined.

Methods

Study Site Selection

Sixteen lakes in northeast Indiana (LaGrange, Noble, Steuben, and Whitley Counties) were selected for the study (Fig. 1; Table 1). Best professional judgment was used to assess the quality of each lake *a priori* based on aerial photographs and Indiana Trophic State Index (ITSI) scores

(Jones and Medrano, 2006). Lakes were chosen to ensure that a wide range of lake quality and morphometry was represented. This was done to confirm that the aquatic macrophyte-based indices would function over a wide range of human disturbance levels. Lakes ranged in size from 9 ha to 125 ha (mean lake size = 50 ha). All lakes were located within the Northern Lakes Natural Area (Homoya et al., 1985) and the underlying geologic parent material is principally glacial till and outwash (Fleming et al., 1995).

Sampling methodology

Each of the sixteen lakes was sampled twice between July 1st and August 24th 2008. On the first visit, lakes were sampled using a modification of techniques described in Nichols et al. (2000). This method utilizes a stratified, random sampling technique with sampling points randomly distributed around each lake *a priori* using GIS technology. A sampling point consisted of a two meter diameter circle divided into quadrants. Sampling points were assigned to each lake by means of a digital copy of each lake's bathymetric map, created by the Indiana DNR, Division of Water, (http://www.sportsmansconnection.com). These maps were georeferenced to orthophotograph quarter-quads downloaded from Indiana University's Spatial Data Portal (http://www.indiana.edu/~gisdata/) using ArcView™ version 9.2 GIS software from ESRI®. The perimeter of each lake was traced (digitized) using ArcMap™, and polygons were created as feature classes in a geodatabase. Within a lake polygon, separate polygons were created for each five-foot contour interval up to 25 feet in depth. Random sampling points were generated for each five-foot depth class using the random point generator feature of Hawth's Analysis Tools for ArcGIS® (Beyer, 2004). The number of sampling points for each lake and its individual depth classes was determined from the Indiana DNR's Tier II Aquatic Vegetation Survey Protocol (Indiana Division of Fish and Wildlife, 2007). This protocol assigns a number of sampling points to each five-foot depth class based on a lake's size and Indiana Trophic State Index score. The sampling points were then downloaded into a Magellan® Mobile Mapper CX GPS unit using ArcPad™ 7.1 from ESRI®. A GPS unit and a 16 foot aluminum boat were used to navigate to each sampling point. If the sampling point was located at a depth that did not match the *a priori* assigned depth, the boat was moved directly perpendicular to the closest shoreline until the appropriate depth was reached. Once at a point, the boat was anchored using a front and rear anchor, with the front end of the boat directly over the sampling point and a sampling rake was thrown from the tip of the boat four times to sample the four quadrants. The sampling rake used was a two-headed garden rake attached to a braided polyester rope (Indiana Division of Fish and Wildlife, 2007). The presence of individual aquatic macrophyte species was recorded at each sampling point. All aquatic macrophytes were identified in the field using appropriate manuals (Voss, 1972; Gleason and Cronquist, 1995; Crow and Hellquist, 2000a,b; Mohlenbrock, 2002). Unknowns were taken to the laboratory for identification. After identification, they were added to the Taylor University Herbarium. Plant nomenclature follows Rothrock (2004) which is based upon the Flora of North America and the Biota of North America database. Taxonomic treatment of Characeae follows Daily (1953) with nomenclatural revisions where necessary (e.g., see Wood, 1965).

On the second visit, lakes were sampled using PIBI sampling outlined in Rothrock et al. (2008). This technique is a modified relevé sampling approach with a modification of the Braun-Blanquet Cover Abundance Scale Method of estimating percent cover (Mueller-Dombois and Ellenberg, 1974). Five hundred meters of shoreline were surveyed from a boat and overall abundance ratings were assigned to each species encountered. Lakes greater than 100 ha received four 500 meter sites, while lakes less than 100 ha were sampled using two 500 meter sites. Adams Lake in LaGrange County was the only lake in the study that was sampled using four 500 meter sites. Half of each lake's samples were conducted in areas with the least amount of anthropocentric disturbance along the shoreline and littoral zone (Rothrock et al., 2008). The other half of samples were located in areas that represented the “average” littoral vegetation. This sampling method is designed to capture the overall range of aquatic vegetation for assessment purposes (P. Simon, personal communication, 2008). A Magellan® Mobile Mapper CX and ArcPad™ 7.1 software were used to measure each 500 meter sample. Abundance ratings were determined by the occurrence of each plant species in the 500 meter sample using the following scale: 1 = observed, only one individual of a species was found; 2 = rare, a plant species was found two to four times; 3 = rare/common, a species was observed more than four times, but was not a common component of the plant community at the site; 4 = common, a species was easily located at a site; 5 = very common, a species was slightly dominant and comprised up to 25% of the site; and 6 = abundant, a species comprised from 25% to almost 100% of the plant community. A second modified Braun-Blanquet Cover Abundance Scale Method was used to calculate FQA scores weighted by cover (Bourdaghs et al., 2006a). In this scale, 1 = <1%, 2 = 1 to <5%, 3 = 5 to <25%, 4 = 25 to <50%, 5 = 50 to <75%, and 6 = 75 to 100% coverage. Prior to data analysis, cover classes were converted to the mid-point percent cover of each class. Plant species were recorded to the maximum depth of plant growth and on shore up to 4 m from the water’s edge or until upland vegetation became dominant. If the identity of submergent aquatic macrophytes could not be obtained from visual observations, the rake used in the AMCI procedure was deployed to collect the vegetation. Occasional stops also were made along the shoreline, and closer inspections of unidentified plant specimens were made from land.

Index Calculations

AMCI

The Aquatic Macrophyte Community Index (AMCI) was determined from data collected during the first visit to each lake. Using frequency of occurrence for each species encountered, seven metrics were calculated (Table 2) as outlined in Nichols et al. (2000). Species were considered sensitive if they had a C value from 8 to 10 (Rothrock, 2004). Exotic species designations were described in Rothrock (2004). All species of the genus *Chara* were combined into one group and only recorded as a single taxon (Nichols et al., 2000). Each metric had been previously calibrated from 1 to 10 for lakes throughout Wisconsin (Nichols et al., 2000). Low scores represented lower plant community quality and higher scores represented increased plant community quality. Metric scores from the 16 lakes sampled in this study used the same 1 to 10 values listed in Nichols et al. (2000). All metric values were summed together to give an overall index score for each lake and scores could theoretically range from 7-70.

PIBI

Plant Index of Biotic Integrity (PIBI) scores were calculated using data from the second visit to each lake. Visual estimates of abundance were used to score eleven metrics (Table 2) according to Rothrock et al. (2008). Sensitive and tolerant species had C values ranging from 8 to 10 and 0 to 2 respectively. All C values and designations of obligate and facultative wetland, woody, and exotic used in the PIBI were found in Rothrock (2004). Pioneer species designations followed Rothrock et al. (2008). Any species encountered in this study that were not previously listed as pioneer/non-pioneer in Rothrock et al. (2008) were given pioneer/non-pioneer classifications based on best professional judgment. All species of the genus *Chara* were identified to the genus level and recorded as a single taxon. Rothrock et al. (2008) had previously scaled each metric with the following scale: 1 (low), 3, or 5 (high). The metric values from the 16 lakes used in this study utilized the same scaled values to calculate PIBI scores. Potential PIBI scores could range between 11 and 55. The index scores for each 500 meter stretch (2 or 4 per lake) were summed together and divided by the total number of 500 meter stretches sampled to produce the final (mean) PIBI score for that lake.

IAMCQ

Index of Aquatic Macrophyte Community Quality (IAMCQ) scores were calculated using data from rake-based sampling conducted during the initial visit to each lake. The IAMCQ is determined by twelve metrics (Table 2) as outlined in Alix (2006). IAMCQ metrics utilize the C values reported in Alix (2006). Aquatic macrophytes were considered tolerant if they attained C values from 0 to 2. Taxa ascribed C values of 8 to 10 were considered sensitive. Individual metrics were previously calibrated by Alix (2006) and scaled scores of 1 (low), 3, or 5 (high) were developed for each metric. Metric scores developed in this study used equivalent scaled values. Total IAMCQ scores potentially could range from 12-60.

