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At the request of the U.S. Global Change Research Program, the Great Lakes Integrated Sciences and Assessments Center (GLISA) and the National Laboratory for Agriculture and the Environment formed a Midwest regional team to provide technical input to the National Climate Assessment (NCA). In March 2012, the team submitted their report to the NCA Development and Advisory Committee. This white paper is one chapter from the report, focusing on potential impacts, vulnerabilities, and adaptation options to climate variability and change for the coastal systems sector.

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Summary

1. Great Lakes water levels will generally remain within the natural historical range of water levels with annual means slightly below long term mean water levels. Increased precipitation, storm severity and frequency during winter and spring months, and more drought-like conditions in the summer and early fall have implications for short-term, seasonal, and interannual water level variability and the phenology of organisms that rely on those seasonal and interannual water levels. Increased short-term, seasonal, and interannual water level variability will support and maintain coastal wetland biodiversity and associated fish and wildlife habitats.

2. Major winter and spring precipitation events will increase nutrient and sediment loadings into the Great Lakes. Reduced ice cover on large lakes will increase surface water temperatures and evaporation, increase productivity, initiate longer-term thermal stratification , and increases the probability for low DO events in shallow embayments and other great lakes areas (Lake Erie dead zone). Combined with warmer surface water temperatures, increased loadings may result in more widespread algal and cyanobacterial (Microcystin) blooms.

3. Increased storm magnitude and frequency coupled with warmer surface water temperatures will reduce ice cover, increase wave power, and reduce winter ice shore protection which will increase the risk for coastal flooding and result in accelerated beach, shore, and bluff erosion.

4. During extended periods of low water levels, shallow-water areas will offer potential new habitat for submergent aquatic vegetation and new coastal wetland communities. But exposed lakebed areas may be vulnerable to expansion by *Phragmites australis* or other invasive wetland plant species.

5. Increased surface water temperatures will cause gradual ecotonal shifts in aquatic species distributions from cold-water species to warm-water species in intermediate- to shallow-water nearshore and coastal areas of the Great Lakes.

Introduction

The Great Lakes basin contains more than 20% of the world's surface freshwater supplies and supports a population of more than 30 million people. Most of the population either lives on, or near one the Great Lakes. Coastal margin areas are where socioeconomic, environmental, and Great Lakes interests intersect, and therefore it is important to understand how potential changes in climate may impact coastal margin areas.

Climate stressors on Great Lakes and nearshore coastal systems include: 1) changing water level regimes, 2) changing storm patterns and precipitation, and 3) altered thermal regimes. These stressors have the potential to significantly alter the physical integrity of Great Lakes nearshore and coastal systems, which may affect both environmental and economic interests. The objective of this white paper is to provide a brief overview of each of the climate stressors and to assess how future climate scenarios will impact Great Lakes nearshore and coastal systems. Fundamental to this assessment is the understanding that climate change impacts are primarily physical in nature, i.e. how changes in water level regime; storm frequency and magnitude; precipitation and evaporation; ice cover; and air and surface water temperatures impact nearshore and coastal systems. Climate-induced changes to physical processes will impact not only the physical characteristics of the shoreline, but create vulnerabilities for both environmental and economic interests as well. It is important to identify those vulnerabilities so that appropriate adaptive management actions can be taken.

Climate Stressors

Great Lakes Water Level Regimes (Water Levels)

Within Great Lakes coastal margin and open water systems, the equivalent of the natural flow regime is the natural water-level regime. Great Lakes water-level regimes are controlled by the interaction of two master variables, climate and hydrology. Water levels represent the integrated sum of water inputs and losses from the system – typically expressed by a hydrologic water balance equation – that are driven by climate (long-term and seasonal weather patterns), hydrology and flow regime (surface water, ground water, and connecting channel flows), and water use within the basin (water withdrawals, diversions, and connecting channel flows) (Quinn 2002).

Climatic controls, including precipitation, evapotranspiration, and the frequency, duration, and distribution of major storm events are typically driven by seasonal and longer-term climatic cycles (Quinn 2002; Baedke and Thompson 2000). Long-term and seasonal changes in precipitation and evaporation result in the interannual and seasonal variability of water levels and associated connecting channel flows within, and between, all of the Great Lakes (Derecki 1985; Lenters 2001; Quinn 2002). Seasonal Great Lakes water levels and connecting channel flows are higher in the early summer months and lower in the late winter months.

Also influencing Great Lakes water levels are short-term fluctuations in water level that are caused, in part, by local wind or storm events that perturb the water surface, such as a storm surge or seiche event (a seiche is an oscillatory change in the water level surface due to wind or storm event). These short-term fluctuations typically do not reflect a change in the net basin supply (NBS) or overall water balance of the lake or basin.

