Ecosystem Responses to Regulation-based Water Level Changes in the Upper Great Lakes

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Executive Summary

This synoptic overview summarizes knowledge of the relationships between coastal ecosystems and water level variation in the upper Great Lakes (UGL). It proposes sensitive indicators that may be used to distinguish among effects of new outflow regulation schemes for Lake Superior, relative to the existing regulation plan, Plan 77A. The report identifies databases, tools, and models that have been developed for a range of existing ecosystem impact assessments and that may be suitable for addressing anticipated proposed water level regulation changes for the UGL. The primary frames of reference for evaluating potential ecosystem effects were the five ‘fencepost’ water regulation scenarios (commonly referred to as Plan 77A, MH Plan, HPP Plan, SupPlan, and PreProj) proposed for the UGL relative to current regulation.

Although the UGL have been extensively studied, most research has occurred over relatively short time frames, and few studies have addressed ecological effects of changing water levels. The ecological characteristics of coastal margin ecosystems reflect dynamic interactions among physical, geochemical, and biological components of the environment. UGL ecosystems have evolved under natural climatic variability since de-glaciation and cyclical changes in lake levels over time periods ranging from seasonal to millennial play an important role in the coastal processes that structure nearshore ecosystems.

The hydrogeomorphic areas most likely to be affected by changes to natural variability and absolute water levels are coastal, protected and riverine wetlands, beaches and dune systems, tributary connections and their estuaries, islands, and perhaps other coastal margin environments. Most biota associated with coastal margins respond directly to habitats formed, maintained, and made accessible through water level fluctuations. However, they are also influenced by antecedent conditions, biogeography, climate, weather events, and anthropogenic stresses to those habitats, such as nonpoint and point source pollution, invasive species, shoreline development, and upstream landscape or watershed influences. The relative importance of these factors and their consideration in the assessment of water regulation is particularly relevant to this evaluation. Also of note would be the evaluation of the important additional effects of climate change on future water levels and limits to outflow regulation, but this important adjunct assessment is not within the scope of this document. It will be considered in subsequent efforts.

The ecological attributes especially susceptible to Great Lakes water level fluctuations are physical shoreline structure, aquatic vegetation and the nutrient dynamic processes that the vegetation drives and regulates, suitable habitat availability for aquatic animals, concomitant fish distributions and productive capacity (especially with respect to spawning and nursery success), and amphibian/reptile and wetland/shore bird population success.

To make adequate projections about habitat changes, adequate spatial data are necessary for a minimum number of nearshore characteristics. Currently, appropriate high-resolution bathymetric and substrate data are lacking for much of the UGL shoreline, which is a major data deficiency. Without such data, it is difficult to predict, project, or compare changes in nearshore coastal processes and associated nearshore physical habitat structure. Existing NOAA/DFO 1-m bathymetry is available, and these data (although poor for coastal regions) have been used as a coarse filter to identify areas most susceptible to shoreline position changes. Such maps can be combined with an overlay of areas of special biological or ecological significance (e.g. Nature Conservancy of Canada 2005) to identify critical sites where changes in UGL water levels will have the most significant potential impact on biological communities and ecosystem function. Using these types of analyses as a guide, a limited number of sites have been identified for more detailed data collection and modelling efforts to assess the impact of changing water levels on different types of coastal environments and associated biological communities and ecosystem functions.
Analyses and modelling should focus on identifying important indicators to be used in assessing alternate regulation plans. These indicators range from the physical to the biological. Hydrological indicators of water regulation effects could be based on mathematical (or statistical) comparisons of the magnitude, frequency, and timing of water level differences among the fencepost scenarios that are relevant to biotic short and long term cycles. A second indicator could evaluate the potential (or susceptibility) for change in shoreline structure and connectivity between the UGL, tributaries, and associated coastal margin wetlands. Both types of indicators could be used to identify geographic areas susceptible to water level change and to prioritize potential effects to fisheries/wildlife and wetlands due to a loss (or gain) in hydraulic connectivity.

Great Lakes coastal wetlands often contain predictable gradients of chemical and physical conditions that extend from open water toward shorelines. These gradients, which are central to the biodiversity of these systems, are driven largely by hydrology. The dynamics of water level fluctuations create and maintain plant zonation, which in turn creates its own chemical and physical gradient. Water regulation impacts will primarily influence vegetation structure and interrelated features that are affected by the presence and type of vegetation at a site. Vegetation provides the physical three-dimensional template of habitat for organisms living at or near coastal margins. Coastal habitats are commonly characterized by the hydrogeomorphic attributes of aquatic habitats (e.g. ‘riverine,’ ‘protected,’ etc.) and/or the names of the dominant and subdominant plant community types (e.g. emergent, floating leaf, submergent, and unvegetated zones).

However, individual plant species likely cannot be used to indicate effects of altered water level regulation because of climatic differences among ecoregions, site-specific aspects such as size, topography/bathymetry, geomorphology, and disturbance and stressors unrelated to water level. Consequently, we recommend using detailed bathymetry and digitization of aerial photographs documenting historical and current wetland distribution (in high-importance areas for which suitable background data exist) to model historical responses to water level and flow fluctuations. Models will be used to forecast and compare the areal extent and zonation pattern changes likely to occur under the various fencepost, current, and natural scenarios. Where possible, existing models should be used that are either developed for specific regions or that can be modified for such purposes. Plant community type indicators should be developed to gauge the relative differences among scenarios (e.g. fencepost plans or subsequent regulation plans).

Microbial processes, and the cycling of nitrogen, phosphorus, and heavy metals, are particularly likely to be sensitive to altered water regulation patterns, largely because alternate wetting and drying of sediments promote reduction and oxidation processes, respectively. Since water level fluctuations are the main drivers of these processes, we do not feel that the proposed water level regulation scenarios will contribute substantially to the further activation of these processes; thus no performance indicators are proposed.

Nearshore macroinvertebrate and fish distribution and their community composition reflect plant zonation and associated chemical and physical gradients established by water level fluctuations described above. Other rare coastal habitats and their availability (such as cobble beaches) may also be affected by low water levels, but the extent of these is largely unknown except for some documented shore types (Nature Conservancy of Canada). Water level changes are expected to affect wetland macroinvertebrate habitat primarily by altering wetland extent, type, plant composition and diversity, plant zonation, sediment composition, and backwater sheltered areas. Long-lived, wetland-obligate invertebrates (e.g. dragonflies and damselflies) are relatively easy to collect and their presence indicates that water levels and habitat conditions have been relatively stable over the course of their annual or semiannual life cycle.

Resident wetland coastal fish species and migratory fishes that use tributaries will most likely be influenced by absolute water levels and variation at different time scales. The complex interaction
between water depth, vegetation and other physical, chemical, and biotic variables will determine future location, extent, and accessibility of fish habitats for life processes. In particular, the regulatory effect of temperature on the life cycle of fishes, the interaction between the seasonality of the thermal and water level cycles is important. Nearshore fish species at risk and resident fishes or their habitats could be used as indicators of impact. Migratory fishes would have to be further assessed based on expected changes to accessibility of upstream habitats.

Moreover, intact Great Lakes coastal wetlands with several plant zones (affected by water level fluctuations), and other coastal margin aquatic habitats, provide cover, prey, spawning sites, nurseries and critical habitat for over 80 species of fish, more than 50 of which are obligate wetland species. Thus, Great Lakes coastal wetlands with plant zonation established and maintained by natural water level fluctuations are critical to the Great Lakes fisheries either directly or as prey base. Useful indicators to model the effects of altered water levels and/or water level variability on the Great Lakes fish community include estimating the amount of habitat available for various guilds of fishes, for species of particular interest (commercial species, top predators, species at risk etc), and population density indices where possible. Spawning and nursery habitat availability, including accessibility to spawning streams, could be simplified indicators. In some rare cases, especially for species at risk, adult habitat availability may also be limiting.

Amphibians, birds, mammals, and reptiles are ubiquitous in the UGL coastal region. Their distribution and abundance are closely associated with vegetation as well as the physical and chemical structure of the habitat. As water levels flow through connecting channels change, and subsequently habitats change in the region, the vertebrate species composition changes. Few studies have specifically examined the effects of water level changes on semi-aquatic or terrestrial vertebrates in the UGL region. Consequently, examination of the effects of water level change on these species is best linked with their associations with habitat conditions, including wetted area necessary for different life functions. We suggest the focus should be on species at risk, obligate wetland breeding bird species, breeding and migratory waterbirds (e.g. loons, grebes, ducks, geese, and herons), anuran populations, and selected mammal species that would be most affected by water level changes. The mosaic of wetland vegetation zones (submergent, emergent, sedge, and forested) and beach habitats available to the semi-aquatic and terrestrial wildlife in the UGL coastal region are key linkages with these performance indicators.

Geospatial and biotic response models served a critical role in assessing the potential impacts of regulation changes on habitat distribution and associated biota in the Lake Ontario-St. Lawrence River study (e.g. Limno-Tech, Inc. 2005, Werick et al. 2007, Minns et al. 2004). Often, modelling is the only tractable approach to assessment given limited budgets, time-frames, impracticality of large scale experiments, and lack of availability of data. We believe that similar modelling approaches will be a critical element of assessing the relative effects of alternative water level regulation plans for the International Upper Great Lakes Study (IUGLS). Discussion regarding the modelling approaches most suited to the IUGLS should be a central focus during a proposed experts workshop. Model selection, evaluation process and type, and the data needed to populate models and assess different scenarios of water level changes in the UGL should be proposed and discussed. Mechanistic types of models, multivariate statistical approaches, meta-analysis of previous studies, and habitat suitability models developed for key species may be suitable and acceptable (e.g. Limno-Tech, Inc. 2005, Minns et al. 2004, Doka et al. 2006, Ingram et al. 2006, Mortsch et al. 2006).

Because most data available for coastal ecosystems represent a ‘snapshot’ of Great Lakes water level, additional field and retrospective studies are recommended to verify the relationship between ecosystems and water level variation for scenarios specific to the IUGLS. In addition, assembly of bathymetric/elevation, sediment type, and other physical data will be required (at a minimum), for the intensive study sites. Elevation data currently available for most of the UGL lack sufficient resolution for coastal ecosystem analysis, so improved information from LIDAR or other technologies, plus field-level
elevation surveys, will be needed. Assembly of new and existing ecosystem maps from high resolution aerial photography will also be required to develop performance indicators and response models. The availability and usefulness of existing data layers will be assessed at the upcoming experts workshop. In addition, linkages with coastal and hydrodynamic/thermal modelling efforts should be thoroughly explored.

Data interpretation and forecasting ecological responses will require sophisticated modelling capable of interpolating spatial trends and anticipating changes through time. A dedicated modelling workshop may be required to identify the approach or approaches most suited to addressing these issues, which include model evaluation before implementation of regulation changes. Evaluation of all possible ranges in climate drivers should also be undertaken, including climate change forecasts. We recommend implementing the following strategy timetable (details in the body of text) to evaluate and assess the most likely ecosystem impacts of changes to water level regulation in the UGL:

i) Assemble a team of collaborators with a breadth of expertise for data gathering, compilation, and interpretation and modelling of the ecosystem performance indicators, preferably individuals familiar with the representative suite of study sites chosen across the UGL,

ii) Evaluate and choose from a suite of 18 proposed study sites that we believe are especially vulnerable to water level regulation. Evaluation should take place at the experts workshop and be based on set criteria, including the existence of preliminary data for the study areas,

iii) Determine the need for, and possibly convene, a dedicated workshop to select the most appropriate modelling approaches and identify the existing models or data needed to develop, calibrate and apply these approaches and

iv) Undertake a program of data collection to fill gaps and to provide the response models and performance indicator assessments to answer three overarching questions:
   a. How will the new regulation plans, based on scenario testing under different climate conditions, influence water levels and water level variability, change habitats and, subsequently, key environmental performance indicators in the IUGLS relative to the existing plan and to pre-project levels and flows?
   b. How consistent are the water level/variability changes and the responses of key environmental performance indicators across the study sites, site types, lakes, and ecoregions? Are there local or regional tradeoffs between indicators?
   c. How well do the models predict (hindcast) or project (forecast, which would involve a monitoring program) the behavior of key environmental performance indicators in response to water level regulation scenarios so that uncertainty can be addressed and adaptive management be undertaken?
Introduction

This synoptic overview summarizes knowledge of the relationships between coastal ecosystems and water level variation in the upper Great Lakes (UGL). This document identifies the important indicators, and some existing databases, tools, and models that should be responsive to the range of changes that can be anticipated as a consequence of proposed new water level regulation rules and criteria for the dam and compensating works at Sault Ste. Marie. The document builds on our current state of knowledge, data availability, and the underlying in our understanding of the complex interactions associated with water level fluctuations and coastal ecosystems. The primary focus is on selecting study sites, indicators, and an approach for comparing and distinguishing among the ecosystem effects of five ‘fencepost’ regulation plans (commonly referred to as Plan 77A, MH Plan, HPP Plan, SupPlan, and PreProj) and the current regulation scheme (Fay and Dahl 2008). The evaluation addresses the entire study area of the IUGLS, but focuses on Lakes Huron, Michigan, and Superior, and the St. Marys River connecting channel between Superior and Huron (Fay and Dahl 2008). The specific objectives of this white paper are to:

- Recommend a suite of performance indicators that can be used to identify the most likely environmental consequences of changes in Lake Superior regulation rules to the UGL,
- Specify research necessary to address critical gaps in our knowledge that limit our ability to make predictions and response models, and
- Outline a strategy for improving our understanding of the positive and negative ecosystem effects of new regulation plans.

We first describe the conceptual approach that has guided our organization of existing knowledge on the relationship between water level dynamics and biological organization at coastal margins. We then summarize how hydrologic processes affect the shoreline and its biological processes, especially the vegetation and the groups of organisms that depend on the vegetation. We document where the greatest gaps in information and data exist, and propose ecological performance indicators that may be suitable for detecting the effects of water level regulation on each group. Finally, we recommend a list of research needs, a timeline of activities that should be undertaken to achieve those needs, and a suite of high priority study areas. This document is intended as a synoptic overview that will form the basis of informed discussion, leading to the creation of more comprehensive literature reviews and research plans.