FQA

The Floristic Quality Assessment (FQA) used in this study contains two components: the mean coefficient of conservatism (MC) and Floristic Quality Index (FQI) as outlined in Swink and Wilhelm (1994). C values were based on the values listed in Rothrock (2004). MC and FQI scores were calculated with only native species (nMC and nFQI) or with total species, both native and non-native (tMC and tFQI). When non-native species were included in the calculations, they received a C value of 0 (Wilhelm and Masters 2000). Each lake in this study received two sets of FQA scores (Table 3). One set of FQA scores (MC_{AMCI} and FQI_{AMCI}) was calculated using the species list from AMCI sampling. The second set of FQA scores (MC_{PIBI} and FQI_{PIBI}) was calculated using the species lists from PIBI sampling. Each 500 meter stretch recorded in PIBI sampling received a MC_{PIBI} and FQI_{PIBI} score. These 500 meter stretch scores were averaged to give a final MC_{PIBI} and FQI_{PIBI} score for each lake. FQA scores were determined by the *Floristic Quality Assessment Computer Programs*, developed by Wilhelm and Masters (2000), and the inventory approach to FQA calculations was used.

Recent efforts have begun to use relative frequency or cover in FQA calculations (Cohen et al., 2004; Alix and Scribailo, 2006; Bourdaghs et al., 2006a; Bowles and Jones, 2006). The FQA calculations based on AMCI sampling were weighted by relative frequency in the following manner. For each lake, the C value of each species was multiplied by the relative frequency of that species. These values were summed together to obtain a weighted MC ($wtMC_{AMCI}$) for each lake. Total species were used in $wtMC_{AMCI}$ scores. FQI_{AMCI} scores were re-calculated using the $wtMC_{AMCI}$ to acquire a weighted FQI ($wtFQI_{AMCI}$) score for each lake. FQA scores based on PIBI sampling ($wtMC_{PIBI}$ and $wtFQI_{PIBI}$) were weighted by relative cover in the same manner, except relative frequency was replaced by relative cover. In order to assess the impact of non-native species on native-only FQA metric scores, Alix and Scribailo (2006) created a method that incorporates the relative frequency of non-native species into the FQA metric calculations. The impact of non-native species (T) was calculated by the following equation: $T = (\sum R_{nn}) * FQI_{native}$ ($\sum R_{nn}$ is the sum of the frequencies of non-native aquatic taxa, and FQI_{native} is the FQI calculated without the inclusion of non-native taxa) (Alix and Scribailo, 2006). The value of T can be used to calculate the FQI with non-native impact (FQI_{nni}) as follows: $FQI_{nni} = FQI_{native} - T$. This approach was used to calculate FQI_{nni} that incorporated the impact of non-native species based on the AMCI sampling data.

Measures of Human Disturbance

L-QHEI

The Lake Qualitative Habitat Evaluation Index (L-QHEI) was developed by the Ohio Environmental Protection Agency to detect human-caused changes to near shore macro-habitats along Lake Erie (Thoma, 2006). The L-QHEI was previously used as a measure of human disturbance to calibrate the PIBI for inland lakes in northwest Indiana (Rothrock et al., 2008). The

L-QHEI consists of five metrics based on shoreline habitat quality: 1) substrate type/quality, 2) cover type, 3) shoreline morphology, 4) riparian zone and bank erosion, and 5) aquatic vegetation quality. L-QHEI scores were calculated at each lake during the first visit. The entire shoreline of the lake was assessed and metric scores recorded on an L-QHEI field sheet. Scores could theoretically range between 0 and 110 (low scores represented low habitat quality/high human disturbance and high scores indicated high habitat quality/little human disturbance).

LDI

The Landscape Development Intensity Index (LDI) was created as an index of human disturbance for watershed assessment in Florida (Brown and Vivas, 2005). The LDI also has been used as a measure of human disturbance for wetlands in Ohio (Mack, 2006) and Minnesota (Bourdaghs et al., 2006b) and in Florida lakes (Fore et al., 2007). The LDI is a weighted land use index based on the non-renewable energy required to maintain specific land uses. Values are assigned to each type of land use based on the amount of emergy they require. Emergy is energy that has been corrected for different qualities, and its unit of measure is the solar emergy joule (Brown and Vivas, 2005). Emergies used in calculating the LDI are non-renewable energies including electricity, fuels, fertilizers, pesticides, and water, both public water supply and irrigation (Brown and Vivas, 2005). To calculate LDI scores, land use values are multiplied by the percent of area surrounding the lake that are devoted to each land use. A buffer of 50 meters was used in calculating LDI scores for this study. Initially, a buffer of 100 meters was utilized to calculate LDI scores (Brown and Vivas, 2005; Fore et al., 2007). However, the use of a 50 meter buffer resulted in higher correlations to the aquatic macrophyte-based indices and was therefore employed in this study. The buffer was constructed using ArcView™ version 9.2 GIS software (ESRI). Land use data (raster form) from the National Land Cover Dataset (NLCD) 2001 was downloaded from the Indiana Spatial Data Portal (http://www.indiana.edu/~gisdata/) and imported into ArcMap™.

ArcMap™ Spatial Analyst was used to capture NLCD raster data found within the 50 meter buffer surrounding each lake. The percentage of land use for each land use type was calculated. Final LDI scores were the sum of all multiplications between the percentage of each land use type and the land use values listed in Brown and Vivas (2005).

Measure of Lake Quality

ITSI

The Indiana Trophic State Index (ITSI) was used as the independent measure of lake quality. The most recent ITSI scores for all lakes were obtained from the Indiana Lake Water Quality Assessment Report for 1999 - 2003 (Jones and Medrano, 2006) or from unpublished ITSI scores obtained from Bill Jones (personal communication, 2008) at Indiana University's School of Public and Environmental Affairs. All ITSI scores were based on sampling conducted between the summers of 2002 and 2008. An ITSI score was not available for Failing Lake. The ITSI is composed of ten metrics based on physical, chemical, and biological components of each lake. The physical components were secchi disk transparency and light transmission; the chemical components were soluble reactive phosphorus, total phosphorus, nitrate, ammonia, organic nitrogen, and dissolved oxygen; and the biological components were plankton and chlorophyll *a* (Jones and Medrano, 2006).

Results

Species richness of lake macrophyte assemblages

The lakes of northeastern Indiana support a diverse community of aquatic macrophytes. The 16 lakes sampled in this study contained 77 families, 146 genera and 240 species of obligate and facultative macrophytes. The largest families included Cyperaceae (27 species), Asteraceae (17 species), Poaceae (16 species), and Potamogetonaceae (14 species). Of the 240 species, 40 were classified as woody, 32 submergent, eight floating-leaved, 160 emergent, 22 non-native, 69 tolerant, and 42 sensitive. Twelve species in this study (Table 4) were listed on Indiana’s Heritage Data Base List of endangered, threatened, and rare vascular plants of Indiana (Indiana Division of Nature Preserves, 2007). These species were all encountered during PIBI sampling. The greatest number of species recorded in one lake using PIBI sampling was 110 (Crooked and Latta Lake) and the least number was 53 (Tamarack Lake) as shown in Table 5. The greatest number of species recorded using AMCI sampling was 29 (Crooked Lake) and the least number was 4 (Waldron Lake). AMCI sampling encountered 17 families, 23 genera, and 47 species. The largest families were Potamogetonaceae (12), Najadaceae (4), and Lemnaceae (4). Twenty-eight submergent, eight floating-leaved, 11 emergent, seven tolerant, 12 sensitive, and five non-native species were recorded utilizing the AMCI sampling methodology.

Aquatic macrophyte-based lake assessment score evaluations

To determine the effectiveness of the four aquatic macrophyte-based lake assessment techniques, each of the techniques was compared to measures of human disturbance or water quality. Index response hypotheses were made *a priori* for each index as compared to the two measures of human disturbance and one measure of water quality. The aquatic macrophyte-based lake assessment index scores were hypothesized as having a positive correlation to L-QHEI scores and a negative correlation to LDI and ITSI scores. When compared to each other, the aquatic macrophyte-based lake assessment indices scores were all hypothesized to attain a positive correlation.