There is considerable uncertainty in how climate change, particularly changes in precipitation and evaporation may impact net basin water supplies and water levels and flows in the Great Lakes region. A more detailed evaluation of Great Lakes water resources (including water levels) based on Global Climate Model (GCM) and Regional Climate Model (RCM) scenarios are presented in a separate NCA white paper (Lofgren and Gronewold 2012).

The IJC International Upper Great Lakes Study (IUGLS) recently completed a 5-year binational study examining sector impacts related to changes in water level regime resulting from Lake Superior water level regulation (IUGLS 2012). Analysis of the future sequences provided the context to determine plausible ranges of future net basin supplies (NBS). The different future water supply scenario approaches included dynamic and statistical downscaling of GCM scenarios (Angel and Kunkel, 2010; Lofgren and Hunter, 2010; MacKay and Seglenieks, 2010), stochastic generation of contemporary and climate change NBS sequences (Fagherazzi, 2011) and the use of paleo NBS sequences (Ghile *et al*., 2012).

The IUGLS study evaluated output of 565 model runs from 23 GCMs compiled by Angel and Kunkel (2010) from the fourth IPCC report (IPCC 2007) and used the GLERL AHPS Great Lakes hydrology model (Lofgren et al. 2002; Croley 2005) to calclulate anticipated changes in Great Lakes water levels. The model runs utilized future emission scenarios B1 - relatively low, A1B - moderate, and A2 – high emission scenarios. The high emissions scenario A2 corresponds most closely to recent experience (Angel and Kunkel 2010). Predictions of estimated water level changes at the 5th, 50th, and 95th percentiles for Lakes Michigan-Huron by Angel and Kunkel (2010) are presented in Table 1. Estimated water-level changes for Lakes Erie and Ontario are comparable to those for Lake Michigan-Huron, but water level change estimates for Lake Superior may be somewhat less. By 2050, water levels may be 20 to 25 cm lower than the current long term mean for Lakes Michigan-Huron, Erie, and Ontario and 25 to 40 cm lower by 2080,

Table 1. Estimated Lake level changes for Lake Michigan-Huron at the 5th, 50th and 95th percentiles

Year	*5th*	*50th*	*95th*
B1 Low Emission Scenario			
2020	-0.60 m	-0.18 m	0.28 m
2050	-0.79	-0.23	0.15
2080	-0.87	-0.25	0.31
A1B Moderate Emission Scenario			
2020	-0.55 m	-0.07 m	0.46 m
2050	-0.91	-0.24	0.40
2080	-1.43	-0.28	0.83
A2 High Emission Scenario			
2020	-0.63 m	-0.18 m	0.20 m
2050	-0.94	-0.23	0.42
2080	-1.81	-0.41	0.88

IUGLS Final Report (IUGLSB 2012), modified from Angel and Kunkel (2010)

but uncertainties associated with emission scenarios and the GCM/RCM models are high and the confidence level for future estimated water level changes is *<u>low</u>*.

Results of a detailed hydroclimate analysis based on Regional Climate Models (RCMs) run for the IUGLS Study suggests that Great Lakes water levels will generally remain within the natural historical range of water levels with annual means slightly below long term mean water levels (Lofgren *et al*., 2011; MacKay and Seglenieks, 2010). New methods for RCM-type modeling that include and account for important atmospheric feedbacks were evaluated and found to be important. Even though uncertainties are high, these projections are generally supported by a suite of both RCM and GCM models that indicate that evaporative losses and overlake precipitation will continue to increase due to increasing surface water temperatures and reductions in winter ice cover. However, these losses may be partially offset by increasing local precipitation in the winter and early spring months suggesting increased seasonal variability due to loss of winter lake ice cover, loss of connecting channel ice cover, increased spring storminess, and increased wind speeds (Hayhoe 2010). Current models are unable to accurately predict storm track changes which may have an impact on precipitation patterns within the Great Lakes, thus adding to the uncertainty associated with lake level predictions. Based on the most recent models, a major conclusion of the IUGLS study was that "water level changes in the near-term future may not be as extreme as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within a relatively narrow historical range. While lower levels are likely, the possibility of higher levels cannot be dismissed."(IUGLS 2012).

The confidence level for predictions of the overall direction and magnitude of future Great Lakes water levels is low.

Changing Storm Patterns and Precipitation

Modeling results attempting to estimate future mean annual precipitation are equivocal and highly variable. A majority of models generally agree that there may be a slight increase in mean annual precipitation ranging from 2 to 7% over the next 30 years, which continues the documented historical trend of increased precipitation in the region (Hayhoe *et al.* 2010). However, there appears to be general agreement between models that the frequency and magnitude of extreme precipitation events (interpreted to mean severe storms) increases (+30% for A2 scenario, +20% for B1 scenario) during the winter and spring months, and is less during the summer and early fall months. Increased precipitation and storm severity (and frequency) during winter and spring months and more drought-like conditions in the summer and early fall has implications for short-term, seasonal, and interannual water level regimes and the phenology of organisms that rely on those seasonal and interannual water level cycles.