Background to the Study

The ecosystems of the UGL cover a broad spectrum of the valuable natural resources of North America. Absolute water levels and fluctuations have major influences on the nearshore and coastal regions of the Great Lakes and their ability to support aquatic organisms. UGL ecosystems have evolved under natural climatic variability since the Holocene glaciation, and changes in lake levels over time play an important role in coastal processes and nearshore ecosystems (Thompson and Baedke 2000). Hence, a key issue is to assess the extent to which regulation, that results in higher or lower absolute water levels and greater or lesser water level variability, will affect coastal ecosystem structure and function over time relative to natural levels and variability. This document presents a brief synthesis of existing information on key coastal and nearshore ecosystem components. Ecosystems of particular interest are those most likely affected by water level changes and variability in changes due to regulation: coastal wetlands, beaches, dunes, tributaries, islands, and the coastal margin. Even though climate change will also have important effects on water levels, climate change is not considered within the scope of this document. Its role will be assessed in a subsequent effort.

The UGL region has received considerable study. For instance, in the past five years a series of documents summarizing the results of several integrative studies of the biological, physical, and chemical aspects of Great Lakes coastal ecosystems have appeared (Mackey and Goforth 2005, Simon and Stewart 2007, Niemi et al. 2006, 2007, Burton et al. 2008). Unfortunately, most of the research on which these
studies were based was completed over relatively short periods of time. Furthermore, very few addressed the effects of changing water levels as their primary objective. Among the primary exceptions are studies of the effects of water level changes on vegetation and plant communities (e.g. Wilcox 2004, Wilcox and Nichols 2008, Mortsch et al. 2008), while Bain (2007) assessed the effects of water level regulation in the St. Marys River system on fish and invertebrates. We firmly believe, however, that many historical data sets could likely be exploited with respect to water level variation. To improve our understanding of these effects, it is imperative that these data sets be identified and explored. We identify a strategy to accomplish this at the end of this document.

**Conceptual Approach**

The key ecosystem issues addressed here relate to the interaction between altered water depth (relatively higher or lower than the current coastal margin), changes in seasonal depth variability or interannual water supplies (either lesser or greater variability) (Figure 1). A significant challenge for the ecosystem group will be to define a baseline against which comparisons can be made to enable assessment of the independent and interactive drivers of regulation components on key ecosystem indicators given that most data, and therefore models are derived from an already regulated system.

![Conceptual Map](image)

*Figure 1. The characteristics of coastal and nearshore ecosystems of the UGL are primarily governed by the independent and interacting effects of water depth and the variation in water levels at different time scales. These can be considered ‘fencepost’ scenarios for which ecosystem response should be gauged in the IUGLS assessment.*

Our conceptual approach to assessing the ecosystem effects of water level changes must be undertaken in the context of the multiple factors that affect the quantity and quality of coastal habitats. The ecological characteristics of coastal margin ecosystems reflect dynamic interactions among many physical, geochemical, and biological components of the environment. The IJC, through its State of the Lakes Environmental Conference (SOLEC), recognizes this diversity by noting that a healthy ecosystem is characterized by physical, chemical, and biological integrity, and has proposed independent suites of indicators to reflect each component (e.g. SOLEC 2007). In practical terms, however, the components are intricately interdependent. Furthermore, the strength of these connections varies through time and from place to place.

We summarize our best understanding of the possible interactions among ecosystem components with a conceptual map (Figure 2). The polygons (ovals and rectangles) represent attributes of the ecosystem, some of which can be directly measured (rectangles), while others represent composite concepts (ovals). Purported links between the attributes are represented by arrows. Feedback loops are shown by bidirectional arrows. If we have only subjective impressions and best professional judgment of the strength of relationships among the components, representations like Figure 2 can be interpreted as ‘fuzzy cognitive maps’ (e.g. Hobbs et al. 2002, Ozesmi and Ozesmi 2004, Joss et al. 2008); we can only describe
Figure 2. Conceptual diagram of the key factors thought to determine performance of indicators of the structure and condition of the UGL coastal margin as a consequence of altering water depth and variability. In a structural equation model schematic, attributes that can be directly measured (exogenous variables) are represented by rectangles. Those that are composite qualities are termed ‘latent variables’ and are represented by ovals. For ease of viewing, selected exogenous variable names are listed inside or beside latent variable polygons. The model emphasizes that most of the effects of water level alteration on biota are mediated through vegetation at the coastal margin, which ameliorates or even defines habitat characteristics. Blue polygons and arrows represent environmental drivers. Orange symbols are anthropogenically controlled factors. Green polygons can be used as biologically-based environmental performance indicators.
and analyze the relationships in qualitative terms (‘weak,’ ‘strong,’ etc.). Alternatively, the same diagrams can be viewed as flowcharts representing the critical components of proposed or existing explanatory or response models. Such models can use limited but good quality data or simulations to assess relationships and make predictions about ecosystem key components (e.g. Limno-Tech, Inc. 2005, Werick et al. 2006). Ultimately, if data exist that describe the state of each of the components, the diagram can be treated as a structural equation model (SEM), and the correlations among the various elements can be estimated and used to infer which types of relationships are most important or sensitive in determining the state of the components of greatest interest (i.e. forcing functions) (e.g. Grace et al. 1998, Kang et al. 2004, Grace 2006). Most biota associated with coastal margins respond directly to the habitat conditions that are under the direct control of the physical structure of the shoreline but which are mediated by hydrology. However, biota are also influenced by antecedent conditions, biogeography, climate, weather events, and anthropogenic stresses to those habitats, such as nonpoint and point source pollution, invasive species, and landscape influences (Figure 2; Brazner et al. 2007a, b). Hence, one must distinguish between both direct and indirect effects of water level regulation on performance indicators. The complexity of this conceptual framework emphasizes the need to model the impacts of water level changes across the broad geographic region of the UGL using representative sities.

In many cases, vegetation provides the physical three-dimensional template of habitat for organisms living at or near coastal margins. Indeed, habitat characterizations are often expressed by the names of the dominant and subdominant plant species (e.g. Nature Conservancy of Canada 2005) and/or physical attributes of aquatic habitats (emergent, floating leaf, submergent, unvegetated zones). In areas that are saturated with water, vegetation characteristics depend on the extent of exposure to wave action, temperature cycle, water depth, substrate characteristics, and water quality (particularly nutrient concentrations and clarity). The primary consumers of plants and their predators all depend on the amounts and types of vegetation present. The particular species found vary according to ecoregion, Great Lake, and the amount of local anthropogenic disturbance. We employ many of these organisms (invertebrates, fish, amphibians, birds, small mammals) as integrated indicators of ecosystem health (Niemi and McDonald 2004, Limno-Tech Inc. 2005).

Hydrological and Geomorphological Issues Related to Water Levels and their Fluctuations

Water levels in the UGL vary daily, seasonally, annually, and in longer-term cycles that range from several years to more than 160 years (Figure 3; Thompson and Baedke 2000). The longer-period cycles (~33 and 160 years) have been expressed for the last 4,500 years (Thompson and Baedke 2000). The amplitude and period of the 33-year cycles brackets both the magnitude and natural range of variability of water levels for the UGL. Thus, a minimum evaluation period of at least 33 years (one major cycle or longer) should be used to evaluate the impacts of different water level regulation scenarios. The Lake Ontario reference study used a 100-year time period, which would meet the recommended minimum evaluation period and would be appropriate for the UGL study as well (i.e. roughly three 33-year cycles).

Water Level Change Effects at the Coastal Margin

Water level changes for Lakes Superior and Michigan-Huron are illustrated in Figures 4 and 5 under several different proposed regulation scenarios (Fay and Dahl 2008). Alterations of the natural range and variability of UGL water levels through regulation may change the location and type of the natural shoreline, expose or inundate shallow-water areas at inopportune times, alter nearshore flow and circulation patterns, and hydraulically isolate and disconnect coastal wetland complexes that cannot migrate downslope. Changes in nearshore habitat structure could be significant, especially in areas adjacent to beaches with highly mobile substrates. When the thickness of the mobile substrate is reduced below a minimum threshold (approximately 200 m$^3$/m of sand cover, measured from the top of the beach
out to the 4-m contour) due to beach erosion, the underlying cohesive clays become exposed and are eroded by a process called lakebed downcutting. This permanently lowers the elevation of the lakebed, increases nearshore water depths, and results in degraded water quality in nearshore areas of the UGL (Nairn 1992). Nearshore lakebed downcutting occurs under all water level regimes because the process is dependent on the available littoral sediment supply. The rate at which the process will occur depends on local geomorphology and substrate characteristics. However, lakebed downcutting processes may be accelerated during periods of lower water level due to a redistribution and concentration of wave energy in shallow-water areas and accelerated transport of littoral sediment.

Along shorelines with natural beaches, beach widths may increase or decrease as a function of altered water levels. When water levels decline, more of the beach face is exposed. Wider beaches may reduce erosion of coastal bluffs (and adjacent upland areas) and provide a sand source for coastal dune complexes (transport by wind deflation). Narrower beaches result in increased erosion of coastal bluffs, reduced water quality, and a long-term coarsening of nearshore habitat substrates. These changes do not occur instantaneously, but generally develop over years. Additional investigation is needed to document the effects and lag times associated with increased (or decreased) frequency and altered seasonal timing of water level fluctuations on nearshore sediment transport and lakebed downcutting, especially in ecologically sensitive areas. Regulation plans may affect coastal sand resources that supply major coastal dune complexes and protect nearshore habitat areas from lakebed downcutting.

Figure 3. Water level cycles for Lakes Michigan-Huron (Thompson and Baedke 2000). Major long and medium-term cycles include 160-year and 33-year fluctuations in water level (Thompson and Baedke 2000). For the UGLs, 33 years should be the absolute minimum time period over which the proposed water-level scenarios should be evaluated.
Figure 4. Simulated Lake Superior water levels – modelled on Plan 77A and Fencepost plans. The Pre-project time series represents modelled ‘natural’ water levels as if no regulation was applied (Fay and Dahl 2008).

Figure 5. Simulated Lake Michigan-Lake Huron water levels – modelled on Plan 77A and Fencepost plans. The Preproject curve represents modelled ‘natural’ water levels as if no regulation was applied (Fay and Dahl 2008).

From an ecological perspective, the importance of water-level variability on biological communities and ecosystem function cannot be overemphasized (Wilcox et al. 2002, Burton et al. 2004, Minns et al. 2004). Water level variability is one of the primary drivers of biodiversity in coastal ecosystems (Burton et al. 2004, Albert et al. 2005). The life stages of many native species are linked to the natural range and variability of UGL water levels. For example, spawning and nursery habitats of many native fish species are maintained by and tied to the natural range of seasonal water-level cycles and flows in UGL and their
tributaries (Jude et al. 2005). In addition, access to spawning streams and barrier beach wetlands may be adversely affected by permanently lowered water levels, particularly in bedrock areas of Lake Superior where streams cannot rapidly downcut to reach the new lake level or wetlands that cannot migrate downslope because of unsuitable substrate types. Therefore, regulation plans that alter the natural range and timing of seasonal water-level cycles may adversely affect fish recruitment because of accessibility and stranding issues and, ultimately, the UGL fishery will be affected because of disrupted nearshore/offshore connections in food web dynamics and habitat use.

Two Great Lakes hydrogeomorphic classification schemes have been developed for coastal wetlands (Keough et al. 1999, Albert et al. 2005), both of which are based on dynamic coastal physical characteristics that may be altered by changes in UGL water levels and flows. For example, coastal barrier systems and the wetlands they protect could be either augmented or degraded as a function of altered coastal processes. It is important to understand how these nearshore coastal processes may change under different water regulation scenarios. Even though quantitative models exist to predict how sediments are eroded and transported in nearshore environments, the data required to run those models either do not exist or are available at inappropriate spatial scales or only for localized areas of the basin.

Currently, appropriate high-resolution bathymetric and substrate data do not exist for much the UGL shoreline, which is a major data gap (deficiency). Without such data, it is difficult to predict changes in nearshore coastal processes and associated changes in nearshore physical habitat structure. However, existing NOAA/DFO 1-m bathymetry is available, and this can be used as a coarse screening tool to identify areas where potential changes in UGL water levels will most likely result in a shift in shoreline location or coastal margin connectivity (e.g. Figures 6-8). The areas identified on Figures 6-8 are based on an average 1 m drop in UGL water levels, with a +/- 10 cm variation about the mean. These areas are where changes in UGL water levels, particularly lower levels will have the most potential impact on nearshore and coastal margin habitat availability and structure. We recommend that several demonstration sites be selected for more detailed data collection and modelling analyses to assess the potential effects of different water level regulation scenarios. The sites selected should be representative of a range of environmental and hydrogeomorphic types prevalent within the UGL, with ecological characteristics that are dependent upon water-level variability. At a minimum, higher-resolution (15 cm precision) bathymetric (1-m precision) and substrate data are needed. Concomitantly, more detailed biological sampling and monitoring of key indicator species/communities, along with physical assessments, are needed to establish baseline conditions and answer specific hypotheses at these sites. This is elaborated upon in future sections.

