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# Hydrogeomorphic Classification for Great Lakes Coastal Wetlands

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***ABSTRACT:*** *A hydrogeomorphic classification scheme for Great Lakes coastal wetlands is presented. The classification is hierarchical and first divides the wetlands into three broad hydrogeomorphic systems, lacustrine, riverine, and barrier-protected, each with unique hydrologic flow characteristics and residence time. These systems are further subdivided into finer geomorphic types based on physical features and shoreline processes. Each hydrogeomorphic wetland type has associated plant and animal communities and specific physical attributes related to sediment type, wave energy, water quality, and hydrology.*

***INDEX WORDS:*** *Classification, coastal wetlands, Great Lakes, geomorphology.*

## INTRODUCTION

There is a long-standing interest in classifying Great Lakes coastal wetlands to better understand wetland processes and biological composition, as well as to improve management (Geis and Kee 1977, Herdendorf *et al.* 1981a, Herdendorf 1988, Bowes 1989, Dodge and Kavetsky 1995, Edsall and Charlton 1997). Several other articles relevant to Great Lakes wetland classification were contained in a 1992 book edited by Busch and Sly on aquatic classification of lacustrine systems (Herdendorf *et al.* 1992; Leach and Herron 1992; McKee *et al.* 1992; Sly and Busch 1992a and b). This classification proposes finer distinctions between wetland types than found in the previously published Great Lakes wetland classifications, as well as physical attributes for each wetland type. In recent years, a hydrogeomorphic model (HGM) has been explored as a framework for wetland classification over a broad range of geographic and geologic conditions (Smith *et al.* 1995, Brinson 1996). The HGM approach to wetland classification was expanded to include Great Lakes coastal wetlands (Minc 1997, Chow-Fraser and Albert 1998, Keough *et al.* 1999, Albert and Minc 2001). It has also been observed that the distribution of geomorphic types is often regional, with certain hydrogeomorphic types concentrated on specific lakes or shoreline segments of

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lakes (Minc 1997, Chow-Fraser and Albert 1998, Albert and Minc 2004, Wei *et al.* 2004).

In 2002, a working group of Great Lakes wetland biologists, all members of the Great Lakes Coastal Wetland Consortium, developed a hydrogeomorphic wetland classification system that can be used to consistently characterize and potentially map all of the coastal wetlands of the Great Lakes. This paper presents that hydrogeomorphic classification, along with oblique aerial photographs to illustrate the types and attribute tables developed from existing wetland sampling studies (Albert *et al.* 1987, 1988, 1989; Environment Canada and Central Lake Ontario Conservation Authority 2004; Wilcox *et al.* 2002; Wilcox 2005). The above-mentioned wetland sampling studies were conducted in over 200 wetlands within all of the Great Lakes. Classifications were built with data collected from the U.S. Great Lakes (Minc 1997, Minc and Albert 1998, Albert and Minc 2004), but subsequent sampling was conducted in all of the Ontario Great Lakes, including the North Channel of Lake Huron and Georgian Bay.

## A HYDROGEOMORPHIC CLASSIFICATION FOR GREAT LAKES WETLANDS

Great Lakes coastal wetlands can be separated into three specific hydrogeomorphic systems, lacustrine (L), riverine (R), and barrier-protected (B), based on geomorphic position, dominant hydrologic source, and current hydrologic connectivity to the lake. In this classification, each wetland type is given a four character code (Fig. 1). The first character (L, R, or B) is for the *hydrologic system*. The second character (C, D, L, O, P, R, S) is for the *geomorphic type*. The third and fourth characters are further *geomorphic modifiers*.

**Lacustrine (L---)** system wetlands are controlled directly by waters of the Great Lakes and are strongly affected by lake-level fluctuations, nearshore currents, seiches, and ice scour. Geomorphic features along the shoreline provide varying degrees of protection from coastal nearshore processes. Lacustrine, as defined by the U.S. National Wetland Inventory (NWI), would also include dammed river channels and topographic depressions not related to Great Lakes. NWI does not consider wetlands with trees, shrubs, persistent emergents, emergent mosses or lichens with greater than 30% cover to be lacustrine; in contrast, in this classification these vegetation cover classes are considered to be lacustrine wetlands, focusing the classification on the lacustrine formation process. In addition, NWI only considers wetlands larger than 8 hectares to be lacustrine, while this classification includes smaller wetlands linked to the Great Lakes. NWI will include wetlands smaller than 8 hectares if a) a wave-formed or bedrock feature forms part or all of the shoreline or, b) it has a low-water depth greater than 2 meters in the deepest part of the basin.

**Riverine (R---)** system wetlands occur along and within rivers and creeks that flow into or between the Great Lakes. The water quality, flow rate, and sediment input are controlled in large part by their individual drainages. However, water levels and fluvial processes in these wetlands are directly or indirectly influenced by coastal processes because lake waters flood back into the lower portions of the drainage system. Protection from wave attack is provided in the river channels by bars and channel morphology. Riverine wetlands within the Great Lakes also include those wetlands found along large connecting channels between the Great Lakes; these connecting channels have very different dynamics than smaller tributary rivers and streams. NWI excludes palustrine wetlands, defined as dominated by trees, shrubs, persistent emergents, and emergent mosses or lichens, from riverine systems. In contrast, this classification includes all of these types of vegetation within the riverine system if the wetlands or portions of wetlands are regularly influenced by riverine processes.

**Barrier-Protected (B---)** system wetlands originate from either coastal or fluvial processes, but coastal nearshore and onshore processes separated these wetlands from the Great Lakes by a barrier beach or other barrier feature. The barriers may be active or part of relict coastal systems abandoned along the lake's margin. These wetlands are protected from wave action but may be connected directly to the lake by a channel crossing the barrier. When open to the lake, water levels in these wetlands are determined by lake levels, but the rate of water-level change in the wetlands is tempered by the rate of flow through the connecting channel. During isolation from the lake, groundwater and surface drainage to the basin of the individual wetland provide the dominant source of water input, although the lake level may influence groundwater flow and, hence, wetland water levels. Inlets to protected wetlands may be permanent or ephemeral, as nearshore processes can close off connecting channels. The frequency and duration of closures is related to the rate of sediment supply to the shoreline,