All data used in the following statistical tests passed normality assumptions. Pearson's correlations were run between each aquatic macrophyte-based lake assessment technique and each of the human disturbance gradients (L-QHEI and LDI) and the measure of water quality (ITSI) as listed in Tables 6, 7, and 8. FQA calculations used in index performance comparisons included native species only because they had the highest correlations to all three human disturbance or water quality measures. Each sampling method (AMCI and PIBI) had two corresponding FQA scores (MC and FQI) calculated. Each FQA score was compared separately to the three human disturbance or water quality measures, which resulted in four FQA metric scores (nMC_{AMCI}, nMC_{PIBI}, nFQ_{IAMCI}, and $nFQI_{PIBI}$) for index comparisons. All seven macrophyte-based assessment scores were significantly correlated to the L-QHEI (r = 0.546-0.794, all p values ≤0.015). The nMC_{PIBI} (r = 0.794, p <0.001) and nMC_{AMCI} (r = 0.770, p <0.001) produced the strongest correlations with the L-QHEI. Six of the index scores were significantly correlated to the ITSI (r = −0.453-0.689, all p values ≤0.021). The PIBI was the only technique that did not show a significant correlation to the ITSI. IAMCQ and AMCI scores (r = −0.689, p = 0.003 and r = −0.682, p = 0.003 respectively) produced the strongest relationship with the ITSI scores. Four index scores ($nFQI_{PIBI,}$ $nMC_{PIBI,}$ $nMC_{AMCI,}$ and PIBI) had a significant, but weak, correlation with the LDI index (r = −0.478-0.578, all p values ≤0.031). AMCI, IAMCQ, and $nFQI_{AMCI}$ scores failed to produce significant correlations with the LDI. Scores of the nMC_{AMCI} had the strongest correlation to LDI scores (r = −0.578, p = 0.01).

Six variations of MC scores (Table 7) and seven variations of FQI scores (Table 8) were calculated using data from AMCI and PIBI sampling. Nearly all the FQA metric variations had strong to moderately strong correlations to L-QHEI scores (r = 0.664-0.825, all p values ≤0.003). The $wtMC_{PIBI}$, nMC_{PIBI}, and the $wtFQI_{PIBI}$ had the strongest correlations to L-QHEI scores (r = 0.825, p <0.001; r = 0.794, p <0.001; and r = 0.784, p <0.001 respectively). The $wtFQI_{AMCI}$ was the only index score that did not produce a significant correlation to L-QHEI scores. Ten of the 13 FQA variations had significant correlations to the ITSI, though strength varied (r = −0.453-0.844, all p values ≤0.045). Scores from the $wtMC_{PIBI}$ and $wtFQI_{PIBI}$ had the highest correlation to ITSI scores (r = −0.844, p <0.001 and r = −0.733, p <0.001, respectively). Six FQA metric scores (nMC_{AMCI}, nMC_{PIBI}, tMC_{PIBI}, $wtMC_{PIBI}$, $nFQI_{PIBI}$, and $tFQI_{PIBI}$) had significant, but weak, correlations to LDI index scores (r = −0.478-0.588, all p values ≤0.031). One FQA metric, the $wtFQI_{AMCI}$, did not have a significant correlation to L-QHEI, ITSI, or LDI scores. Five FQA metrics (nMC_{AMCI}, nMC_{PIBI}, tMC_{PIBI}, $wtMC_{PIBI}$, and $nFQI_{PIBI}$) were significantly correlated to all three measures of human disturbance and water quality.

Nearly all aquatic macrophyte-based lake assessment scores were significantly correlated to each other (r = 0.442-0.912, all p values ≤0.044), except for the $nFQI_{AMCI}$ versus the $nFQI_{PIBI}$ (Table 9). The strongest correlations were between the AMCI versus the IAMCQ (r = 0.912, p <0.001) and the nMC_{AMCI} versus the $wtMC_{AMCI}$ (r = 0.889, p <0.001). Some correlations, though significant, were weak to moderate. They were: PIBI vs AMCI (r = 0.598, p = 0.007), PIBI vs IAMCQ (r = 0.569, p = 0.011), nMC_{AMCI} vs IAMCQ (r = 0.521, p = 0.02), and $nFQI_{AMCI}$ vs $wtFQI_{AMCI}$ (r = 0.442, p = 0.044).

Discussion

Multiple studies have created indices to assess the quality of lake macrophyte communities (Nichols et al., 2000; Alix, 2006; Fore et al., 2007; Rothrock et al., 2008). The use of these indices removes investigator bias by utilizing characteristics, termed “metrics”, to provide descriptions of a lake’s community integrity (Simon et al., 2001). The techniques used to assess aquatic macrophytes in these indices are rapid and allow for a quick and effective assessment of a lake’s biotic community (Fore et al., 2007). In this study, aquatic macrophye-based indices were shown to be significantly, and in some cases strongly, correlated with measures of human disturbance or water quality. These results are consistent with other studies that have shown indices derived from aquatic macrophytes can successfully assess the biotic integrity of lake ecosystems (Nichols et al., 2000; Fore et al., 2007; Rothrock, 2008). Of the four aquatic macrophyte-based lake assessment techniques, the FQA scores (FQI and MC) demonstrated the greatest ability to detect lake quality in relation to anthropocentric disturbance in northeast Indiana lakes. In particular MC scores of both AMCI and PIBI sampling produced the highest correlations to all three measures of human disturbance or water quality (Table 7). FQI scores based on PIBI sampling also had significant correlations to all three human disturbance or water quality measures. Other studies have found the FQI and MC to be effective indicators of biotic integrity in wetlands (Fennessy et al., 1998; Mack, 2001, 2007; Lopez and Fennessy, 2002; Albert and Minc, 2004; Bourdaghs et al., 2006a; Miller and Wardrop, 2006). Miller and Wardrop (2006) and Bourdaghs et al. (2006a) suggest that FQI and MC scores alone can be used to indicate biotic conditions of wetland ecosystems. Results from this study support this idea. Additionally, MC scores appear to be the best at assessing lake quality and could be used alone to assess the biotic quality of a lake. However, Bernthal (2003) cautions that the univariate FQA scores should not be used alone for regulatory decisions because FQA scores alone may not be able to detect a wide range of stresses and disturbances at a site. Additional aquatic macrophyte metrics, such as those found within the AMCI, could provide a more comprehensive assessment of conditions and disturbances within a lake for regulatory purposes (Bernthal, 2003).

The inclusion of non-native species into MC and FQI calculations had a minimal impact on the FQA's ability to indicate lake quality. In four cases ($tFQI_{PIBI}$ vs. LDI, tMC_{PIBI} vs. LDI, FQI_{nni} vs. L-QHEI, and FQI_{nni} vs. ITSI) the use of non-native species increased the correlation between un-weighted FQA scores and L-QHEI, LDI, or ITSI scores. Eleven of the 15 correlations between un-weighted FQA scores and L-QHEI, LDI, or ITSI scores decreased when non-natives were included (Table 7 and 8). The use of non-natives in FQA calculations shows no clear advantage when using FQA scores to detect lake quality measures. FQI_{AMCI} scores weighted by species frequencies ($wtFQI_{AMCI}$) had no significant correlation with any of the three lake quality measures. Weighted MC_{AMCI} values had a more complex relationship (Table 7 and 8). Weighting the MC_{AMCI} does not demonstrate a clear advantage over using only natives to calculate FQA scores. Using percent cover to weight FQA scores based on PIBI sampling did demonstrate an advantage over using un-weighted FQA scores. Both $wtMC_{PIBI}$ and $wtFQI_{PIBI}$ had the highest correlations to L-QHEI and ITSI scores. Because un-weighted FQA scores are easier to calculate, it would be better to use un-weighted FQA scores if the FQA is used to assess lake quality based on AMCI sampling. However, if PIBI sampling methods are used, then FQA scores should be weighted by species coverage to best capture a lake's biotic integrity.

Of the three multimetric indices used in this study, the AMCI generated the highest correlation to the L-QHEI ($r = 0.749$, $p < 0.001$) and nearly the highest correlation to the ITSI ($r = -0.682$, $p = 0.003$). Though this index was created for Wisconsin lakes, it appears to be effective in detecting lake quality measures within northeast Indiana lakes. This index was calibrated for a large range of lakes throughout the entire state of Wisconsin. This range of Wisconsin lakes produced an index that also could be incorporated into current sampling actions in northeast Indiana. Only one metric used in the AMCI (percent of littoral zone vegetated) was in obvious need of calibration on northeast Indiana lakes. This metric received a score of 10 for all 16 lakes. A potential weakness of the AMCI was its inability to detect decreases in lake quality caused by the surrounding detrimental landscape usage as expressed through the LDI. However, as will be discussed later, LDI scores did not show a strong correlation with any of the macrophyte-based lake assessment techniques. Lake monitoring with the AMCI could be complimented by running nMC_{AMCI} calculations. The nMC_{AMCI} scores could help assess the impact of disturbances caused by the land usage surrounding a lake. The state of Indiana currently requires that lakes be sampled using rake-based methods very similar to the AMCI methodology when lake management actions are proposed (Indiana Division of Fish and Wildlife, 2007). The AMCI and calculations of nMC_{AMCI} could easily be incorporated into this current sampling strategy to assess lake quality in northeast Indiana. As suggested by Nichols et al., (2000), additional studies should be conducted to see if AMCI scores need to be recalibrated for statewide use within Indiana or other areas outside of Wisconsin.