Within the UGL, water level declines may cause increased erosion and channel deepening at smaller river mouths as channels equilibrate to a lower base level. Erosional effects in tributary channels may incise into underlying materials, which may contain previously buried sediments contaminated with legacy pollutants. These materials may be resuspended and then transported to coastal margins, nearshore, and deeper water areas located adjacent to the tributary mouth. To meet commercial and/or recreational navigation needs, major river channels and embayments may be periodically dredged to maintain navigable water depths. Dredging activities cause short-term water quality degradation and create a need to dispose of potentially undesirable dredge spoil materials in a confined disposal facility or upland disposal facility. Dredging may also alter channel bed and the extent of flooded area, contributing to the hydrologic isolation of adjacent riparian/deltaic/coastal wetland areas. Many of these wetland and estuarine areas provide critical spawning, nursery, and forage habitat for UGL fish communities (Goodyear et al. 1982, Jude and Pappas 1992, Doka et al. 2006b).
Figure 6. Coastal areas of Lake Superior most likely to be affected by lower water levels. Red shading highlights areas that would be affected by a 1 m drop in lake levels. Darker green areas are provincial, federal or state parks. The detailed insets are representative and may not include all coastal areas in Lake Superior potentially affected by fluctuating water levels. Recommended study sites can be found in Table 2.
Figure 7. Coastal areas of Lake Michigan most likely to be affected by lower water levels. Red shading highlights areas that would be affected by a 1 m drop in lake levels. Darker green areas are provincial, federal or state parks. The detailed insets are representative and may not include all coastal areas in Lake Michigan potentially affected by fluctuating water levels. Recommended study sites can be found in Table 2.
Figure 8. Coastal areas of Lake Huron-St. Clair most likely to be affected by lower water levels. Red shaded areas would be affected by a 1-m drop in lake levels. Darker green areas are provincial, federal or state parks. The detailed insets are examples and may not include all coastal areas potentially affected by fluctuating water levels. [Please note: Lake Erie was not assessed] Recommended study sites can be found in Table 2.
Figure 9. Comparison of areas affected by lower water levels (red color) with areas of special biological significance identified in the Aquatic Biodiversity Blueprint (Nature Conservancy of Canada 2005; Kraus 2005) for one site on Lake Superior (A - Black and Nipigon Bay) and two sites on Lake Huron (B - northeast Georgian Bay and C - southeastern Lake Huron). Nature Conservancy biodiversity areas: dark purple = wetland, green = stream, cyan = lake, blue = coastal, and lavender = other.
These shallow-area maps (Figures 6-8) can be combined with an overlay of areas of special biological or ecological significance (e.g. Nature Conservancy of Canada 2005) and species distribution and biodiversity information (Staton and Mandrak 2005, Niemi et al. 2007) to identify critical sites where changes in UGL water levels will have the most significant potential impact on biological communities and ecosystem function. Examples of these types of comparisons are illustrated in Figure 9. Based on the area of biological or ecological significance, these sites could be evaluated using the recommended suite of indicators or metrics to determine if the sites are especially susceptible to water level fluctuations under the fencepost scenarios. Moreover, this approach illustrates how to potentially integrate geospatial datasets with long-term water-level time series to predict shoreline and water depth changes, initially using the fencepost scenarios to gauge extremes. Ultimately, the most likely future locations of critical spawning and nursery habitats within the UGL can be predicted (Bakelaar et al. 2004). This information is essential when developing long-term protection, rehabilitation, and restoration plans within the context of UGL water level regulation impacts and possibly adaptive management.

Long-term, continuous water level data are available for the UGL. The fencepost water-level plots (Figures 4,5) provide information on how water levels may differ under extreme regulation scenarios. A useful set of indicators could be based on a mathematical (or statistical) comparison of differences in the magnitude, frequency, and timing of water level changes between proposed scenarios and two baselines: the current regulation plan and the preproject time series (Table 1). This would provide a quantitative measure of both historical and future differences between water-level scenarios and allow for the development of potential linkages with other indicators. A second indicator would evaluate the potential (or susceptibility) for change in connectivity between the UGL, tributaries, and associated coastal margin wetlands (Table 1). This indicator could be used to identify geographic areas susceptible to water level change at finer scales than previous figures and also to help prioritize potential effects to fisheries and wetlands due to a loss (or gain) in hydraulic connectivity (i.e. it may not be a cause for concern, depending on water level differences and timing).

**Water Level Change Effects in the Nearshore**

Water level changes can potentially have subtle but important influences on the characteristics of lakewater at the water-sediment interface within the lake. The substrate conditions of areas covered by epilimnetic water are different than those in the hypolimnion. This affects temperature, mixing, and nutrient dynamics and, hence, the composition and secondary production of benthos as well as spawning activities of fishes dependent on other substrates (lithophils). Preliminary modelling is warranted to determine whether a 10-cm change in water levels would substantially alter the area of substrate covered by epilimnetic water in important nearshore spawning areas of the UGL. This would involve adequate thermal modelling being undertaken to predict the depth of thermocline establishment given different supply scenarios, including historic patterns.

In the longer term, indicator(s) could be developed that consider and summarize human reactions and activities in response to changes in water levels (e.g. dredging, the addition or removal of structures, beach grooming, etc.), both when levels rise and when they fall.

**Effects of Water Level Fluctuations on Ecosystem Processes**

Great Lakes coastal wetlands often contain predictable gradients of chemical and physical conditions that extend from open water toward shorelines. These gradients, which are central to the biodiversity of these systems, are largely driven by hydrology. The dynamics of water level fluctuations create and maintain plant zonation, which in turn creates a chemical and physical gradient. Dense aquatic vegetation dampens wave impacts, but pelagic water is advected into the outer edge of a wetland, creating a chemical/physical signature comparable to that of the open water (Cardinale et al. 1998). At the other extreme, areas of the wetland closest to shore receive little advected pelagic water. Instead, upwelling groundwater (if present)
creates a different chemical/physical environment. These two extremes in chemical/physical conditions form a natural gradient that extends perpendicular to the shoreline and set the stage for biota to find their environmental optima within a given system (Figure 2; Cardinale et al. 1998, Minns et al. 1999, Uzarski 2009).

Water regulation will primarily influence vegetation structure and interrelated features that are regulated by the presence and type of vegetation at a site or its interaction with other habitat features. Ecosystem processes that will be influenced by water level change (higher or lower) and water level variability (greater or lesser variability; altered timing of intra-annual peaks and lows) include: nutrient and contaminant cycling, rates and effects of community metabolism (including primary production, decomposition, and carbon cycling), and phenology of plant development and the synchrony of processes that depend on plant community development (e.g. suitable microhabitats for oviposition, spawning, and nest building by insects, fishes and birds, respectively). Here, we focus on nitrogen and heavy metal cycling, two processes relevant to the nearshore zones of the UGL, plus we comment on microbiological processes.

**Nitrogen Cycling**

Humans artificially fix nitrogen, or make it available for biological use, by producing fertilizers and using them on lawns and crops. Manure and septic tank seepage also contribute nitrogen compounds to surface waters. Excess nitrogen running off from the landscape into Great Lakes waters contributes to production of nuisance algal blooms and many other undesirable conditions associated with cultural eutrophication. The process of denitrification is important for removing nitrogen pollution from the Great Lakes.

Nitrogen cycling is closely tied to wetting and drying cycles in tributary floodplains, wetlands, and littoral zones (Figure 10). It is mediated by the type and presence of vegetation at a site, as well as substrate type and composition.

The nitrogen cycle (and other nutrient cycles) depends on microbial activity, which is regulated by oxygen and organic carbon concentrations in the water. In fringing wetlands, dissolved oxygen concentrations tend to decrease from the open water-vegetation margin to the vegetation-dense shoreline. This may seem counterintuitive because the abundance of rooted plants and phytoplankton increases as one moves deeper into a wetland. However, breaking waves and currents continuously replenish the open areas with well-oxygenated water. Vegetation dampens wave penetration deep into the marsh (Cardinale et al. 1998) and allows organic materials to settle and build up in the sediments, enriching them in carbon and nutrients. In riverine and barrier-protected wetlands, oxygen levels are dictated by flow regime (riverine) and other biotic/abiotic processes. The decomposition of organic matter by microbial respiration reduces dissolved oxygen concentrations. This process is essential for nutrient cycling, especially nitrogen, and food web dynamics.

Nitrogenous compounds are reduced and transformed into ammonia, which quickly ionizes in water to form ammonium (a transitory step in the nitrification process; Figure 10). Ammonium builds up in sediments unless it is used by actively growing vegetation. Otherwise, during dry periods, organic matter and nutrients are mineralized (oxidized and subsequently broken down into inorganic components). Ammonium reacts with the air and is converted to nitrate. Upon inundation, dissolved oxygen concentrations are greatly reduced, and other microbial activity converts nitrate to nitrogen gas (denitrification). Denitrification is one of the many ways that wetlands act as nutrient ‘filters,’ deactivating nitrogenous pollutants and removing excess nutrients before they reach the Great Lakes. Longer inundation periods (i.e. periods of prolonged wetting as would occur under stable water levels) promote greater nitrogen, organic matter, and sediment deposition in the floodplain or littoral zone (Junk et al. 1989).
Long flood periods and high organic matter accumulation create anaerobic conditions, which favor mineralization (White and Reddy 2003) and denitrification, and limit nitrification (Miguel et al. 1999; Figure 10). Mineralization produces ammonia. Ammonia quickly ionizes in water to form ammonium hydroxide, which dissociates into ammonium and hydroxide at pH less than approximately 9. High water levels in conjunction with greater water level variability will therefore be more likely to promote accumulation of ammonium hydroxide. This occurs when dense algal blooms engage in such intense primary production that their absorption of carbonate from the water causes the pH to rise during the daytime. The rising pH stops the dissociation of ammonium hydroxide. This compound is toxic to invertebrates and fish at high concentrations.

At low water levels with lesser variability, nitrogen cycling processes could be limited by the amount and type of organic matter (Figure 10). Initially, organic matter levels may be low if water levels have dropped and vegetation and resulting organic matter have not reestablished.

Nitrogen cycling activity varies greatly with shoreline type. Fringing wetlands typically accumulate less organic matter than other hydrogeomorphic classes of wetlands (Keough et al. 1999) because they are more exposed and subject to greater wave and current action. However, a gradient of organic matters exists from the shore to the open water. Thus, mineralization and denitrification processes are less likely to be limiting near the shore, where water level changes will have the greatest impact. Riverine/drowned river mouth wetlands and barrier beach wetlands accumulate increasing amounts of organic matter; however, oxygen availability may differ among these types depending on the flow regime. We recommend that organic matter accumulation or removal from within wetland zones be tracked and correlated with water levels (total OM, and its labile and refractory components). The effects of regulation on nitrogen cycling can then be inferred using these data along with published literature.

**Heavy Metal Cycling**

Heavy metals are a concern primarily in areas of the Great Lakes associated with areas of concern (AOC); however, atmospheric deposition still accounts for a significant amount (Evers et al. 2007). Mercury concentrates in organic sediments, and fluctuations in water levels and soil moisture influence the release of heavy metals from reservoirs and dried sediments in the littoral zones of lakes and wetlands (Bodaly et al. 1984, Mastalerz et al. 2001, Dollar et al. 2001). Wetlands supply dissolved organic carbon, which is associated with the transport of ionic mercury and methylmercury, making wetland sites of methylmercury production. Water level fluctuations enhance methylmercury production; the mechanism is believed to be related to increasing sulfate levels, which increase when sediments are exposed to the atmosphere. Rewetted sediments mobilize sulfate, which is the fuel for the sulfate-reducing bacteria that are responsible for mercury methylation (Sorenson et al. 2005). This phenomenon is expected to result in higher levels of methylmercury production when sediments have been dry for a period of time (e.g. several years) before being rewetted. Mercury concentrations have been found to be elevated in reservoirs with fluctuating water levels. When water levels in the reservoir are high, methylation proceeds until sulfate becomes limited. During low water periods, exposed sediments become oxygenated and the sulfides undergo reoxidation to sulfate. The newly ‘re-available’ sulfate re-establishes the methylation cycle (Chen et al. in review). Seasonal patterns of mercury concentrations and availability in the sediments were highly correlated with mercury concentrations in young-of-the-year yellow perch (Sorenson et al. 2005).
Figure 10. Conceptual diagram of the nitrogen cycle under various hydrologic conditions: A) initial precipitation after extended dry period, B) during inundation, and C) after inundation. Thickness of arrows and size of text denotes relative rates and concentrations. During extended dry periods (A), nitrification rates are high and denitrification rates are low, accumulating nitrate. Initial precipitation washes surface nitrate to nearby receiving water, and leaching increases. As river water levels rise (B), flood waters bring in nutrients and organic matter, oxygen levels decrease, decreasing nitrification and increasing denitrification. As a result, ammonium concentrations increase, nitrate concentrations decrease, and nitrogen gas is released to the atmosphere. After waters recede (C), organic nitrogen is deposited in the floodplain, nitrification rates again increase, increasing nitrate concentrations, and denitrification is limited to deeper depths, reducing the rate of nitrogen gas production. (from Jicha 2008)
There is a growing recognition that nitrate serves as a powerful electron acceptor in anoxic sediments, potentially limiting sulfate reduction processes; as a result, mercury methylation by sulfate-reducing bacteria can be slowed or reduced in the presence of nitrate. Overall environmental conditions that favor mercury methylation include: Total P > 30 ug/L; DOC > 4 mg/L; pH < 6; acid neutralizing capacity (ANC) < 100ueq/L (Evers et al. 2007).

Increased oxygen concentrations in exposed soils, especially when accompanied by acid precipitation, may also release metals such as cadmium, manganese, lead, and zinc (Perkins et al. 2000, Dollar et al. 2001). Wetlands downstream of industrial effluents could face increased risk of heavy metal contamination when wetlands are flooded following periods of low water.

Impacts of the ‘fencepost’ water regulation scenarios are uncertain. High water conditions are likely to flood areas with high levels of organic material. Such material serves as a substrate for metal cycling. Low water conditions, in contrast, expose the sediments to the atmosphere. Upon inundation, these sediments serve as a source of nutrients and heavy metals. Since water level fluctuations are the main drivers of these processes, we do not feel that the proposed water level regulation scenarios will contribute substantially to the activation of these processes; thus no performance indicators are proposed. However, we feel the fundamental processes driving the production and cycling of mercury and other metals within the nearshore shore are still poorly understood with respect to the role of nutrients such as nitrate and phosphate, and should be further studied.