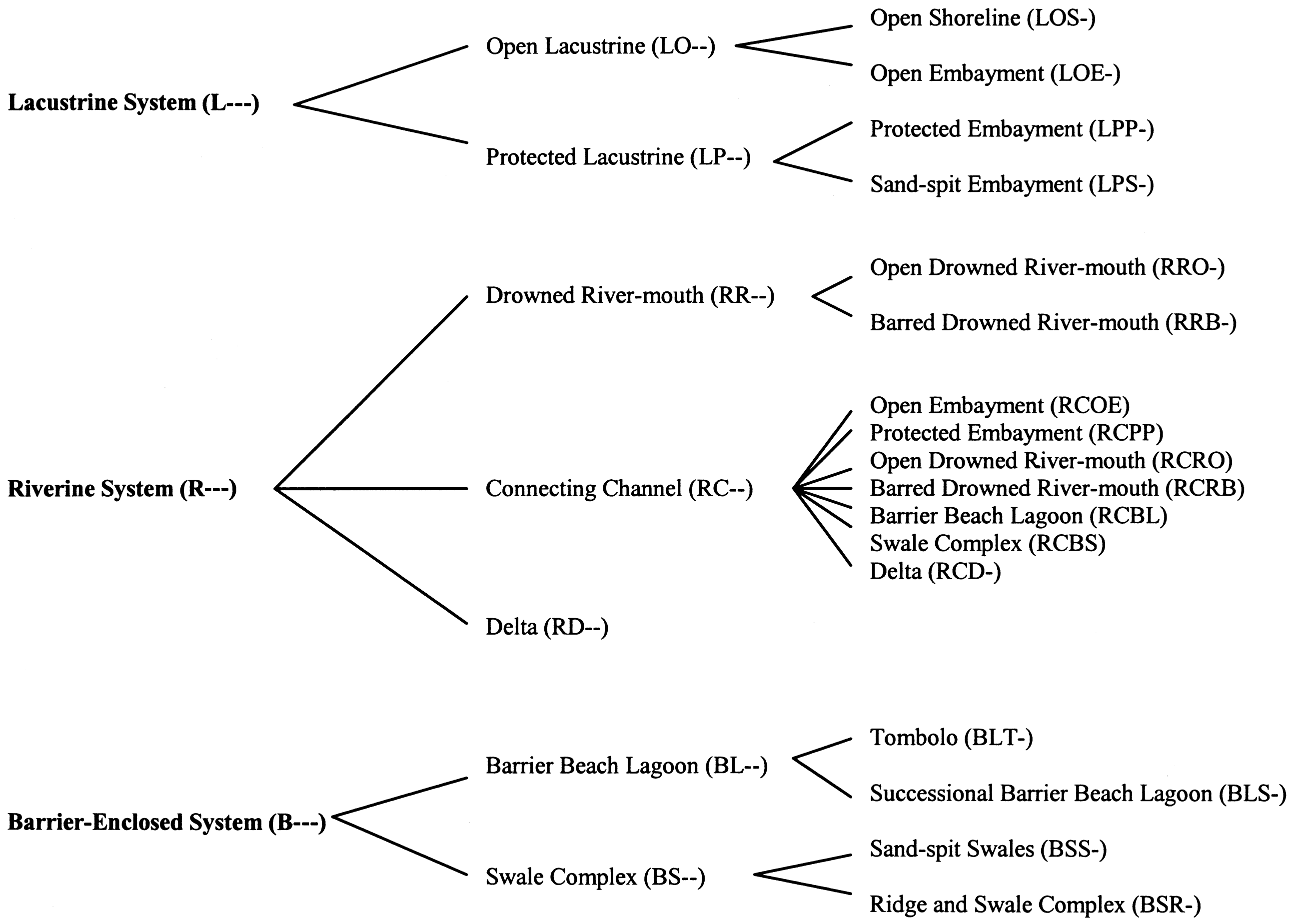


*FIG. 1. Hydrogeomorphic classification for Great Lakes marshes.*

grain size and sorting of sediment, type and duration of nearshore processes, lake-level elevation and rate of change, and discharge rate of water exiting through the inlet. Most of these wetlands would be classified by NWI as palustrine, with small water bodies or streams within the wetland possibly being classified as inclusions of either lacustrine or riverine system.

Within these hydrologically based systems, Great Lakes coastal wetlands can be classified further based on their geomorphic features and shoreline processes (Fig. 1).

## Lacustrine System (L---)

### Open Lacustrine (LO--)

These lake-based wetlands are directly exposed to nearshore processes, with little or no physical protection by offshore geomorphic features (bars and spits). This exposure results in little accumulation of organic sediment and restricts vegetation development to relatively narrow nearshore bands. Exposure to nearshore processes also results in a variable bathymetry, ranging from relatively steep profiles to more shallow sloping beaches.

***Open Shoreline.*** **(LOS-)** This wetland type is typically characterized by an erosion-resistant substrate of either rock or clay, with occasional patches of mobile substrate. Such systems are starved of detrital sediment. The resultant expanse of shallow water serves to dampen waves, and if littoral sediment is available may result in sand-bar development at some sites. There is almost no organic sediment accumulation in this type of environment. Vegetation development is limited to narrow fringes of emergent vegetation extending offshore to the limits imposed by wave climate. Some smaller

*FIG. 2. Lacustrine hydrologic system: Open embayment (LOE-), St. Martin Bay (MI), Lake Huron. Sand bars in the foreground are indicative of a high-energy coastal environment.*

embayments also fit into this class due to exposure to prevailing winds; most of these have relatively narrow vegetation zones of 100 meters or less. Examples include Epoufette Bay (MI) on Lake Michigan and shoreline reaches in the Bay of Quinte (ON) on Lake Ontario. In past mapping efforts along the Great Lakes, few *open shoreline* wetlands were identified by either Herdendorf et al. (1981a–f) or NWI. Many *open shorelines* do not have large or dense enough areas of aquatic plants to be identified from aerial photography.

***Open Embayment.*** **(LOE-)** This wetland type can occur on gravel, sand, and clay (fine) substrates (Fig.2). The embayments are often quite large—large enough to be subject to storm-generated waves and surges and to have established nearshore circulation systems. Most bays greater than three or four kilometers in diameter fit into this class. These embayments typically support wetlands that are 100 to 500 meters wide over broad expanses of shoreline. Most of these wetlands accumulate only shallow organic sediments near their shoreline edge. Large parts of Saginaw and St. Martin bays (MI) on Lake Huron, Little Bay de Noc (MI) and Green Bay (WI) on Lake Michigan, Long Point Bay (ON) on Lake Erie, and Black River Bay (NY) on Lake Ontario all fit in this category.

**Protected Lacustrine (LP--)**

This wetland type is also a lake-based system; however, it is characterized by increased protection by a sand-spit, offshore bar, or till- or bedrock-enclosed bay. Subsequently, this protection results in increased mineral sediment accumulation, shallower off-shore profiles, and more extensive aquatic vegetation development than the open lacustrine counterpart. Organic sediment development is also more pronounced.

***Protected Embayment.*** **(LPP-)** Many stretches of bedrock or till-derived shorelines form small protected bays, typically less than three or four kilometers in width (Fig. 3). These bays can be completely vegetated with emergent or submergent vegetation. At the margins of the wetlands there is typically 50 to 100 cm of organic accumulation beneath wet meadow vegetation. Examples include Duck Bay and Mackinac Bay in the Les Cheneaux Islands (MI) in Lake Huron,

***FIG. 3. Lacustrine hydrologic system: Protected embayment (LPP-), Duck Bay (MI), northern Lake Huron.***

***FIG. 4. Lacustrine hydrologic system: Sand-spit embayment (LPS-), Pinconning Bay (MI) within Saginaw Bay, Lake Huron.***

***FIG. 5. Riverine hydrologic system: Open drowned river-mouth (RRO-), Crooked Creek (NY), St. Lawrence River.***

Matchedash Bay (ON) in Lake Huron, and Bayfield Bay (ON) on Wolfe Island in Lake Ontario. A type of protected embayment encountered along localized stretches of the Great Lakes shoreline is the ***solution embayment*** **(LPPS)**. These roughly circular indentations in the bedrock are formed by solution processes in carbonate rock. These indentations are occasionally open to the Great Lakes, forming a protected embayment. The latter wetland type occurs along the shoreline of northern Lakes Michigan, Huron, and Ontario. One example is El Cajon Bay (MI) in northern Lake Huron.

