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Use of ecological indicators to assess the quality of Great Lakes coastal wetlands

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ABSTRACT

Over 2000 coastal wetland complexes have been identified in the Laurentian Great Lakes watershed, each providing critical habitat for numerous aquatic and terrestrial species. Research has shown there is a direct link between anthropogenic activities (urbanization and agricultural development) and deterioration in wetland health in terms of water quality and biotic integrity. In this study, we evaluate coastal marshes throughout the Great Lakes basin using a suite of published ecological indices developed specifically for coastal wetlands of the Great Lakes (Water Quality Index (WQI), Wetland Macrophyte Index (WMI), and the Wetland Fish Index (WFI_{Basin})). We surveyed 181 wetlands, including 19 in Lake Superior (11%), 11 in Lake Michigan (6%), 13 in Lake Huron (7%), 92 in Georgian Bay and the North Channel (51%), 18 in Lake Erie (10%), and 28 in Lake Ontario (15%), over a 13 year period (1995–2008). Water quality parameters were measured at every site, while paired fyke nets were used to assess the fish community (132 sites) and macrophytes were surveyed and identified to species (174 sites); all of this information was used to calculate the associated index scores. One-way ANOVA results showed that there were significant differences in wetland quality among lakes. According to the WQI, we found that over 50% of marshes in Lakes Michigan, Erie, and Ontario were in degraded condition, while over 70% of marshes in Lakes Superior, Huron, and Georgian Bay were minimally impacted. Georgian Bay had the highest proportion of wetlands in very good and excellent condition and least number of wetlands in a degraded state. The WMI and WFI showed similar results. This is the largest bi-national database of coastal wetlands and the first study to provide a snapshot of the quality of coastal habitats within the Great Lakes basin. We recommend this information be used to guide conservation and restoration efforts within the Laurentian Great Lakes.

1. Introduction

Wetlands are one of the most biodiverse systems in the world and provide essential ecosystem services valued globally at trillions of dollars per year (Costanza et al., 1997). Within the Laurentian Great Lakes, which include Lakes Superior, Huron, Michigan, Erie and Ontario, there are more than two thousand coastal wetlands covering over 216,000 ha along a total shoreline of 17,071 km (GLCWC; Ingram et al., 2004). Majority of these wetlands are marshes, which are hydrologically connected with the Great Lakes and extremely important for the Great Lake fish community. They provide critical spawning and nursery habitat for 80% of the Great Lakes fish species at some time in their life cycle (Chow-Fraser and Albert, 1999) and provide shelter, food, and refuge for resident fishes (Jude and Pappas, 1992; Randall et al., 1996). Talhelm (1988) estimated that anglers in the Great Lakes spent $1 to $2 billion (U.S. dollars) in 1985, and that a total impact of this spending on the regional economy would have ranged from $2 to $4 billion (U.S. dollars). When adjustment for inflation is factored in, the 2010 dollars could be twice this amount.

Besides fish species, coastal marshes in the Great Lakes are also essential habitat for invertebrates, birds, turtles, amphibians, and large mammals such as bear and moose. Since European settlement in the mid 1800s, this critical habitat has been destroyed by urban and agricultural development in settled areas of the Great Lakes shoreline (Jude and Pappas, 1992; Mayer et al., 2004). It has been estimated that less than 30% of the pre-European wetlands that once existed in the Laurentian basin are currently available as Great Lakes fish habitat (Snell, 1987; Smith et al., 1991; Jude and Pappas, 1992) and many of these are in a degraded condition because of land-use alteration in wetland catchments (Chow-Fraser, 2006).

Agriculture is one of the two primary factors responsible for habitat loss and deterioration and dominates in the southern portion of the basin due to favourable climate and soil conditions; urbanization is the second factor, and is especially prominent on the U.S. coast where major cities have been established (e.g. Lakes Erie and Michigan), while large cities on the Canadian shoreline exist mainly on the northern coastline of Lake Ontario and the St. Lawrence River (Mayer et al., 2004). The result of this land-use alteration is increased sediment and nutrient loads into the coastal

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watersheds (Chow-Fraser, 2006; Danz et al., 2007; Trebitz et al., 2007; Morrice et al., 2008), including runoff from improper sewage facilities (e.g. Chow-Fraser, 1998).

A large body of published work has documented the relationship between water-quality condition and wetland health for Great Lakes coastal wetlands. Crosbie and Chow-Fraser (1999), McNair and Chow-Fraser (2003) and Trebitz et al. (2007, 2009) have shown that both point-source and diffuse-source pollution can lead to eutrophication and increased algal growth that diminish light penetration for growth and establishment of aquatic plants. As a result, turbidity-intolerant macrophyte species tend to decline and assemblages become dominated by a few disturbance-tolerant taxa and increased representation of exotic species (Lougheed et al., 2001; Croft and Chow-Fraser, 2007; Trebitz and Taylor, 2007; Trebitz et al., 2009). In response, invertebrate and zooplankton communities change (Lougheed and Chow-Fraser, 2002; Kostuk, 2006) and the fish assemblage shifts to a community dominated by non-native species and accompanied by low species richness and diversity, (Brazner and Beals, 1997; Seilheimer and Chow-Fraser, 2007; Seilheimer et al., 2007; Trebitz et al., 2009).

Chow-Fraser (2006) was one of the first to use the relationship between water-quality and wetland health to develop an indicator of human activities for coastal wetlands in the Great Lakes basin. Water chemistry was sampled across a large disturbance gradient throughout Canada and U.S. to develop the Water Quality Index (WQI), which was shown to be directly related to land-use alteration in wetland watersheds (Chow-Fraser, 2006). In the Great Lakes Environmental Indicators (GLEI) project, Danz et al. (2007) developed a stress gradient for the U.S. portion of the Great Lakes, based on several anthropogenic metrics including agricultural inputs, human population, atmospheric deposition, land cover, and point source pollution; various investigators have subsequently related the GLEI indicator to various biota to assess the suitability of these organisms as bioindicators of disturbance (Brazner et al., 2007; Morrice et al., 2008; Niemi et al., 2009). In addition, Trebitz et al. (2007) examined the correlation between water-quality parameters and the GLEI stressor for coastal wetlands and confirmed that a metric combining a suite of water-quality variables could be used as a predictor of agricultural intensity.

It is clear that there is a direct decline in the quality of coastal habitat as a result of anthropogenic activities (Minns et al., 1994; Trebitz et al., 2007; Danz et al., 2007; Morrice et al., 2008), and a variety of indices have been developed to track the health of coastal wetlands in response to land-use changes (Lougheed and Chow-Fraser, 2002; Uzarski et al., 2005; Chow-Fraser, 2006; Simon and Stewart, 2006; Niemi et al., 2007). Despite the availability of these indices, however, no study has been undertaken to compare wetland conditions across the Great Lakes region at one time because these lake basins include two countries, eight states and two provinces, and it has been difficult to muster the resources to conduct a contemporaneous analysis. Nevertheless, there have been several large-scale efforts to survey coastal wetlands over the past ten years, and it would be desirable to bring this information together to assess the coastal marsh conditions across the whole basin.

In this study, our main objective is to compare the health of coastal marshes across the five Great Lakes, including the rarely sampled eastern arm of Lake Huron, Georgian Bay. Specifically we compare wetland quality by using published ecological indices, the Water Quality Index (WQI; Chow-Fraser, 2006), Wetland Macrophyte Index (WMI; Croft and Chow-Fraser, 2007), and Wetland Fish Index (WFI; Seilheimer and Chow-Fraser, 2007) that were created specifically for these Great Lakes coastal wetlands. These index scores will be used to compare 181 wetlands sample on both Canadian and American shorelines, and give an indication of the general condition of numerous sites spread throughout the basin. Since a single research group collected these data using a set of standardized sampling protocols, we feel justified in pooling these data for comparison. In so doing, we will produce the first snapshot of coastal marsh conditions in the Great Lakes basin across Canada and the United States over a decade (1995–2008), and it is our hope environmental managers will be able to use these results to evaluate current and future efforts to restore, protect and conserve coastal wetlands.

Table 1
Comparison of number of coastal wetlands of the Great Lakes based on the Great Lakes Coastal Wetland Consortium (GLCWC). Number of wetlands sampled in each lake that were assembled for this study is also presented.

Lake	Number of wetlands		% Sampled	
	U.S.A.	CAN	U.S.A.	CAN
Superior	265	42	4	21
Michigan	524	N/A	2	N/A
Huron	224	269	4	2
Georgian Bay and North Channel	N/A	166	N/A	55
Erie	89	60	2	27
Ontario	240	248	4	7
Total	1387	739	3	19

2. Methods

2.1. Inventory of Great Lakes Coastal Wetlands

Limited data exist on the exact number of remaining Great Lakes coastal wetlands (Smith et al., 1991; Herdendorf, 2004), which is understandable due to the vast quantity of shoreline in the basin. The Great Lakes Coastal Wetland Consortium (GLCWC) conducted the most recent and exhaustive survey of coastal wetlands. In 2004, the GLCWC was formed to address the need for a basin-wide monitoring system for Great Lakes coastal wetlands. The ultimate goal was to create a long-term implementable monitoring plan, including a classification system and best methods for sampling, cost-efficiency, and effectiveness (Lawson, 2004). In addition, the Consortium produced an inventory that documents existing coastal wetlands in the Great Lakes watershed, focusing on marshes greater than 2 ha in size, by assembling existing data from Canadian and U.S. agencies using available aerial photographs. GLCWC has summarized the number of coastal wetland complexes within the Great Lakes basin.