**Microbial Contamination**

Fecal coliform bacteria (FCB) and *Escherichia coli* (*E. coli*) are microorganisms that live in the lower intestines of warm-blooded animals, including wildlife, farm animals, pets, and humans, and are excreted in their feces. The presence and concentrations of FCBs are used by regulatory agencies as indicators of possible exposure to potentially harmful bacteria; the US EPA also recommends the use of *E. coli* assays as an indicator of fecal contamination at beaches (US EPA 2004). Sources of bacteria to the lakes include municipal sewage discharge (particularly during large storms when sewage treatment facilities are overwhelmed with storm water resulting in sewage overflows), leaking septic systems in coastal areas, and agricultural runoff from confined feeding operations. Wildlife such as birds and household pets are other sources (Santo Domingo and Sadowsky 2007).

The beaches themselves can behave as sources and sinks for these organisms, harboring viable populations in the interstices of beach sand grains and riverine sediments (Ishii et al. 2006, 2007). Storms wet and then resuspend beach sand and sediments, thereby providing fresh source materials to the nearshore waters, causing FCB concentrations to be highest nearest the shore.

While enteric bacteria were previously believed to be incapable of surviving outside the gut of warm-blooded animals, there is now substantial evidence that these microorganisms can not only survive in the environment, but have also become naturalized to habitats including beach sand interstices (Ishii et al. 2006), within the periphyton biofilm attached to rocks (Ksoll et al. 2007), and in association with mats of benthic filamentous algae such as *Cladophora* (Byappanahalli et al. 2003). Aquatic vegetation in the nearshore zone that traps fine sediments also provides habitat for such bacteria populations to persist and flourish (Hemond and Benoit 1988). Impacts of low water levels and water level stabilization will be quite site-specific and will largely depend on the location of sewage discharge and overflow locations relative to beaches, as well as the depth of water intake pipes and their location relative to sewage overflow locations. Thus, we do not recommend that FCB be used as performance indicators for water level responses. We do, however, feel that the potential role of large algal mats in posing as a source of harmful microorganisms should continue to be studied.
Vegetation Effects

Wetland Vegetation Response to Flooding

Water level variability is responsible for zonation and plant species composition in coastal wetlands. The regular wetting and drying of sediments at different cycles creates an intermediate disturbance pattern that increases biodiversity because of plant succession and varying species tolerances. Recurring high and low water periods, such as those that have occurred under the current plan (Plan 77a) due to climatic conditions in combination with water level regulation, result in a continuum of vegetation zones with dynamic expansion or contraction of some zones associated with interannual and longer-term water level variation.

Water saturated soils or standing water for significant periods during the growing season (two weeks or more) are a dominant factor in determining the presence of wetland plants (National Research Council 1995) and the particular species composition. Wetland plants are variously able to cope with hypoxic environments; thus vegetation zones develop, composed of suites of species having similar tolerance to flooding. A successional series of zones extends from the upland (very seldom flooded) downslope to continuously flooded habitats (shallow open water) (Figure 11). Most tree species and other woody plants are intolerant of prolonged standing water. Obligate wetland plant species have structural and physiological adaptations that permit their survival and growth in flooded conditions. Some species, such as upright sedge (*Carex stricta*), form tussocks whose living roots extend above the flooded soils and form an environment suitable for other species on the tussocks. Other species then associate with tussocks. Secondary to flooding effects, competition for light and nutrients, as well as ability to become established, are important factors that structure wetland vegetation.

Coastal wetland communities of the Great Lakes have evolved in a variable flooding regime (Wilcox 1995, 2004, Albert et al. 2005, Keough et al. 1999, Mayer et al. 2004). The dynamic nature of coastal wetland vegetation has been referred to as ‘pulse stability’ or ‘centrifugal organization’ (Wilcox 2004). Daily variation (seiches and storm surges), seasonal variation, and especially interannual variation serve to maintain zonation, foster biodiversity, and control vegetation succession (Wilcox 2004, Keough et al. 1999). Where variability in flooding pattern has been restricted (e.g. in Lake Ontario or in some diked situations), wetlands have lost diversity and some of the community zonation. Wilcox et al. (2007) and Wilcox and Meeker (1991, 1992, 1995) demonstrated how restriction of lake level variation simplified coastal wetland vegetation, encouraging large, competitive species at the expense of sedge/grass communities. On Lake Ontario, Wilcox et al. (2007) reported that reduction of water level variation by regulation, begun in 1960, resulted in sedge/grass meadow replaced by shrub cover on the upland side and robust emergents, such as cattail monocultures, on the lake side. Narrowing the ‘wetted edge’ also concentrates the zone for erosion; in Lake Ontario, this resulted in property owners and managers constructing various hard structures to protect the shore, but such structures reduce sediment movement in the coastal zone, further narrowing the diversity of coastal surfaces for wetland and beach ecosystems.

Plant Zonation and Hydrology

“Hydrologic variability is central to the structure and function of Great Lakes coastal wetlands. Wetlands only form where there is sufficient protection from hydrologic energy to allow rooted macrophytes to establish. Where wetlands do establish, hydrologic variability, including waves, long shore currents, flood pulses, and storm surges create distinct plant zonation, while washing away or depositing organic matter in the sediments” (Burton et al. 2004); Uzarski 2009. The amount of energy reaching the lakeward portion of the wetland is related to fetch, bathymetry/slope, water level, and amount of protection. For example, shallow shoals extending far off shore will cause waves to break, thus diffusing their hydrologic energy and allowing different types of plants to become established (Uzarski 2009).
Superimposed on the hydrologic energy gradient is one of depth and duration since last inundation (Hebb et al. 2006). Deep water, low-energy habitats that never dewater tend to harbor true aquatic vegetation, or submersed aquatic vegetation (SAV; Doka et al. 2006). Shallower, low-energy areas that never dewater tend to contain emergent vegetation that can out-compete SAV for sunlight and can withstand having roots and rhizomes in soils devoid of oxygen (anaerobic soils). Further inland, in areas that are often inundated with shallow water, but sometimes dry up, SAV and most emergent aquatic vegetation can no longer persist. However, these areas are often too wet for most woody vegetation, which can only withstand short periods of anaerobic soil conditions. Consequently, these areas are dominated by hummock-forming grasses and sedges. “The combination of the hydrologic energy gradient and water level fluctuations results in distinct plant zones or a vegetation gradient” (Figure 11; Uzarski 2009). The act of stabilizing water levels compresses wetlands from four zones (shrub, wet meadow, marsh, SAV) to two (shrub, SAV) (Keddy 1991).

![Plant zonation in open coastal (fringing) wetlands associated with large lakes and subject to wave energy and natural water level variability](from Uzarski 2009)

“A fringing wetland may extend many meters toward open water even where fetch is great, provided that there is a shallow slope extending offshore for some distance and/or water levels are low” (Uzarksi in press). “Specialized vegetation can develop and withstand wave exposure along relatively high energy shorelines. The cumulative influence of a dense array of plant stems creates drag, which dampens energy shoreward. Stem density increases shoreward until a threshold density is reached where physical limits are replaced by intraspecific competition. In many fringing wetlands of the Laurentian Great Lakes, waves in excess of 1 m are completely dissipated 100 m or more from shore, allowing vegetation of more complex growth-forms to establish, and more organic matter to accumulate nearshore even during high water years” (Uzarski 2009). At the lakeward wave-swept portion, harsh environmental factors (waves and currents) shape plant community composition. As energy is dissipated inland, interspecific competition for sunlight and nutrients becomes much more important in influencing community composition” (Uzarski 2009). This continuum between abiotic forces (hydrologic energy) and biotic forces (competition) shifts with changing water levels. Along the open water-to-shore gradient, thickness
of the organic sediment layer and associated nutrient cycling should generally increase as the effects of hydrologic forces weaken and vegetation density increases.

Submerged aquatic vegetation plays a very important role in providing habitat for aquatic life, such as fishes, amphibians, aquatic reptiles, wading or other aquatic birds, and their food web support. Factors that limit SAV distribution include light availability (i.e. water clarity), disturbance of water and sediment by currents and wave action, ice scour, activities of benthic fish, (e.g. carp), and availability of propagules (seeds and vegetative propagules). SAV typically do not occur below 10 m water depth, although macroalgae such as Chara are commonly found in deeper water. Light availability can be reduced when nutrient enrichment stimulates growth of planktonic and periphytic algae, by turbulence, and through shading by emergent and floating leaved plants. However, SAV often coexist with these types of wetland plants and sometimes occur ‘behind’ stands of emergent plants, where they are protected from turbulence.

Wet meadow areas and other intermediate elevation wetland vegetation are not influenced by waves. Instead these zones are maintained by the effects of seiches and groundwater seeps, as well as occasional exposure to flooding during high water years. Upland from the wet meadow, the shrub-scrub and forested swamps are influenced primarily by groundwater and landscape hydrology rather than by Great Lake surface water fluctuations. However, these areas are still connected to the lake via subsurface hydrology, and their zone will migrate lakeward during low water years and landward during high water years.

**Vegetation Response to Water Level Variability**

The spatial location and boundaries of plant zones established by hydrology are dynamic as a result of long-term water level variation. Maintenance of vegetation zones and integrity of the flora across the zones are dependent upon the ability of wetland vegetation to expand and contract upslope and downslope in concert with interannual and longer variations in water level. The longer cycles (e.g. 30 years), with more random variation within cycles, are key to maintaining typical arrays of wetland vegetation communities (e.g. Wilcox 2004, Wilcox et al. 2008). *Increasing the predictability of interannual variation will result in simplification of wetland mosaics* (e.g. Wilcox and Meeker 1991).

Fluctuations occur on three major time-scales: short-term, seasonal, and interannual. Each adds to the dynamic nature of these systems. Seiches are quasi-daily (< 24 hours) water level fluctuations caused when persistent wind forcing and/or differences in atmospheric pressure cause water level on one side of a large lake to be higher than the other. The result in the Great Lakes is a persistent and cyclic inundation and dewatering of shoreline and wetland ecosystems for the duration of the seiche event. “Seiches that are present when persistent winds are low or moderate result in water levels rising and falling with almost tide-like regularity on ‘cycles’ of less than an hour up to 24 hours; these fluctuations are the result of the lake continuously ‘rocking’ long after a storm event subsides. Seiches that develop when strong to gale force winds blow across the lake are often accompanied by high energy waves and storm surges. When this occurs, damage to plant stems can result. In some areas seiches can change water levels by nearly a meter in a matter of hours. Seiches as high as 1.5 m have been recorded on Lake Michigan and as high as 3 m on Lake Huron following high wind events. However, 10 to 20-cm changes in water levels are typical in most areas of the Laurentian Great Lakes. Biota found in these environments are adapted to abrupt changes in depth or even complete dewatering” (Uzarski 2009). Seiche frequency and amplitude are not likely to be affected by altered water regulations, but the elevation at which they occur will. However, seiches influence short-term wetting and dewatering of wetland surfaces and circulate water; seiches continue under seasonal and interannual water level cycles and the ‘reach’ (upper and lower extent across coastal habitats) of seiches varies accordingly.

“Overlaid on short-term variation in water levels are seasonal changes. For example, water levels in the Laurentian Great Lakes reach seasonal maxima in June (Ontario and Erie), August (Michigan and Huron),
and September (Superior). Seasonal lows generally occur during the winter months as evaporation coincides with a reduction of inflows from precipitation and runoff. The effects of annual water level fluctuations on biota have not been well studied in these systems, but some research suggests that they are important for the germination and survival of many types of emergent vegetation” (Uzarski 2009). It is also very important that seasonal water level maxima and minima are not shifted as interannual water level varies. In considering indicators of sensitivity to altered outflow regulation in the UGL, seasonal aspects of indicators and seasonal hydroperiod (as mentioned above for each lake) will need to be taken into account. “Interannual fluctuations result from the variability in weather patterns from year to year and are not predictable. The most pronounced result of interannual water level fluctuations is a shift in plant zonation, either lakeward or toward the upland. Vegetation zones (Figure 11) adjust to hydrologic conditions that are the optimum for each community type via germination of propagules from seed banks or buried roots and rhizomes” (Hebb et al. 2006, Uzarski 2009). As previously discussed, Thompson and Baedke (2000) have described 33-year and 160-year cycles in the UGL, with considerable variation within those cycles.

Regulation Plan Aspects That May Affect Wetland Vegetation

A fundamental consideration in changing in Lake Superior outflows is identifying aspects of vegetation that would be positively or negatively altered over a span of many years (e.g. 50 or more). Could the structure and function of wetland vegetation persist or even benefit under altered regulation schemes? What facets could be monitored as indicators of change? This section addresses sensitive aspects of wetland vegetation to regulation scenarios compared to vegetation behavior under the current plan, 77A.

Studies that inform the above questions are few, but the results do give us insights into the natural resiliency of wetland vegetation to altered water level regime. Wilcox and Nichols (2008) examined a wetland in Saginaw Bay during a period of drought. Submerged aquatic vegetation did not persist, although a few non-native SAV did survive. Mudflat annuals quickly colonized the dewatered strand, followed by emergent perennials such as certain bulrushes (Schoenoplectus spp.). Diversity in the emergent zone increased as a result. Over a period of 2-4 years succession included establishment of meadow species downslope from locations previously inundated. In addition, invasive species such as narrow-leaf cattail (Typha angustifolia) and common reed (Phragmites australis) became established in the strand zone. This study provides a model that illustrates how drying in combination with stable water levels can change species richness. Also illustrated was the importance of moist soil exposure associated with low water, which is necessary for seed germination and vegetation succession in maintaining both diversity and zonation (also see Hebbs et al. 2006).

Mortsch et al. (2008) examined the cover of wetland habitat from aerial photos for a set of wetlands on Lake Huron; the photos were taken during various periods of low and high lake level. The area of ‘strand’ (unvegetated) habitat, emergent marsh, and meadow marsh expanded and contracted with low and high lake levels, respectively. Strand habitat consistently expanded and contracted in high and low water years, respectively; this is a physical process of exposure and flooding of shallow lake sediments. Vegetated habitats exhibited variable response. Meadow marsh was capable of some expansion and contraction consistent with water level. Emergent marsh response across the sites was variable. Fen habitat also responded to varying water level, but the response was inconsistent across sites and was apparently related to the proximity to the shoreline. Roads adjacent to the inland edge of a wetland may restrict vegetation response and water movement. These authors recognized that these ‘snapshots’ of wetland zonation were influenced by the variability of lake level during intervening periods. This study was not able to examine response of SAV but these were modeled in previous studies based on known parameters that impact SAV extent (Doka et al 2006).
Wilcox et al. (2008) documented the effect of regulation of water level in Lake Ontario using aerial photo interpretation. Meadow marsh area apparently increased during low water years in the 1960s, and decreased when lake levels were higher in the 1970s. Cattail (Typha X glauca and T. angustifolia) coverage increased beginning in the 1970s, continuing to 2001 as the higher water level was sustained regulation. This paper provided a review of the factors associated with Typha dominance, including their tolerance to flooding, competitive ability, response to nutrients, and sedimentation.