The confidence level for values of estimated mean annual precipitation is <u>low</u>. The confidence level for extreme precipitation events is <u>moderate to low</u>, with decreasing certainty toward the end of this century.

Great Lakes Thermal Regimes

The Great Lakes region could see substantial increases in annual and seasonal air temperatures and extreme heat events, particularly under the A2 (higher emissions) scenario (Wuebbles *et al.* 2010). Over the next few decades (2010–2039), it is anticipated that annual-averaged air temperatures will increase on the order of 0.6–0.8°C. Near the end of the century (2070–2099), annual-averaged air temperatures could increase by 1.7–2.2 °C under the B1 (lower emissions) scenario , and by 4.5°C under the A2 (high emissions) scenario. The greatest air temperature increases will occur during the summer months (up to 6°C or 10°F). Along with warming temperatures, there will be a timing shift where the last frost date will occur 30 days earlier under the A2 scenario and 20 days earlier under the B1 scenario (Wuebbles *et al*. 2010).

Increasing air temperatures in the Great Lakes region will affect Great Lakes surface water temperatures by reducing the extent and duration of Great Lakes winter ice cover. An empirical temperature model developed by Trumpikas et al. (2009) was used to estimate Great Lakes surface water temperatures for several emission scenarios. For all of the Great Lakes, surface water temperatures are estimated to increase on the order of 1.5 to 3.9°C under the A2 (high emissions) scenario and 1.6 to 3.2°C for the B2 (low emissions scenario) by 2050. At the end of the century, surface water temperatures are expected to increase on the order of 3.3 to 6.7°C for the A2 scenario and 2.4 to 4.6°C for the B2 scenario.

Along with warming surface water temperatures there will also be a timing shift where surface water temperature values will increase earlier in the spring (35 to 47 days earlier) and later in the Fall (26 to 51 days later) under the A2 scenario. Similarly, surface water temperature values will increase 24 to 31 days earlier in the Spring and 18 to 36 days later in the Fall under the B2 scenario. For Lake Superior, and to a lesser extent Lakes Michigan-Huron, summer surface water temperature warming generally exceeds the rate of atmospheric warming due to reduced winter ice cover, which results in an earlier onset of thermal stratification and a longer surface warming period (Austin and Colman 2007). Over time, it is anticipated that thermal stratification will occur earlier in the spring, and later in the fall as surface water temperatures continue to increase thereby increasing evaporation Great Lakes surface waters and lengthening the surface warming period.

The estimated surface water temperature values within the next 30 years have a moderate confidence level, and surface water temperature values estimated toward the end of the century have a low confidence level.

Vulnerability of Great Lakes Coastal Systems to Climate Change

Anticipated long-term changes in climate have the potential to significantly alter the physical integrity of Great Lakes basin (e.g. Lee *et al.* 1996; Kling *et al.* 2003; Mackey *et al.* 2006; Solomon *et al.* 2007; Ciborowski et al. 2008; Wuebbles et al. 2010). Potential climate-change induced alterations due to weather, i.e. precipitation, evapotranspiration, and storm frequency, severity, and patterns will alter the physical and habitat integrity of the Great Lakes basin, including:

- *Great Lakes water levels and flow regimes* – changing net basin water supplies and water level regimes; increased water level variability (frequency and magnitude); altered coastal circulation patterns and processes; seasonal changes in flooding; loss of hydraulic connectivity; altered coastal margin and nearshore habitat structure;
- *Storm frequency, severity, and patterns* – seasonal changes storm magnitude, frequency, and direction (storm tracks); changes in flood frequency and magnitude; changes in coastal wave power and direction; altered littoral sediment transport rates and processes; increased shore erosion; reduced nearshore water quality; reduced marina/harbor/port access (increased dredging activity);
- *Precipitation*- seasonal alterations in precipitation and flow regimes; spatial and temporal shifts in seasonal timing; altered riverine and floodplain habitat structure and connectivity;
- *Thermal regimes* – altered open-lake and nearshore surface water temperatures; reduced ice cover; deeper and stronger thermal stratification; spatial and temporal shifts in seasonal timing; and
- *Latitudinal shifts in ecoregions* – regional changes in land and vegetative cover and associated terrestrial and aquatic communities and habitats (affecting coastal margin areas).

Habitat is the critical component that links biological communities and ecosystems to natural physical processes and the underlying physical characteristics of the basin. The pattern and distribution of habitats are controlled, in part, by interactions between energy, water, and the landscape (e.g., Sly and Busch 1992; Higgins *et al.* 1998; Mackey and Goforth 2005; Mackey 2008). Habitats are created when there is an intersection of a range of physical, chemical, and biological characteristics that meet the life stage requirements of an organism, biological community, or ecosystem (Mackey 2008).