***Sand-Spit Embayment.*** **(LPS-)** Sand spits projecting along the coast create and protect shallow embayments on their landward side (Fig. 4). Spits often occur along gently sloping and curving sections of shoreline where there is a positive supply of sediment and sand transport is not impeded by natural or man-made barriers. These wetlands are typically quite shallow. Moderate levels of organic soils are typical, similar to those found in other protected embayments. Examples include Pinconning Marsh (MI) in Saginaw Bay, Dead Horse Bay (WI) in Green Bay, and Long Point (ON) in Lake Erie.

**Riverine System (R---)**

***Drowned River-Mouth*** **(RR--)**
The water chemistry of these wetlands can be affected by both the Great Lakes and river water, depending on Great Lakes water levels, season, and amount of precipitation (drainage discharge). These wetlands typically have deep organic soils that have accumulated due to deposition of watershed-based silt loads and protection from coastal processes (waves, currents, seiche, etc.). The terms "estuarine" or "fresh-water estuarine" are used by some researchers (Herdendorf et al. 1981a) as alternatives to *drowned river-mouth*.

***Open Drowned River-Mouth.*** **(RRO-)** Some drowned river-mouths do not have barriers at their mouth, nor do they have a lagoon or

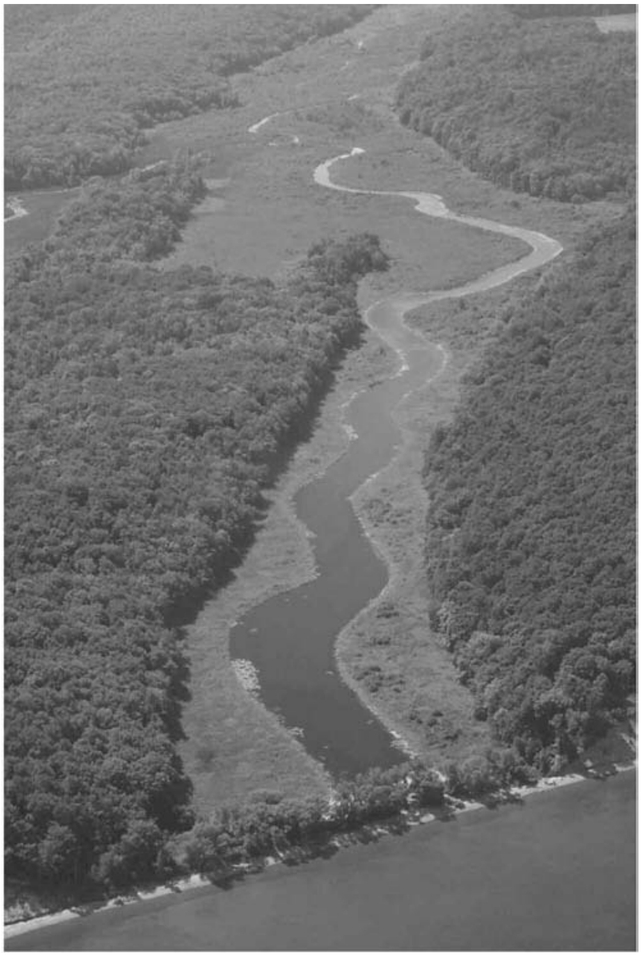

***FIG. 6. Riverine hydrologic system: Barred drowned river-mouth (RRB-), Beaver Creek (ON), Lake Ontario.***

small lake present where they meet the shore (Fig. 5). The wetlands along these streams occur along the river banks, and their plant communities are growing on deep organic soils. Examples include the West Twin River on the Wisconsin shore of Lake Michigan, the Kakagon River on the Wisconsin shore of Lake Superior, and the Greater Cataraqui River on the Ontario shore of Lake Ontario.

***Barred Drowned River-Mouth.* (RRB-)** Most streams that are considered drowned river-mouths actually have a barrier that constricts the stream flow as it enters the lake (Fig. 6). Very often, a lagoon forms behind the barrier. However unlike barrier beach wetlands, these wetlands maintain a relatively constant connection to the lakes because of the large prism of water that must exit through the barrier. The lagoons seldom support large wetlands and vegetation is concentrated where the stream enters the lagoon (if present), but can extend several kilometers upstream, typically forming a fringe of emergent and submergent vegetation along the edges of the channel. Organic deposits are often greater than two meters thick. Barred drowned river-mouths include both large rivers and small streams. The channel is seldom completely barred when the rivers are large, while smaller streams are often completely separated from the lake by a sand barrier. Smaller streams are occasionally or frequently separated from the lake until pressure from stream flow blows out the sand barrier. Most large rivers now have dredged channels with jetties that are maintained open for boat traffic year round. Examples of barred, drowned river-mouths on large rivers include the Kalamazoo, Muskegon, and Manistee rivers (MI) in Lake Michigan. Small barred streams include the Dead River (IL) in Lake Michigan, Old Woman Creek (OH) in Lake Erie, Sixmile Creek (MI) in Lake Superior, and Duffins Creek (ON) in Lake Ontario.

***Connecting Channel (RC--)***

This wetland type includes the large connecting rivers between the Great Lakes; the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence rivers (Fig. 7). These wetlands are distinctive from the other large river wetlands (drowned river-mouth) by the general lack of deep organic soils and the often strong currents. The St. Marys and St. Lawrence rivers contain some of the most extensive fringing shoreline and tributary drowned river-mouth wetlands in the Great Lakes, while those along the Detroit and Niagara rivers have been largely eliminated or degraded. The Detroit River still has major beds of submergent aquatic plants.

Connecting channels are large enough to contain several types of wetlands, each with their classification. Recent mapping of the St. Marys and St. Lawrence rivers included 1000s of hectares of open embayment (*Connecting Channel, open embayment* (RCOE)), protected embayment (*Connecting Channel, protected embayment* (RCPP)), open drowned river-mouth (*Connecting

***FIG. 7. Riverine hydrologic system: Connecting channel (RC--), St. Marys River (MI, ON).***

*Channel, open drowned river-mouth* (RCRO)), barred drowned river-mouth (*Connecting Channel, barred drowned river-mouth* (RCRB)), (*Connecting Channel, barrier beach lagoon* (RCBL)), (*Connecting Channel, swale complexes* (RCBS)), and deltaic wetlands (*Connecting Channel, delta* (RCD-)). Other subtypes were also represented along the connecting channels, but with lesser coverage.

***Delta (RD--)***

Deltas formed of both fine and coarse alluvial materials support extensive wetlands that extend out into the Great Lake or connecting river (Fig.8). These are extensive wetlands, typically with 30 to 100 cm of organic soils associated with their wet meadow zone, and often with deep organics occupying abandoned distributary channels and interdistributary bays. Both fluvial processes and wave action can contribute to the morphology of deltas along the Great Lakes. Examples are the St. Clair River (MI and ON), Goulais River (ON), and the Munuscong River (MI) deltas. The Munuscong River delta (Fig. 8) enters into the much larger St. Marys River, a connecting river between Lake Superior and Lake Huron. Fluvial processes are evident in the morphology of all three of these deltas, but the morphology of portions of the Goulais River delta are strongly affected by wave action.