Chow-Fraser (2005) reported an association between low annual water level and total suspended solids (TSS); shallow water can be associated with wave disturbance that reduces light and buries SAV propagules. This effect overshadowed the beneficial effect of carp removal in Cootes Paradise Marsh, Lake Ontario. Two threshold water level effects for SAV were identified: 1) a maximum water level threshold that limits light availability, and 2) a minimum water level threshold that is too dry for most SAV species.

Croft and Chow-Fraser (2007) demonstrated the importance of nutrients and turbidity in controlling SAV communities in Great Lakes coastal ecosystems as they developed a wetland macrophyte index for fish habitat quality. Processes that affect these water quality parameters, especially water clarity/turbidity, affect the presence of SAV. Their report discussed the general role that prolonged unfavorable conditions can play in delaying the response of SAV to improved conditions because vegetative and seed propagules may be depleted.

Vegetative and seed propagules can also be depleted during low water periods through human activity. Extensive shoreline areas became exposed during drought conditions between 2000 and 2004 in shallow bays such as Saginaw Bay, Lake Huron, and Green Bay, Lake Michigan, and were rapidly colonized by emergent plants. This resulted in ‘beach grooming’ activities by landowners who wished to maintain clear waterfront access to the lakes. Uzarski et al. (2009) discussed grooming activities that removed buried propagules of cattails and bulrush. The removal resulted in almost complete eradication of these plants, preventing their re-establishment when water levels again rose. This activity also negatively impacted fish and invertebrate communities in these areas. Furthermore, the exposed sediments were subject to erosion, producing turbidity that affected the integrity of adjacent fringing wetland areas (Uzarski et al. 2009). Thus, local activities created permanent habitat degradation at a scale that significantly exceeded the groomed area.

**Indicator Plant Species**

Albert et al. (2008) summarized common species of the Great Lakes coast that are sensitive to lake-level variation and could be used as indicators. These include: bulrush (Schoenoplectus acutus and S. pungens), purple loosestrife (Lythrum salicaria), wild rice (Zizania aquatica/Z. palustris), narrow-leaved and hybrid cattail (Typha angustifolia and T. X glauca), common reed (Phragmites australis), upright sedge (Carex stricta), and bluejoint reedgrass (Calamagrostis canadensis). Albert suggested a few rare plant species that are sensitive to water level; these included Pitcher’s thistle (Cirsium pitcheri), eastern prairie fringed orchid (Platanthera leucophaea), Smith’s bulrush (Schoenoplectus smithii), and a species of arrowhead (Sagittaria montevidensis). These species reflect variable lake level, either because they are early colonizers (bulrush, loosestrife, cattail, common reed), because they are specialists of variable water levels (upright sedge, bluejoint reedgrass), or because they are rare species that require recently exposed substrate. Individual species likely cannot be used to indicate effects of altered water level regulation because of climatic differences among ecoregions, site-specific aspects such as size, topography/bathymetry, geomorphology, and disturbance and stress unrelated to water level, although particular vegetation types, such as ‘robust perennial’ or ‘invasive perennial’ would be indicative of habitat that may reflect disturbance from pollution, soil disturbance, or reduced variation in hydroperiod.
Invasive Species

The Great Lakes continue to experience invasion and expansion of foreign and invasive species (invasive species are native species that colonize rapidly or compete successfully). Coastal development, hydrologic alteration, and pollution exacerbate the situation by providing opportunities for expansion of foreign and invasive species. The UGL are experiencing expansion of several invaders, including purple loosestrife, non-native cattail, common reed (*Phragmites*), and a few others. Most of these species can take advantage of exposed moist soil, and some are more tolerant than native species to pollution by salts, nutrients, and chemicals commonly associated with roads, agriculture, urbanization, industrialization, and similar human development.

Possible Effects of ‘Fencepost Plans’ on Vegetation

Aspects of the ‘fencepost’ scenarios (Fay and Dahl 2008) suggest, at this point, how the Superior plan, Michigan-Huron plan, and hydropower plan might alter interannual variation of water level for Lake Superior and Lakes Michigan-Huron and St. Clair. The following types of changes to the hydrologic regime may forecast some general effects on vegetation. For instance:

- Narrowing of interannual water level amplitude (either lowered high-water years, higher low-water years, or a reduction in both extremes) will compress or eliminate zonation, even in areas that are not geologically constrained. Some smaller wetlands may lose certain zones, such as meadow marsh and fen. **We recommend using detailed bathymetry and digitization of aerial photographs documenting historical and current wetland distribution (focusing on high-importance areas for which suitable background data exist) to model historical trends and develop comparative models and indicators of the areal extent and pattern of zonation changes likely to occur between the various fencepost scenarios and the current regulation scheme;**

- Increasing the frequency of flooding in part of the wetland continuum may result in expansion of the emergent and SAV zones, and the concomitant contraction and potential loss of other habitats (meadow and fen). However, **in areas constrained upslope by geology or human development, increased high water years would result in the compression or loss of some zones. These predictions should also be evaluated by modelling;**

- Reducing interannual variation (reducing the frequency or entirely eliminating high-water or low-water years) will reduce species diversity, encourage dominance by the most competitive species (often invaders), and promote succession of woody plants in fens and meadows, decreasing their extent;

- Altering the timing of annual water level maxima and minima may affect the reproductive success of both wetland vegetation and the biota that depend on the microhabitats they provide for breeding/spawning and nesting/nurseries; and

- Increasing the frequency of annual drawdowns will facilitate woody plant succession into fens and wet meadows. More frequent and extended periods of low water level will also favor establishment and dominance by emergent macrophytes, including invasives in the drawdown zone. In areas constrained by bathymetry, limiting the ability of wetland zones to migrate downslope, these intermediate zones (such as fens and meadows) will be compressed or lost.

Suggested Vegetation Indicators

Challenges to development of indicators of vegetation sensitivity to the types of hydrologic changes that may take place between regulation plans (Fay and Dahl 2008), include the following:

- UGL coastal wetlands are geomorphically and biologically diverse. Local bathymetry/topography, size and shape, differing levels of anthropogenic stressors in the watershed, fetch, geologic setting, and ecoregion all influence the wetland types and species composition vegetation zones. Wetlands frequently exist as complexes, containing some elements
of each of the three major coastal wetland types, riverine, fringing, and protected (Keough 1999, Albert et al. 2005, Wilcox 2004, Chadde 1998), and

- Funding and time are insufficient to test performance indicators in a large sample of coastal wetlands, so it is unlikely that the UGL study results can be applied to all coastal wetlands. **We recommend that performance indicators be assessed in a suite of areas distributed throughout ecoregions that encompass all wetland types.** The sites selected for evaluation should have existing data from previous studies and should also span a gradient of ecological integrity. It is essential that detailed elevation surveys and aerial photographs be available at the sites selected.

We recommend that the following performance indicators be assessed to compare the fencepost scenarios vs. Plan 77A hydrology (Table 1). These performance indicators reflect the role of vegetation as habitat supporting aquatic ecosystems and food webs. Vegetation indicators are designed to describe habitat for coastal fish, wildlife, and invertebrate communities. All indicators would be compared/normalized to the condition under Plan 77A, recognizing that all of the UGL have recently experienced a number of years of low annual water level. General performance indicators include:

- Area of each vegetation zone vs. expected, based on elevation range and condition under Plan 77A,
- Number and interspersion of vegetation zones relative to condition expected in appropriate elevation ranges under Plan 77A, and
- Extent (percent of wetland area) of invasive plant species-dominated habitat based on intensity and local extent of agriculture and urbanization, and distance between study areas and source populations of invasive species (i.e. propagule pressure).

**Invertebrates and Fishes**

**Macroinvertebrates**

Macroinvertebrate distribution and community composition reflects the plant zonation-induced chemical and physical gradients that are established by water level fluctuations described above. More than 260 invertebrate taxa have been documented from Great Lakes coastal wetlands (Burton et al. 2004). The actual number of species is likely 3-4 times greater because most organisms are only identified to the family or genus level (Uzarski 2009).

“Many invertebrate taxa may be considered generalists along the exposure gradient from high wave energy to inland protected systems (Burton et al. 2002). Others are specific to a level of exposure to waves, seiches, upwellings and currents. The highest diversity likely occurs in the middle of this gradient from exposed to protected marshes where the protected community, often made up of collector/gatherers with some predators, and the very exposed community, often made up of very small organisms and good swimmers, overlap” (Uzarski 2009).

A schematic, conceptual model of how hydrologic variability, including exposure to waves, influences invertebrate-community composition in coastal marshes was developed for the Great Lakes by Burton et al. (2004; Figure 12). During very low water years some marshes are protected from waves by a sand ridge; therefore, the source of water is primarily in the form of groundwater or interflow from uplands and precipitation. However, some water still accrues via overland flow and/or from the lake proper, depending on lake level. Thus, water levels fluctuate both seasonally and annually. Organic matter can accumulate extensively, but the degree depends on the amount of primary productivity and the amount of runoff that the system receives. The lack of turbulence in these systems often results in low turbidity. The rich organic substrates and decomposition result in low oxygen levels in the sediments, especially overnight
and under ice in winter when respiration outweighs photosynthetic oxygen production. These low oxygen levels likely prevent some invertebrate taxa from inhabiting these areas.

Figure 12. A conceptual model of responses of wetland invertebrate communities to wave energy in Great Lakes coastal wetlands, as redrawn from Burton et al. 2004. Macroinvertebrate community composition can be predicted from the amount of wave energy a wetland experiences. Waves and currents dictate organic sediment accumulation, detritus accumulation, and stem density. (From Uzarski 2009). This model reflects not only a gradient of hydrologic energy within a given fringing wetland, but can also be used to predict invertebrate communities among wetland types, with the most protected riverine wetlands to the left of the continuum and the most exposed fringing wetlands to the right.

The lakeward, well-mixed edge of the wetland is dominated by filtering-collectors (macroinvertebrates that filter their food out of the water column) such as Orthocladiinae or Tanytarsini midges (Diptera: Chironomidae) (Cardinale et al. 1998). The lake water carries suspended organic particles, plankton, and inorganic nutrients. The nutrients promote development of epiphytic algae (algae that grow on plants) that provide food for the grazing and filtering collectors. In very exposed and sparsely vegetated areas, the community typically contains water boatmen (Corixidae genera Sigara and Trichocorixa), segmented worms (Oligochaeta: Tubificidae; Naididae, Stylaria), snails (Gastropoda: Valvata), and biting midges (Ceratopogonidae: Bezzia) (Burton et al. 2002, Uzarski 2009).

Further into the wetland, toward shore, plant stems dampen wave energy and particles settle (Cardinale et al. 1998). Inorganic nutrients are sequestered, and, consequently, epiphytic algae are sometimes replaced by planktonic forms. Therefore, densities and diversity of grazing and filtering invertebrates also decrease. The highest macroinvertebrate diversity likely occurs in the middle of the gradient where taxa characteristic of wave exposure (very small organisms, filter-feeders, and good swimmers) co-occur with less mobile collector/gatherers and some predators (Burton et al. 2002, Uzarski 2009).
The typical community found in areas of intermediate exposure is primarily made up of amphipods (*Hyalella*), predatory midges (*Chironomidae: Tanypodinae*), aquatic mites (*Hydracarina*), caddisflies (*Trichoptera: Phryganeidae*), dragonflies (*Odonata: Libellulidae*), mayflies (*Ephemeroptera genera Caenis, Callibaetis*), and snails (*Gastropoda: Physa*) (Burton et al. 2002, Uzarski 2009). During times of low water, or in areas of wetlands that are more protected from waves and currents, higher densities of gathering-collectors and visual predators such as dragonflies, damselflies, backswimmers, and other water bugs are supported. The predatory midges such as Tanypodinae (*Diptera: Chironomidae*) can dominate invertebrate densities in the nearshore bulrushes (Burton et al. 2002, Uzarski 2009). Research from the Great Lakes suggests that in very extensive coastal marshes that are subject to high energy events during high water years, waves are completely dissipated approximately 150-200 m from open water (Cardinale et al. 1998). Fauna that are carried into marshes from the open water zone by storm surges and currents (e.g. dreissenid mussel larvae) often accumulate at this distance from open water, likely altering the spatial distribution of invertebrates in the wetland (Brady et al. 1995).

The most protected areas are those in which substantial organic matter accumulates. Consequently, food resources are rich, but water may be subject to hypoxia. This zone is typically dominated by taxa such as amphipods (*Gammarus, Crangonyx*), isopods (*Caccidota*), midges (*Chironomidae: Chironomini, Tanytarsini*), caddisflies (*Trichoptera: Leptoceridae genus Mystacides*), and predacious diving beetles (*Coleoptera: Dytiscidae*). Most snails (*Gastropoda: Amnicola, Oxyloma*), limpets (*Gastropoda: Ferissia, Laevopex*), and fingernail clams (*Sphaeriidae: Musculium, Pisidium*) dominate very protected areas with organic matter accumulation (Burton and Uzarski 2009).

“Organic matter produced in exposed lacustrine marshes is often swept up onto the adjacent shore or out to pelagic waters by waves, ice scour, and storm surges, leaving sediments dominated by sand, especially during high water years. Very few invertebrates are found in this type of habitat. Most often, the only stable substrates are bulrush stems” (Uzarski 2009) or, occasionally, *Typha* stands. When *Typha* stands occur, they can trap organic matter in similar amounts as protected or inland marshes. Therefore, invertebrate communities in such stands are often comparable to a hybrid of very protected and exposed systems (Uzarski 2009).