A total of 2127 wetland complexes have been identified, including: 307 in Lake Superior, 524 in Lake Michigan, 493 in Lake Huron, 166 in south-eastern Georgian Bay, 149 in Lake Erie, and 488 in Lake Ontario (Table 1; based on the GLCWC inventory reported in Ingram et al., 2004). There were sufficient existing aerial photography to yield almost a complete photographic coverage of wetlands along the coast of Lakes Superior, Erie, and Ontario (including the connecting channels), however, the Consortium acknowledged the deficient coverage of eastern and northern Georgian Bay and suggested that future effort be expended to complete the inventory for this region. In response to the data gaps in the GLCWC inventory, a recent project was undertaken to update the GIS inventory of eastern and northern Georgian Bay marshes. The McMaster Coastal Wetland Inventory (MCWI; Midwood et al., unpublished data) shows that there are at least four times as many wetland complexes in eastern and northern Georgian Bay (i.e. over 700) than had been included in the GLCWC inventory.

2.2. Geomorphological differences across the basin

Because of the vastness of the Great Lakes basin, it is important to point out differences in the geomorphology of coastal wetlands in the three physiographic provinces: the Canadian Shield, Central Lowlands, and the St. Lawrence Lowlands. The northern and northwestern portions of the Laurentian Great Lakes basin (mainly most of Lake Superior and Georgian Bay, as well as the northern portion of Lake Ontario) are composed of the granitic bedrock from the Canadian Shield (Precambrian Era). The remainder of the Great Lakes is dominated by softer, more erodible sedimentary rock (e.g. limestone, sandstone) deposited during the Paleozoic Era.

A study by De Catanzaro et al. (2009) examining the effect of watershed features on coastal water-quality demonstrated that bedrock type did not have a significant influence on nutrient concentration (e.g. nitrogen, phosphorus) and other water-quality parameters (e.g. conductivity, suspended solids) in Georgian Bay watersheds. Instead, factors such as wetland cover, watershed area, and road density were significantly correlated with water chemistry and overall water-quality condition in these low-impact marshes. Similarly, results from McNair and Chow-Fraser (2003) showed regional variation in climate and geology did not significantly affect water-quality differences in Great Lakes coastal wetlands. Trebitz et al. (2007) found that while DOC (dissolved organic content) did not respond to an agricultural gradient it acted to decrease water clarity via Secchi depth in some Lake Superior wetlands; however turbidity measures are not affected by DOC and can provide an alternate metric for water clarity. Hence, the underlying geology of our study sites should not have had a significant impact on measured water-quality parameters.

2.3. Representativeness of the wetlands

Since data assembled here come from previous studies that had diverse goals, the wetlands were not chosen randomly and should not be considered as being a representative subset of all coastal wetlands in a particular Great Lake. To the extent possible, however, the wetlands represent the range of human disturbance that are likely to be encountered across the various reaches of the Great Lakes shoreline. It was not possible to keep the sampling effort proportionate to the number of wetlands present in each lake because most of the sampling had been carried out prior to the publications of the GLCWC and the MCWI. Suffice it to say that we have sampled less than 10% of the wetlands available on a basin-wide basis and that there is a heavy bias towards Canadian wetlands (Table 1). If wetlands from the MCWI were included, the proportion of wetlands sampled in Georgian Bay and the North Channel would drop to 13% (i.e. 92 of 700 available wetlands) rather than 51% (92 of 181 available wetlands). Irrespective of the actual proportion sampled, data for all these wetlands are directly comparable, because they had been collected with standardized protocols during the growing season between 1995 and 2008 (late May to late August).

The assembled dataset is the largest bi-national database of standardized water-quality and biotic assessment information. Most of the information included in this study has been used in previous publications including Chow-Fraser (2006), Croft and Chow-Fraser (2007), Seilheimer and Chow-Fraser (2007), De Catanzaro et al. (2009) and Cvetkovic et al. (2010). All of our sites were sampled contemporaneously for water quality, fish and macrophyte information. The compiled data for this study includes 181 wetlands from Lake Ontario (28), Lake Erie (18), Lake Michigan (11), Lake Huron (13), Georgian Bay and the North Channel (92), and Lake Superior (19) (Table 1, Fig. 1).

2.4. Sampling protocols

To ensure direct comparability of our water-quality data, we only included information that had been collected with standardized protocols and analytical methods following the methods described in Chow-Fraser (2006). Variables included primary nutrients (total phosphorus (TP), soluble reactive phosphorus (SRP), total ammonia nitrogen (TAN), total nitrate nitrogen (TNN) and total nitrogen (TN), water clarity (chlorophyll (CHL), total suspended solids (TSS) and total inorganic suspended solids (TISS), turbidity (TURB)), as well as physical parameters (temperature (TEMP), pH and conductivity (COND)). To ensure that water was not contaminated with periphytic algae, samples were always collected at mid-depth, away from submerged macrophytes or floating plants. Water was collected with a 1 L Van Dorn, and TURB was measured *in situ* with a field turbidimeter (Hach or LaMotte Turbidimeter). TEMP, pH and COND were collected *in situ* with either a multi-probe (YSI 6600 and YSI 650 display; YSI, Yellow Springs, OH, USA) or a Hydrolab^{TM} minisonde (Hydrolab, Austin, Texas). Samples were analyzed for TAN and TNN on-site within 4 h of collection with a portable Hach colorimeter. Water was filtered for CHL and TSS in the field, after which filters were frozen, and transported back to McMaster University for further processing. All other samples were frozen, then transported back to the lab and processed for nutrients (TP, SRP, TN) according to standard limnological methods (see Chow-Fraser, 2006). Geographic coordinates were taken with a GPS unit (Garmin^{TM}Etrex GPS) recorded at 3–6 m accuracy.

All inundated portions of the marsh were sampled for vegetation, including the emergent (shallow), floating and submergent (deeper) zones. A stratified random method used to survey vegetation has been described in Croft and Chow-Fraser (2007, 2009), where a minimum of eight (but usually 10–12) 1-m^2 quadrats are sampled for all growth forms of macrophytes. All vegetation along the water's edge was surveyed by foot, while deeper areas were surveyed from a canoe. The field crew also used a rake to obtain samples of submersed plants at depths up to 2 m. Due to potential differences in survey results among samplers over the years, statistical analyses were conducted to ensure that data were comparable, and no significant differences were found among samplers (Croft, 2007). Whenever possible, plants were identified to the species level following Newmaster et al. (1997) and Chaade (2002).

Fish were collected with a standardized protocol, using three sets of paired fyke nets (two large sets with 13 and 4 mm bar mesh, 4.25 m length, 1 m × 1.25 m front opening and one small set with 4 mm bar mesh, 2.1 m length, 0.5 m × 1.0 m front opening) deployed overnight at each site (approximately 24-h). The fyke nets had 2.5 m wings on each side and were connected by a 7 m lead. They were placed parallel to shore, in depths of 1 m (large nets) and 0.5 m (small nets), and in contact with submergent or floating vegetation whenever possible. Following the overnight period, fish were identified to species according to Scott and Crossman (1998) and released on site. Complete details of fish sampling protocols can be found in Seilheimer and Chow-Fraser (2007).

2.5. Published ecological indices

Due to increasing concern over the ongoing loss and degradation of Great Lakes marshes there has been a concerted effort over the past twenty years to develop indicators that would track the health of these ecosystems. The Water Quality Index (WQI; Chow-Fraser, 2006), the Wetland Fish Index (WFI_{Basin}; Seilheimer and Chow-Fraser, 2007) and the Wetland Macrophyte Index (WMI; Croft and Chow-Fraser, 2007) are recently published indices that were specifically developed for large-scale, long-term monitoring programs to track changes in habitat quality of Great Lakes coastal wetlands. In every case, indices were developed with at least 100 wetlands

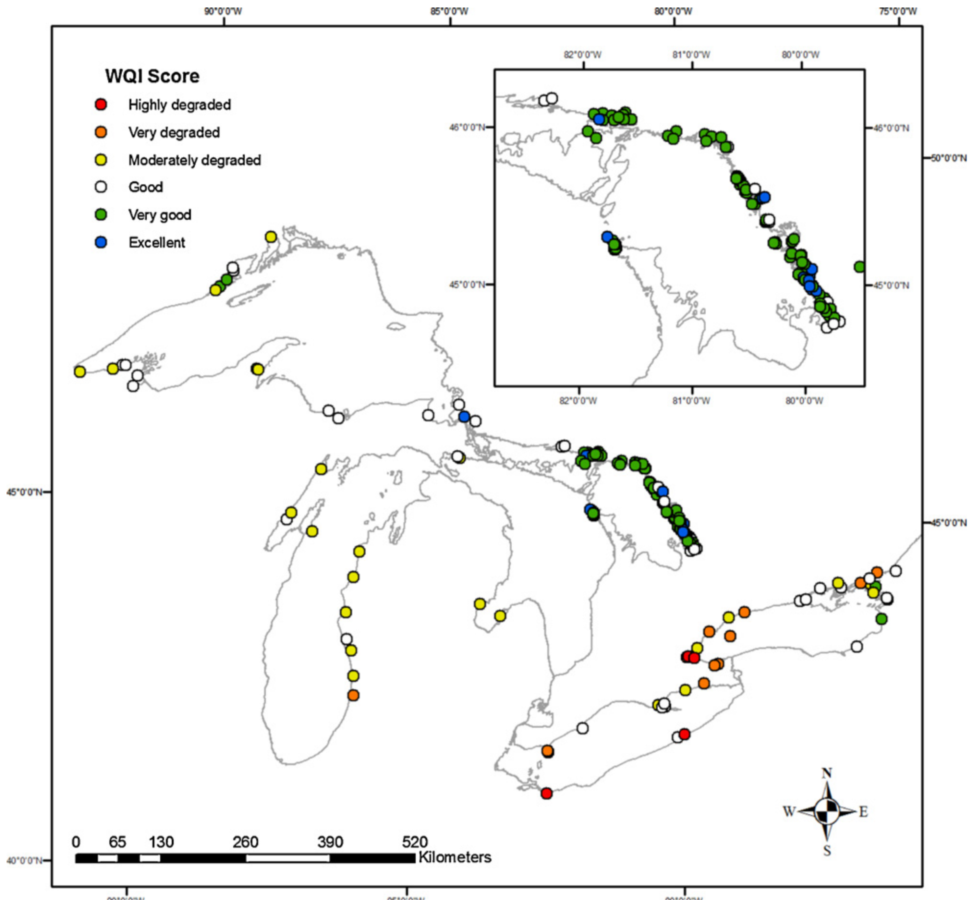

Fig. 1. Map of 181 coastal wetlands sampled between 1995 and 2008 in the Laurentian Great Lakes. Distribution of WQI scores (after Chow-Fraser, 2006) is plotted for the five Great Lakes.