**Barrier-Enclosed System (B---)**

***Barrier Beach Lagoon (BL--)***

These wetlands form behind a sand barrier (Fig. 9). Because of the barrier, there is reduced mixing of Great Lakes waters and exclusion of coastal processes within the wetlands. Multiple lagoons can form and water discharge from ground water, upland areas, and incoming drainages may all contribute significantly to the water supply. These wetlands are common at the east end of Lake Ontario and also on the Bayfield Peninsula (WI) in western Lake Superior. Thick organic soils characterize these wetlands in Lake Superior and in many, but not all, of the Lake Ontario wetlands. Examples of barrier beach lagoon wetlands include Oshawa Second Marsh and Big Sand Bay (ON), South Colwell Pond (NY), and Round Pond (NY) in Lake Ontario,

*FIG. 8. Riverine hydrologic system: Delta (RD--), Munuscong River (MI). Because the Munuscong River is a tributary of the St. Marys River, a connecting channel between Lake Superior and Lake Huron, the Munuscong River delta would be coded RCRD.*

*FIG. 9. Barrier-enclosed hydrologic system: Barrier beach lagoon (BL--), Big Bay (WI), Lake Superior.*

***FIG. 10. Barrier-enclosed hydrologic system: Tombolo (BLT-), Stockton Island (WI), Lake Superior.***

and Bark Bay, Siskiwit Bay, and Allouez Bay (WI) in Lake Superior. Great Marsh (IN, IL) at the southern tip of Lake Michigan formed in a similar setting. In addition to barrier beach lagoons, *tombolo* (BLT-) are present in selected areas of the Great Lakes (Fig. 10). These are defined as islands attached to the mainland by barrier beaches, some of which consist of one or two lagoons with deep organic soils. Small swale complexes are sometimes included within a tombolo. Small barrier beach lagoons often are completely dominated by vegetation, with no open water remaining. Such completely vegetated barrier beach lagoons are classified as *Successional Barrier Beach Lagoons* (BLS-).

***Swale Complexes (BS--)***

There are two primary types of swale complex wetlands—those that occur between recurved fingers of sand spits and those that occur between relict beach ridges (Fig. 11). These are known respectively as *sand-spit swales* (BSS-) and *ridge and swale complexes* (BSR-) (also referred to as dune and swale or strandplain). The former are common within some of the larger sand spits of the Great Lakes, primarily Presque Isle (PA) and Long Point (ON) in Lake Erie and Whitefish Point (MI) in Lake Superior. Numerous small swales are separated from the Great Lakes, often becoming shrub swamps with shallow organic soils. Within these sand-spit formations, there are often embayments which remain attached to the Great Lakes, thus maintaining their herbaceous flora.

Ridge and swale complexes are composed of a series of beach ridges separated by narrow swales. These systems commonly occur in embayments where there is an abundant supply of sediment. More than 100 of these complexes occur in the upper Great Lakes alone (Comer and Albert 1991, Comer and Albert 1993, Baedke *et al.* 2004). The ridges are interpreted to have formed in response to quasi-periodic fluctuations in lake level that have occurred during the past several thousand years (Thompson and Baedke 1995, 1997; Baedke and Thompson 2000). For many of these complexes, only the first couple of swales are in direct hydrologic connection to the lake, but in some, like Pte. Aux Chenes (MI) along northern Lake Michigan, the connection continues for several swales and hundreds of meters inland (Comer and Albert 1991). Organic soil depths are quite variable, as is the vegetation, which ranges from herbaceous to swamp forest to peatland. Of particular importance to these types of wetland systems is the amount of groundwater

***FIG. 11. Barrier-enclosed hydrologic system: Ridge and swale complex (BSR-), Stockton Island (WI), Lake Superior.***

supply that the embayment receives and the relative importance of drainages. The former can enhance groundwater discharge into the system, whereas the latter is instrumental in removing groundwater and surface water. Other examples of this wetland type include the Ipperwash Interdunal Wetlands Complex along southern Lake Huron (ON), the Grand Traverse embayment on the Keweenaw Peninsula (MI) in Lake Superior, and the adjacent Manistique and Thompson embayments (MI) in northern Lake Michigan.

### System Modifiers of Naturally Occurring Great Lakes Wetlands

The hydrology and/or geomorphology of all Great Lakes coastal wetlands have been affected by human activities within the Great Lakes basin. These impacts are through whole-lake regulation, watershed alterations, or activities within the wetland itself (i.e., diking, dredging, and in-filling). Direct modification of the hydrologic connection with the lake results in different hydrologic and wetland community responses to Great Lake events (e.g., high/low water level) than would be observed in wetlands of the same classification. Identification of human modifiers in naturally occurring coastal wetlands is important to understanding coastal processes and response to change and thus should be noted when classification is undertaken. In this Great Lakes wetland classification, codes for system modifiers have not been developed for mapping purposes.

## DISCUSSION

### Hydrologic Systems

The greatest physical and biological differences between coastal wetlands are typically seen at the Hydrologic System level, resulting from differences in water-flow characteristics and residence time (Sly and Busch 1992a). Sly and Busch identified four aquatic systems, lacustrine, connecting channel, riverine, and estuarine. In this classification, aquatic systems are modified into three hydrologic systems, lacustrine, riverine, and barrier-enclosed. The lacustrine class is identical for both classifications, including all of the wetlands directly connected to the Great Lakes. Three of Sly and Busch's classes are joined, connecting channel, riverine, and estuarine, into a single "riverine" class, separating these flowing systems at a lower level in the classification. All members of the riverine class are characterized by flowing water, with variable levels of influence by the Great Lakes water chemistry and movement. A third class of "barrier-enclosed" wetlands is also added. These wetlands are nearly or completely separated from the open Great Lakes by a barrier created by wave or current deposition of mineral sediment. The most common form of barrier is a sand-dune-capped beach ridge, but gravel and cobble bars form where the coastal sediment is coarse and wave action extreme. Separation by a barrier results in barrier-enclosed wetlands having greater levels of distinction from the connected lacustrine and riverine wetlands. In earlier classifications, lacustrine and barrier-enclosed wetlands were joined by some researchers (Minc 1997, Albert and Minc 2001) because both wetlands were formed by lacustrine processes.

This classification shares classes with that developed by Keough *et al.* (1999), but further divides their hydrogeomorphic types into finer types. This finer subdivision is based on wetland differences observed during sampling; some of these physical differences result in major floristic differences. For example, protected embayments and sand-spit embayments are both protected lacustrine types, but the slope gradient of most protected embayments is greater than that of sand-spit embayments. Floristic change in response to water-level fluctuations is much more rapid and dramatic in the shallow sand-spit embayments. Many sand-spit embayments become mudflats during low water levels, resulting in massive seed production by emergent plants like stiff arrowhead (*Sagittaria rigida*), nodding beggarticks (*Bidens cernuus*), soft-stem bulrush (*Schoenoplectus tabernaemontani*), bur-reeds (*Sparganium* spp.), and nodding smartweed (*Polygonum lapathifolium*). Another strong contract can be seen between barrier beach lagoons and ridge-and-swale complexes, both barrier-protected wetland types. Barrier beach lagoons are typified by large areas of open water, while ridge-and-swale complexes are often only flooded in one or two swales close to the shoreline. Such differences in water area result in major floral and faunal contrasts.