Aquatic macroinvertebrates have long been used as indicators of environmental conditions (e.g. Hilsenhoff 1987, Rosenberg and Resh 1993). They are species-rich, respond to a broad range of environmental conditions, and are relatively immobile and live in close contact with both bottom sediments and the water column, thereby having the potential for exposure to stresses via both sediment and aqueous pathways.

Brady et al. (cited in Brazner et al. 2007b) examined variation in seven zoobenthic indicators calculated from samples collected at 75 coastal margin locations as part of the Great Lakes Environmental Indicator project. These indicators included taxonomic richness and four function- and five taxon-based indicators, all quantified as proportional abundances. The four function-based indicators were burrowers, clingers, predators, and insect filter-gatherers (Merritt and Cummins 1996, Thorp and Covich 2001), all of which have been used as indicators of condition in streams and inland wetlands, and had previously been proposed as index of biotic integrity metrics in the Great Lakes (Uzarski et al. 2004). The five taxon-based indicators were the mayfly genera *Caenis* spp. (*Ephemeroptera: Caenidae*) (soft sediment inhabitants), the damselfly genera *Coenagrion/Enallagma* spp. (restricted to vegetation), the caddisfly genera *Oecetis* spp. (*Trichoptera: Leptoceridae*) (hard-substrate inhabitants), the dragonfly genera *Aeshna* spp. (long-lived predator species), and the mayfly genera *Procloeon + Callibaetis* spp. (short-lived genera, one or the other of which would be expected in most coastal wetlands). Although the zoobenthos showed considerable variation with respect to human disturbance gradients, the pattern of response tended to vary as a complex function of the Great Lake and wetland type being examined (Brazner et al. 2007b).
Water level changes are expected to affect wetland macroinvertebrate habitat primarily by altering plant zonation, wetland extent, wetland type, sediment composition, and wetland plant diversity and species composition. Because benthic invertebrate communities depend so strongly on aquatic plant habitat zones and types, invertebrate-based indicators are often stratified by plant zone (Burton et al. 1999, Uzarski et al. 2004). Hydrologic variability and anthropogenic disturbances are superimposed on plant zonation (Burton et al. 2004) in shaping invertebrate community composition. While these attributes make macroinvertebrates prime candidates for indicating significant impacts of water level change and fluctuation, we recommend only using them in a restricted sense. Long-lived, wetland-obligate invertebrates such as dragonflies and damselflies are relatively easy to collect and their presence indicates that water levels and habitat conditions have been relatively stable over the course of their development, which can be a year or more; therefore, we recommend their use as performance indicators of water level responses (Table 1).

Alternatively, the effect of water level and water level variability alterations on wetland macroinvertebrates can be inferred using indicators collected for the wetland plant community (zones, diversity, extent, etc.). It may be preferable to sample wetland plant community indicators rather than macroinvertebrates due to the greater time required to process and identify invertebrate samples, particularly those from productive wetlands. The value of wetland macroinvertebrates as forage for fish can be determined by estimating macroinvertebrate and microcrustacean biomass per hectare of marsh (Table 1). This simplifies sample processing because identification is not necessary beyond major group and size.

**Fishes**

Wetzel (1990) suggested that the highest density and diversity of fishes is associated with high primary productivity in the form of macrophytes and algae. Intact coastal wetlands with several plant zones (sustained by water level fluctuations) provide cover, prey, spawning and nursery habitats (Goodyear et al. 1982, Lane et al. 1006a,b,c). Great Lakes coastal wetlands provide essential habitat for more than 80 species of fish (Jude and Pappas 1992). More than 50 of these species are strictly dependent on wetlands, while another 30+ migrate into and out of them during different periods in their life history (Jude and Pappas 1992, Wilcox 1995). An additional 30+ species of fish may be occasional visitors to coastal wetlands based on occurrence in adjacent habitats (Jude and Pappas 1992). Uzarski et al. (2005) found a relationship between plant zonation and fish community composition. High productivity and structural diversity of Great Lakes coastal wetlands are maintained by natural cycles of high and low water levels (Geis 1979, Herdendorf 1990), as well as the natural annual water level fluctuations described above. Thus, Great Lakes coastal wetlands with plant zonation established and maintained by natural water level fluctuations are critical to the Great Lakes fisheries. The interaction of these important vegetated habitats and water depth, temperature, and substrate preferences (sometimes surrogates for food availability) create a complex dynamic that may be locally specific to structuring fish communities depending on ecoregion and local bathymetry and geology. Therefore, water levels play an important role in determining community compaction and productive capacity that may not be directly related to absolute water level or vegetation (sensu Figure 2). The response of the fish community or individual indicator species (see below and Table 1 for species of particular interest) should be modeled separately but link to underlying physical and biotic drivers that may also be indicators.

Even cool-water fishes that cannot tolerate warm summer wetland temperatures sometimes spawn in specific vegetation zones within coastal wetlands early in the year. Often larval and juvenile fishes are more tolerant of high temperatures and can take advantage of the abundance of food resources while hiding in dense vegetation to escape predation. A study in Green Bay wetlands reported 98% of all yellow perch (*Perca flavescens*) captured were young-of-the-year (Jude et al. 2005). This high number of young yellow perch suggests that coastal wetlands may be a critical source of recruitment in the Great Lakes as

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these fish disperse to the adjacent lake within a year of hatching. These fish contribute to the overall ecosystem food-web dynamics as predators and prey, and rely on plant zonation established by water level fluctuation (Jude et al. 2005). Other indicator species, such as northern pike, which are reliant on very shallow marsh habitats for spawning and emergent/SAV for ambush of prey, have been used in the LOSLR Study (Farrell et al. 1996, Minns et al 2004) and is an indicator recommended by Albert et al. (2008).

Fish assemblages have been used as land use or water quality indicators of environmental conditions at the Great Lakes coastal margins (Seilheimer et al. 2006, Chow-Fraser 2007, Uzarski et al. 2005, Bhagat et al. in review). Three indices currently exist that relate 24-hour trap net catches to land-use or water quality-based measures of environmental condition at Great Lakes coastal margins. The wetland fish index (WFI; Seilheimer et al. 2006) reflects a nutrient-dominated water quality index (WQI; Chow-Fraser 2007). A habitat productivity index (HPI) was developed by Randall and Minns (2002). Uzarski et al. (2005) and Randall et al. (1996) developed indices of biotic integrity (Fish-IBI) based on multiple metrics. Great Lakes Environmental Indicator (GLEI) researchers derived indices from multivariate analyses of fish species relative abundances (Bhagat et al. in review). Other coastal margin fish metrics have been developed using electrofishing methods (Randall et al. 1996, Chow-Fraser et al. 2007, Thoma 1999, Brazner et al. 2007b). Fyke netting and electrofishing sample disproportionately different components of the fish community and therefore cannot be compared (Ruetz et al. 2007) except possibly when using presence/absence data (Bouvier et al. in press). Despite the robust responses to disturbance and other environmental gradients, more among-site variation in fish indicator scores is accounted for by wetland hydogeomorphic type and Great Lake than by ecoprovince or human-related disturbances (Brazner et al. 2007b). This suggests that fishes as a group can be especially useful as performance indicators of altered water levels mediated through vegetation change and other interactions.

Useful performance indicators to model the effects of altered water levels and/or water level variability on the Great Lakes fish community include:

i) Estimates of the amount of habitat available for various guilds of fish and species of particular interest (commercial species, top predators, species at risk, etc),

ii) Indices of population density/biomass for several species of particular interest, particularly those with a strong affiliation for wetlands,

iii) Estimates of the availability of spawning and nursery habitat for species of particular interest, including accessibility to spawning streams, and

iv) Estimates of species richness for obligate wetland fishes (Table 1).

Semi-Aquatic and Terrestrial Vertebrates

Amphibians, birds, mammals, and reptiles are ubiquitous throughout the UGL coastal region. Their distribution and abundance are closely associated with plant species as well as the physical and chemical structure of the habitat. As water levels and, subsequently, habitats change in the region, the vertebrate species composition changes concomitantly. A host of studies have described the habitat associations of semi-aquatic and terrestrial vertebrates in Great Lakes coastal regions. For instance, Heenar (2004), Heenar and M’Closkey (1997), and Price et al. (2005, 2007) have described amphibian species and communities in Great Lakes wetlands. Similarly, several studies (e.g. Hanowski et al. 2007, Howe et al. 2007a, 2007b, Miller et al. 2007, Peterson and Niemi 2007, Rifflle et al. 2003) have documented breeding bird distributions in the UGL coastal region. Even though studies of reptiles and mammals are less common, their life histories and use of Great Lakes coastal areas are well-known.

Few studies have specifically examined the effects of water level changes on semi-aquatic or terrestrial vertebrates in the UGL region. Examination of the effects of water level change on these species is best linked with their associations with habitat conditions. For instance, the approach of Howe et al. (2007a, 2007b) and Price et al. (2007) that links breeding birds and amphibians, respectively, with stress gradients
provides a framework to examine variations in water level change in the coastal region of the UGL. One exception to studies of water depth and wildlife is Grandmaison and Niemi (2007), whose study of red-winged blackbird (*Agelaius phoeniceus*) nesting success included water depth as one of several variables in the analysis. Water depth was not a significant factor in nest success for red-winged blackbirds in wetlands of western Lake Superior, but this may be partly due to little variation in water depth during the course of the study (Grandmaison and Niemi 2007). Other studies (e.g. Robertson 1972, Picman et al. 1993) outside of the Great Lakes have found water depth to play a significant role in nest success of wetland breeding birds because lower water depths are associated with increased predation of nests. We have not included breeding success as a performance indicator for the UGL because there is insufficient information on the breeding biology for most species in the region. In contrast, we suggest the focus should be on habitats, the linkage with how habitats would change with variations in water levels, with species at risk, obligate wetland breeding bird species, breeding and migratory waterbirds (e.g. loons, grebes, ducks, geese, and herons), anuran populations, and selected mammal species that would be most affected by water level changes.

Albert et al. (2008) completed an extensive literature review of common species and rare, threatened, and endangered species that are directly affected by lake level fluctuations. Many of their recommended species were plants and fish. Regarding vertebrates with a semi-aquatic or terrestrial life history, they recommended four threatened or endangered bird species and three common mammal species as direct indicators of water-level fluctuations. No amphibian or reptile species were identified; however, one reptile, the rare eastern fox snake (*Elaphe vulpina*), was of questionable use as an indicator. Similarly, the mallard (*Anas platyrhynchos*) was also identified as of questionable use. The four bird species with legal status included the piping plover (*Charadrius melodus*), least bittern (*Ixobrychus exilis*), king rail (*Rallus elegans*), and black tern (*Chlidonias niger*). The piping plover is endangered in many states of the US and in Canada. The least bittern is listed as threatened in Canada, endangered in Indiana, and threatened in Michigan, Illinois, and Ontario. The king rail is listed as endangered in Canada and in several US states. The black tern is listed as endangered in Illinois and New York and of special concern in Canada and Michigan. The three common mammal species included the muskrat (*Ondatra zibethicus*), meadow vole (*Microtus pennsylvanicus*), and heather vole (*Phenacomys intermedius*).

With the exception of the piping plover, all of the vertebrate species identified by Albert et al. (2008) are linked to wetland habitats found in the UGL. The piping plover is highly associated with open, exposed beaches with a mix of sand, cobble, and sparse vegetation (Haig 1992). There are many factors that have affected the distribution and abundance of the piping plover in the UGL. Fluctuations in lake levels and the availability of protected open sand/cobble beach habitat are important aspects of their continued survival in the region (US FWS 2003). The piping plover is a key performance indicator of open, sandy beach habitat (Table 1). Lower lake levels would be beneficial to this species because more beach habitat would be exposed, while higher lake levels would be detrimental for the opposite reason. The availability of beach habitat, however, is not sufficient by itself. The availability of beach habitat that is relatively free of human disturbance and protected from predators is critical. Therefore, active management of sites colonized or used by piping plovers must also be considered.

Birds and mammals are highly associated with specific wetland habitat types found in the coastal region of the UGL, and many of the wetland habitats are greatly influenced by water levels and variation in water levels. For instance, three of the endangered bird species (least bittern, king rail, black tern) identified as susceptible to water level fluctuations can be found nesting in emergent wetlands. Least bittern and black tern are found in the deeper water areas with scattered openings within these wetlands (Evers 1997). In contrast, king rail are generally found in drier portions or at the interface of emergent wetlands with sedge meadows or shrub wetlands (Evers 1997, Albert et al. 2008). Muskrat are found in emergent wetlands and can be partially responsible for engineering the mosaic of patterns within these wetlands (Errington 1961). Emergent wetlands are also important to many waterfowl species such as
mallard, blue-winged teal (Anas discors), and the rare American black duck (Anas rubripes). The degree to which water levels change within specific areas, and the degree to which wetlands change, will determine the effects on these species that are important to many societal groups such as conservationists, bird watchers, and hunters.

The two common species of mammals identified by Albert et al. (2008), the meadow vole and heather vole, are primarily found in sedge meadows that are affected by water level fluctuations. Many other species of interest to conservationists and bird watchers, such as the yellow rail (Coturnicops novaboracensis), northern harrier (Circus cyaneus), short-eared owl (Asio flammeus), sedge wren (Cistothorus platensis), and LeConte’s sparrow (Ammodramus leconteii), are also found in sedge meadows. The availability of more sedge meadow habitat would be beneficial to this group of species.

Forested wetlands are important to many bird species. These habitat types house many species of neotropical migrants that are of national interest (Rich et al. 2004), such as American redstart (Setophaga ruticilla), northern waterthrush (Seiurus novaboracensis), Nashville warbler (Vermivora ruficapilla), and rose-breasted grosbeak (Pheucticus ludovicianus) (Hanowski et al. 2007, Peterson and Niemi 2007). Forested wetlands also provide breeding habitat for many hole-nesting ducks such as wood duck (Aix sponsa), hooded merganser (Lophodytes cucullatus), common merganser (Mergus merganser), and red-breasted merganser (Mergus serrator). Again, the availability of forested wetlands within a specific UGL coastal region would depend on the topography and geomorphology of the area.