Seasonal changes in water level and flow regimes, thermal structure, and water mass characteristics, interact with the underlying landscape to create repeatable patterns and connections within tributaries, lakes, and shorelines within the basin. The pattern of movement of water, energy, and materials through the system (which depends on connectivity) also exhibits an organizational pattern, persists, and is repeatable . For example, these patterns and connections, in part, control the seasonal usage of Great Lakes fish spawning and nursery habitats (Chubb and Liston 1985). Moreover, high-quality coastal margin habitats (both aquatic and wetland) are created by a unique set of environmental conditions and processes that together meet the life-stage requirements of a species, biological community, or ecological function (Mackey 2008). These processes play a significant role, ultimately determining the distribution and utilization of essential coastal margin habitats within the Great Lakes system.

Great Lakes coastal margins can be delineated into four major hydrogeomorphic groups, nearshore; beaches, barriers, and dunes; wetlands; and bluffs. These areas are defined by the hydrogeomorphic characteristics of the shoreline and the dominant physical processes that act on those shorelines. Climate change impacts to coastal margins are primarily physical in nature, i.e. changes in water level regime; storm frequency and magnitude; precipitation and evaporation; ice cover; and air and surface water temperatures. Climate-induced changes to physical processes will impact not only the physical characteristics of the shoreline, but create vulnerabilities for coastal habitats, biological communities, and ecosystems that rely on those shorelines as well.

Table 2 Summarizes the vulnerability of Great Lakes coastal margin hydrogeomorphic groups, ecosystem components, and socioeconomic sectors to climate stressors. The confidence level associated with each hydrogeomorphic group, ecosystem component, and socioeconomic sector is stated in parentheses ()_and is based on the understanding we have of the interaction and resulting impacts between climate change stressors and the group, component, or sector. The confidence levels provided in this table do not incorporate the uncertainty associated with the climate change stressor, which is generally high (low confidence level).

Nearshore areas represent the area encompassed by water depths ranging from 3 to 30 m in all of the Great Lakes except Lake Erie. In Lake Erie, the nearshore is defined by the area encompassed by water depths ranging from 3 to 15 m. Dominant physical processes acting on the nearshore zone include wind-driven coastal circulation patterns; storm generated wave energy; nearshore lakebed sediment transport processes; and nearshore lakebed downcutting. Great Lakes nearshore areas are vulnerable to climate-induced changes in storm magnitude, frequency, and storm direction (i.e. changing storm tracks). Anticipated physical impacts include altered nearshore circulation patterns, erosion and removal of protective sand cover from the lakebed, increased potential for lakebed downcutting, and degradation of nearshore water quality (increase in nearshore turbidity). Nearshore spawning and nursery habitats may be impacted by a coarsening of lakebed substrates and active erosion and sediment transport on the lakebed. The resulting coarse lakebed substrates provide additional habitat for lithophylic invasive species such as dreissenids (zebra and quagga mussels) and the round goby (e.g. Janssen *et al*. 2004; Meadows *et al*. 2005).

Beaches, barriers, and dunes include high energy areas within 0 to 3 m water depths and adjacent low-relief coastal margin, embayed, and back-bay areas. Beaches and barriers are created and maintained by littoral sediment transport processes and dune complexes are created by wind-driven sand deflation processes. Dominant physical processes affecting these coastal margin areas include wind and storm generated wave energy; littoral sediment transport processes; and both long- and short-term fluctuations in Great Lakes water levels. Anticipated physical climate impacts include increased littoral sediment transport rates, beach erosion and reduction in beach widths, degradation of nearshore water quality (increase in nearshore turbidity) and thermal effects resulting in the reduction or loss of winter ice cover during the winter months (Assel 2005) and increase in wave energy and loss of winter ice shore protection (USACE 2003).

During periods of high water levels, barrier systems are more vulnerable to major storm events which may result in eventual breaching of the barrier beach. During periods of low water levels, benthic and fish communities are vulnerable to lakeward shifts of the shoreline, which may change the location and distribution of nearshore spawning and nursery habitats in low-relief shallow water areas (Mackey et al. 2006). Moreover, adjacent wetland areas may become hydraulically isolated from adjacent tributary and lake water bodies disconnecting potential spawning and nursery habitats (e.g. Mortsch 1998; Wilcox et al. 2002; Wilcox 2004; Mortsch et al. 2006). Newly created shallow-water areas will offer potential new habitat for establishment of submergent aquatic vegetation and coastal wetland communities. But exposed lakebed areas may be vulnerable to the expansion of invasive species such as Phragmites australis (e.g. Tulbure et al. 2007).

In response to historically high water levels in the mid-1980s, extensive coastal engineering works and the resulting loss of littoral sand from adjacent coastal margin and nearshore areas have created habitats that are now much more coarse-grained and heterogeneous than would have naturally been present along many Great Lakes coastlines. It is anticipated that as Great Lakes water levels decline, littoral sand deposits will become stranded at higher shoreline elevations and lost to the active littoral system (M. Chrzastowski, Illinois DNR, pers. communication, 2006). The loss of these sand resources may be significant, especially along sand-poor Great Lakes cohesive shorelines.