located throughout all 5 Great Lakes, including sites within Georgian Bay. Chow-Fraser (2006) developed the WQI using data from 110 sites and a Principal Components Analysis. The index uses 12 variables to measure the degree of water-quality impairment that could be attributed to anthropogenic disturbance caused by altered land use or direct nutrient influx (Chow-Fraser, 2006). Using water-quality parameters an overall score of water-quality can be determined using the equation below:

$$\begin{aligned}\mathrm{WQI} = {} & 10.0239684 - (0.3154965 \times \log \mathrm{TURB}) \\ & -(0.3656606 \times \log \mathrm{TSS}) - (0.3554498 \times \log \mathrm{ISS}) \\ & -(0.3760789 \times \log \mathrm{TP}) - (0.1876029 \times \log \mathrm{SRP}) \\ & -0.0732574 \times \log \mathrm{TAN}) - (0.2016657 \times \log \mathrm{TNN}) \\ & -(0.2276255 \times \log \mathrm{TN}) - (0.5711395 \times \log \mathrm{COND}) \\ & -(1.1659027 \times \log \mathrm{TEMP}) - (4.3562126 \times \log \mathrm{pH}) \\ & -(0.2287166 \times \log \mathrm{CHL})\end{aligned} \tag{1}$$

Since WQI scores can range from −3 to +3, Chow-Fraser (2006) created six arbitrary categories at unit intervals that separated wetlands from highly impacted to least impacted: −3 to −2 ("highly degraded"), −2 to −1 ("very degraded"), −1 to 0 ("moderately degraded"), 0 to 1 ("good"), 1 to 2 ("very good"), and 2 to 3 ("excellent"). WQI scores decreased inversely with proportion of altered land (Chow-Fraser, 2006). De Catanzaro et al. (2009) showed that the WQI was sensitive to anthropogenic degradation of water quality in coastal marshes even in relatively undisturbed sites such as those in Georgian Bay. We therefore feel that the WQI is an appropriate index of human degradation that can be used to assess wetland condition across the entire Great Lakes basin.

The $\mathrm{WFI}_{\mathrm{Basin}}$ and the WMI are biotic indices that have been developed as surrogates of the WQI because water-quality sampling and analyses can be expensive. The WMI uses macrophyte species presence-absence to infer the condition of the wetland, while the $\mathrm{WFI}_{\mathrm{Basin}}$ (hereafter referred to as WFI) can use fish presence-absence or abundance. Taxonomic and water-quality information were entered into a partial Canonical Correspondence Analysis (pCCA) to quantify species-environment relationships, while accounting for seasonality. In this manner, the authors were able to assign specific scores of tolerance and niche breadth to each species (61 fish species, 94 plant species). These species-specific scores are then used in the following formula to ascertain the overall quality of wetland health:

$$\mathrm{WFI\ or\ WMI} = \left(\frac{\sum_{i=1}^{n} Y_i T_i U_i}{\sum_{i=1}^{n} Y_i T_i} \right) \tag{2}$$

where: Y_i = if the species is present, this value is 1; if absent, it is 0; T_i = value from 1–3 or niche breadth of species i; U_i = value from 1–5, tolerance of species i to degradation.

The indices range from 1 to 5, with higher scores indicating higher wetland quality. Biotic indices have an advantage because environmental agencies are more likely to collect species information than water-quality information, and the formula used to calculate scores are relatively simple to use. For convenience of readers, a list of all fish and macrophyte species included in the indices and their corresponding *U* and *T* values can be found in Appendix A (Tables A2 and A3).

Table 2
Summary of ANOVA statistics comparing WQI ($n = 181$), WMI ($n = 174$), and WFI ($n = 132$) according to lake origin. p values and F statistics are reported for ANOVAs conducted for each ecological index. Lakes sharing the same letter superscript denotes they are not statistically significant as indicated by post-hoc Tukey-Kramer analyses.

Lake	WQI (mean, SE)	WMI (mean, SE)	WFI (mean, SE)
Superior	0.61 (0.13)^{b}	2.97 (0.10)^{b}	3.48 (0.07)^{a,b}
Michigan	−0.33 (0.17)^{c}	2.56 (0.13)^{b,c}	3.33 (0.10)^{b,c}
Huron	1.02 (0.26)^{a,b}	2.84 (0.18)^{b}	3.53 (0.13)^{a,b}
Georgian Bay/North Channel	1.52 (0.06)^{a}	3.51 (0.04)^{a}	3.69 (0.03)^{a}
Erie	−0.40 (0.24)^{c}	2.15 (0.12)^{c}	3.12 (0.23)^{b,c}
Ontario	−0.46 (0.20)^{c}	2.01 (0.08)^{c}	3.12 (0.09)^{c}
ANOVA	$p < 0.0001$; $F_{(5, 175)} = 47.3720$	$p < 0.0001$; $F_{(5, 168)} = 80.7461$	$p < 0.0001$; $F_{(5, 126)} = 13.6005$

In a recent study, Seilheimer et al. (2009) showed that both WMI and WFI scores were positively and significantly correlated with WQI scores, demonstrating that they are appropriate surrogate indicators of water quality for sites within the Great Lakes. In this study, WFI scores will refer to WFI-PA (presence-absence) because abundance data generally yielded identical trends; if relevant, abundance results will be indicated by WFI-AB. Unlike the WQI, WMI and WFI scores were not created with corresponding "quality" categories; however, a generalization can be made that a WQI score of zero is accompanied by a WMI score of 2.5 (Croft and Chow-Fraser, 2007) and a WFI score of 3.25 (Seilheimer and Chow-Fraser, 2007; Cvetkovic, 2008). Wetlands receiving scores below these threshold values are considered degraded to some extent, as it has been empirically shown in WQI-WMI and WQI-WFI relationships (Seilheimer et al., 2009) that scores below these thresholds correspond to WQI scores below zero, and scores below zero indicate degradation.

2.6. Statistical analyses

We compared index scores for wetlands on a lake-by-lake basis to obtain a snapshot of wetland quality across the Great Lakes. Specifically, we wanted to document the relative contribution of wetlands in each of the six WQI categories given in Chow-Fraser (2006). After sorting the 181 wetlands according to lake origin, we calculated the proportion of wetlands corresponding to each of the six water-quality categories. Similar analyses were conducted using the WMI and WFI, where wetlands were sorted into two categories, "impacted" and "not impacted", based on their scores. We also compared ecological conditions across the basin using all three ecological indices. Wetlands were sorted according to lake origin and a one-way ANOVA was conducted to determine if there were significant differences among lakes with respect to index scores of WQI, WMI, and WFI. Post-hoc Tukey–Kramer analyses were conducted if $p < 0.05$. SAS JMP in 4.0 (SAS Institute, Cary, North Carolina, U.S.A.) was used for all analyses.

3. Results

One-way ANOVA results showed significant differences among lakes with respect to all three ecological indices (Table 2). Post-hoc tests for the WQI analysis showed that Georgian Bay wetlands had significantly higher scores compared to all other lakes except Huron. Those associated with Lakes Michigan, Erie, and Ontario were also significantly lower than scores associated with Lake Superior and Lake Huron. WMI results for Georgian Bay wetlands were significantly higher than those for marshes in the other lakes (Table 2). Lakes Superior and Huron wetlands were associated with significantly higher WMI scores compared with wetlands in Lakes Ontario and Erie, but not Michigan. WFI scores for Georgian Bay were significantly higher than all other lakes with the exception of Huron and Superior, and scores associated with Lake Ontario were also significantly lower than those associated with Lakes Huron and Superior (Table 2). While WFI-AB results follow essentially the same pattern as WFI-PA, abundance scores indicated that Huron and Superior wetlands were also significantly greater than Erie scores.

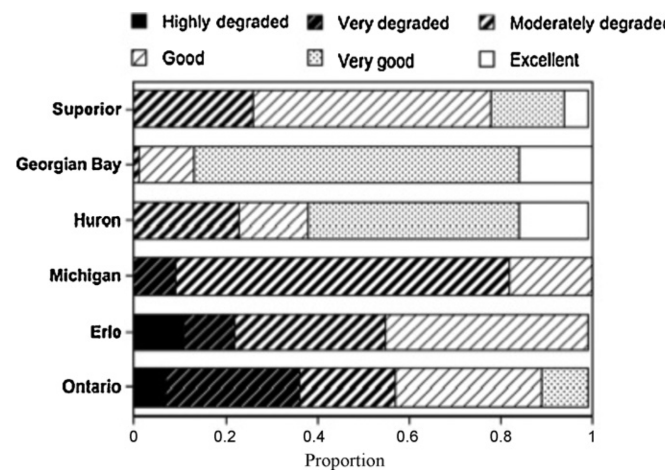

Fig. 2. Proportion of wetlands in each of the water quality categories (WQI: Chow-Fraser, 2006) sorted according to Great Lake origin.

Lakes Erie and Ontario were the only two lakes with wetlands in highly degraded states (11% and 7%, respectively; Figs. 1 and 2). Lakes Michigan, Ontario, and Erie were the only lakes with wetlands in very degraded categories (9%, 29% and 11%, respectively) and also tended to have a high proportion of marshes in moderately degraded conditions (73%, 21% and 33% respectively). Lakes Superior and Huron had approximately one-quarter of their wetlands in moderately degraded condition (25% and 23%), whereas Georgian Bay had only 1% of its wetlands in the moderately degraded state. All lakes had sites in the good category, where approximately half of the marshes sampled in Lakes Superior and Erie were in this condition. With the exception of Lake Erie, we found wetlands in very good condition for all other Great Lakes; however, Lakes Huron and Georgian Bay contained the highest numbers in this category (46% and 72% of wetlands, respectively). Lakes Superior (5%), Huron (15%), and Georgian Bay (16%) were the only water bodies in the Great Lakes that had sites that were classified as excellent quality (Fig. 2).