It should be noted that these systems are different than those defined by the United States Fish and Wildlife Service in the National Wetlands Inventory (NWI) (Cowardin *et al.* 1979) and the Ontario Ministry of Natural Resources, Wetland Evaluation System (WES) (Ontario Ministry of Natural Resources 1993). Both classifications define three *systems* or *site types*, Lacustrine, Riverine, and Palustrine, with an additional Isolated type in the WES. Both systems also have wetland *classes* or *types (Aquatic bed* or *Emergent)* that are included within this wetland classification, which are identified based upon vegetative, hydrologic, and/or substrate attributes. This hydrogeomorphic classification is viewed primarily as a tool for better understanding the dynamics and biota of coastal wetlands, not as a replacement or substitute for NWI or WES. However, it should also be noted that while participating in a Great Lakes-wide wetland classification and mapping project, it has became clear that there is a lack of consistence in NWI and WES coding of Great Lakes coastal wetlands, and many wetlands were also not mapped by NWI.

The subdivisions of riverine wetlands by Sly and Busch (1992a) into connecting channel, riverine, and estuarine have been largely reworked in this classification, although connecting channels continue to be recognized as a distinctive type. The connecting channels are limited to only five rivers, the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence, but these rivers and their wetlands are distinctly different from other Great Lakes riverine wetlands. All of the channels are characterized primarily by large flow from the upstream Great Lake rather than water flowing from adjacent uplands (Edsall *et al.*1988, Hudson *et al.* 1992). Some are large enough to support wetlands along their margins that resemble lacustrine wetlands. All of these large rivers are channelized and modified to allow ship traffic between the lakes. This classification divides tributary streams into two classes, delta and drowned river-mouth. Delta wetlands form where river-borne sediments are deposited into the shallow waters of the Great Lake. Where fluvial processes dominate, the delta is more bird's-foot shaped. Wave-dominated deltaic systems are more wedge- or triangle-shaped. In contrast, drowned river-mouth wetlands form when Great Lakes water levels rise high enough to flood the lower reaches of a stream valley. Drowned river-mouths have been called estuaries or freshwater estuaries by some (Herdendorf 1990, Sly and Busch 1992a, Albert and Minc 2001), but the term estuary continues to be controversial in the freshwater environment of the Great Lakes.

## Lacustrine Wetlands

The majority of the Great Lakes shoreline is characterized by high wave energy that does not allow for the development of coastal wetlands. Wetland plants cannot establish in this environment, either because the sediment is too mobile for plants to root or because plant tissues are destroyed by wave action. A few emergent plants, primarily bulrushes or spike rushes (*Eleocharis* spp.), can establish locally in some open shore environments (Tables 1 and 2). Bulrushes can survive by sending roots and rhizomes into underlying dense clay or by rapidly expanding roots into shifting sand. Stems of bulrush are quite flexible, allowing survival in high wave-energy environments. The spike rushes in this extreme environment are often annuals exploiting new, open habitat. None of the plants in this habitat require accumulations of organic material.

Open embayments are also characterized by relatively high wave energy, but shallow water and more stable sediments reduce the destructive effects of wave action on the existing emergent plant communities (Tables 1 and 2). All of the open embayments studied by the authors were underlain by fine-textured (clay) soils, where much of the rooting occurred. Even when the above-ground portions of bulrushes were destroyed by wave action during storms, the rhizomes persisted. Thin accumulations of sand, typically less than 30 cm in depth, are

***TABLE 1. Attributes of Great Lakes hydrogeomorphic wetland types: mineral sediment, organic sediment, wave energy, and hydrologic connection to lake.***

| Hydrologic System | Geomorphic Type | Mineral Sediment | Organic Sediment | Wave Energy | Hydrologic Connection to Lake |
|---|---|---|---|---|---|
| Lacustrine (L) | Open shore (LOS) | Variable: cobble-clay | None to localized | High | Direct |
| | Open embayment (LOE) | Variable: cobble-clay | Thin (0–10 cm) | Moderate- High | Direct |
| | Protected embayment (LPP) | Variable: sand-clay | Moderate (10–60 cm) | Low- Moderate | Direct (less exchange in shallow water near shore) |
| | Sand-spit embayment (LPS) | Spit sediments: sand-gravel. Bay sediments variable: sand-clay | Moderate (10–60 cm) | Low- Moderate | Direct (less exchange in shallow water near shore) |
| Riverine (R) | Connecting channel (RC) | Variable: sand-clay | Moderate (10–60 cm) | Low to High | Direct |
| | Delta (RD) | Variable: gravel-clay | Moderate-thick (10 cm to > 1 m), layered with fine to coarse mineral soil | Low to High | Direct on outer edge. Greater stream influence in main channel and distributaries |
| | Drowned river-mouth, barred (RRB) | Variable: gravel-clay. Sand barrier separates lake. | Thick (>1m) at stream margins and often in channel as well | Low | When periodically barred, greater influence from stream than lake; two-way seepage; fluctuations of lake level influences river near lake |
| | Drowned river-mouth, open (RRO) | Variable: gravel-clay | Thick (> 1 m) at stream margins; often absent in main channel | Low to Moderate | Direct; fluctuations of lake can influence river several kilometers upstream |
| Barrier-enclosed (B) | Barrier beach lagoon (BL) | Barrier sediments: Cobble-sand. Lagoon sediments: sand-clay | Thick (>1 m); May be layered with sand-clay | Low or none | Restricted: some indirect seepage through barrier; prime influences stream or precipitation |
| | Swale complex (BS) (ridge and swale complex, sand-spit swales, tombolo) | Sand | Thin to thick (0 cm to >1m); thickness dependent on local to regional groundwater flow systems | None | Restricted: some indirect seepage through barrier; prime influence of stream, precipitation , and groundwater focusing from surrounding uplands |

