Climate Change and Wisconsin's Great Lakes Ecosystem

Photo: Morning Blues, 2017 Great Lakes Photo Contest, natural category Grant Park by Edward Deiro

A report submitted to the
Wisconsin Initiative on Climate Change Impacts by
the Great Lakes Working Group

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Contents

Key Takeaways

Climate change is occurring

- A healthy Great Lakes future requires understanding climate change impacts
  - Annual average air temperature in Wisconsin is 2.1 °F warmer than the 1950's
  - Large precipitation events are becoming more frequent and more extreme
- Need to understand feedback between climate change effects on the Great Lakes and the Great Lakes moderation of regional climate
  - For example, Warmer water temperatures may enhance lake-effect snow

Photo: Striking Sky, 2020 Great Lakes Photo Contest natural category, by Mason Morris

Photo: Menekaunee Harbor Restoration, 2018 Great Lakes Photo Contest stewardship category, by Cheryl Bougie

Diverse planning approaches are needed

- Resistance strategies protect existing structures in attempt to maintain historical conditions
- Resilience strategies reduce vulnerability and maintain function following disturbance
- Adaptation strategies anticipate ecosystem change and facilitate change to desired state
- Acceptance strategies let climate change cause transformation

Threatened coastlines

- Coastal wetlands shrink and expand with natural water level fluctuations; however extreme fluctuations can result in loss of habitat
  - Natural wetland upland and downland migration is likely too slow to adapt to the climate change-induced shorter time periods between extreme high water and low water
- Extreme water levels, increased wave action from storm events increase shoreline erosion

Photo: From the Dark Side, 2014 Great Lakes Photo Contest calendar photo, by Mark Straub

Key Takeaways

Extreme water levels, warmer water

- Extreme low and extreme high water level conditions are becoming more frequent
  - Less time between extreme conditions
- Increasing water temperature; longer warm seasons
  - Longer periods when warm surface water does not mix with cool deeper water
  - More harmful algal blooms, depleting bottom water oxygen
- Less ice cover, which increases summer water temperature and winter shoreline erosion

Photo: Water Power, 2016 Great Lakes Photo Contest natural category, by Kristine Hinrichs

Photo: Siskiwit Curves, 2015 Great Lakes Photo Contest natural category, by Gervase Thompson

Decreasing water quality

- Increased precipitation and more extreme storm events increase nutrient loading to the Great Lakes, lowering water quality
  - Water quality degradation is the most acute in nearshore areas
  - Increasing *E. coli* + other beach contaminants
- Increased nutrient availability + warmer water temperatures and stronger thermal stratification promotes harmful algal blooms

Species and food web changes

- Warmer water temperatures and longer growing seasons increase phytoplankton when nutrients are available, with unknown food web effects
- Invasive species spread and success may be facilitated by climate change
- Fish species most at risk from climate change include lake whitefish, lake trout, cisco, and brook trout
- Manoomin (wild rice), with specific growing requirements, is vulnerable to climate change

Photo: Great Blue Heron, 2016 Great Lakes Photo Contest natural category, by Janna Soerens

1. Introduction

The Great Lakes contain 20 percent of the world's surface freshwater, provide drinking water and livelihood to more than 34 million people, and allow for key economic and cultural services, quality of life, and recreation.[1] Wisconsin is bordered by two of these lakes – Lake Superior to the north and Lake Michigan to the east – with more than 1,000 miles of coastline. Lake Superior is the largest freshwater lake in the world in terms of surface area and one of the deepest at over 1,300 feet, while Lake Michigan is the sixth largest lake in the world and over 900 feet deep. Both lakes are ecologically and culturally important to the people of Wisconsin and are home to over 3,500 different species of fish and wildlife.