We calculated the proportion of wetlands considered to be "impacted" and "not impacted" using threshold values from all three indices (WQI = 0, WMI = 2.5, WFI = 3.25). Scores below these thresholds indicated sites that were in impacted condition as a result of anthropogenic use (see Table 3). All three indices showed that Georgian Bay, Huron, and Superior wetlands were primarily not impacted, as more than 50% of wetlands sampled were classified in this way (Table 3). While WQI scores found 82% of MI sites to be impacted, WMI and WFI scores classified more than half of MI wetlands as not impacted. Both WQI and WMI showed majority of ER and ON wetlands to be impacted, whereas WFI scores placed a

Table 3
Summary of percentage of wetlands in two quality categories, impacted and not impacted, sorted according to lake origin, for three ecological indices. Threshold scores indicating degradation are 0, 2.5 and 3.25 for WQI, WMI, and for WFI, respectively. Number of sites sampled and used in each index is indicated.

Lake	Condition	Ecological index		
		WQI	WMI	WFI
Superior	*N*	19	19	16
	Not impacted (%)	74	95	69
	Impacted (%)	26	5	31
Georgian Bay/North Channel	*N*	92	94	69
	Not impacted (%)	99	99	96
	Impacted (%)	1	1	4
Huron	*N*	13	11	8
	Not impacted (%)	77	82	75
	Impacted (%)	23	18	25
Michigan	*N*	11	3	8
	Not impacted (%)	18	67	75
	Impacted (%)	82	33	25
Erie	*N*	18	18	8
	Not impacted (%)	44	22	63
	Impacted (%)	56	78	37
Ontario	*N*	28	29	23
	Not impacted (%)	43	7	52
	Impacted (%)	57	93	48

minority of ER wetlands in this category (37%), and found ON sites to be approximately evenly distributed among the two states (48% and 52%, respectively).

4. Discussion

Our cross-lake comparisons provide confirmation of the high variability in wetland quality that exists within the Great Lakes basin. In doing this assessment, we have produced the first comprehensive survey of coastal wetland conditions across Canada and the United States, and provided baseline information against which impacts of future development may be measured. The resulting standardized database will be useful for establishing baseline conditions to track impacts of future development on minimally disturbed systems such as Lakes Huron, Superior, and Georgian Bay and to monitor the recovery of degraded wetlands in developed areas of the Lower Great Lakes (Lake Erie and Lake Ontario). Our results are in accordance with other studies that have evaluated anthropogenic impacts on different portions of the Great Lakes basin (e.g. Danz et al., 2007; Trebitz et al., 2007; Morrice et al., 2008). Furthermore, we have found that Georgian Bay, an under-studied area of Lake Huron, contains some of the most pristine, high-quality habitats in the entire Great Lakes basin.

Consistent with previous publications, our results show that wetlands in the southern portion of the Great Lakes basin are in a more degraded state compared to wetlands in the northern part. One reason is that the physical setting of the Lower Lakes that has led to enhanced growing conditions have enabled large human populations to settle in this region. Based on WQI scores, we can characterize Lakes Ontario and Erie as having the broadest disturbance gradient, with coastal wetlands spanning 5 of the 6 water-quality categories (no sites were found to be in excellent condition). They also had the highest proportion of degraded sites, where more than 20% were a combination of very degraded and highly degraded conditions. Majority of the sites we sampled in Lake Michigan were in the degraded categories (80%), and this seems to be consistent with the fact that human impact in the watershed of Lake Michigan is highest within the entire Great Lakes basin. Conversely, more than 70% of the coastal marshes in Lakes Superior, Huron, and Georgian Bay were in good or better condition, with Georgian Bay having the least number of wetlands in a degraded state. With the exception of Lake Huron, Georgian Bay had the highest WQI scores and Lakes Michigan, Erie and Ontario had significantly lower scores than those in Lakes Superior and Huron.

Danz et al. (2007) used a cumulative stress index (ranging from 0 to 5), based on individual stressors such as agriculture, atmospheric deposition, human population, land cover and point source pollution, to assess the differential impacts of human activities. They found Lake Superior to be on the lower end of the stress index (∼1.0), Lakes Michigan and Huron in the low-to-middle (∼2.3), and Lakes Ontario and Erie scoring highest on the stress index (∼3.0). Their results indicated that sites receiving the most human impact occurred in western Lake Michigan, southwestern Lake Erie, and southeastern Lake Ontario. Trebitz et al. (2007) showed Lake Erie coastal wetlands had the greatest nutrient and particulate levels, and lowest water clarity of 58 sites sampled on the U.S. coastal shore. Lakes Michigan and Ontario sites were intermediate, while Lakes Superior and Huron were the least disturbed (Trebitz et al., 2007). McNair and Chow-Fraser (2003) reported similar trends, with minimally impacted wetlands being located in Lake Superior while the most disturbed tended to be in Lake Erie's western basin.

In our study, majority of sites sampled in Lake Huron were located in the northern portion, with most occurring at the tip of the Bruce Peninsula (an archipelago of Lake Huron) within Fathom Five National Marine Park, which explains the relatively high quality scores calculated for the wetlands in this lake. This shore of Lake Huron is naturally oligotrophic (Parker and Munawar, 2001) and has much lower development than sites in the south. Only two wetlands from the southern portion were included, which is reflected in the moderately degraded scores (23%). We acknowledge that this study contains an under-representation of Lake Huron wetlands in both Canada and the U.S.; had we been able to sample more wetlands in the southern portion and near Saginaw Bay, we would have likely obtained a lower mean WQI score, which is reflective of the increased human development and disturbed status of those wetlands. This trend has been reported by Uzarski et al. (2005), where Saginaw Bay, Lake Huron proved to be more degraded than marshes located along the northern shore. Likewise, Niemi et al. (2009) described a north-south gradient of increasing deterioration in Lake Huron. Trebitz et al. (2007) exemplified similar effects for Lake Michigan, where Green Bay and other southern Michigan wetlands were associated with poorer water-quality conditions relative to those in the northern portion. Higher mean WQI scores would have been obtained for Lake Michigan if more sites along the north shore had been included.

A study by Morrice et al. (2008) described the relationship between water chemistry and various types of human disturbance for U.S. Great Lakes coastal wetlands, and found that water chemistry parameters were highly correlated to agricultural practices and other human activities. Their trends were very similar to those observed in this study, where we included data from both U.S. and Canada. Consistency between our basin-wide WQI scores and independently derived scores based on anthropogenic impacts confirms the utility of the WQI as an indicator of overall human-induced disturbance in the entire Great Lakes basin. A water-quality metric based on similar parameters that comprise the WQI (e.g. TN, TP, CHL, COND, TSS, etc.) was shown to vary predictably with an agricultural index for coastal wetlands along the U.S. shoreline (Trebitz et al., 2007). Comparable to the WQI, this water-quality metric requires a large number of variables to be computed; however Trebitz et al. (2007) suggested using a simpler version of the metric that only requires four variables (COND, Secchi, TN, and TP) and predicts the original metric with 94% accuracy. Likewise, WQI scores can be deduced from a much smaller subset of parameters: TURB, TSS, TP, COND, and TN, which are in fact analogous to those

Table A1
Summary of 181 Great Lakes coastal marshes sampled in this study, including site code, lake code (ER = Erie, GB/NC = Georgian Bay/North Channel, HU = Huron, MI = Michigan, ON = Ontario, SU = Superior), year surveyed, GPS coordinates, WQI (Chow-Fraser, 2006), WMI (Croft and Chow-Fraser, 2007), and WFI (Seilheimer and Chow-Fraser, 2007) scores.