One of the consequences of these substrate changes is the rapid colonization and spread of aquatic invasive species (such as *dreissenid* spp.) that have adversely impacted food web-dynamics and the Great Lakes ecosystem. It is only now recognized that many of the physical changes that have occurred in the nearshore zones of the Great Lake have provided the opportunity for massive expansion of these invasive species along with significant associated ecological impacts (e.g. Janssen *et al.* 2004, Meadows *et al.* 2005).

Coastal wetlands are commonly found landward of protective beach-barrier systems, within protected embayments, along open-coast shorelines (i.e. fringing wetlands), and in unaltered (natural) rivermouths. 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 solely dependent on wetlands, while more than 30 additional species utilize wetlands during a portion of their life history (Jude and Pappas 1992, Wilcox 1995). Other fish species may use wetlands for short periods of time as refugia (predator avoidance) and for forage (food supply). Waterfowl, nesting birds, amphibians, mammals, and reptiles also utilize wetland and coastal margin habitats. Their distribution and abundance are intimately tied to wetland vegetative cover and the hydrogeology of the wetland (e.g. Timmermans 2001; Timmermans *et al.* 2008)

Table 2. Summary of Climate Stressors and Coastal Margin Vulnerabilities

Stressors	Great Lakes Water Levels	Water Level Vulnerability	Storms and Precipitation	Thermal Regime
Climate Impact *(Low Confidence Level)*	Mean Annual Water Levels Slightly Below Long-Term Mean	Increase in Magnitude and Frequency of Water Level Change; Increased Range of Variability	Increase Magnitude and Frequency of Storms; Change in Precipitation Timing and Patterns	Increase Surface Water Temp
Regional Effects *(Low Confidence level)*	Long-term mean water levels generally within normal historical range; slightly below long-term mean; Possible seasonal shifts in annual highs and lows	Generally within historical ranges, but possible short-term, seasonal, and interannual exceedances above and below historical highs and lows	Stronger more frequent storms; Increase in magnitude and frequency of storm generated waves; Increased precipitation during winter-early spring months, decreased precipitation (drier) during summer-fall months.	Increase in Great Lakes surface water temperatures; Reduced ice cover, later fall ice formation, earlier spring breakup; Stronger thermal stratification; More frequent low DO occurrences; Expansion of low DO zones (e.g., Lake Erie dead zone)
Hydrogeomorphic Group				
Nearshore *(Moderate Confidence level)*	Levels within historical range	Low water: increased potential for lakebed downcutting; reduction in nearshore water quality	Increased potential for lakebed downcutting; reductions in nearshore water quality	Increase in surface water temperature
Beaches, Barriers, and Dunes *(Moderate to High Confidence Level))*	Relatively static shoreline position; slight increase in mean beach width due to slightly lower water levels	High water: reduction effective beach widths (loss of natural shore protection) Low water: increase effective beach widths;	Increased variability in beach width; increased variability in littoral sediment transport rates; increased potential for beach erosion due to increased wave energy; increased potential for lakebed downcutting; reductions in nearshore water quality	Increase in surface water temperature; increased wave power due to lack of ice cover; reduced winter ice shore protection
Coastal Wetlands *(Moderate Confidence Level)*	Levels within historical range	Increased wetland zonation and biodiversity; Increased probability of phenological shifts due to altered timing; Low water: potential loss of hydraulic connectivity	Increased short-term inundation; increased potential for erosion/ destruction of open-coast fringing wetlands; short-term impacts to wetland-dependent nesting birds and waterfowl	Increase in surface water temperature; increased productivity; northward expansion of invasive species (both terrestrial and aquatic)
Bluffs *(Moderate to High Confidence Level)*	Relatively static shoreline position; slight decrease erosion potential due to wider beaches	High water: increase bluff erosion (narrower beaches); Low water: reduce bluff erosion (wider beaches)	Increased erosion of coastal bluffs due to elevated water levels and increased wave power; increased precipitation accelerates surface erosion	Increase in bluff erosion/recession rates during winter months; increased wave power due to lack of ice cover; reduced winter ice shore protection
Ecosystem Component	**Great Lakes Water Levels**	**Water Level Vulnerability**	**Storms and Precipitation**	**Thermal Regime**
Productivity/Water Quality *(Moderate to High Confidence Level)*	Levels within historical range	Low water: potential loss of hydraulic connectivity with coastal wetlands (nutrient processing and export)	Lake Erie, Lake St. Clair, Shallow embayments experience increased nutrient, contaminant, and sediment loads from increased winter-early spring precipitation/runoff; increased algal blooms Microcystin (productivity); lower overall Lake water quality, Increased turbidity; increased number of beach closings	Increase in primary production; increased algal blooms Microcystin; stronger thermal stratification; more frequent low DO occurrences; expansion of low DO zones (e.g., Lake Erie dead zone, but linked to Lake Erie water levels) Low water: thinner hypolimnion. increased number low DO events, longer dead zone duration
Coastal Fisheries *(Low to Moderate Confidence Level)*	Levels within historical range	Increased probability of phenological shifts due to change in water level timing; Low water: potential loss of connectivity between spawning and nursery habitats	Increased probability of phenological shifts due to change in tributary flood-pulse timing; increased storm impacts on spawning/ nursery habitats affecting recruitment; Low water: potential short-term loss of connectivity between spawning and nursery habitats	Shift in distribution of cold and warm-water fish species; Increased probability of phenological shifts due to change in temperature triggers to initiate spawning; change in egg/larval maturation rates; northward expansion of aquatic invasive species.
Socioeconomic Sector				
Ports and Harbors/ Infrastructure *(Moderate to High Confidence Level)*	Levels within historical range, but slightly lower than long-term mean	High water: increased coastal flood risk during storm events Low water: increased dredging of commercial and recreational channels; light load commercial vessels; decrease in available marina slips (water depth limited)	Increased littoral and riverine sediment transport rates; increased dredging frequency due to storm derived sediments; High water: increased coastal flood risk during; increased risk of storm damage to navigation structures	Reduced ice cover, later fall ice formation, earlier spring breakup; extended commercial shipping and recreational boating season;
Coastal Property *(Moderate to High Confidence Level))*	Levels within historical range, but slightly lower than long-term mean	High water: increased coastal flood risk during storm events; increased shoreline erosion due to narrower beaches Low water: re-establishment of SAV and emergent wetland vegetation; wider beaches	High water: increased coastal flood risk during periods of high water; increased shoreline erosion; increased risk of storm damage to shore protection structures	Increase in shoreline erosion/ recession rates during winter months; increased wave power due to lack of ice cover; reduced winter ice shore protection