The conceptual model (Figure 2) presents the framework that links hydrology and water level fluctuations under different water regulation scenarios with the extent and distribution of wetland habitat types or open beach habitat that would be available. This availability is critical for assessing the ecosystem responses of the species and vertebrate communities identified above. The mosaic of wetlands (submerged, emergent, sedge, forested) and beach habitat available to the semi-aquatic and terrestrial wildlife in the UGL coastal region are key linkages with the performance indicators (Table 1). Water level changes within the specific study areas identified (see below) need to be linked with the purported changes in wetland and beach habitat to assess the potential effects on the species or vertebrate communities identified here. New probability functions of the type described by Howe et al. (2007a, 2007b) and Price et al. (2007) that link water levels and habitats with the habitat associations of the performance indicators are an effective means to assess these ecosystem effects. These functions can be developed from existing information as well as empirical relationship for the species at risk and the vertebrate species and communities identified as performance indicators. Alternatively, habitat suitability functions of the type described by DePinto (Limno-Tech, Inc. 2005) can be developed for the obligate species that occur in the range of wetland habitats found in the key study areas described below. We recommend that these functions be developed for the performance indicators (Table 1) found in the coastal regions of the UGL area.

**Biological Indicators of Coastal Margin Condition as Ecological Performance Indicators**

Development and testing of indicators of Great Lakes coastal ecosystem integrity/health have been the focus of research in recent years. The development of biological indicators of habitat suitability and environmental condition has a long history in streams (Karr 1981), but development of similar indicators for wetland and lake coastal margins has lagged. Minns et al. (1994) proposed and evaluated an IBI for fish assemblages in Great Lakes littoral zone areas of concern, following the methodology developed and recommended by Karr (1981). Since that time, several different approaches to indicator development have been recommended and adopted (Niemi and McDonald 2004, Niemi et al. 2006).
The recognition that suitable bioindicators of Great Lakes coastal margin condition were lacking (e.g. SOLEC 1998) stimulated several agencies to provide research funding to support their development. Chow-Fraser, funded from various sources including NSERC and the Great Lakes Fishery Commission, derived quantitative and effective indices of water quality (Chow-Fraser 2007), phytoplankton (McNair and Chow-Fraser 2003), zooplankton (Lougeed and Chow-Fraser 2002), macrophytes (Croft and Chow-Fraser 2007), and fishes (Seilheimer and Chow-Fraser 2006, 2007). The US EPA GLNPO-funded Great Lakes Coastal Wetland Consortium independently derived multimetric-based indices of zoobenthos (Burton et al. 1999, Uzarski et al. 2004), fish (Uzarski et al. 2005), macrophyte (Albert et al. 2005, 2008), amphibian (Timmermans et al. 2008a), and bird (Timmermans et al. 2008b) community condition. The US EPA STAR program supported the Great Lakes Environmental Indicators (GLEI program; Niemi et al. 2006), which derived indicators of various taxa including diatoms (Reavie 2007), fish (Bhagat 2005, Bhagat et al. 2007, Bhagat et al. in review), bird assemblages (Howe et al. 2007, Miller et al. 2007), emergent plant species (Johnston et al. 2007), and anurans (Price et al. 2007).

Different sampling design approaches, geographic and habitat coverage, and analytical techniques were used by each group, reflecting the groups’ unique research questions and priorities. Chow-Fraser’s research emphasized quantifying biological responses to wetland water quality and habitat degradation. The mandate of the GLCWC was to develop a binational monitoring program to assess and inventory the condition of Great Lakes coastal wetlands that could be reported to SOLEC (2007). In contrast, GLEI proposed to develop and test indicators of ecological condition of all Great Lakes coastal margins, not just wetlands. This also entailed special interest in defining and quantifying the bounds of reference condition. The emphasis of Chow-Fraser was on prediction, that of GLCWC was on monitoring status and trends of ecosystem health, and that of GLEI was on diagnosis and understanding cause/effect relationships.

Although each of these approaches to indicator development has focused more on water quality and habitat alteration stresses than on water level fluctuations, many of the effects are still mediated through degradation of the structure and extent of aquatic plant communities. Thus, some are amenable to modification for the assessment of effects of water level fluctuations. The relationships between water level and biological organization have been extensively discussed above. The performance indicators that we deem to have the most value for diagnosing likely effects of water level alteration are summarized in Table 1. The indicators in this section could also be modified or adopted in concert with other modelling approaches to diagnose the impacts of altering water regulation in the UGL.

**Modelling Approaches to Assessing Impacts of Alternative Water Regulation Scenarios**

Geospatial and response models served a critical role in assessing the potential impacts of changes to water levels and variability on habitats and their associated biota in the Lake Ontario-St. Lawrence River study (e.g. Limno-Tech, Inc. 2005, Werick et al. 2007). Often modelling is the only tractable approach to assessment given limited budgets, time frames, and availability of data. We believe that similar modelling approaches will be a critical element in assessing the relative effects of alternative water level regulation plans for the UGL.

The short timeframe allowed for completion of this review precludes any detailed assessment of the modelling approaches most suited to the IUGLS. This should be a cornerstone topic of discussion during the proposed experts workshop or a subsequent workshop dedicated to modelling approaches. Both model selection and possible approaches to organizing, simulating, and integrating the data to be gathered and
interacted to assess different scenarios (both regulation and supply) of water level changes in the UGL should be discussed.

The fundamental questions that can be supported by models are:

a. How will the regulation plan scenarios influence water levels and water level variability, leading to changes in affected habitat and, subsequently, key environmental performance indicators in the UGL?

b. How consistent are the water level/variability changes and the responses of key environmental performance indicators across the study sites, types, lakes, and ecoregions?

c. How well do the models predict the behavior of key environmental performance indicators in response to water level regulation scenarios? (model validation and model comparison).

Potential modelling approaches include mechanistic and statistical types of models such as those described by DePinto (Limno-Tech, Inc. 2005). Other modelling exercises could employ other statistical approaches such as multivariate, fuzzy cognitive mapping (e.g. Hobbs et al. 2002, Ozesmi and Ozesmi 2004, Joss 2008), Bayesian approaches, or structured equation modelling (e.g. Grace et al. 1998, Kang et al. 2004, Grace 2006). Another possibility is to use a meta-analysis approach in which a number of studies across the UGL region could be analyzed, even though their original intent was not specifically to consider water level fluctuations. Some basic population modelling could also be undertaken as in the LOSLR Study (Minns 2004) given the appropriate selection of indicator species and the availability of life history information for those species by ecoregion.

Some examples of species rankings based on sensitivity to coastal zone changes are available (Mortsch et al. 2006, Doka et al. 2006, Ingram et al. 2006) which could be used in species selection but more information on the ecoregional fish assemblages would be needed from the experts. The Lake Ontario-St. Lawrence River study (Limno-Tech, Inc. 2005, Minns et al. 2004) examined guilds of biota (e.g. vegetation-dependent coolwater fishes and marsh breeding birds) to develop aggregate response metrics (e.g. habitat availability and breeding success). Statistical or Bayesian approaches to model selection and indicator evaluations should be explored to ensure that the output is useful to decision makers. Once model selection and framework is in place gap analysis should be completed before further field collection of data is undertaken. **We recommend that time be allocated at the experts workshop to identify: a) the most relevant and readily available modelling approaches, and b) the critical data needs and available datasets. The experts panel may ultimately decide that a separate workshop dedicated to model selection is needed.**

**Sources of Data and Expertise**

In recent years, the Great Lakes scientific community has generated considerable data on coastal ecosystems. Most of the biological and environmental data were collected for other objectives; nevertheless, a great deal will be useful to the UGL study. Of course, there are few long-term data sets available to examine coastal features and processes through a full cycle of high and low lake levels (i.e. 30-y cycle).

Short-term research datasets for the UGL are available from the Great Lakes Environmental Indicators project (GLEI; e.g. Niemi et al. 2006, Niemi et al. 2007), Great Lakes Coastal Wetland Consortium (GLCWC; e.g. Burton et al. 2008), US National Park Service Great Lakes Network, McMaster University (the Chow-Fraser lab; e.g. Chow-Fraser 2005), US EPA (e.g. Trebitz et al. 2007, Simon and Stewart 2007), and region and site specific data (e.g. Wilcox et al. 2007, Kaus 2005). Some data include significant watershed information that may be useful in understanding the anthropogenic stressors that
may affect response to water level variation associated with regulation or climate change. Researchers who collected and previously analyzed these data should be considered for inclusion in studies needed by the IUGLS ETWG.

Because most data available for coastal ecosystems were collected during a ‘snapshot’ of Great Lakes water level, field studies to verify the relationship between ecosystems and water level variation scenarios specific to the IUGLS will be required. In addition, assembly of bathymetry/elevation, sediments, and other physical data will be required, at least for the intensive study sites. The elevation data currently available for most of the UGL are not of sufficient resolution for coastal ecosystem analysis, so improved information from LIDAR or other technology will be needed. Assembly of new and previous ecosystem maps from high resolution aerial photography will also be required for development of models and performance indicators of habitat availability and type.

The scope and deadline for this paper preclude exhaustive analysis of data available or needed for each performance indicator. We suggest a stepwise approach: use the ‘expert workshop’ to solicit specific information on available data; task a GIS workgroup to identify relevant spatial data; and provide funds to assemble biological and environmental data and identify specific new data needs for models and performance indicators. A modelling subgroup should be established that works in concert with the other tasks identified so gaps are ensured to be filled and approaches are solidified. A representative from each of the other subgroups (i.e. vegetation, fishes, mammals, etc.), preferably someone with mathematical/programming/geospatial analysis knowledge, would effectively engage experts to facilitate model development and evaluation.

**Overall Strategy**

We recommend implementing the following strategy to assess the most likely ecosystem effects of water level regulation changes possible for the UGL region.

1. Assemble a team of collaborators with a breadth of expertise (Figure 13) to provide the essential elements for data gathering, compilation, modeling, and interpretation of the performance indicators for a suite of study sites across the UGL (Table 2). Given the available deadlines to evaluate water level regulation scenarios, gathering of any field data will be extremely limited. Rather, existing data will need to be identified and the collaborators should be familiar with the Great Lakes region and with the existing data. Research collaborators should be distributed across the UGL for logistical efficiency and breadth of understanding of the UGL. Timeframe to assemble teams: January-May 2009.

2. Select study areas that represent coastal-nearshore complexes vulnerable to water level fluctuations. We have identified a series of 18 such potential study areas (Table 2). The selected areas should be studied over the course of the remaining time dedicated to the UGL study. Besides considering areas vulnerable to water level fluctuation, the study area selection process should include a consideration of the following:
   a. Availability of historical data on performance indicators,
   b. Water level and variability data,
   c. Availability of aerial photography, especially over time,
   d. Availability of bathymetry data in relevant aquatic and terrestrial zones potentially affected by water level change, and
   e. Length of the historical data record. Time frame to select final list of study areas: March-June 2009.
3. Identify the most relevant and readily available modelling approaches suitable for the questions described below (step 4), the critical data needs, and available datasets required to undertake the proposed modelling exercises. Early in the process, potential modelers and collaborators will need to meet to come to agreement on a modeling approach, a common understanding of the goals and objectives of the study, and a timetable for accomplishment of the overall objectives. It is clear from the limited time available (approximately 12 months) that the input performance indicator variables will need to rely on readily available information for the selected study sites and expert knowledge of the collaborators. Relationships between water levels and the performance indicators will need to be developed from a combination of these data and empirical understanding. This approach is a data-heuristic-Delphi modeling effort. Heuristics are “rules of thumb,” educated guesses, intuitive judgments or simply common sense (Gigerenzer et al. 1999). Whereas the Delphi approach is a technique to gather the opinions of a group of experts with the aim of producing an accurate unbiased estimate. It is a structured technique of expert judgment. Timeframe: June 2009-September 2010.

4. Each of the collaborators investigating the study area should address these three basic questions:
   a. How will the regulation plan scenarios influence water levels, water level variability, and coastal habitats, and, subsequently, key environmental performance indicators in the UGL?
   b. How consistent are the water level/variability changes and the responses of key environmental performance indicators across the study sites, types, lakes, and ecoregions?
   c. How well do the models predict the behavior of key environmental performance indicators in response to water level regulation scenarios? To the extent possible, this should be based on historical information and associated data on the performance indicators. We suspect there is limited availability of such information, but study areas that include such information should be high priorities for inclusion in the study (model validation and model comparison).

5. Undertake data summary, data analysis, model evaluation, and report preparation by the UGL collaboration. It is essential that the collaborators and the modelers work closely together through this phase of the UGL study. Timeframe: September 2010-September 2011
Figure 13. The Ecosystem TWG serves as an oversight and guidance organization for the study consortium and provides formal linkages to the IUGLS study board. The study consortium steering committee consists of Canadian and US study team leads as well as the ETWG co-chairs. This group essentially manages the consortium and oversees funding and delivery of products. Consortium teams are formed to undertake the actual data analyses in the general areas described. Each team will have co-leads from Canada and the US.
References


to climate change and response to adaptation strategies. Final report to CCIAP, Natural Resources Canada. Environment Canada and Fisheries and Oceans Canada. 251 pp. + appendices.


Table 1. Key performance indicators identified for the UGL region. Indicators or descriptions labeled ‘TBD’ will be decided by teams of experts. Data in bold are those that are needed and for which the source is not known or for which we believe the data do not yet exist.