Wetland	Code	Lake code	Year	Latitude	Longitude	WQI	WMI	WFI
Big Pond 1	BP1	ER	2005	41.96565	−82.52061	−0.21	2.33	–
Big Pond 2	BP2	ER	2005	41.96442	−82.50592	−0.39	–	–
Buckhorn	BU	ER	2001	43.056	−78.971	–	–	3.08
East Cranberry	EC	ER	2005	41.97153	−82.50759	−0.45	2.62	–
Grand River	GR	ER	2001	42.90000	−79.60000	−1.88	1.25	2.40
Long Point Big Creek	LPBC	ER	2001	42.95389	−80.44500	−0.82	–	–
Holiday Conservation	HO	ER	1996	42.03335	−83.05000	–	1.83	–
Long Point Big Rice	LPB	ER	2001	42.58930	−80.33550	−0.03	2.38	–
Long Point Inner Bay	LPI	ER	2001	42.59650	−80.34180	0.61	2.38	3.57
Long Point Inner Channel	LPC	ER	2001	42.59130	−80.33550	0.70	3.00	–
Long Point Little Rice	LPL	ER	2000	42.58930	−80.33550	0.33	2.22	–
Long Point Provincial Park	LPK	ER	1998	42.58333	−80.38333	0.73	2.24	–
Old Woman Creek	OW	ER	2001	41.38217	−82.51453	−2.42	1.00	1.88
Presque Isle	PR	ER	2000	42.15900	−80.09850	0.01	2.52	3.54
Redhead Pond	RH	ER	2005	41.95378	−82.50657	0.07	2.27	–
Rondeau Bay	RN	ER	2001	42.28800	−81.86700	0.41	2.75	3.38
Sanctuary Pond	SN	ER	2005	41.98032	−79.68722	−2.20	1.92	–
Selkirk Prov Park	SK	ER	1998	42.81667	−79.95000	−0.70	1.38	–
Spicer Creek	SP	ER	2001	43.023	−78.897	–	–	3.26
Turkey Creek	TC	ER	1996	41.97453	−83.08528	–	1.88	–
Turkey Point	TP	ER	2002	42.63359	−80.34170	0.64	2.48	3.81
West Cranberry	WC	ER	2005	41.97453	−82.51620	−1.69	2.28	–
Beaverstone	BV	GB/NC	2006	45.98478	−81.14576	1.53	3.41	3.31
Black Rock	BLR	GB/NC	2006	45.04196	−79.97280	–	3.68	–
Boom Camp	BC	GB/NC	2004	46.17320	−82.34966	0.90	3.21	3.65
Charles Inlet	CHI	GB/NC	2004	45.64623	−80.56799	1.19	3.07	3.83
Corbman Bay	CRB	GB/NC	2006	45.40907	−80.34146	1.39	3.49	4.04
Coffin Rock	CFR	GB/NC	2006	45.04797	−79.98839	–	3.66	–
Cormican Bay	CM	GB/NC	2006	45.40607	−80.30735	0.81	3.67	3.82
Cows Island	CI	GB/NC	2005	46.09859	−81.81942	1.32	3.78	–
David's Bay	DV	GB/NC	2006	45.04436	−80.00179	2.04	3.70	4.08
Dead Horse	DH	GB/NC	2005	46.10463	−81.60802	1.36	3.23	3.08
Deer Island	DI	GB/NC	2006	45.95841	−81.21973	1.94	3.63	3.93
Dogfish Bay	DF	GB/NC	2005	46.08091	−81.73593	1.36	3.28	3.79
Echo Bay	EB	GB/NC	2002	46.49453	−84.07597	0.05	3.38	3.50
Flat Point	FL	GB/NC	2006	46.09308	−81.89600	1.73	3.95	–
Francis Point	FP	GB/NC	2006	45.41439	−80.33293	1.40	3.73	3.96
French River Main	FRM	GB/NC	2005	45.96796	−80.88779	1.64	3.73	3.50
Gagons Pond	GP	GB/NC	2004	46.18951	−82.28385	0.86	3.12	–
Ganyon Bay	GY	GB/NC	2005	44.92052	−79.81763	1.43	3.86	3.46
Garden Channel	GC	GB/NC	2004	45.18506	−80.12245	1.62	3.61	4.00
Go Home Bay	GH	GB/NC	2004	44.99889	−79.92596	1.83	–	–
Gooseneck	GN	GB/NC	2004	45.20688	−80.10749	1.46	3.15	–
Green Island	GI	GB/NC	2004	44.78862	−79.74900	1.38	3.40	3.80
Herman's Bay	HRM	GB/NC	2005	45.21824	−79.86969	1.59	3.71	3.38
Hockey Stick Bay	HS	GB/NC	2005	44.94461	−79.86297	1.42	3.81	3.53
Hog Bay	HG	GB/NC	2004	44.73520	−79.80530	0.72	2.56	3.69
Hole in the Wall	HW	GB/NC	2007	45.52337	−80.43768	1.87	3.63	3.75
Ingersoll Bay	IB	GB/NC	2005	45.28132	−80.25588	1.78	3.84	4.12
Inukshuk Bay	IN	GB/NC	2006	45.55703	−80.38746	1.99	3.62	–
Iroquois Island	IQ	GB/NC	2004	46.08907	−81.63451	1.84	3.24	3.64
Isle of Pines	IP	GB/NC	2006	45.59791	−80.51900	1.88	3.78	4.04
Jumbo Bay	JB	GB/NC	2005	46.05244	−81.81858	1.77	3.71	3.81
Kenrick Bay	KB	GB/NC	2007	45.70101	−80.59750	2.08	3.53	3.23
Key River	KE	GB/NC	2003	45.88742	−80.67858	0.66	3.22	3.09
Key River 2	KE2	GB/NC	2006	45.88557	−80.69967	2.18	3.73	–
Key River 3	KE3	GB/NC	2006	45.88612	−80.69537	1.81	3.75	3.58
Kirk Creek	KC	GB/NC	2004	46.05806	−81.55288	1.23	3.27	–
La Cloche	LA	GB/NC	2006	46.05883	−81.85058	2.04	3.93	3.67
Lake St. Patrick	LSP	GB/NC	2006	44.97903	−79.93073	2.35	3.90	3.42
Lily Pond	LY1	GB/NC	2005	44.87037	−79.81478	−0.46	3.05	3.53
Little Current	LTC	GB/NC	2006	45.98240	−81.95436	1.07	3.08	3.62
Longuissa Bay	LG	GB/NC	2004	44.96727	−79.89125	2.03	3.86	3.55
Lost Channel	LCH	GB/NC	2006	45.59346	−80.51059	1.87	3.69	–
Matchedash Bay	MB	GB/NC	2006	44.76948	−79.68722	0.13	2.45	3.87
Miner's Creek Bay	MNC	GB/NC	2006	45.06153	−79.94913	2.46	3.54	3.75
Moon River Bay	MR	GB/NC	2003	45.12053	−79.97500	1.84	3.63	–
Moon River Falls	MF	GB/NC	2003	45.10733	−79.92995	2.09	3.52	–
Moose Bay	ME	GB/NC	2004	45.07210	−80.04958	1.85	3.22	3.82
Moreau Bay	MO	GB/NC	2004	45.01108	−79.94326	1.16	3.64	3.97
Musky Bay	MS	GB/NC	2004	44.81040	−79.78265	1.23	3.48	3.73
Naiscoot North 1	NN1	GB/NC	2004	45.66660	−80.56533	1.20	2.68	–
Naiscoot North 2	NN2	GB/NC	2004	45.67438	−80.57217	1.37	2.96	–
Naiscoot South	NS	GB/NC	2004	45.63708	−80.53516	1.36	3.42	–

Table A1 (*Continued*)

Wetland	Code	Lake code	Year	Latitude	Longitude	WQI	WMI	WFI
Ni Bay	NI	GB/NC	2005	45.40924	−80.45599	1.02	3.44	4.14
North Bay	NB	GB/NC	2005	44.89638	−79.79377	0.43	3.52	3.70
North Bay 2	NB2	GB/NC	2006	44.54074	−79.47043	1.03	–	–
Oak Bay	OB	GB/NC	2004	44.79630	−79.73158	1.12	2.86	3.63
Ojibway Bay	OJ	GB/NC	2005	44.88758	−79.85585	1.73	3.67	3.70
Otter Creek	OT	GB/NC	2005	45.95403	−80.82421	1.17	3.77	3.50
Pamplemousse Bay	PP	GB/NC	2006	45.05309	−80.00310	2.76	3.80	4.00
Parry Island 1	PY1	GB/NC	2006	45.28113	−80.10519	1.26	–	3.84
Parry Island 2	PY2	GB/NC	2006	45.28113	−80.10159	1.26	–	–
Parry Island 3	PY3	GB/NC	2006	45.29767	−80.08439	1.18	–	3.69
Port Rawson	RW	GB/NC	2003	45.19512	−80.02350	2.28	3.44	–
Port Rawson East	RWE	GB/NC	2004	45.17973	−80.02022	1.66	3.44	–
Port Rawson West	RWW	GB/NC	2004	45.19334	−80.02711	1.79	3.44	–
Prisque Bay 1	PQ1	GB/NC	2007	45.68822	−80.58307	1.78	3.56	3.69
Prisque Bay 2	PQ2	GB/NC	2007	45.69033	−80.58740	1.77	3.70	–
Quarry Island	QI	GB/NC	2004	44.83217	−79.80550	1.34	3.48	3.84
Rhodes Marsh 2	RM2	GB/NC	2007	45.52154	−80.46329	1.96	3.80	–
Robert's Bay	RB	GB/NC	2004	44.85540	−79.82855	1.44	3.11	3.89
Roseborough	RS	GB/NC	2006	44.99491	−79.92316	1.82	3.83	3.47
Salt & Pepper	SNP	GB/NC	2007	45.68613	−80.60104	1.80	3.58	3.91
Sand Channel	SCH	GB/NC	2006	45.61271	−80.51300	1.41	3.84	3.48
Sandy Island	SI	GB/NC	2003	45.26865	−80.25065	1.83	3.87	–
Sandy Island Lake	SIL	GB/NC	2005	45.27374	−80.25543	–	3.86	–
Sandy Island West	SIW	GB/NC	2005	45.27659	−80.26755	1.89	3.64	3.84
Shadow Bay	SHW	GB/NC	2006	45.94855	−80.73524	1.59	3.69	3.76
Shawanaga River	SWR	GB/NC	2006	45.56226	−80.36492	2.40	3.79	3.64
Spanish River	SR	GB/NC	2002	46.18339	−82.31691	–	2.50	–
Strawberry Island	SIS	GB/NC	2006	45.93766	−81.87421	2.00	3.24	3.91
Sturgeon Bay Central	ST	GB/NC	2003	45.61782	−80.43260	0.19	3.42	3.25
Sturgeon North	SG-N	GB/NC	2004	44.75365	−79.75706	–	–	3.42
Sturgeon South	SG-S	GB/NC	2004	44.75624	−79.74341	0.64	2.75	4.00
Sugar John	SJ	GB/NC	2006	45.93866	−81.17431	1.63	3.71	3.79
Tadenac Bay	TD	GB/NC	2004	45.13742	−79.99287	1.40	3.88	3.67
Tadenac Bay 1	TD1	GB/NC	2005	45.03444	−79.99145	1.41	4.10	3.79
Tadenac Bay 2	TD2	GB/NC	2005	45.03916	−79.98792	1.63	3.96	3.80
Tadenac Lake	TDL	GB/NC	2005	45.03437	−79.95509	2.79	3.84	3.56
Treasure Bay	TB	GB/NC	2005	44.86854	−79.86049	1.71	3.55	3.67
Thunder Bay	THB	GB/NC	2006	45.05144	−79.97033	–	3.90	–
Vincent's Bunk	VB	GB/NC	2004	46.05836	−81.62638	1.27	3.16	3.38
Walden's Pond	WP	GB/NC	2005	45.92294	−80.87577	1.51	3.62	3.35
Wardrope Island	WI	GB/NC	2005	46.05486	−81.71651	1.74	3.44	4.05
Waterfall Bay	WTF	GB/NC	2006	45.56276	−80.34467	2.50	3.90	3.61
West Bay	WE	GB/NC	2003	45.42228	−80.30727	0.52	3.50	3.68
West Bay	WBM	GB/NC	2007	46.07372	−81.67122	1.52	–	–
Wilson's Bay	WN	GB/NC	2006	44.99551	−79.95316	2.54	3.83	–
Woods Bay	WO	GB/NC	2004	45.48129	−80.20820	1.45	3.16	–
Baide Du Dore	BD	HU	1998	44.33670	−81.55570	–	1.58	–
Boat Passage	BG	HU	2005	45.28953	−81.71899	1.83	3.42	3.91
Cedarville	CV	HU	2002	45.98345	−84.35011	−0.02	–	3.38
Collingwood Harbour	CO	HU	1998	44.50920	−80.23260	–	2.00	–
Cove Island North	CN	HU	2005	45.31340	−81.76227	2.01	3.00	3.15
Cove Island North Pond	CNP	HU	2005	45.31436	−81.76046	–	3.36	–
Hay Bay 1	HB1	HU	2005	45.24089	−81.68385	1.12	3.29	3.88
Hay Bay 2	HB2	HU	2005	45.23341	−81.69424	0.79	3.35	3.60
Hay Bay 2a	HB2a	HU	2005	45.23459	−81.69380	1.60	–	–
Hay Bay 3	HB3	HU	2005	45.23483	−81.70277	1.22	–	–
Mackinac	MAC	HU	2002	46.00010	−84.40014	0.04	–	–
Mismer	MM	HU	2000	46.00510	−84.46060	–	3.14	–
Oliphant Bay	OL	HU	1998	44.73131	−81.28203	–	2.64	–
Ragged Bight	RG	HU	2005	45.24137	−81.69059	1.65	–	–
Russell Island East	RUE	HU	2005	45.26604	−81.68941	1.91	–	–
Russell Island West	RUW	HU	2005	45.26458	−81.70412	2.00	3.00	3.92
Wigwam Bay	WW	HU	2001	43.97020	−83.85430	−0.07	2.41	3.00
Wildfowl Bay	WF	HU	2000	43.81220	−83.46000	−0.79	–	–
Betsie	BE	MI	2000	44.61292	−86.21419	−0.26	–	3.50
Kalamazoo River	KZ	MI	2002	42.63348	−86.16682	−1.36	–	2.72
Lincoln	LN	MI	2002	44.85001	−87.15001	−0.71	–	3.25
Manistee	MN	MI	2002	44.26222	−86.29583	−0.47	–	3.20
Muskegon River	MU	MI	2002	43.25011	−86.25005	−0.03	–	3.28
Pentwater Marsh	PW	MI	2001	43.76280	−86.40780	−0.30	2.32	3.43
Peshtigo	PE	MI	2001	44.98400	−87.66070	0.91	2.61	–
Pigeon River	PG	MI	2002	42.89970	−86.18830	−0.33	–	3.67
Portage Creek	PC	MI	2001	45.70620	−87.08000	−0.55	2.75	–
Seagull Bar	SB	MI	2000	45.08440	−87.58940	−0.71	–	–
White River	WR	MI	2002	43.40024	−86.35001	0.15	–	3.57
Bayfield Marsh	BY	ON	2000	44.19758	−76.36500	−0.93	1.75	–
Blessington Bay	BB	ON	2002	44.16700	−77.33300	0.14	2.44	3.38