Multiple species of fish and birds are very rare or endemic to the regions, including federally and state endangered and threatened species. In the basin, 46 species are found nowhere else in the world. The Great Lakes provides habitat for more than 180 fish species to complete their life cycles and provides stopover habitat for more than 350 migratory bird species.[2]

Photo: Breaking Blue, 2016 Great Lakes Photo Contest, natural category Cave Point County Park by Michael Braaten

The Lake Superior and Lake Michigan ecosystems provide vital ecosystem services to the people of Wisconsin. The Great Lakes are home to numerous species of significant cultural importance to Ojibwe people in Wisconsin.[3] Ojibwe ways of life, supported by treaty rights that guarantee their continued ability to hunt, fish, and gather off-reservation, are threatened by climate change, as numerous species ranges may shift out of their Ceded Territory or go extinct.[3] Additionally, the Great Lakes provide key ecosystem services to coastal communities in Wisconsin through direct uses such as fisheries and recreation and through indirect uses such as water quality regulation, cultural and family identities, and psychological well-being.[4]

The importance of the Great Lakes to people in the region is clear from numerous polls and surveys. A binational poll in 2015 and 2018 showed that most Great Lakes basin residents (85% or more) believe it is important to protect the Great Lakes, largely because they are a valuable, environmentally important resource.[5,6] In the same poll, 73 percent of residents ranked climate change as having an extremely negative impact on the region, just behind other issues of invasive species, algae blooms, and runoff. **Climate change is today's top concern for the region**: the public has called for all levels of government to prioritize and respond to these climate change impacts[7] and experts rated climate change as one of the top stressors affecting the Great Lakes.[8] At a more local level, residents of Wisconsin's Lake Superior shoreline express fear and concern over ecological loss associated with climate change.[9]

Given the importance of the Great Lakes to the people, plants, and animals that call them home, it is imperative that we understand how to protect and sustain them as the climate changes. This report aims to assess the current and projected impacts of climate change on **Wisconsin's unique Great Lakes ecosystem** and provide potential solutions and climate adaptation strategies. While not exhaustive, this assessment provides a thorough examination of impacts, solutions, and strategies that, if acted upon, will lead to a more resilient future for the region.