More recent research has documented a relationship between wetland plant zonation (biodiversity) and fish community composition (Uzarski et al. 2005; 2009; Albert *et al*. 2005). Intact coastal wetlands with several plant zones (sustained by water level fluctuations) provide cover, prey, spawning and nursery habitats (Goodyear *et al.* 1982; Jones 1996b; Lane *et al*. 2006a). The high productivity and structural diversity of Great Lakes coastal wetlands are maintained by natural cycles of high and low water levels as well as natural seasonal water level fluctuations (Wilcox 1995; 2004, Albert *et al*. 2005, Keough *et al*. 1999, Mayer *et al.* 2004). On Lake Ontario, water level regulation resulted in range compression and loss of wetland biodiversity, plant community zonation, and ecological functionality (Wilcox *et al.* 2007; Wilcox and Meeker 1991; 1992; 1995; Busch and Lary 1996).

As Great Lakes water levels regimes are expected to remain slightly below the long-term mean, an anticipated increase in short-term, seasonal, and interannual variability of water levels driven by changes in local precipitation and increased storm frequency will benefit Great Lakes wetlands by maintaining and/or restoring plant community zonation, increasing wetland biodiversity, and enhancing environmental benefits. However, increased variability in water level regimes may alter the phenology of wetland-dependent fish communities and other aquatic organisms due to alterations in seasonal timing and duration (Casselman et al. 2002, Kling et al. 2003; Uzarski et al. 2005; 2009; Shimoda et al. 2011)

Coastal bluffs are a dominant shoreline type in the Great Lakes and are created when upland areas are subject to mass-wasting processes initiated by instabilities created by wave erosion at the base of the bluff. These processes have been active along Great Lakes shorelines for thousands of years and have contributed most of the sediments that maintain beaches along Great Lakes shorelines. Physical processes affecting these coastal bluffs areas include the expenditure of wind and storm generated wave energy; littoral sediment transport processes; and both long- and short-term fluctuations in Great Lakes water levels. Anticipated physical climate impacts include increased bluff erosion/recession rates; degradation of nearshore water quality (increase in nearshore turbidity) and thermal effects resulting in the reduction or loss of winter ice cover during the winter months (Assel 2005) and increase in wave energy and loss of winter ice shore protection (USACE 2003).

Erosion of coastal bluffs is episodic and is driven primarily by a combination of wind and storm-driven waves (wave power) expended along Great Lakes shorelines and Great Lakes water levels (e.g. Brown et al. 2005). As Great Lakes water level regimes are expected to remain slightly below the long-term mean, anticipated increases in local precipitation and increased storm magnitude and frequency will increase the cumulative wave power expended along Great Lakes shorelines. The increase in cumulative wave power combined with possible changes in storm direction could significantly alter the rate and direction of littoral sediment transport increasing the exposure of Great Lakes coastal bluffs to wave attack. During periods of high water levels, beaches become narrower, reducing the effectiveness of beaches as natural shore protection. Erosion of coastal bluffs and adjacent upland areas increases, resulting in the reduction of nearshore water quality. During periods of low water levels, more of the beach face is exposed resulting in wider beaches that provide natural shore protection and may reduce erosion of coastal bluffs and adjacent dune and upland areas (Meadows et al. 2005; Brown et al. 2005). Moreover, the reduction or loss of winter ice cover during the winter months due to anticipated warmer air and surface water temperatures will result in an increase in wave power and loss of winter ice shore protection.