Table A1 (*Continued*)

Wetland	Code	Lake code	Year	Latitude	Longitude	WQI	WMI	WFI
Bronte Creek	BR	ON	2002	43.39340	−79.71546	−0.98	2.00	2.80
Cootes Paradise Marsh	CP	ON	2002	43.26667	−79.91672	−1.56	2.13	2.52
Credit River	CR	ON	2002	43.55007	−79.08358	−1.48	1.90	2.39
Darlington	DA	ON	2001	43.87300	−78.79700	−1.02	1.20	2.80
Fifteen Mile Creek	FM	ON	2002	43.16693	−79.31668	−1.99	1.73	2.56
Frenchman's Bay	FB	ON	2001	43.81233	−79.09467	−0.29	2.06	2.89
Goose Bay	GO	ON	2002	44.35005	−75.86671	0.11	2.22	3.70
Grass Bay	GS	ON	2002	44.15018	−76.26681	1.13	2.46	3.18
Grindstone Creek	GD	ON	2002	43.28333	−79.88333	−2.31	1.00	2.36
Hay Bay Marsh	HB	ON	2002	44.16675	−76.93335	0.45	2.44	3.53
Humber River	HM	ON	2002	43.61673	−79.48333	−1.42	1.50	2.64
Johnstown Creek	JN	ON	1998	44.73300	−76.46700	−1.23	1.69	–
Jordan Harbour	JH	ON	2002	43.15014	−79.38333	−1.95	1.79	2.96
Little Cataraqui Creek	LQ	ON	2002	44.21667	−76.55000	−1.28	2.11	3.44
Little Sodus	LS	ON	2001	43.33942	−76.69447	0.33	2.01	3.30
Madoma Creek	MA	ON	2002	44.26667	−76.38333	0.73	2.23	3.30
Mud Bay	MD	ON	2002	44.06682	−76.31672	−0.72	2.05	3.20
Muskellunge River	MK	ON	2002	43.96682	−76.05010	−0.43	2.24	3.48
Napanee River	NP	ON	1998	44.23333	−76.98333	−0.44	1.40	–
Perch River	PF	ON	2002	43.98361	−76.06688	0.14	2.66	3.43
Presqu'ile Prov Pk	PI	ON	2002	44.00000	−77.73060	0.47	2.78	3.43
Salmon River	SA	ON	2002	48.56667	−76.20004	1.28	2.16	3.65
Sandy Creek	SC	ON	2002	43.70089	−76.19647	1.06	2.48	3.38
Sawguin Creek	SW	ON	1996	44.10000	−77.38333	–	1.62	–
Second Marsh	SM	ON	1995	43.87500	−78.81320	–	2.47	–
Van Wagner's Pond	VW	ON	2007	43.25385	−79.76255	−2.03	–	–
Wellers Bay	WB	ON	2002	44.01679	−77.61670	1.00	2.20	3.48
West Lake	WL	ON	1998	43.93333	−72.28333	0.32	1.56	–
Au Train	AT	SU	2002	46.43334	−86.81681	0.67	2.94	3.73
Bark Bay	BK	SU	2000	46.85042	−91.19819	0.46	3.13	3.20
Batchawana 1	BW1	SU	2000	46.54558	−84.31062	–	–	3.70
Batchawana 2	BW2	SU	2004	46.54508	−84.30179	2.06	3.75	–
Chippewa Park	CW	SU	2002	48.31700	−89.20000	0.70	1.50	3.93
Cloud Bay	CB	SU	2002	48.08280	−89.43720	1.24	3.38	3.78
Flag	FG	SU	2002	46.78667	−91.38778	−0.11	3.14	3.62
Goulais River Oxbow	GX	SU	1998	46.71667	−84.41667	0.55	2.75	–
Hurkett Cove	HC	SU	2002	48.83080	−88.49470	−0.09	3.21	3.29
Laughing Whitefish	LF	SU	2002	46.51675	−87.01688	0.72	3.23	3.59
Lost Creek	LC	SU	2001	46.85861	−91.13583	0.71	3.28	3.45
Michipicoten River	MC	SU	2004	47.93336	−84.84595	–	3.00	–
Mission Island	MI	SU	2002	48.36480	−89.21420	0.76	–	–
Nemadji River	NJ	SU	2002	46.68353	−92.03340	−0.16	2.96	3.04
Pike River	PK	SU	2002	47.01676	−88.51679	1.01	3.12	3.07
Pine Bay	PB	SU	2001	48.03330	−89.51950	−0.02	3.05	3.50
Sioux River	SX	SU	2000	46.73430	−90.87790	0.57	2.81	3.23
Sturgeon Bay Slough	SU	SU	2002	47.00024	−88.48348	−0.13	3.00	3.43
Sturgeon Bay Superior	SS	SU	1998	48.19020	−89.31160	1.04	2.63	–
Taquamenon River	TQ	SU	2002	46.55010	−85.01691	0.90	2.71	3.83
West Fish Creek	WS	SU	2001	46.58420	−90.94610	0.70	2.75	3.24

described by Trebitz et al. (2007), and still achieve a prediction comparable to using all 12 parameters ($r^2 = 0.965$; Chow-Fraser, 2006). These simplified water quality indices can offer alternative solutions for researchers and may be an attractive avenue for researchers and managers facing diminished budgets for sampling and analyses.

When it comes to indicators of landuse and other anthropogenic-related impacts, water-quality metrics have proven to be very accurate because of their highly correlated relationship with pollutant loading from activities such as agriculture, urban development, and point-source pollution. These indicators are generally too costly to use by all environmental agencies, and thus, use of biotic indicators to assess and monitor coastal wetland condition has been viewed favourably over the past decade (Lougheed and Chow-Fraser, 2002; Wilcox et al., 2002; Uzarski et al., 2005; Niemi et al., 2007). The WMI and WFI are published indices that use macrophyte and fish species, respectively, to gauge water-quality conditions in coastal marshes, since both are significantly correlated with the WQI (Croft and Chow-Fraser, 2007; Seilheimer and Chow-Fraser, 2007; Seilheimer et al., 2009). In our basin-wide study, the WMI was able to discriminate between differences in quality among the lakes, such that Georgian Bay wetlands had significantly higher scores than all other lakes, and Lakes Superior and Huron had significantly greater values than Lakes Ontario and Erie. These results were similar to those conducted with WQI scores. It is noteworthy that mean WMI scores for Lakes Huron, Georgian Bay, and Superior are above 2.5, indicating that they do not yet show signs of degradation from human activities. By contrast, WMI scores for Lakes Erie, Ontario, and Michigan are close to or below 2.5, indicating that they show signs of human-induced degradation.