While FQA metric calculations based on PIBI sampling correlated well with lake quality measures, the PIBI itself did not demonstrate the same strength of correlation. Only two correlations where significant (PIBI versus L-QHEI and PIBI versus LDI), but both were weak. PIBI scores from Rothrock et al. (2008) had a stronger correlation with L-QHEI scores ($r = 0.825$, $p < 0.001$) than did PIBI scores in this study ($r = 0.546$, $p = 0.0145$). However, caution should be exercised in comparing these results because Rothrock et al. (2008) used Spearman's correlations were as this study used Pearson's correlations. Preliminary review of PIBI metric scores indicates that nine metrics showed significant correlation to at least one of the three measures of human disturbance or water quality; however, most correlations were weak. The only metrics that demonstrated a strong correlation to at least one of the disturbance or water quality measures were total number of submergent species, total number of sensitive species, and relative abundance of exotic species. The lack of strong correlation to the disturbance and water quality measures suggests that the PIBI is not as effective in predicting biotic integrity in northeast Indiana lakes in its current state and needs to be recalibrated for this area.

Scores of both the AMCI ($r = -0.099$, $p = 0.358$) and the IAMCQ ($r = 0.095$, $p = 0.364$) showed no ability to indicate human stresses placed on a lake as assessed by the LDI (Table 6). In

Florida lakes, Fore et al. (2007) found higher correlations between their multimetric plant index and LDI scores using Spearman's correlations ($r = 0.62$, $p < 0.01$). In comparison, FQI and MC scores versus LDI scores in Fore et al. (2007) had similar (though slightly higher) correlations compared to FQI and MC scores versus LDI scores in this study. Multiple possibilities exist as to why LDI scores did not have higher correlations with PIBI, AMCI, and IAMCQ scores in this study. First, there are some questions as to whether LDI scores can adequately capture human disturbance in the Midwest for use in biotic index calibration. Both Mack (2006) and Bourdaghs et al. (2006b) reported that local factors in the immediate area surrounding the wetlands in their studies could "trump" the influence of the surrounding landscape and have a greater impact on the aquatic ecosystem than LDI scores reported. This may be the reason why in this study LDI scores had higher correlations to the macrophyte-based lake assessment index scores in a 50 meter buffer compared to a 100 meter buffer. Bourdaghs et al. (2006b) observed that LDI scores calculated around wetlands in Minnesota were significantly, but not strongly, correlated to various IBI's that had been previous calibrated within the area. Fennessy et al. (2007) reported that LDI scores were not highly correlated with Vegetative Index of Biotic Integrity (VIBI) scores for wetlands in northeast Ohio. The LDI has shown potential as a measure of human disturbance for biotic integrity index calibration, but the correlations typically are expected to be lower than other measures of human disturbance (Bourdaghs et al., 2006b). There are several possible causes of the poor LDI performance. First, LDI scores used in this study were calculated with data based on satellite imagery from the middle to late 1990s (Homer et al., 2004). Land use changes (the construction of new or larger homes near the shoreline, land being put into or taken out of agriculture use, etc.) could have been made between the mid-1990s and the summer of 2008 that would affect lake quality. Second, the pixel size of the National Land Cover Dataset is 30 × 30 meters. This resolution is most likely too "coarse" to capture land use surrounding the lakes. Third, the buffer used to calculate LDI scores in this study may not be large enough to capture an adequate portion of the watershed that is contributing to lake quality conditions. Finally, the PIBI, AMCI, and IAMCQ may need to be recalibrated to assess the negative impact of land usage on lake quality.

The results of this study also suggest that the IAMCQ scores calculated using AMCI sampling had the ability to detect lake quality as measured by the L-QHEI and ITSI. In fact, IAMCQ scores had one of the strongest correlation with ITSI scores ($r = -0.689$, $p = 0.003$) indicating a relationship between the macrophyte-based index and water quality. However, the strong correlation between the AMCI and the IAMCQ ($r = 0.912$, $p < 0.001$) indicates that they are both detecting some of the same lake quality components. This is very likely because they share some of the same metrics. Six out of the seven AMCI metrics were adopted for use in the IAMCQ. One difference between the IAMCQ and the AMCI is the IAMCQ requires a higher degree of taxonomic ability because members of the Characeae family are identified to the species level. If rake-based sampling is used for lake quality assessments, the AMCI would be more straightforward and easier to use.

The sampling protocol used in the PIBI was faster on average than the AMCI sampling procedure. It took an average of 5 hours to complete sampling on a lake (mean lake size 50 ha) for the PIBI, while AMCI sampling took an average of 8.3 hours. Herricks and Schaeffer (1985) suggest that, all other attributes being equal, the method that is the most time and resource efficient would be preferable. Additionally, FQI and MC scores derived from PIBI sampling had stronger correlations, in general, to the measures of human disturbance or lake quality than did FQI and MC scores from AMCI sampling (Table 6, 7, and 8). PIBI sampling lists the presence of both in-lake and shoreline species and records many more species than AMCI sampling. Therefore, results from this study indicate that the fastest and arguably best way to get an assessment of overall lake quality is to sample each lake using PIBI sampling and then calculate $nFQI_{PIBI}$ and nMC_{PIBI} scores for each lake.

The AMCI sampling technique does offer several advantages over PIBI sampling. First, AMCI sampling encounters far fewer species than PIBI sampling (Table 5). Consequently, training practitioner in species recognition is more straightforward. Second, the AMCI is a multimetric index and should detect a wider range of environmental conditions than a univariate index (Miller and Wardrop, 2006). Another advantage of AMCI sampling is that a state wide protocol already exists in Indiana that could easily be modified to include the AMCI sampling methodology (Indiana Division of Fish and Wildlife, 2007). Results from this study suggest that both sampling methods show a similar ability to indicate lake quality. Therefore, the reason that an assessment is performed should dictate which sampling methodology is used.

In conducting this study, some areas of future research became apparent. First, similar studies utilizing a larger number of lakes over a wider geographic area could help demonstrate whether observations made in this study are applicable to a broader geographic range. It also would be useful to investigate the relationship between aquatic macrophyte-based indices and other measures of biotic integrity. A comparison to other ecological indicator species, such as fish and macroinvertebreates, would help determine the extent to which aquatic macrophytes can detect ecosystem degradation. Further research also could be conducted to see if updating and improving LDI data would affect correlation results between LDI scores and the aquatic macrophyte-based lake assessment index scores. To capture the most resent land use types surrounding each lake, land use could be traced (digitized) in GIS using the most recent aerial photographs available for each lake. Another area of research could be investigating how much of a lake’s watershed must be assessed to capture the effects of land use around a lake. In their validation of the multimetric Lake Vegetation Index (LVI), Fore et al. (2007) found a 100 meter buffer to be adequate in assessing the negative impact of land use on Florida lakes. Fennessy et al. (2007) reported that land use in buffers of 100 meters were more influential in determining wetland quality than buffers of 250, 500, 1000, 2000, or 4000 meters. However, they also reported that LDI scores alone did not correlate strongly with wetland quality in the Cuyahoga River watershed of Ohio. Further studies that evaluated the impact of land use types on lake quality using various buffer distances would help to answer this question. Finally, it did not escape the author's notice that the L-QHEI shows great potential as a stand alone indicator of lake quality. Not only did the L-QHEI have the strongest correlations to all aquatic macrophyte-based lake assessment techniques in this study (Table 6, 7, and 8), but it also had strong correlations to ITSI scores ($r = -0.775$, $p < 0.001$). Future research could be conducted to investigate the correlation of the L-QHEI to other components of aquatic quality in Indiana lakes and the applicability of the L-QHEI to a broader geographic range.