***TABLE 2. Attributes of Great Lakes hydrogeomorphic wetland types: chemical, turbidity, vegetation, and fauna.***

| Hydrologic System | Geomorphic Type | Chemical[1] | Turbidity | Vegetation | Fauna |
|---|---|---|---|---|---|
| Lacustrine (L) | Open shore (LOS) | Lake controlled | Lake controlled | Thin-stem emergents (bulrushes), or aquatic vegetation absent due to high wave energy | Low diversity of invertebrates, fish, and waterbirds |
| | Open embayment (LOE) | Lake controlled | Lake controlled | Low diversity emergent zone adapted to high wave energy and ice scour, narrow wet meadow | Moderate diversity of invertebrates, fish, and waterbirds tolerant of high wave energy |
| | Protected embayment (LPP) | Lake and watershed controlled | Lake and watershed controlled | Broad, high diversity emergent, wet meadow, and submergent zones | High diversity of invertebrates and fish, with moderate diversity of waterbirds |
| | Sand-spit embayment (LPS) | Lake and water-shed controlled, shallow and warm | Lake and watershed controlled | Broad, high diversity emergent, wet meadow, and submergent zones | High diversity of invertebrates, fish, and waterbirds |
| Riverine (R) | Connecting channel (RC) | Lake and ground-water controlled | River and lake controlled | Variable; narrow to broad emergent and wet meadow zones, submergent zone often present | Variable diversity of invertebrates, fish, and waterbirds |
| | Delta (RD) | River and lake control | Lake and river controlled | Variable; emergent, submergent, and wet meadow zones all typically present and broad; wild rice often common; plants tolerant of short-term flooding | High diversity of invertebrates, fish, and waterbirds |
| | Drowned river-mouth, barred (RRB) | River controlled | River controlled | Dense emergent and submergent zones; wild rice often common. Peatland vegetation common in wet meadow zone on Lake Superior. | Invertebrates and fish tolerant of low oxygen levels and high temperatures; moderate diversity of waterbirds |
| | Drowned river-mouth, open (RRO) | River and lake controlled | River and lake controlled | Broad wet meadow and emergent zones. Submergents restricted to portions of stream with low flow conditions. | Moderate diversity of invertebrates and fish; moderate diversity of waterbirds |
| Barrier-enclosed (B) | Barrier beach lagoon (BL) | Ground-water and precipitation control, vegetation and precipitation can acidify | Lagoon controlled with only minor lake influence | Submergent, emergent, and wet meadow zones can be present; all species tolerant of organic soils. On Lake Superior, Georgian Bay, and eastern Lake Ontario peatland vegetation often dominant. | Invertebrates and fish tolerant of low oxygen levels and high temperatures; high diversity of waterbirds |
| | Swale complex (BS) (ridge and swale complex, sand-spit swales, tombolo) | Ground-water, precipitation, and minor lake control; vegetation and precipitation can acidify | Lagoon or swale controlled with only minor lake influence | Shallow systems often with shrub, emergent, and wet meadow zones; all species tolerant of organic soils. On Lake Superior, Georgian Bay, and eastern Lake Ontario peatland vegetation often dominant. | Invertebrates and fish tolerant of low oxygen levels and high temperatures; fish often absent or quite localized; moderate diversity of waterbirds |

[1]All of the Great Lakes have circumneutral pH, including Lake Superior. Alkalinity of all Great Lakes is high, with the exception of Lake Superior.

common throughout the shallow marsh. The high wave energy results in little organic sediment accumulation and relatively low plant diversity, as most emergent and submergent aquatic plants cannot tolerate this high energy environment. Higher diversity could be found locally in shallow, nearshore areas. In the shallowest open embayments, a strong chemical gradient develops between the outer marsh and the protected inner marsh, resulting in distinctly different invertebrate and fish fauna for these marsh zones (Cardinale *et al.* 1998, Burton *et al.* 2002). Although the overall productivity of open embayments is typically low, the overall area of the wetlands can be large, making them quite significant as wildlife and fish habitat.

Protected embayments are typically much smaller than open embayments, creating a protected environment where the emergent and submergent marsh zones are broad and biologically diverse (Tables 1 and 2). The wet meadow zone is also typically broad and biologically diverse, with significant accumulations of organic material. Wave action remains strong enough to limit the accumulation of organic material, but allows for a diverse flora of floating and submergent plants. Major water-level fluctuations of the Great Lakes do not typically result in major changes in vegetation; this is one of the most biologically stable wetland types in the Great Lakes. Wave energy increases with the size of protected embayments, resulting in greater response to water level fluctuations. Basin morphology is diverse in this wetland type and determines the range of plants found in a specific wetland.

Sand-spit embayments, a specialized type of protected embayment, also have broad zones of wet meadow, emergent, and submergent vegetation, but are subject to more severe erosion during Great Lakes high water conditions (Harris *et al.* 1977, 1981; Albert, personal observation), when storm waves can almost eliminate submergent and emergent vegetation (Tables 1 and 2). Small sand-spit embayments, such as those found in Saginaw Bay (MI) in Lake Huron and Green Bay (WI) in Lake Michigan, are typically shallow, often with water less than 2 meters deep; vegetation often covers the entire bay in these smaller wetlands. Water depth can be much greater and wave action much more severe in the larger bays, such as those associated with Presque Isle (PA) and Long Point (ON) in Lake Erie. These large embayments have vegetation much more similar to that found in open embayments. Sediment accumulation can be considerable in the shallow sand-spit embayments, but these sediments can be redistributed to the larger lake during high-water storm events. Inter-annual water-level fluctuations result in some of the most dramatic vegetation changes encountered in the Great Lakes. The organic sediments of the sand-spit embayments contain a high diversity of seeds, with tremendous changes in plant composition, coverage, and structure sometimes occurring on an almost annual basis.

## Riverine Wetlands

The connecting channels are the riverine wetlands most similar to the lacustrine wetlands. Portions of the channel shorelines are protected, allowing for broad, diverse wetlands to develop, with organic sediment accumulation reaching 50 cm in the wet meadow zone (Tables 1 and 2). Other portions of the channel are subject to ice scour and wave action, resulting in narrower zonation. Great Lakes water-level fluctuations can affect the vegetation of large segments of some connecting rivers, such as the St. Marys. High water levels in 1987 resulted in erosion of extensive areas of cattail in Munuscong Bay on the St. Marys River, while the same areas were being recolonized by a diversity of plants under 1989 low-water conditions (Albert, unpublished data).

Deltas occur on both tributary rivers and connecting channels. Main channels of these larger rivers are generally open, with little or no submergent vegetation, while smaller distributary channels support diverse beds of submergent vegetation. Variability is perhaps the greatest in the deltas, providing habitat for a broad range of plants and animals (Duffy *et al.* 1987, Edsall *et al.* 1988). Water flow and temperature variability allow both warm and cold-water fish to feed and spawn within the larger Great Lakes deltas. Sediment ranges from mineral to organic, depending on the differing flow rates within the wetland.

Drowned river-mouths are often separated from their associated Great Lake by a dune or sand-spit barrier, resulting in distinctive differences in water chemistry between the two (Tables 1 and 2). The barrier and river channel also provide protection from storm waves, resulting in accumulation of deep organic soils within the riverine wetland. The lower reaches of the stream are often wide and deep enough to form small lakes behind a protective sand barrier, and delta-like wetlands form where the streams meet these small lakes. The majority of this wetland type is sedge-, grass-, or cattail-dominated wet meadow growing on deep organic soils. The open channels on smaller, slower flowing streams are typically rich in submergent vegetation, while the main channel of larger streams supports little or no submergent vegetation due to strong currents and unstable sediment. Water-level fluctuations of the Great Lakes can result in major changes to this wetland type, especially during low-water conditions. As water levels drop, exposed organic-rich sediments along the stream margins are rapidly colonized by annuals or short-lived perennials, such as soft-stem bulrush, cut grass (*Leersia oryzoides*), and nodding beggar-ticks. The wet meadow vegetation can also change dramatically as the deep organic soils are exposed, sometimes forming steep banks above the level of the river. Urban development characterizes the watershed of many drowned river-mouths, resulting in heavy nutrient and sediment loading and highly turbid waters, often eliminating submergent vegetation.