Similar to the WMI and WQI, the WFI was able to distinguish the higher average condition of Georgian Bay wetlands (mean WFI score of 3.68) from those of Lakes Erie and Ontario (both below 3.25). The WFI was also able to separate Lakes Huron and Superior (means above 3.25) from Lake Ontario, and the WFI-AB showed further that scores were significantly higher relative to Lake Erie as well, implying that differences in total abundance data led to significant differences between Huron, Superior and Erie wetlands. These findings tend to support the use of 3.25 as a threshold of degradation for the WFI.

Table A2
Summary of all macrophyte taxa included in the Wetland Macrophyte Index (WMI; Croft and Chow-Fraser), and their corresponding *U* (tolerance, 1 to 5) and *T* (niche breadth, 1 to 3) scores. % occurrence is based on the percentage of wetlands the species occurred in (*n* = 176). Asterisk (*) indicates species is non-indigenous. Reproduced from Croft and Chow-Fraser (2007).

Code	Taxon	Common name	*U* value	*T* value	% occurrence
Emergent					
ELAC	*Eleocharis acicularis*	Needle spike rush	4	3	9.1
ELSM	*Eleocharis smallii*	Marsh spike rush	4	2	32.9
EQFL	*Equisetum fluviatile*	Water horsetail	4	2	6.8
ERAQ	*Eriocaulon aquaticum*	Pipewort	5	3	17.6
LYSA	*Lythrum salicaria*	Purple loosestrife*	1	1	21.6
PLAM	*Polygonum amphibium*	Water smartweed	1	1	8.0
PLSP	*Polygonum* sp.	Smartweed	1	1	4.5
POCO	*Pontederia cordata*	Pickerelweed	3	2	48.3
SGCU	*Sagittaria cuneata*	Small arrowhead	3	1	9.7
SGLA	*Sagittaria latifolia*	Broad arrowhead	2	1	33.6
SGSP	*Sagittaria* sp.	Arrowhead species	2	1	6.8
SCAC	*Scirpus acutus*	Hardstem bulrush	4	2	30
SCAM	*Scirpus americanus*	Three-square bulrush	5	3	5.1
SCSP	*Scirpus* sp.	Bulrush	4	1	31.8
SCVA	*Scirpus validus*	Softstem bulrush	4	1	21.6
SPAD	*Sparganium androcladum*	Branched bureed	4	3	2.3
SPAN	*Sparganium angustifolium*	Narrow-leaf burreed	5	1	1.7
SPCL	*Sparganium chlorocarpum*	Greenfruit burreed	2	2	2.3
SPEM	*Sparganium emersum*	Unbranched burreed	1	2	2.5
SPEU	*Sparganium eurycarpum*	Giant burreed	3	2	10.8
SPSP	*Sparganium* sp.	Burreed	2	2	15.3
TYAN	*Typha angustifolia*	Narrow-leaf cattail*	1	1	21.0
TYLA	*Typha latifolia*	Broadleaf cattail	3	2	16.5
TYSP	*Typha* sp.	Cattail	1	1	23.3
TYXG	*Typha x glauca*	Hybrid cattail*	1	2	7.4
UTCO	*Utricularia cornuta*	Horned bladderwort	5	3	1.7
Floating					
BRSC	*Brasenia schreberi*	Water shield	4	1	21
EICR	*Eichhornia crassipes*	Water hyacinth*	1	1	0.6
HYMO	*Hydrocharis morsus-ranae*	Frogbit*	1	2	11.4
LEMI	*Lemna minor*	Lesser duckweed	1	1	11.4
LETR	*Lemna trisulca*	Ivy duckweed	2	2	7.4
NELU	*Nelumbo lutea*	American lotus	1	1	1.2
NUAD	*Nuphar advena*	Spatterdock	1	3	4.5
NUVA	*Nuphar variegata*	Common yellow pond lily	2	1	56.7
NYOD	*Nymphaea odorata*	Fragrant water lily (white)	2	1	66.5
NMCO	*Nymphoides cordata*	Little floating hearts	5	3	2.8
PIST	*Pistia stratiotes*	Water lettuce*	1	1	0.6
PONA	*Potamogeton natans*	Broad-leaved pondweed	2	1	30.7
SPFL	*Sparganium fluctuans*	Floating burreed	4	2	17.6
SPIR	*Spirodela polyrhiza*	Greater duckweed	1	1	5.1
TRNA	*Trapa natans*	Water chestnut*	1	1	0.6
WOLF	*Wolffia* sp.	Watermeal*	1	2	1.7
Submergent					
BIBE	*Bidens beckii*	Beck's marsh marigold	4	2	22.7
CABO	*Cabomba*	Fanwort	1	1	4.5
CASP	*Callitriche* sp.	Water starwort	4	2	10.2
CEDE	*Ceratophyllum demersum*	Coontail	1	1	45.5
CHSP	*Chara* sp.	Muskgrass	3	2	55.1
ELCA	*Elodea canadensis*	Canadian waterweed	2	1	63.6
HIVU	*Hippuris vulgaris*	Mare's tail	3	3	1.7
ISSP	*Isoetes* sp.	Quillwort	4	3	12.5
LODO	*Lobelia dortmanna*	Water lobelia	5	2	6.3
MYAL	*Myriophyllum alterniflorum*	Alternate water-milfoil	5	3	7.4
MYFA	*Myriophyllum farwellii*	Farwell's water-milfoil	3	1	0.6
MYHE	*Myriophyllum heterophyllum*	Two-leaf water-milfoil	3	2	8.0
MYSI	*Myriophyllum sibiricum*	Common water-milfoil	3	2	35.8
MYSC	*Myriophyllum spicatum*	Eurasian water-milfoil*	1	1	30.7
MYTE	*Myriophyllum tenellum*	Slender water-milfoil	4	3	8.5
MYVE	*Myriophyllum verticillatum*	Whorled water-milfoil	4	1	0.6
MYSP	*Myriophyllum* sp.	Water-milfoil	1	1	30.1
NAFL	*Najas flexilis*	Slender water nymph	3	2	51.7
NEAQ	*Neobeckia aquatica*	North american Lake-Cress	5	3	1.1
NISP	*Nitella* sp.	Stonewort	3	1	13.1
POAM	*Potamogeton amplifolius*	Large-leaved pondweed	4	2	25.0
POCR	*Potamogeton crispus*	Curly-leaf pondweed*	1	1	25.6
POEP	*Potamogeton epiphydrus*	Ribbon-leaf pondweed	4	3	10.8
POFO	*Potamogeton foliosus*	Leafy pondweed	2	1	0.6
POFR	*Potamogeton friesii*	Fries' Pondweed	2	1	1.1
POGR	*Potamogeton gramineus*	Variable pondweed	4	2	29.5
POIL	*Potamogeton illinoensis*	Illinois pondweed	3	2	8.0
POOB	*Potamogeton obtusifolius*	Bluntleaf pondweed	2	1	0.6

Table A2 (*Continued*)

Code	Taxon	Common name	*U* value	*T* value	% occur-rence
PO SLEN	*Potamogeton pusillus*	"Slender" pondweed	2	1	2.3
PORI	*Potamogeton richardsonii*	Clasping-leaved pondweed	3	2	64.8
PORO	*Potamogeton robbinsii*	Fern-leaf pondweed	4	2	25.0
POSP	*Potamogeton* sp.	Pondweed	1	2	21.0
POSR	*Potamogeton spirillus*	Northern snailseed pondweed	5	2	14.2
POVA	*Potamogeton vaseyi*	Vaseyi pondweed	2	1	0.6
POZO	*Potamogeton zosteriformis*	Flat-stemmed pondweed	3	1	38.1
RALO	*Ranunculus longirostris*	Buttercup, crowfoot	2	1	16.5
RASP	*Ranunculus* sp.	Crowfoot	2	1	1.1
SGGR	*Sagittaria graminea*	Grassy arrowhead	4	3	5.7
SCSU	*Scirpus subterminalis*	Water bulrush	5	2	13.6
SPON	Fresh water sponges	Sponges	5	3	9.7
STPE	*Stuckenia pectinata*	Sago pondweed	1	1	37.5
STVA	*Stuckenia vaginata*	Sheathed pondweed	2	1	0.6
UTGE	*Utricularia geminiscapa*	Hidden fruit bladderwort	5	3	1.1
UTGI	*Utricularia gibba*	Humped bladderwort	5	2	1.1
UTIN	*Utricularia intermedia*	Flatleaved bladderwort	3	2	5.1
UTMI	*Utricularia minor*	Lesser bladderwort	5	2	1.7
UTPU	*Utricularia purpurea*	Purple bladderwort	5	2	1.7
UTSP	*Utricularia* sp.	Bladderwort	3	2	4.0
UTVU	*Utricularia vulgaris*	Common bladderwort	3	2	30.0
VAAM	*Vallisneria americana*	Tape grass, eel grass	3	1	64.2
ZIPA	*Zizania* sp.	Wild rice	4	2	30.1
ZODU	*Zosterella dubia*	Water stargrass	2	2	5.7

All three indices were in agreement that majority (i.e. greater than 50%) of Georgian Bay, Huron, and Superior wetlands were not adversely impacted by human activities. There were, however, some discrepancies among index scores for Lakes Ontario, Michigan, and Erie. WFI scores showed Lake Ontario sites were evenly distributed between impacted and not impacted states, and the WQI and WMI scores did not support this. For Lake Erie on the other hand, WFI scores indicated that majority were not impacted, while corresponding WQI and WMI scores showed otherwise. Both WFI and WMI scores for Lake Michigan sites implied that most sites were not impacted, whereas results from WQI scores show that majority of these are impacted. These discrepancies may be attributed to insufficient sampling effort in some of the Lakes. Water quality parameters had been collected in 11 Michigan wetlands, while macrophyte and fish information had only been collected in 3 and 8 wetlands, respectively. This discrepancy in sampling effort is likely the reason that trends in WMI and WFI scores did not match that of the WQI. In the same way, fewer than half of the Erie sites sampled for water quality and macrophytes (18 and 18 sites, respectively) had been sampled for fish (8 sites), while fewer Ontario sites were sampled for fish than for water quality and plants (23 compared to 29 and 28, respectively). In all cases, we speculate that parallel sampling effort for all three indices would have led to more similar assessments and this should be ascertained in a proper study with randomly selected sites.