Conclusion

The four aquatic macrophyte-based lake assessment techniques varied in their ability to detect lake quality measures in northeast Indiana lakes. The univariate FQI and MC scores demonstrated the greatest ability to detect lake quality measures assessed by the L-QHEI, LDI, and ITSI. The calculation of FQA metrics is straight forward and provides a powerful lake assessment tool for aquatic resource managers and environmental monitoring agencies. Of the three multimetric indices, the AMCI had the highest correlation to L-QHEI and ITSI scores. Though created for Wisconsin lakes, the AMCI still successfully assessed lake quality measures in northeast Indiana. The use of AMCI scores in conjunction with MC scores based on AMCI sampling could provide a robust monitoring tool for northeast Indiana lakes. Because the IAMCQ had such strong correlation with the AMCI, requires more taxonomic knowledge to compute, and was originally calibrated using SCUBA or snorkeling sampling techniques, the AMCI would be a better choice for rapid lake assessment. The PIBI had significant correlations to L-QHEI and LDI scores, but both correlations were relatively low in comparison to scores from northwest Indiana. To be effectively used in northeast Indiana, the PIBI metrics should be recalibrated. The use of only native species in FQA metric calculations results in stronger correlations between the FQA metrics and L-QHEI, LDI, and ITSI scores in most comparisons. For lake quality assessment purposes, it appears advantageous to use native species only in FQA metrics. Weighting MC scores by species frequency either did not show an advantage over non-weighted scores or decreased the ability of FQA metric scores to assess lake quality measures using AMCI sampling. However, if PIBI sampling techniques are used, weighting the MC and FQI by relative cover appears to provide a better assessment of in-lake and immediate littoral zone quality as measured by the L-QHEI and ITSI. The fastest sampling method was that of the PIBI. Sampling both shoreline and in-lake vegetation using PIBI sampling and running weighted FQI and MC calculations on the data would be the most time and resource efficient way to assess lake quality in northeast Indiana lakes. Aquatic macrophytes continue to demonstrate the ability to indicate waterbody biotic integrity and their use in both multimetric and univariate lake quality indices should continue to be utilized and investigated.

Acknowledgments

The author thanks Paul Rothrock, Robert Reber, and Mitchell Alix for their help in all aspects of this project, from the initial design to final data analysis and manuscript review. Also, special thanks to Tom Simon and Stanley Nichols for experimental design and data analysis advice, Ken Constantine for statistical advice, Bill Jones for the most recent ITSI scores, Angela Sturdevant for her assistance in grant funding communications, Byron Getz and Steve Brittenham for the use of field sampling equipment, and my wife, Emily Brittenham, for her faithful assistance everyday this summer as we collected data. This project was funded primarily through a Lake and River Enhancement Grant from the Indiana Department of Natural Resources, Division of Fish and Wildlife. Although this study was funded by the IDNR, no official endorsement should be inferred.

References

Adams, M., Sand-Jensen, K., 1991. Ecology of submersed aquatic macrophytes. Aquatic Botany 41, 261-261.

Albert, D.A., Minc, L.D., 2004. Plants as regional indicators of Great Lakes coastal wetland health. Aquatic Ecosystem Health and Management 7, 233-247.

Alix MS. 2006. Indiana Lakes as a Model for the Use of Aquatic Macrophyte Community Information in the Development of Indexes for the Assessment of Lake Quality. Doctoral Dissertation, Purdue University Graduate School, 2006. p 223 Proquest No. AAT 3251579.

Alix, M. S., Scribailo R. W., 1998. Aquatic plant species diversity and floristic quality assessment of Saugany Lake, Indiana. Proceedings of the Indiana Academy of Sciences 107, 123-139.

Alix, M. S., Scribailo, R. W., 2006. The history and aquatic flora of Silver Lake, Porter County, Indiana, with comments on the adequacy of floristic quality assessment for lakes. Proceedings of the Indiana Academy of Sciences 115, 13-31.

Bernthal, T. W., 2003. Development of a floristic quality assessment methodology for Wisconsin. Final report to the U.S. Environmental Protection Agency Region V. Wetland Grant # CD975115-01-0, 18 pp.

Beyer, H. L., 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools.

Bourdaghs, M., Johnston, C.A., Regal, R.R., 2006a. Properties and performance of the floristic quality index in great lakes coastal wetlands. Wetlands 26, 718-735.

Bourdaghs, M., Campbell, D. E., Genet, J. A., Gernes, M. C., Brandt-Williams, S. L., 2006b. Development of the landscape development index as a wetland condition assessment tool. Final Report to U.S. E.P.A. (assistance number AW96569201-0).

Bowles, M., Jones, M., 2006. Testing the efficacy of species richness and floristic quality assessment of quality, temporal change, and fire effects in tallgrass prairie natural areas. Natural Areas Journal 26, 17-30.

Brown, M.T., Vivas, M.B., 2005. Landscape development index. Environmental Monitoring and Assessment 101, 289-309.

Cohen, M., Carstenn, S., Lane, C., 2004. Floristic quality indices for biotic assessment of depressional marsh condition in Florida. Ecological Applications 14, 784-794.

Cronk, J. K., Fennessy, M. S., 2001. Wetland Plants: Biology and Ecology. Lewis Publishers, Boca Raton, FL, USA, p. 462.

Crow, G.E., Hellquist, C.B., Fassett, N.C., 2000a. Aquatic and Wetland Plants of Northeastern North America, Volume 1: Pteridphytes, Gymnosperms, and Angiosperms: Dicotyledons. University of Wisconsin Press, Madison, WI, USA, p. 480.

Crow, G.E., Hellquist, C.B., Fassett, N.C., 2000b. Aquatic and Wetland Plants of Northeastern North America : Volume 2: Angiosperms: Monocotyledons. University of Wisconsin Press, Madison, WI, USA, p. 400.

Daily, F., 1953. The Characeae of Indiana. Butler University Botanical Studies 11, 5-49.

Deppe, E., Lathrop, R., 1992. A comparison of two rake sampling techniques for sampling aquatic macrophytes. Wisconsin Department of Natural Resources Research Management Findings No. 32. Madison, WI, USA.

Dodds, W. K., 2002. Freshwater Ecology: Concepts and Environmental Applications. Academic Press, San Diego, CA, USA. p. 592.

Fennessy, M.S., Geho, R., Elifritz, B., Lopez, R., 1998. Testing the floristic quality assessment index as a indicator of riparian wetland quality. Final Report to U.S. E.P.A. Ohio Environmental Protection Agency, Division of Surface Water, Columbus, OH, USA.

Fennessy, M., Mack J.J., Deimeke E., Sullivan M.T., Bishop J., Cohen M., Micacchion, M. Knapp M., 2007. Assessment of wetlands in the Cuyahoga River watershed of northeast Ohio. Ohio E.P.A. Technical Report WET/2007-4. Ohio Environmental Protection Agency, Division of Surface Water, Wetland Ecology Group, Columbus, OH, USA.

Ferreira, M.T., Rodriguez-Gonzalez, P.M., Aguiar, F.C., Albuquerque, A., 2005. Assessing biotic integrity in Iberian rivers: development of a multimetric plant index. Ecological Indicators 5, 137-149.

Fleming, A.H., Bonneau, P., Brown, S.E., Grove, G., Harper, D., Herring, W., Lewis, E.S., Moeller, A.J., Rupp, R.F., Steen, W.J., 1995. Atlas of hydrogeologic terrains and settings of Indiana. Indiana Geological Survey Open-file Report 94-17. Bloomington, IN, USA.

Fore, L.S., Frydenborg, R., Wellendorf, N., Espy, J., Frich, T., Whiting, D., Jackson, J., Patronis, J., 2007. Assessing the biological condition of Florida lakes: development of the lake vegetation index (LVI). Final Report to Florida Department of Environmental Protection. Tallahassee, FL, USA, http://ftp://ftp.dep.state.fl.us/pub/labs/assessment/sopdoc/lvi_final07.pdf.

Gleason, H. A., Cronquist, A., 1995. Manual of the Vascular Plants of Northeastern United States and Adjacent Canada. New York Botanical Garden, Bronx, NY, USA. p. 910.

Herricks, E.E., Schaeffer, D.J., 1985. Can we optimize biomonitoring? Environmental Management 9, 487-492.

Homer, C., Huang, C., Yang, L., Wylie, B., Coan, M., 2004. Development of a 2001 National Landcover Database for the United States. Photogrammetric Engineering and Remote Sensing 70, 829-40.

Homoya, M.A., Abrell, D. B., Aldrich, J. R., Post, T. W., 1985. Natural regions of Indiana. Proceedings of the Indiana Academy of Sciences 94, 245-68.

Indiana Division of Fish and Wildlife, 2007. Tier II aquatic vegetation survey protocol. Indiana Department of Natural Resources, Division Fish and Wildlife, Indianapolis, IN, USA, 30 pp.

Indiana Division of Nature Preserves, 2007. Endangered, threatened, and rare vascular plants of Indiana. http://www.in.gov/dnr/naturepreserve/files/etrplants.pdf.

Jessen, R., Lound, R., Minnesota Fish and Wildlife Surveys Unit, 1962. An evaluation of a survey technique for submerged aquatic plants. Minnesota Department of Conservation, Division of Game and Fish, Section of Research and Planning, Fish and Wildlife Surveys Unit, Game Investigational Reports No. 6. St. Paul, MN, USA, 10 pp.