Productivity and Water Quality - Warmer surface water temperatures combined with lower Great Lakes water levels affects the thermal structure of the Great Lakes causing changes in both lake chemistry and lake ecology (Sousounis and Grover 2002). During periods of low water levels, higher surface water temperatures will create a deeper and stronger thermocline that will reduce the water volume in the hypolimnion and result in more frequent episodes of anoxia. In the central basin of Lake Erie, reduced hypolimnion water volumes combined with altered nutrient cycling by invasive zebra/quagga mussels (*Dreissenid* spp*.)* may result in more frequent occurrences of an expanded dead zone" (Lam *et al*. 1987, 2002; Charlton and Milne 2004). As water temperatures increase, dissolved oxygen levels decrease as warm water holds less oxygen than cold water. Moreover, warm waters increase respiration rates for aquatic species further depleting dissolved oxygen levels. Even though the deep northern lakes are relatively immune from low DO levels, shallower water bodies, embayments, and some tributaries may be susceptible to low DO levels as water temperatures increase. Moreover, Warmer water temperatures combined with increased nutrient loads may increase productivity and nutrient recycling, which may stimulate the growth of filamentous blue-green algae (*Cladophora* spp) which has been shown to impact nearshore water quality, habitats, and is an aesthetic problem for coastal property owners and beaches, and may contain pathogens (Hellman *et al.* 2010). As these organisms die and settle to the bottom and decompose, oxygen is consumed reducing DO levels even further. In Lake Erie, warm surface water temperatures and increased nutrient loads have resulted in more widespread and frequent Microsystin blooms.

Coastal Fisheries - The abundance of several species of important recreational and commercial fish (lake trout, walleye, northern pike, and lake whitefish) varies with the amount of thermally suitable habitat (Christie and Regier 1988; Lester *et al*. 2004; Jones *et al.* 2006a). A warm thermal structure may cause a northward shift of boundaries for both warm and cold-water fishes, affecting abundance, distribution, and resilience to exploitation (Minns and Moore 1992; Shuter and Meisner 1992; McCormick and Fahnenstiel 1999; Magnuson *et al.* 1997; Casselman 2002; Brandt 2002; Kling *et al*. 2003; Sharma 2007). Increasing surface water temperatures could also remove existing thermal constraints that have protected the Great Lakes from invasive organisms in the past, and increase the potential number of organisms that can successfully invade the lake (Mandrak 1989). In response to these shifted thermal boundaries, zebra/quagga mussels, round gobies, and other aquatic nuisance species may be able to expand their existing ranges further northward into the upper Great Lakes (GLFC 2005). Moreover, water temperature increases are positively correlated with mercury methylation rates and increase the availability of methyl mercury for incorporation into fish tissue. Warmer surface water temperatures may facilitate (increase) the rate of mercury contaminant uptake into the food chain that may result in increased levels of mercury contamination in fish (Bodaly *et al*. 1993; Yediler and Jacobs 1995).

Ports and Harbors/Infrastructure – These coastal structures are generally larger than private structures and therefore may have a significant impact on the coastal margin. The structures are typically designed to protect and maintain both commercial and recreational navigation channels and associated infrastructure. Maintenance of these structures is typically a Federal or State responsibility. Depending on use, the navigation channel may be dredged on an annual basis to accommodate large commercial vessels. Increased storm severity and frequency and loss of ice cover during the winter months will increase littoral sediment transport rates requiring more frequent dredging to maintain navigation channels. During high water periods, there is an increased risk of coastal flooding during major storm events and increased risk of storm damage to the navigation structure and port infrastructure. During low water periods, there will be a need for increased dredging of navigation channels to maintain design depths; light-loading of commercial vessels to maintain draft over shallow areas in navigation channels; and a decrease in the number of available commercial or recreational slips in marinas due to low water conditions. As a benefit, reduced winter ice cover due to increasing surface water temperatures may provide an opportunity to extend the commercial navigation and recreational boating seasons.