### Barrier-enclosed Wetlands

These wetlands, largely separated from the adjacent Great Lake, often have water chemistry and temperatures very different from the adjacent lake (Tables 1 and 2). Lake water may enter during storm overwash or seep through the porous sand or gravel barrier separating the two water bodies. The protective barrier also allows for accumulation of thick organic sediments, especially in barrier beach lagoons. Succession to swamp forest, shrub swamp, or peatland is common in this wetland type. Barrier-enclosed wetlands are prevalent where there is abundant seasonal deposition of sand and where bedrock or cobble form the shoreline. On Lake Superior's rocky, steep shoreline, almost all wetlands are protected behind a sand, gravel, or cobble barrier.

Barrier beach lagoons form where a barrier separates a bay from the larger lake. Decomposing vegetation accumulates and often acidifies the lagoon, especially along Lake Superior, where alkalinity of the bedrock and water is low. As Sphagnum mosses establish at the margins of the wetlands, conditions become increasingly acidic, resulting in the dominance of peatland vegetation (Crum 1976, 1988). These peatlands are typically a stable wetland type that can persist for thousands of years. The combination of shallow, warm water and vegetation accumulation create an extreme environment that has low invertebrate and fish diversity, as well as reduced waterbird diversity. In some of the more southern barrier beach lagoon systems, warmer temperatures and higher alkalinity result in less accumulation of organic material. These more open lagoons support a greater diversity of plants and animals.

Swale complexes are also isolated from the open lake (Tables 1 and 2). The upper portions of these complexes are completely isolated from the lake, receiving their water from ground-water flow and precipitation. These wetlands may be flooded only seasonally and are typically dominated by shrub or treed swamp or peatlands in more northerly areas. The undisturbed accumulation of organic materials has allowed stratigraphic documentation of the age and historic vegetation of these wetlands (Thompson 1992, Thompson and Baedke 1995, Lichtner 1998). Small streams flowing from the swale complexes allow small fish tolerant of low oxygen conditions to use portions of the wetland complex, and it is common to see raptors and other birds nesting in the wetland conifers. In the lower Great Lakes, hardwood swamps often dominate the swales.

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## REFERENCES

Albert, D.A., and Minc, L.D. 2001. Abiotic and floristic characterization of Laurentian Great Lakes' coastal wetlands. Stuttgart, Germany. *Verh. Internat. Verein. Limnol.* 27:3413–3419.

_____, and Minc, L.D. 2004. Plants as indicators for Great Lakes coastal wetland health. *Aquat. Ecosys. Health Manage.* 7(2):233–247.

_____, Reese, G., Crispin, S.R., Wilsmann, M.R., and Ouwinga, S.J. 1987. *A survey of Great Lakes marshes in Michigan's Upper Peninsula.* Michigan Natural Features Inventory, Lansing, MI.

_____, Reese, G., Crispin, S.R., Penskar, M.R., Wilsmann, L.A., and Ouwinga, S.J. 1988. *A survey of Great Lakes marshes in the southern half of Michigan's Lower Peninsula.* Michigan Natural Features Inventory, Lansing, MI.

_____, Reese, G., Penskar, M.R., Wilsmann, L.A., and Ouwinga, S.J. 1989. *A survey of Great Lakes marshes* *in the northern half of Michigan's Lower Peninsula and throughout Michigan's Upper Peninsula.* Michigan Natural Features Inventory, Lansing, MI.

Baedke, S.J., and Thompson, T.A., 2000. A 4,700-year record of lake level and isostasy for Lake Michigan. *J. Great Lakes Res.* 26:416–426.

_____, Thompson, T.A., Johnston, J.W., and Wilcox, D.A., 2004. Reconstructing Paleo Lake Levels from Relict Shorelines along the Upper Great Lakes. Special Issue on Lake Superior. *Aquat. Ecosys. Health Manage.* 7:435–449.

Bowes, M.A. 1989. *Review of the geomorphological diversity of the Great Lakes shore zone in Canada.* University of Waterloo, Waterloo, Ontario. Heritage Resources Centre Technical Paper No. 4.

Brinson, M.M. 1996. Assessing wetland functions using HGM. *National Wetlands Newsletter* 18:10–16.

Burton, T.M., Stricker, C.A., and Uzarski, D.G. 2002. Effects of plant community composition and exposure to wave action on habitat use of invertebrate communities of Lake Huron coastal wetlands. *Lakes & Reservoirs: Research and Management* 7:255–269.

Cardinale, B.J., Brady, V.J., and Burton, T.M. 1998. Changes in the abundance and diversity of coastal wetland fauna from the open water/macrophyte edge towards shore. *Wetland Ecology and Management* 6:59–68.

Chow-Fraser, P., and Albert, D.A. 1998. *Biodiversity Investment Areas: Coastal Wetland Ecosystems.* State of the Great Lakes Ecosystem conference background paper. United States Environmental Protection Agency and Environment Canada, Buffalo, NY.

Comer, P.J., and Albert, D.A. 1991. *A Survey of Wooded Dune and Swale Complexes in the Northern Lower and Eastern Upper Peninsulas of Michigan.* Michigan Natural Features Inventory, Lansing, MI.

_____, and Albert, D.A. 1993. *A Survey of Wooded Dune and Swale Complexes in Michigan.* Michigan Natural Features Inventory, Lansing, MI.

Cowardin, L.M., Carter, V., Golet, F.C., and LaRoe, E.T. 1979. *Classification of wetlands and deepwater habitats of the United States.* U. S. Fish and Wildlife Service, Washington, DC. FWS/OBS-79/31.

Crum, H. 1976. *Mosses of the Great Lakes Forest.* Ann Arbor, MI: University Herbarium, University of Michigan.

_____. 1988. *A Focus on Peatlands and Peat Mosses.* Ann Arbor, MI: The University of Michigan Press.

Dodge, D., and Kavetsky, R. 1995. *Aquatic habitat and wetlands of the Great Lakes.* State of the Great Lakes Ecosystem conference background paper. Environment Canada and United States Environmental Protection Agency. EPA 905-R-95-104.

Duffy, G.W., Batterson, T.R., and McNabb, C.D. 1987. *The St. Marys River, Michigan: an Ecological Profile.* U.S. Fish Wildlife Service, Washington, DC. Biol. Rep. 85 (7.10).

Edsall, T.A., and Charlton, M.N. 1997. *Nearshore Waters of the Great Lakes.* State of the Great Lakes Ecosystem conference background paper. EPA 905-R-97-015a Cat. No. En40-11/35-1-1997E.

_____, Manny, B.A., and Raphael, C.N. 1988. *The St. Clair River and Lake St. Clair, Michigan: An Ecological Profile.* U.S. Fish Wildlife Service, Washington, DC. Biol. Rep. 85 (7.3).

Environment Canada and Central Lake Ontario Conservation Authority. 2004. *Durham Regional Coastal Wetland Monitoring Project: Year 2 Technical Report.* Downsview, ON: ECB-OR.

Geis, J.W., and Kee, J.L. 1977. *Coastal wetlands along Lake Ontario and the St. Lawrence River in Jefferson County, New York.* SUNY College of Environmental Science and Forestry. Syracuse, NY.