Jones W., Medrano S., 2006. Indiana Lake Water Quality Assessment Report for 1999-2003. School of Public and Environmental Affairs. Indiana University. Bloomington, IN, USA, 27 pp.

Karr, J.R., 1981. Assessment of biotic integrity using fish communities. Fisheries 6, 21-27.

Karr, J.R., Dudley, D.R., 1981. Ecological perspective on water quality goals. Environmental Management 5, 55-68.

Karr, J.R., Chu, E.W., 1999. Restoring Life in Running Waters: Better Biological Monitoring. Island Press, Washington, D.C., USA, p. 220.

Lopez, R.D., Fennessy, M.S., 2002. Testing the floristic quality assessment index as an indicator of wetland condition. Ecological Applications 12, 487-497.

Mack, J.J., 2001. Vegetation Index of Biotic Integrity (VIBI) for Wetlands: Ecoregional, Hydrogeomorphic, and Plant Community Comparisons with Preliminary Wetland Aquatic Life Use Designations. Ohio Environmental Protection Agency. Division of Surface Water, Wetland Ecology Group, Columbus, OH, USA.

Mack, J.J., 2006. Landscape as a predictor of wetland condition: an evaluation of the landscape development index (LDI) with a large reference wetland dataset from Ohio. Environmental Monitoring Assessment 120, 221-241.

Mack, J.J., 2007. Developing a wetland IBI with statewide application after multiple testing iterations. Ecological Indicators 7, 864-881.

Miller SJ, Wardrop DH., 2006. Adapting the floristic quality assessment index to indicate anthropogenic disturbance in central Pennsylvania wetlands. Ecological Indicators 6, 313-326.

Miller S.J., Wardrop D.H., Mahaney W.M., Brooks R.P., 2006. A plant-based index of biological integrity (IBI) for headwater wetlands in central Pennsylvania. Ecological Indicators 6, 290-312.

Mohlenbrock, R., 2002. Vascular Flora of Illinois. Southern Illinois University Press, Carbondale, IL, USA, p. 490.

Mueller-Dombois, D., Ellenberg, H., 1974. Aims and Methods of Vegetation Ecology. John Wiley and Sons, New York, NY, USA, p. 547.

Nichols, S.A, 1999. Floristic quality assessment of Wisconsin lake plant communities with example applications. Lake and Reservoir Management 15, 133-141.

Nichols, S.A., Vennie, J.G., Geological, W., 1991. Attributes of Wisconsin lake plants. Information Cicular 73. Wisconsin Geological and Natural History Survey, Madison, WI, USA, 19 pp.

Nichols, S.A, Weber, S., Shaw, B., 2000. A proposed aquatic plant community biotic index for Wisconsin lakes. Environmental Management 26, 491-502.

Rothrock, P., 2004. Floristic quality assessment in Indiana: the concept, use, and development of coefficients of conservatism. Indiana Department of Environmental Management, Office of Water Quality, Indianapolis, IN, USA. Final Report for ARN A305-4-53, EPA Wetland Program Development Grant CD975586-01. 96 pp.

Rothrock, P.E., Homoya, M., 2005. An evaluation of Indiana's floristic quality assessment. Proceedings of the Indiana Academy of Science, 114, 9-18.

Rothrock P.E., Simon T.P., 2006. A plant index of biotic integrity for drowned river mouth coastal wetlands of Lake Michigan. In: T.P. Simon, and P.M. Stewart, (Editors), Coastal Wetlands of the Laurentian Great Lakes: Health, Habit, and Indicators. Authorhouse, Bloomington, IN, USA, pp. 195-208.

Rothrock, P.E., Simon, T.P., Stewart, P.M., 2008. Development, calibration, and validation of a littoral zone plant index of biotic integrity (PIBI) for lacustrine wetlands. Ecological Indicators 8, 79-88.

Simon, T., Stewart, P., Rothrock, P., 2001. Development of multimetric indices of biotic integrity for riverine and palustrine wetland plant communities along southern Lake Michigan. Aquatic Ecosystem Health and Management 4, 293-309.

Swink, F., Wilhelm, G., 1979. Plants of the Chicago Region, 3rd ed. Morton Arboretum, Lisle, IL, USA, 922 pp.

Swink, F., Wilhelm, G., 1994. Plants of the Chicago Region, 4th ed. Indiana Academy of Science, Indianapolis, IN, USA, 921 pp.

Taft, J., Wilhelm, G., Ladd, D.M., Masters, L.A., 1997. Floristic quality assessment for vegetation in Illinois: a method for assessing vegetation integrity. Erigenia 15, 3-97.

Thoma, R.F., 2006. Development and assessment of a qualitative habitat evaluation index for application in coastal wetlands of the great lakes. In: T.P. Simon and P.M. Stewart, (Editors), Coastal Wetlands of the Laurentian Great Lakes: Health, Habit, and Indicators. Authorhouse, Bloomington, IN, USA, 171 pp.

Voss, E.G., 1972. Michigan Flora; a Guide to the Identification and Occurrence of the Native and Naturalized Seed-Plants of the State. Part 1: Gymnosperms and Monocots. Cranbrook Institute of Science, Bloomfield Hills, MI, USA, 488.

Wilhelm, G., Masters, L., 2000. Floristic quality assessment and computer applications. Conservation Research Institute, 324 N. York Street, Elmhurst, IL 60126.

Wood, R., 1965. Monograph of the Characeae. In: R. D. Wood and K. Imahori, (Editors), A Revision of the Characeae. Vol. 1. Cramer, Weinheim, Germany, 1-904 pp.

Tables:

Table 1 - Name, county, and size of sixteen lakes used in study

Name	County	Size (ha)
Adams	LaGrange	124.6
Cree	Noble	30.8
Crooked	Noble	83.4
Failing	Steuben	8.9
High	Noble	49.8
Jones	Noble	46.1
Latta	Noble	17.0
Little Turkey	LaGrange	54.6
Loon Lake	Steuben	55.8
Messick	LaGrange	27.5
Olin	LaGrange	41.7
Steinbarger	Noble	29.5
Tamarack	Noble	20.2
Waldron	Noble	87.4
West Otter	Steuben	47.8
Witmer	LaGrange	82.6

Table 2 – Aquatic macrophyte-based metrics used in lake assessment indices

Metric	Index			
	FQI	PIBI	AMCI	IAMCQ
MC	**X**			
Total number of species		**X**	**X**	**X**
Total number of native species	**X**			
Total number of tolerant species				**X**
Total number of submersed species		**X**		
Total number of sensitive species		**X**		**X**
Total number of non-native species				**X**
Total number of lemnids				**X**
Total number of floating-leaved species		**X**		
Total number of emergent species		**X**		
Simpson's diversity index			**X**	**X**
Relative frequency tolerant species				**X**
Relative frequency lemnids				**X**
Relative frequencies of submersed species			**X**	**X**
Relative frequencies of sensitive species			**X**	**X**
Relative frequencies/abundance of exotic species		**X**	**X**	**X**
Relative abundance of woody species		**X**		
Relative abundance of pioneer species		**X**		
Relative abundance of obligate wetland species		**X**		
Percentage of littoral zone vegetated			**X**	**X**
Percent of tolerant and exotic species		**X**		
Maximum depth of plant growth			**X**	
Average cover of all species		**X**		

Source: Modified from Alix 2006.

Table 3 - List of aquatic macrophyte-based lake assessment score labels and label's description

AMCI	Aquatic Macrophyte Community Index
FQA	Floristic Quality Assessment
FQI_{NNI}	Floristic Quality Index based on AMCI sampling and calculated using the non-native impact formula outlined in Alix and Scribailo (2006).
IAMCQ	Index of Aquatic Macrophyte Community Quality
ITSI	Indiana Trophic State Index
LDI	Landscape Development Intensity Index
L-QHEI	Lake Qualitative Habitat Evaluation Index
$nFQI_{AMCI}$	Floristic Quality Index based on AMCI sampling with the inclusion of only native species.
$nFQI_{PIBI}$	Floristic Quality Index based on PIBI sampling with the inclusion of only native species.
nMC_{AMCI}	Mean C based on AMCI sampling with the inclusion of only native species.
nMC_{PIBI}	Mean C based on PIBI sampling with the inclusion of only native species.
PIBI	Plant Index of Biotic Integrity
$tFQI_{AMCI}$	Floristic Quality Index based on AMCI sampling with the inclusion of total (native and non-native) species.
$tFQI_{PIBI}$	Floristic Quality Index based on PIBI sampling with the inclusion of total (native and non-native) species.
tMC_{AMCI}	Mean C based on AMCI sampling with the inclusion of total (native and non-native) species.
tMC_{PIBI}	Mean C based on PIBI sampling with the inclusion of total (native and non-native) species.
$wtFQI_{AMCI}$	Floristic Quality Index weighted by species frequency and based on AMCI sampling with the inclusion of only native species.
$wtFQI_{PIBI}$	Floristic Quality Index weighted by species coverage and based on PIBI sampling with the inclusion of only native species.
$wtMC_{AMCI}$	Mean C weighted by species frequency and based on AMCI sampling with the inclusion of total (native and non-native) species.
$wtMC_{PIBI}$	Mean C weighted by species coverage and based on PIBI sampling with the inclusion of total (native and non-native) species.