Seilheimer et al. (2009) evaluated the sensitivity of the WMI and WFI in relation to the WQI for 32 sites in the Great Lakes. They found that the WMI and WQI had the strongest relationship, exhibiting a polynomial correlation ($r^2 = 0.84$). Seilheimer et al. (2009) has suggested that the WMI is a more appropriate index to use than the WFI when evaluating high-quality wetlands such as those in Georgian Bay and Lake Superior. They attributed this to several factors: (1) unlike fish, plants are immobile and therefore unable to move when water quality conditions change, and (2) many fish species are generalists and are therefore able to survive across a large environmental gradient, thereby acting to lower scores in relatively pristine sites. Aside from the fact that macrophytes are extremely sensitive to water quality, Seilheimer et al. (2009) speculated that another reason the WMI performed best is due to the fact that the WMI was developed with many more sites (154) and a larger disturbance gradient relative to the WFI, which was developed with a smaller sample size (100).

Overall, both WFI and WMI were able to correctly match wetland quality to known patterns of land-use alterations and human disturbance throughout the five Great Lakes. Seilheimer et al. (2007) showed that the WFI could distinguish between two regions in Frenchman's Bay, a marsh in Lake Ontario, where scores were significantly lower in the northern portion located adjacent to a highway and urban watershed, compared with a site in the southern portion that received water from Lake Ontario that diluted these pollutants. Similarly, in the development of the WMI, Croft and Chow-Fraser (2007) showed that the WMI was able to successfully monitor changes in RAP sites within the Great Lakes basin. When used appropriately with regards to the points discussed above, both indices can be used to discern the habitat quality of coastal marshes within the Great Lakes and make valuable monitoring tools; however, if time and resources is not a consideration, we recommend using the WQI because it alone yields an accurate assessment of human-induced degradation of water quality in wetlands.

There is a strong theoretical and empirical basis that explains why fish and macrophyte assemblages are good indicators of human activities in coastal wetlands. Brazner and Beals (1997) found increased fish species richness and diversity in the less turbid wetlands in northern Green Bay compared to the highly turbid (agriculturally disturbed) wetlands in the southern portion of the bay. Uzarski et al. (2005) was able to create a fish IBI, after accounting for differences in vegetation communities, that showed fish responded to nutrients and surrounding agriculture within plant zones. A study by Brazner et al. (2007) tested the potential of various biota as indicators using a cumulative stress gradient, and found that in addition to birds, fish (e.g. abundance of rock bass *Ambloplites rupestris*) and wetland vegetation (e.g. number of invasive taxa) had the strongest relationship to human stresses. As for macrophytes, in a review paper investigating plant-based indicators, Albert and Minc (2004) established that a range of wetland disturbances including water-quality deterioration could be monitored using specific plant taxa. Lougheed et al. (2001) demonstrated that aquatic plants responded to water-quality degradation in terms of species richness and community structure, for both coastal and inland sites across the Great Lakes watershed. Clearly, eutrophication in terms of increased nutrient loading and suspended solids has a myriad of deleterious effects on fish and macrophyte assemblages in coastal marshes (Trebitz et al., 2009) and these effects can be used to ascertain information on habitat quality.

Table A3
Summary of all fish taxa included in the Wetland Fish Index (WFI; Seilheimer and Chow-Fraser), and their corresponding *U* (tolerance, 1 to 5) and *T* (niche breadth, 1 to 3) scores, for both the presence/absence (PA) and abundance (AB) index. Information on exotic species is also included (* non-native to Great Lakes, † native to Lake Ontario only). Reproduced from Seilheimer and Chow-Fraser (2007).

Species #	Family	Common name	PA		AB		Exotic
			U	*T*	*U*	*T*	
1	Amiidae	Bowfin	4	2	4	2	
2	Atherinopsidae	Brook silverside	4	2	4	2	
3	Catostomidae	Longnose sucker	5	3	5	3	
4		White sucker	3	1	3	2	
5		Silver redhorse	5	3	5	3	
6		Shorthead redhorse	4	2	4	2	
7	Centrarchidae	Rock bass	4	1	4	2	
8		Green sunfish	1	1	1	1	
9		Pumpkinseed	3	2	3	2	
10		Bluegill	3	1	3	1	
11		Longear sunfish	4	3	4	3	
12		Smallmouth bass	4	2	4	2	
13		Largemouth bass	3	2	3	2	
14		White crappie	1	1	1	1	
15		Black crappie	3	2	3	2	
16	Clupeidae	Alewife	2	2	1	2	*
17		Gizzard shad	1	2	1	2	
18	Cottidae	Mottled sculpin	4	3	4	3	
19		Slimy sculpin	4	2	4	2	
20	Cyprinidae	Goldfish	1	2	1	2	*
21		Spotfin shiner	2	1	1	1	
22		Common carp	2	1	1	1	*
23		Brassy minnow	1	2	1	2	
24		Common shiner	4	3	4	3	
25		Pearl dace	4	3	4	3	
26		Golden shiner	3	2	3	2	
27		Emerald shiner	3	2	3	2	
28		Blacknose shiner	4	2	4	2	
29		Blackchin shiner	5	3	5	3	
30		Spottail shiner	2	1	2	1	
31		Sand shiner	3	1	3	1	
32		Mimic shiner	5	3	5	3	
33		Northern redbelly dace	5	3	5	3	
34		Bluntnose minnow	3	1	4	2	
35		Fathead minnow	2	1	2	1	
36		Creek chub	3	1	3	1	
37	Esocidae	Redfin pickerel	4	3	4	3	
38		Northern pike	4	2	4	2	
39		Muskellunge	4	3	4	3	
40	Fundulidae	Banded killifish	4	3	4	3	
41	Gasterosteidae	Brook stickleback	4	2	4	2	
42		Threespine stickleback	2	2	2	1	†
43		Ninespine stickleback	4	3	4	3	
44	Ictaluridae	Black bullhead	3	2	3	2	
45		Brown bullhead	3	1	2	1	
46		Channel catfish	1	2	1	2	
47		Tadpole madtom	4	2	4	2	
48	Lepisosteidae	Longnose gar	5	3	5	3	
49	Moronidae	White perch	1	1	1	2	*
50		White bass	1	1	1	1	
51	Osmeridae	Rainbow smelt	4	3	4	3	*
52	Percidae	Iowa darter	5	3	4	3	
53		Least darter	4	3	5	3	
54		Johnny darter	3	2	3	2	
55		Yellow perch	3	2	3	2	
56		Logperch	3	2	4	2	
57		Walleye	4	3	4	3	
58	Percopsidae	Trout-perch	4	3	4	2	
59	Salmonidae	Round whitefish	4	3	4	3	
60	Sciaenidae	Freshwater drum	1	2	1	2	
61	Umbridae	Central mudminnow	4	2	4	2	

We acknowledge that our sampling effort was not evenly distributed and proportional to availability of wetlands across all five Great Lakes. To date, there are no comprehensive binational studies because of the problems associated with obtaining appropriate permits from government agencies. Some studies had comprehensive coverage of U.S. wetlands (e.g. Danz et al., 2007; Trebitz, etc.) while others had a binational focus but were not comprehensive (e.g. Uzarski et al., 2005: only Canadian wetlands in Lakes Erie and Ontario, and only U.S. wetlands in Lakes Huron, Michigan and Superior; Chow-Fraser, 2006; Croft and Chow-Fraser, 2007; Seilheimer and Chow-Fraser, 2007). To date, our studies are the only ones that include the pristine wetlands of eastern and northern Georgian Bay. It is challenging to organize collaborative sampling expeditions between U.S. and Canadian teams, but clearly future sampling programs must be designed to reflect proportional representation of wetlands in known inventories (i.e. GLCWC and the MCWI). Data sharing among academic and environmental organizations has been proposed as a mechanism for filling data gaps and building a more comprehensive dataset for the entire Great Lakes basin (Jude and Pappas, 1992; Niemi et al., 2007). By acquiring information from other regions of the Great Lakes we could expand our coverage of the basin and achieve a more comprehensive assessment of water-quality conditions. The advantage of indicators is that once data are acquired it is easy to compute an index score; this is especially true of the WMI and WFI, which merely require species presence-absence data in their calculations.

5. Conclusion

Overall, in this study we assessed the health of Great Lakes coastal marshes using published ecological indices that were developed with water-quality parameters collected from sites across a broad gradient of anthropogenic disturbance. Our analyses indicate that while a considerable number of coastal wetlands are in degraded conditions, particularly in Lakes Michigan, Erie, and Ontario, there are just as many in a healthy state, especially in Georgian Bay and Lakes Huron and Superior. There are some high-quality wetlands remaining on the Canadian shoreline of Lakes Ontario and Erie. Since pressure from human growth and subsequent expansion is expected to increase (Niemi et al., 2007), conservation efforts need to ensure that adequate research and money are allocated for these habitats so that further deterioration is prevented and their integrity is maintained. It is imperative to remember that coastal wetlands provide us with irreplaceable ecosystem services, without which biodiversity in the Great Lakes region would plummet.

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Appendix A.

See Table A1, Table A2, and Table A3.

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