Harris, H.J., Bosley, T.R., and Rosnik, F.D. 1977. Green Bay's coastal wetlands: A picture of dynamic change. In *Wetlands, Ecology, Values, and Impacts: Proceedings of the Waubesa Conference on Wetlands*, eds. C. B. DeWitt and E. Soloway, pp. 337–358. Madison, WI: University of Wisconsin's Institute of Environmental Studies.

_____, Fewless, G., Milligan, M., and Johnson, W. 1981. Recovery processes and habitat quality in a freshwater coastal marsh following a natural disturbance. In *Selected Proceedings of the Midwest Conference on Wetland Values and Management*, ed. B. Richardson, pp. 363–379. St. Paul, MN: Minnesota Water Planning Board.

Herdendorf, C.E. 1988. *Classification of geological features in Great Lakes nearshore and coastal areas. Protecting Great Lakes Nearshore and Coastal Diversity Project*. International Joint Commission/The Nature Conservancy, Windsor, Ontario.

_____. 1990. Great Lakes estuaries. *Estuaries* 13:493–503.

_____, Hartley, S.M., and Barnes, M.D. (eds.). 1981a. *Fish and wildlife resources of the Great Lakes coastal wetlands within the United States, Vol. 1: Overview.* U.S. Fish and Wildlife Service, Washington, DC. FWS/OBS-81/02-v1.

_____, Hartley, S.M., and Barnes, M.D. (eds.). 1981b. *Fish and wildlife resources of the Great Lakes coastal wetlands within the United States, Vol. 2: Lake Ontario*. U.S. Fish and Wildlife Service, Washington, DC. FWS/OBS-81/02-v2.

_____, Hartley, S.M., and Barnes, M.D. (eds.). 1981c. *Fish and wildlife resources of the Great Lakes coastal wetlands within the United States, Vol. 3: Lake Erie.* U.S. Fish and Wildlife Service, Washington, DC. FWS/OBS-81/02-v3.

_____, Hartley, S.M., and Barnes, M.D. (eds.). 1981d. *Fish and wildlife resources of the Great Lakes coastal wetlands within the United States, Vol. 4: Lake Huron.* U.S. Fish and Wildlife Service, Washington, DC. FWS/OBS-81/02-v4.

_____, Hartley, S.M., and Barnes, M.D. (eds.). 1981e. *Fish and wildlife resources of the Great Lakes coastal wetlands within the United States, Vol. 5: Lake Michigan.* U.S. Fish and Wildlife Service, Washington, DC. FWS/OBS-81/02-v5.

_____, Hartley, S.M., and Barnes, M.D. (eds.). 1981f. *Fish and wildlife resources of the Great Lakes coastal wetlands within the United States, Vol. 6: Lake Superior.* U.S. Fish and Wildlife Service, Washington, DC. FWS/OBS-81/02-v6.

_____, Hakanson, L., Jude, D.J., and Sly, P.G. 1992. A review of the physical and chemical components of the Great Lakes: a basis for classification and inventory of aquatic habitats. In *The development of an aquatic habitat classification system for lakes*. Eds. W.-D.N. Busch and P.G. Sly, pp. 109–160. Ann Arbor, MI: CRC Press.

Hudson, P.L., Griffiths, R.W., and Wheaton, T.J. 1992. Review of habitat classification schemes appropriate to streams, rivers, and connecting channels in the Great Lakes drainage basin. In *The development of an aquatic habitat classification system for lakes.* Eds. W.-D.N. Busch and P.G. Sly, pp. 73–108. Ann Arbor, MI: CRC Press.

Keough J.R., Thompson, T.A., Guntenspergen, G.R., and Wilcox, D.A. 1999. Hydrogeomorphic factors and ecosystem responses in coastal wetlands of the Great Lakes. *Wetlands* 19:821–834.

Leach, J.H., and Herron, R.C. 1992. A review of lake habitat classification. In *The Development of an aquatic habitat classification system for lakes*. Eds. W.-D.N. Busch and P.G. Sly, pp. 27–58. Ann Arbor, MI: CRC Press.

Lichtner, J. 1998. Primary succession and forest development on coastal Lake Michigan sand dunes. *Ecological Monographs* 68:487–510.

McKee, P.M., Batterson, T.R., Dahl, T.E., Glooshenko, V., Jaworski, E., Pearce, J.B., Raphael, C.N., Whillans, T.H., and LaRoe, E.T. 1992. Great Lakes aquatic habitat classification based on wetland classification systems. In *The development of an aquatic habitat classification system for lakes*. Eds. W.-D.N. Busch and P.G. Sly, pp. 27–58. Ann Arbor, MI: CRC Press.

Minc, L.D. 1997. *Great Lakes coastal wetlands: An overview of abiotic factors affecting their distribution, form, and species composition*. Michigan Natural Features Inventory, Lansing, MI.

_____, and Albert, D.A. 1998. *Great Lakes coastal wetlands: abiotic and floristic characterization.* Michigan Natural Features Inventory, Lansing, MI.

Ontario Ministry of Natural Resources. 1993. *Ontario Wetland Evaluation System, Southern Ontario Manual*. 3rd Edition. Ontario Ministry of Natural Resources, Peterborough, Ontario.

Sly, P.G., and Busch, W.-D.N. 1992a. Introduction to the process, procedure, and concepts used in the development of an aquatic habitat classification system for lakes. In *The development of an aquatic habitat classification system for lakes*. Eds. W.-D.N. Busch and P.G Sly, pp. 1–14. Ann Arbor, MI: CRC Press.

_____, and Busch, W.-D. N. 1992b. A system for aquatic habitat classification of lakes. In *The development of an aquatic habitat classification system for lakes*. Eds. W.-D.N. Busch and P.G. Sly, pp. 15–26. Ann Arbor, MI: CRC Press.

Smith, R.D., Ammann, A., Bartoldus, C., and Brinson, M.M. 1995. *An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands and functional indices.* U.S. Army Corps of Engineers, Waterways Experimental Station, Vicksburg, MS. Tech. Rpt. TR-WRP-DE-9.

Thompson, T.A. 1992. Beach-ridge development and lake-level variation in southern Lake Michigan. *Sedimentary Geol.* 80:305–318.

_____, and Baedke, S.J. 1995. Beach-ridge development in Lake Michigan: shoreline behavior in response to quasi-periodic lake-level events. *Marine Geol.* 129:163–174.

_____, and Baedke, S.J., 1997. Strandplain evidence for late Holocene lake-level variations in Lake Michigan. *Geological Society of America Bulletin* 109:666–682.

Wei, A., Chow-Fraser, P., and Albert, D. 2004. Influence of shoreline features on fish distribution in the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* 61(7):1113–1123.

Wilcox, D.A. 2005. Lake Michigan wetlands: classification, concerns, and management opportunities. In *State of Lake Michigan*, eds. M. Munawar and T. Edsall, (in press). Amsterdam, The Netherlands: Ecovision World Monograph Series, S.P.B. Academic Publishing.

_____, Meeker, J.E., Hudson, P.L., Armitage, B.J., Black, M.G., and Uzarski, D.G. 2002. Hydrologic variability and the application of index of biotic integrity metrics to wetlands: a Great Lakes evaluation. *Wetlands* 22:588–615.

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