Table 4 – Indiana state listed aquatic macrophyte species encountered

Scientific name	Common name	State Status	Lake
Bidens beckii	Water Marigold	Threatened	Crooked
Carex bebbii	Bebb's Oval Sedge	Threatened	Latta
Carex flava	Large Yellow Sedge	Threatened	West Otter
Larix laricina	American Larch	Watch List	Failing
Liparis loeselii	Green Twayblade	Watch List	High
Najas marina	Holly-leaved Naiad	Watch List	Adams, Latta, Little Turkey, Loon, Messick, Oin, West Otter
Nelumbo lutea	American Lotus	Watch List	Waldron
Potamogeton friesii	Fries's Pondweed	Threatened	Adams, Crooked
Potamogeton pusillus	Small Pondweed	Watch List	Adams, Cree, Failing, High, Latta, Little Turkey, Tamarack
Potamogeton robbinsii	Fern Pondweed	Rare	Messick
Schoenoplectus subterminalis	Water Bulrush	Rare	Loon
Utricularia purpurea	Purple Bladderwort	Rare	Loon

Table 5 – Species richness recorded for each lake and separated by sampling methodology

Lake (County)	PIBI	AMCI
Adams (LaGrange)	93	22
Cree (Noble)	76	15
Crooked (Noble/Whitley)	110	29
Failing (Steuben)	77	21
High (Noble)	96	17
Jones (Noble)	62	13
Latta (Noble)	110	14
Little Turkey (LaGrange)	98	20
Loon (Steuben)	84	24
Messick (LaGrange)	89	20
Olin (LaGrange)	94	13
Steinbarger (Noble)	68	14
Tamarack (Noble)	53	12
Waldron (Noble)	54	16
West Otter (Steuben)	90	21
Witmer (LaGrange)	72	4

Table 6 - Pearson's coefficients and significance level (*p*) between aquatic macrophyte-based indices and two measures of human disturbance, LQHEI and LDI, and one measure of water quality, ITSI.

Index	**PIBI**	**AMCI**	**IAMCQ**	**$nFQI_{AMCI}$**	**$nFQI_{PIBI}$**	**nMC_{AMCI}**	**nMC_{PIBI}**
L-QHEI	0.546 (*0.015*)	0.749 (*<0.001*)	0.603 (*0.007*)	0.745 (*<0.001*)	0.676 (*0.002*)	0.770 (*<0.001*)	0.794 (*<0.001*)
LDI	-0.529 (*0.018*)	-0.099 (*0.358*)	0.095 (*0.364*)	-0.345 (*0.096*)	-0.515 (*0.025*)	-0.578 (*0.01*)	-0.478 (*0.031*)
ITSI	-0.369 (*0.088*)	-0.682 (*0.003*)	-0.689 (*0.003*)	-0.474 (*0.037*)	-0.453 (*0.045*)	-0.533 (*0.021*)	-0.656 (*0.004*)

Table 7 - Pearson's coefficients and significance level (*p*) between variations of Mean C scores and two measures of human disturbance, LQHEI and LDI, and one measure of water quality, ITSI.

Index	nMC_{AMCI}	tMC_{AMCI}	$wtMC_{AMCI}$	nMC_{PIBI}	tMC_{PIBI}	$wtMC_{PIBI}$
L-QHEI	0.770 (*<0.001*)	0.695 (*0.002*)	0.726 (*<0.001*)	0.794 (*<0.001*)	0.733 (*<0.001*)	0.825 (*<0.001*)
LDI	-0.578 (*0.01*)	-0.363 (*0.084*)	-0.359 (*0.086*)	-0.478 (*0.031*)	-0.588 (*0.009*)	-0.181 (*0.251*)
ITSI	-0.533 (*0.021*)	-0.377 (*0.083*)	-0.551 (*0.017*)	-0.656 (*0.004*)	-0.466 (*0.04*)	-0.844 (*<0.001*)

Table 8 - Pearson's coefficients and significance level (*p*) between variations of FQI scores and two measures of human disturbance, LQHEI and LDI, and one measure of water quality, ITSI.

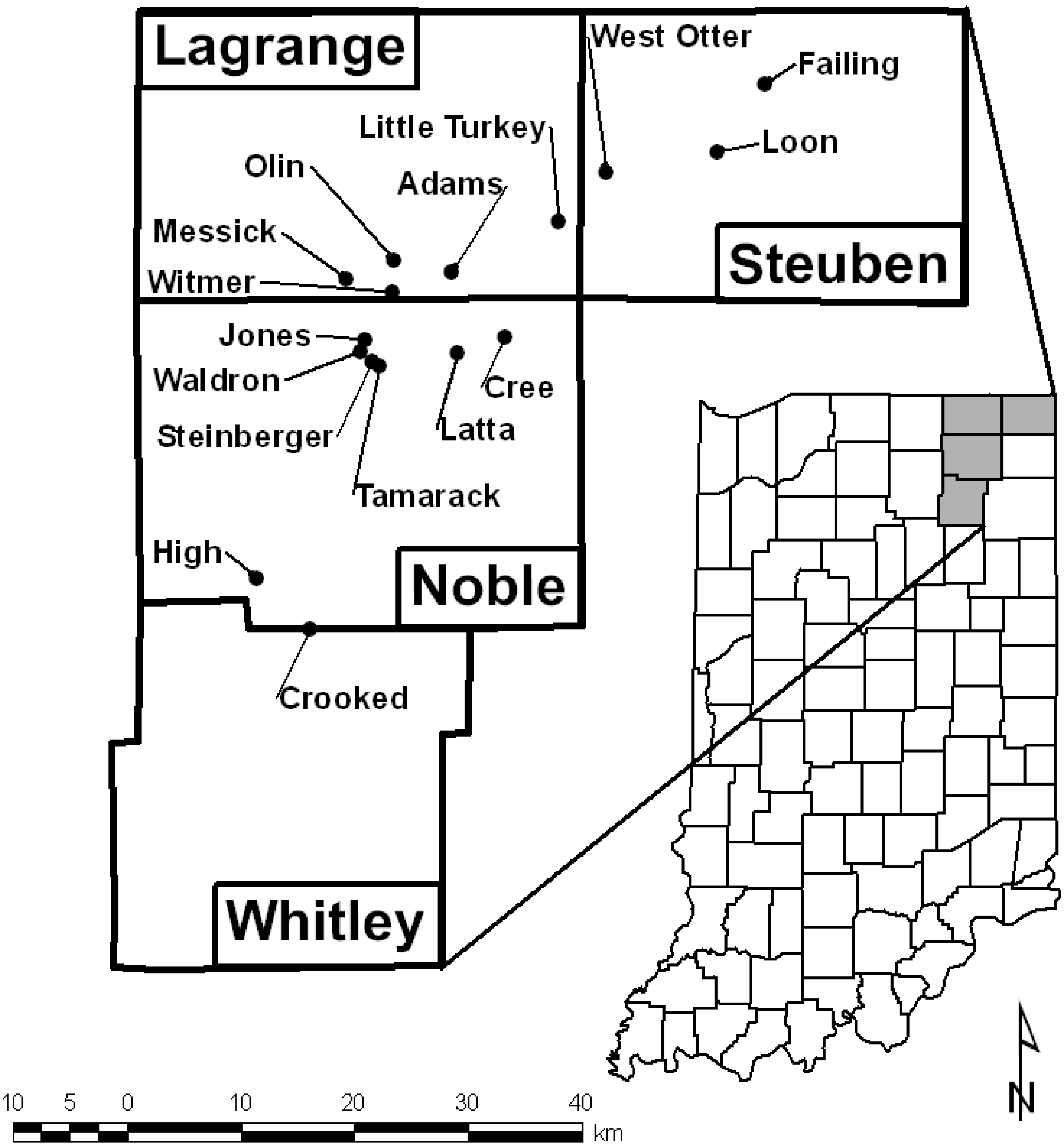
Index	**$nFQI_{AMCI}$**	**$tFQI_{AMCI}$**	**$wtFQI_{AMCI}$**	**FQI_{NNI}**	**$nFQI_{PIBI}$**	**$tFQI_{PIBI}$**	**$wtFQI_{PIBI}$**
L-QHEI	0.745 (*<0.001*)	0.725 (*<0.001*)	0.107 (*0.347*)	0.755 (*<0.001*)	0.676 (*0.002*)	0.664 (*0.003*)	0.784 (*<0.001*)
LDI	-0.345 (*0.096*)	-0.302 (*0.128*)	-0.336 (*0.102*)	-0.253 (*0.172*)	-0.515 (*0.025*)	-0.546 (*0.015*)	-0.198 (*0.231*)
ITSI	-0.474 (*0.037*)	-0.442 (*0.05*)	0.140 (*0.691*)	-0.506 (*0.027*)	-0.453 (*0.045*)	-0.409 (*0.065*)	-0.733 (*0.001*)

Table 9 - Pearson's coefficients and significance level (*p*) between aquatic macrophyte-based lake assessment techniques.