<table>
<thead>
<tr>
<th>PI Category</th>
<th>PI Description</th>
<th>PI Metrics</th>
<th>PI Ratio Approach</th>
<th>Databases Needed and References</th>
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</thead>
<tbody>
<tr>
<td>Site vulnerability</td>
<td>Describes the ability of a habitat to adapt to changing lake levels; Ability of significant habitats (such as wetlands, cobble and sand beaches, dunes, and alvars) to migrate in response to changing water levels</td>
<td>Local topography and bathymetry (m)</td>
<td></td>
<td>Normalize to Plan 77A where appropriate</td>
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<td></td>
<td></td>
<td>Shoreline geology and land use/cover (classes)</td>
<td></td>
<td>• Bathymetry/elevation for study sites</td>
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<td></td>
<td></td>
<td>Distance from water’s edge to nearest disturbed land use (m)</td>
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<td>• Current/new aerial photography and photos (as available) from the early 2000s (low water period)</td>
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<td></td>
<td></td>
<td>Extent and type of shoreline modification (hardening) (e.g., absolute (km; km²) or relative (%); length or area of shoreline converted from natural features to artificial structures (breakwall, sheet piling, paving, dam; levy, causeway, dock, etc.; summarized by class of structure)</td>
<td></td>
<td>• Shoreline vector file</td>
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<td></td>
<td>Spatial position relative to river mouth (m)</td>
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<td>• Road crossings, culverts, and ditches in the vicinity of the coastline</td>
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<td></td>
<td></td>
<td>Hydrologic modification (change in water exchange capacity; unit volume/unit time)</td>
<td>Alteration of fluvial processes (change in annual sediment transport load; alteration of channel structure; area of river mouth delta [ha])</td>
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<tr>
<td>Hydrology</td>
<td>Inundation magnitude, timing and seasonality</td>
<td>Compare seasonal inundation timing (date of start/end; duration (days); magnitude shifts (change in water depth [cm]; and area inundated [ha]), and relative variability (SD of above measures)</td>
<td>Normalize to both 77A and pre-project scenarios</td>
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<td></td>
<td>Change in hydraulic connectivity between lake/river and wetland (same as Fish Habitat Supply and Abundance)</td>
<td>Connection between lake and tributary or wetland; also connection between tributary and wetland Water exchange index - product of time connected (days/year) and the opening size (cross-section area/max</td>
<td>Normalize to Plan 77A</td>
<td>• Bathymetry/elevation</td>
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<td></td>
<td>• Nearshore littoral sand supply</td>
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<td>• Nearshore substrate type</td>
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<td></td>
<td>• Dredging records compared to water level</td>
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<td>• Connection elevation to lake water level</td>
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<td></td>
<td>• Temperature</td>
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<tr>
<td>PI Category</td>
<td>PI Description</td>
<td>PI Metrics</td>
<td>PI Ratio Approach</td>
<td>Databases Needed and References</td>
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</table>
| Wetland vegetation| Wetland vegetation integrity based on presence and maintenance of expected zones of vegetation communities. Habitat structure availability for fish and wildlife and their supporting food webs and ecosystems. | cross-section area, or wetted perimeter/maximum wetted perimeter of the connection opening. A value of zero (0) means no connectivity and a value of one (1) means maximum connectivity 100% of the time. | Normalize to Plan 77A | • Coastal wetland locations (GLEI, Environment Canada, GLCWC, Land Information Ontario)  
• **Bathymetry/elevation for study sites**  
• Current/new aerial photography and photos (as available) from the early 2000s (low water period) linked to lake levels at the time: identify data sets with air photos that match high and low water years; select subset of study areas for which ground truthing has been done  
• **Field data on elevation range for vegetation zones (ground truthing of types is very important)**  
• **Field estimation of extent of invasive species**  
• Need to determine expected time lags for vegetation establishment from the literature and expert opinion |

<table>
<thead>
<tr>
<th>Invertebrates</th>
<th>Density of wetland macroinvertebrates and microcrustaceans (if data from vulnerable areas exist)</th>
<th>Density or biomass per hectare</th>
<th>Normalize to Plan 77a</th>
<th>• Existing estimates of macroinvertebrates (GLEI, GLCWC, US EPA EMAP, McMaster Univ) and microcrustaceans</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Taxa richness of long-lived, wetland obligate species</td>
<td>Taxa richness (species/area)</td>
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<td>PI Category</td>
<td>PI Description</td>
<td>PI Metrics</td>
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<td>Fishes</td>
<td>Habitat-weighted suitable area (hectares) for fish guilds (incl. forage fish, others TBD) and vegetation (low/high) preference, by lake or site as necessary.</td>
<td>Habitat supply (hectares)</td>
<td>Normalize to Plan 77A</td>
<td>• Coastal wetland locations (GLEI, Environment Canada, GLCWC, Land Information Ontario) • Field estimate of vegetation cover</td>
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<td></td>
<td>Habitat-weighted suitable area (hectares) for species: particular species TBD, including special submetrics for</td>
<td>Habitat supply (hectares)</td>
<td>Normalize to Plan 77A</td>
<td>• Coastal wetland locations (GLEI, Environment Canada, GLCWC, Land Information Ontario) • Field estimate of vegetation cover</td>
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<td></td>
<td>a. Habitat in the St. Marys River (consider depth of water, flow, length of time for flows and seasonality)</td>
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<td>• Field estimate of vegetation cover</td>
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<td></td>
<td>b. Habitat for beach-oriented species</td>
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<td></td>
<td>• Field estimates of fish species population estimates, by life history stage</td>
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<td></td>
<td>Species population density indices for multiple life stages (spawn, fry, young-of-year, juvenile, adult) for species: walleye, yellow perch, others TBD</td>
<td>Population density (index)</td>
<td>Normalize to Plan 77A</td>
<td>• Coastal wetland locations (GLEI, Environment Canada, GLCWC, Land Information Ontario) • Field estimate of vegetation cover</td>
</tr>
<tr>
<td></td>
<td>Accessibility of spawning and nursery areas (Lake Superior target species = coaster brook trout, lake sturgeon, others TBD); consider water depth, connectivity and temperature</td>
<td>Connection between tributary or wetland and lake</td>
<td>Normalize to Plan 77A</td>
<td>• Bathymetry/elevation • Nearshore littoral sand supply • Nearshore substrate type • Dredging records at various water levels • Connection elevation to lake relative to water levels • Temperature • Aerial photographs and/or high resolution satellite imagery depicting vegetation zones and types</td>
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<td></td>
<td>Availability of habitat</td>
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<td>PI Category</td>
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<td>PI Metrics</td>
<td>PI Ratio Approach</td>
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<tr>
<td>Fishes, cont’d.</td>
<td>Obligate marsh fish species richness; Northern pike as a sentinel species</td>
<td>Richness (# species)</td>
<td>Normalize to Plan 77A and season</td>
<td>• Assign fish habitat types using literature tables</td>
</tr>
<tr>
<td>Birds</td>
<td>Wetland birds: Change in richness and relative abundance of obligate breeding marsh bird species</td>
<td>Relative area of habitat change (%) in wetlands or change in water level-derived condition index for obligate wetland species (ha)</td>
<td>Normalize to Plan 77A and season</td>
<td>• Niemi et al. (2006)</td>
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<td>Water birds: Change in breeding bird and migratory richness and relative abundance of obligate water-associated species</td>
<td>Relative area of habitat change in wetlands and near-shore habitats or change in water-level derived condition index for obligate water-associated species (ha)</td>
<td>Normalize to Plan 77A and season</td>
<td>• Burton et al. (2008)</td>
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<td></td>
<td>Invasive species (e.g., mute swan) as an indicator</td>
<td>Density (#/ha)</td>
<td>Normalize to Plan 77A and season</td>
<td>• Bird Studies Canada</td>
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<td></td>
<td>McMaster data on bird species and numbers; Katie Kahll, Michigan State</td>
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<td>Sumner Madison data</td>
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<td>Marsh Monitoring Program data</td>
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<tr>
<td>Herptiles</td>
<td>Change in richness and relative abundance of frog and toad wetland habitat Relative area of habitat change in frog and toad habitat (ha),</td>
<td><em>Or</em> change in water-level and habitat quality derived condition indices for frogs and toads</td>
<td>Normalize to Plan 77A</td>
<td>• Price et al. (2005, 2007)</td>
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<td>North American Amphibian Monitoring Program</td>
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<td>data from Great Lakes Coastal Wetlands Consortium</td>
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<td></td>
<td>Change in richness and relative abundance of turtles and snakes of regional interest (e.g., Georgian Bay) Relative area of habitat change in turtle and snake habitat (ha),</td>
<td>change in water-level and habitat quality derived condition indices for turtles and snakes</td>
<td>Normalize to Plan 77A</td>
<td>McMaster turtle/snake program data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>data from State monitoring programs;</td>
</tr>
<tr>
<td>Mammals</td>
<td>Density of muskrat houses in early spring (a surrogate measure of wetland condition)</td>
<td>Density (of limited value) (#/ha); Relative area of habitat suitable for muskrats (percent; requires development)</td>
<td>Normalize to Plan 77A</td>
<td>Limno-Tech, Inc. et al. (2005)</td>
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<td></td>
<td>Albert et al. (2008)</td>
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<tr>
<td></td>
<td>Density of beavers (a surrogate measure of wetland condition)</td>
<td>Density (of limited value) (#/ha); Relative area of habitat suitable for muskrats (percent; requires development)</td>
<td>Normalize to Plan 77A</td>
<td>Limno-Tech, Inc. et al. (2005)</td>
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<td>Albert et al. (2008)</td>
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<td>PI Category</td>
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<td>PI Metrics</td>
<td>PI Ratio Approach</td>
<td>Databases Needed and References</td>
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<tr>
<td><strong>Habitat area for meadow and heather voles</strong></td>
<td>Relative area of sedge-fen wetland habitat (ha)</td>
<td>Normalize to Plan 77A</td>
<td>• Albert et al. (2008)</td>
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<tr>
<td>Extent of wild rice (cultural value; not a species at risk)</td>
<td>Area of wild rice (ha)</td>
<td>Normalize to Plan 77A</td>
<td>• Peter Lee; • Scott Herron at Ferris State</td>
<td></td>
</tr>
<tr>
<td><strong>Fish:</strong> Habitat area for 2 species: coaster brook trout, lake sturgeon and others as appropriate to habitat type (e.g. pugnose minnow, pugnose shiner, blacknose shiner) (spawning, young-of-year, and adult life stages)</td>
<td>Relative area of suitable area (ha)</td>
<td>Normalize to Plan 77A</td>
<td>• Same as for fish spawning accessibility indicators • Sturgeon: AWRI; state DNRs; MNR; Tribes/First Nations • Others: Albert et al. (2008)</td>
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<tr>
<td><strong>Wetland birds:</strong> Change in habitat area for 4 species: <em>least bittern, black tern, king rail, yellow rail</em></td>
<td>Relative area of suitable wetland habitat (ha)</td>
<td>Normalize to Plan 77A</td>
<td>• Niemi et al. (2006) • Burton et al. (2008) • Bird Studies Canada</td>
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<tr>
<td>Piping plover: Change in availability of sand and cobble beach-habitat in areas designated as critical to the Piping Plover</td>
<td>Relative area of habitat change in sand and cobble beach habitat (ha)</td>
<td>Normalize to Plan 77A</td>
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<tr>
<td><strong>Nitrogen cycling</strong></td>
<td>Concentration of nitrogen in sediment; Organic sediment depth by area (cm) Concentration of phosphorus in sediment Sediment organic content (%) (needs development)</td>
<td>Normalize to Plan 77A</td>
<td>• NPS Great Lakes Inventory and Monitoring Network (GLKN)</td>
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<td><strong>Algal productivity</strong></td>
<td>Water column chlorophyll a</td>
<td>Normalize to Plan 77A</td>
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<tr>
<td><strong>Benthic metabolism</strong></td>
<td>Sediment oxygen demand (mg O₂/m²/d)</td>
<td>Normalize to Plan 77A</td>
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</tbody>
</table>
Table 2. Suggested study areas for the UGL region based on vulnerability to water level changes, availability of historical data, and representativeness of the coastal and nearshore zones relative to the Great Lakes anthropogenic stress exposure (Danz et al. 2005, 2007).

<table>
<thead>
<tr>
<th>Lake Huron</th>
<th>Eastern Georgian Bay wetlands</th>
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<tbody>
<tr>
<td></td>
<td>North channel Georgian Bay wetlands</td>
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<tr>
<td></td>
<td>Les Cheneaux Islands</td>
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<td></td>
<td>SE Lake Huron, Sarnia to Bruce Peninsula</td>
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<td></td>
<td>Saginaw Bay</td>
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<td>Manitoulin Island: alvar, islands/shoals</td>
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<td>Lake Michigan</td>
<td>Bays de Noc</td>
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<td></td>
<td>Southern Green Bay</td>
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<td></td>
<td>Eastern shore drowned river mouths and beaches</td>
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<td>Northern Lake Michigan wetlands (southern UP)</td>
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<td></td>
<td>Beaver Island archipelago</td>
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<td>Lake Superior</td>
<td>St. Louis River estuary</td>
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<td></td>
<td>Chequamegon Bay - Kakagon sloughs</td>
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<td></td>
<td>Nipigon Bay</td>
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<td></td>
<td>Bedrock north shore stream mouths (Duluth, Minnesota, to Thunder Bay, Ontario)</td>
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<td></td>
<td>South Bay (Munising, Michigan)</td>
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<td></td>
<td>Apostle Islands</td>
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<tr>
<td>Connecting channels</td>
<td>St. Marys River</td>
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<td></td>
<td>Lake St. Clair and St. Clair River</td>
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</tbody>
</table>
Table 3. Summary of proposed research strategy milestone and tasks.

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Tasks</th>
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<tbody>
<tr>
<td>January-March 2009</td>
<td>Establish collaboration framework for existing data-gathering and compilation</td>
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<tr>
<td>March-May 2009</td>
<td>Identify modelling approaches and data needs; convene a model-selection and data availability/data needs workshop</td>
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<tr>
<td>April 2009</td>
<td>Select candidate study sites based on data availability and vulnerability/sensitivity</td>
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<tr>
<td>June 2009-September 2010</td>
<td>Undertake collaborative field data collection and model development/execution</td>
</tr>
<tr>
<td>September 2010-September 2011</td>
<td>Summarize and evaluate data, execute model simulations, and interpret results; prepare final report and recommendations</td>
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</table>