Coastal Property - The effects of climate change in developed coastal areas will be exacerbated by anthropogenic activities, especially in areas where submerged lands may be exposed and development pressures in coastal areas are high. Climate change projections suggest that even though mean water levels will remain near, but slightly lower than long-term mean water levels, there will be increased short-term variability in water levels in response to increased storm magnitude and frequency, especially during the winter and early spring months. During periods of high water, coastal flooding risks are high; risk of shore and beach erosion due to storm derived waves is high; and an increased risk of damage to infrastructure (shore protection structures) and upland property loss during major storm events. During periods of low water, flooding and erosion risks are low. However, during extended periods of low water, property owners fill shoreline areas for development (encroachment), install shore protection, groom beaches to improve aesthetics, and remove submergent and emergent aquatic vegetation to promote water access and provide a viewshed. These shoreline alterations affect natural coastal processes and the ecosystem, and will have a detrimental effect on Great Lakes nearshore and coastal margin environments. Recent work by Uzarski et al (2009) clearly demonstrated the deleterious effects of vegetation removal on local fish and aquatic plant communities and coastal biodiversity.

Discussion

Both global and downscaled regional climate circulation models have been used to predict changes in temperature, weather, precipitation, storm severity and frequency, and,

Table 3. Cross-Cutting Issues

Climate Stressor	Condition	Condition	Condition	Impacts
Water Level Regime Thermal Regime Storms and Precipitation	Low Water Levels	Strong Thermal Stratification	High Winter-Spring Precipitation, (High Nutrient Loads	Low Dissolved Oxygen, Lake Erie Dead Zone
Storms and Precipitation Water Level Regime Thermal Regime	Increased Wave Power (Storms)	High Water Levels	Reduced Ice Cover, No winter Ice Protection	Increased Shore and Beach Erosion (all seasons)
Thermal Regime Storms and Precipitation	High Surface Water Temperatures	High Winter-Spring Precipitation, (High Nutrient Loads)		Blue-Green Algal Blooms, Microcystin Blooms in nearshore waters

indirectly, Great Lakes water levels. These predictions have a high degree of uncertainty and represent a range of possible futures or scenarios. For all of these scenarios, the physical integrity of the Great Lakes will be modified or altered in response to changing climate conditions. Thus, ecological responses to climate change will be driven primarily by changes in physical integrity, and these responses may be nonlinear, especially if boundaries and thresholds are exceeded (Burkett *et al*. 2005). Synergistic or cross-cutting interactions between climate stressors may be additive and cause unforeseen environmental or socioeconomic impacts. Table 3 provides examples where multiple climate stressors interact to produce an impact (or benefit). Conditions are listed in the same order as the stressor listing. Multiple conditions are listed for each stressor. For example, in the second row of Table 3, more severe and frequent storms will increase wave power along the coastline. Increased wave power coupled with high water levels will increase erosion of coastal bluffs and increase littoral sediment transport rates. Warmer surface water temperatures will reduce or eliminate winter ice cover which will allow erosion and sediment transport to occur during the winter months. This will increase the volume of sediment that will have to be dredged from commercial and private navigation channels and result in further shoreline hardening due to the need for new shore protection. Increased littoral sediment transport rates will also affect hydraulic connectivity with coastal wetlands and riverine spawning/nursery habitats.

Recommendations

Additional work is needed to more fully understand the biophysical linkages between physical habitats, associated biological communities, and the natural processes that connect them. Future changes to the ecosystem may yield changes that have not yet been observed and for which data do not exist. It is only through an understanding of biophysical processes that we may be able to predict the ecological responses of the Great Lakes ecosystem due to changes in water-level regime. Moreover, additional tools/models need to be developed that integrate physical and ecological processes to simulate potential changes in environmental conditions and associated aquatic habitats resulting from long-term changes in water-level regime. Using these models, it will be possible to identify potential long-term management, protection, and restoration opportunities based, in part, on an understanding of biophysical processes.

The resulting management, conservation, and protection strategies must be designed to protect potential refugia, transitional, and newly created coastal margin and nearshore habitat areas from anthropogenic modification and/or degradation. As water levels recede, there will be increasing societal pressure to develop and modify newly exposed areas of the shoreline. Critical reaches of the Great Lakes shoreline (as identified by the long-term models) must be protected and preserved to ensure that essential ecological functions are maintained during periods of transition.

It will also be necessary to establish a long-term, aquatic habitat research and monitoring effort within the Great Lakes to track changes and continually update and refine the heuristic models. An important consideration will be to identify the appropriate variables to be monitored and to establish thresholds or triggers that tell us when to modify resource management and protection policies. This approach will provide the knowledge and science-based tools to build the capacity of key agencies, organizations, and institutions to identify and implement sustainable protection, restoration, and enhancement opportunities.

This discussion highlights the need to incorporate management and research strategies designed to address uncertainty and respond to potential long-term stressors, such as climate change, water diversions, and continued growth and development which have the potential to impair the physical integrity of the Great Lakes. Given the uncertainties associated with climate change, it is necessary to implement a proactive anticipatory management approach (commonly referred to as adaptive management strategies) that identifies long-term planning, protection, and restoration needs in response to climate change-induced stressors and impairments within the Great Lakes basin. Application of adaptive management strategies will help to ensure the physical and ecological integrity of the Great Lakes in the face of major environmental change.

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