Indices under comparison	***r* (*p*)**
PIBI vs AMCI	0.598 (*0.007*)
PIBI vs IAMCQ	0.569 (*0.011*)
AMCI vs IAMCQ	0.912 (*<0.001*)
nMC_{AMCI} vs AMCI	0.708 (*0.001*)
nMC_{AMCI} vs IAMCQ	0.521 (*0.02*)
$nFQI_{AMCI}$ vs AMCI	0.846 (*<0.001*)
$nFQI_{AMCI}$ vs IAMCQ	0.646 (*0.004*)
nMC_{PIBI} vs PIBI	0.747 (*<0.001*)
$nFQI_{PIBI}$ vs PIBI	0.831 (*<0.001*)
nMC_{AMCI} vs nMC_{PIBI}	0.634 (*0.004*)
$nFQI_{AMCI}$ vs $nFQI_{PIBI}$	0.373 (*0.078*)
nMC_{AMCI} vs $wtMC_{AMCI}$	0.889 (<0.001)
$nFQI_{AMCI}$ vs $wtFQI_{AMCI}$	0.442 (0.044)
nMC_{PIBI} vs $wtMC_{PIBI}$	0.757 (<0.001)
$nFQI_{PIBI}$ vs $wtFQI_{PIBI}$	0.823 (<0.001)

Figure:

Figure 1. Location of the sixteen lakes used to compare and validate the four aquatic macrophyte-based lake assessment techniques in northeast Indiana.


Lagrange
West Otter
Failing
Little Turkey
Loon
Olin
Adams
Messick
Witmer
Steuben
Jones
Waldron
Cree
Steinberger
Latta
Tamarack
High
Noble
Crooked
Whitley
10 5 0 10 20 30 40
km
N

Appendix:

Table A – Calibration of aquatic macrophyte community index (AMCI) for lakes in Wisconsin

Metric	Scaled Value	Metric	Scaled Value
1. Maximum depth of plant growth		4. Total number of species	
<1.4 1	1	<5	1
1.4 to 2.0	2	5 and 6	2
2.0 to 2.7	3	7 and 8	3
2.7 to 3.0	4	94	4
3.0 to 3.2	5	10 and 11	5
3.2 to 3.7	6	12 and 13	6
3.7 to 4.0	7	14 and 15	7
4.0 to 4.5	8	16 to 19	8
4.5 to 5.0	9	19 to 25	9
≥5.0 1	10	≥25	10
2. Percentage of littoral zone vegetated		5. Simpson's diversity index	
<18	1	<60	1
18 to 24	2	60 to 70	2
24 to 29	3	70 to 76	3
29 to 32	4	76 to 80.5	4
32 to 34	5	80.5 to 83.5	5
34 to 37	6	83.5 to 85.5	6
37 to 40	7	85.5 to 87.5	7
40 to 45	8	87.5 to 90	8
45 to 50	9	90 to 92	9
≥50	10	≥92	10
3. Relative frequencies of submersed species		6. Relative frequencies of sensitive species	
<34	1	<0.1	1
34 to 43	2	0.1 to 2	3
43 to 49	3	2 to 4	4
49 to 58	4	4 to 9	5
58 to 60	5	9 to 13	6
60 to 65	6	13 to 17	7
65 to 68	7	17 to 22	8
68 to 72	8	22 to 30	9
72 to 75	9	≥30	10
75 to 85	10	7. Relative frequencies of exotic species	
85 to 90	9	0	10
90 to 92.5	8	0.1 to 5	6
92.5 to 95	7	5 to 10	5
95 to 97.5	6	10 to 20	4
≥97.5	5	20 to 30	3
		30 to 45	2
		≥45	1

Source: Derived from Nichols et al., 2000.

Table B – Calibration of plant index of biotic integrity (PIBI) for lakes in northwest Indiana,

Attribute	Scoring		
	1 (worst)	**3**	**5 (best)**
I. Species Richness and Composition			
1. Total number of species	**0-22**	**23-39**	**>39**
2. Total number of submersed species	**Varies with surface area**		
3. Total number of floating-leaved species	**0-1**	**2-3**	**>3**
4. Total number of emergent species	**1-10**	**11-20**	**>20**
II. Species Tolerance			
1. Total number of sensitive species	**0-3**	**4-7**	**>7**
2. Percent of tolerant and exotic species	**>36**	**19-36**	**<19**
III. Guild Structure			
1. Relative abundance of obligate wetland species	**<12**	**12-24**	**>24**
2. Relative abundance of pioneer species	**>30**	**16-30**	**<16**
3. Relative abundance of woody species	**>25**	**12-25**	**<12**
IV. Vegetative Abundance			
1. Average cover of all species	**<2**	**2-3**	**>3**
2. Relative abundance of exotic species	**>16**	**8-16**	**<8**

Source: Derived from Rothrock et al., 2008.

Table C – Calibration of index of aquatic macrophyte community quality (IAMCQ) for lakes in northern Indiana

	Scoring		
Metric	**1 (worst)**	**3**	**5 (best)**
I. Taxa Richness and Diversity			
1. Total number of taxa*	**<19**	**19-29**	**>29**
2. Total number of native species	**>2**	**1-2**	**0**
3. Total number of lemnids	**>4**	**3-4**	**<3**
4. Total number of tolerant species	**>3**	**3**	**<3**
3. Total number of sensitive species	**0**	**1-2**	**>2**
6. Simpson's diversity index	**<82**	**82-88**	**>88**
II. Littoral Zone Composition and Abundance			
1. Percentage of littoral zone vegetated	**<60**	**60-80**	**>80**
2. Relative frequencies of submersed species*	**<40 or >80**	**40-60**	**>60-80**
3. Relative frequencies of non-native species	**>30**	**15-30**	**<15**
4. Relative frequency lemnids**	**>30**	**15-30**	**<15**
5. Relative frequency of tolerant species	**>27.5**	**18.5-27.5**	**<18.5**
6. Relative frequencies of sensitive species	**<4**	**4-8**	**>8**

* Excludes non-native taxa

** Includes members of Azollaceae and Ricciaceae

Source: Printed with permission from Alix (2006).

Table D – Landscape development intensity index (LDI) land use classification and coefficients

Land Use Classification	LDI Value
Natural System	1.00
Natural Open water	1.00
Pine Plantation	1.58
Recreational / Open Space (Low-intensity)	1.83
Woodland Pasture (with livestock)	2.02
Pasture (without livestock)	2.77
Low Intensity Pasture (with livestock)	3.41
Citrus	3.68
High Intensity Pasture (with livestock)	3.74
Row crops	4.54
Single Family Residential (Low-density)	6.79
Recreational / Open Space (High-intensity)	6.92
High Intensity Agriculture (Dairy farm)	7.00
Single Family Residential (Med-density)	7.47
Single Family Residential (High-density)	7.55
Mobile Home (Medium density)	7.70
Highway (2 lane)	7.81
Low Intensity Commercial	8.00
Institutional	8.07
Highway (4 lane)	8.28
Mobile Home (High density)	8.29
Industrial	8.32
Multi-family Residential (Low rise)	8.66
High Intensity Commercial	9.18
Multi-family Residential (High rise)	9.19
Central Business District (Average 2 stories)	9.42
Central Business District (Average 4 stories)	10.00

Source: Derived from Brown and Vivas 2005.