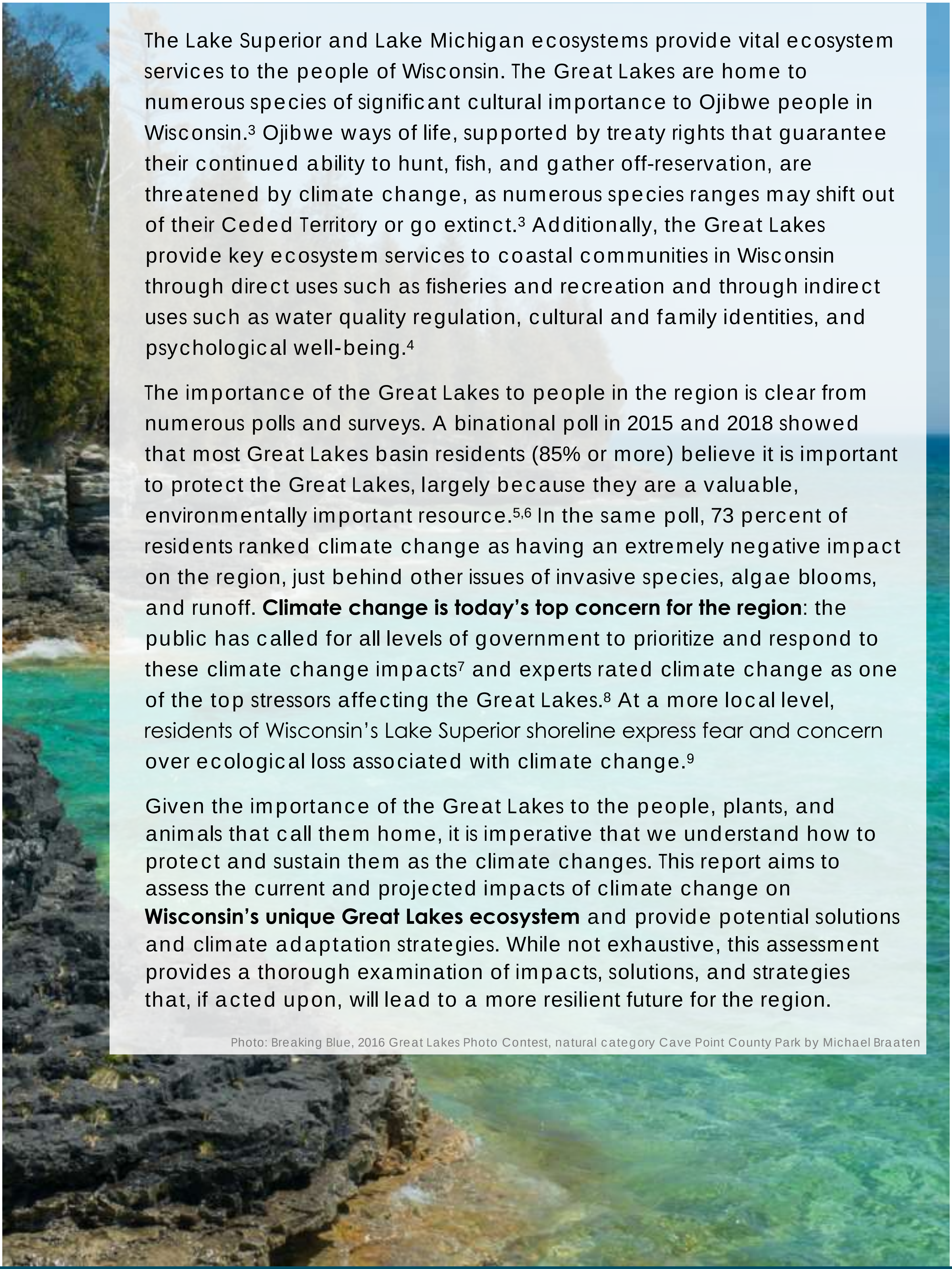


Photo: Breaking Blue, 2016 Great Lakes Photo Contest, natural category Cave Point County Park by Michael Braaten

Photo: Windy Lake Michigan, 2015 Great Lakes Photo Contest, natural category by Eve Schrank

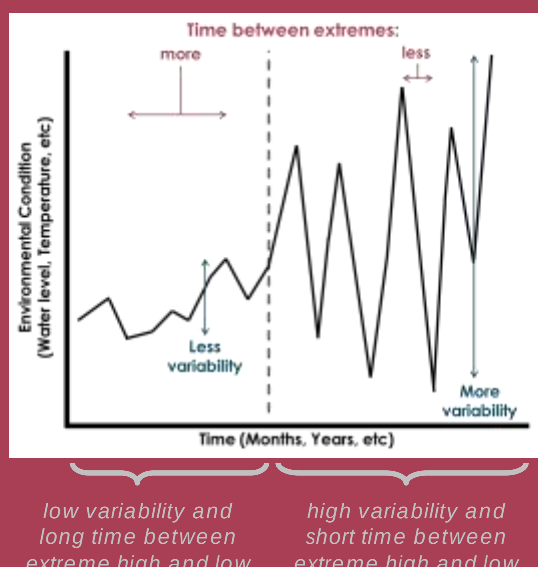
2. Climate Change

More variability, less time between extremes

When considering increasing variability and less time between extreme conditions — the time of focus, from hours to decades — is critical. Short-term extreme events (e.g., hourly rainfall) are becoming more and more extreme, beyond the range of historical observations and past projections. These short-term "surprise" events are becoming more common, whereas longer term metrics (daily rainfall, annual rainfall) have thus far been changing more within expectations.[10]

More extreme and variable precipitation results in more extreme and variable stream flow patterns,[11] causing more extreme water levels (both lower low and higher high water levels). Single extreme runoff events can be major sources of

Example data visualizing changes in variability and time between extremes:



nutrients and pollutants to the lake, causing short-term severe water quality degradation. Further, fast changes in water level drive changes in plant[12] and animal communities.[13] Similarly, extreme response in animal communities has been observed at sub-annual time steps, but not yet in decadal signals.[14] It is the extreme climatic conditions, even potentially short-lived events (e.g., hours or days) that may drive species range shifts or local extirpation.[15] As shorter-term extreme events become more common, the effects may accumulate, resulting in extreme long-term conditions (interaction of fast and slow variables).[16] Therefore, accumulation of short-term extremes may cause longer-term conditions to exceed the range of predictions. Climate change planning requires consideration of different types of signals depending on the time period of focus, from hourly to decadal change, and preparation for more extreme conditions across time scales.

Air temperature increases

By the 2080's, air temperatures in Wisconsin will likely feel more similar to today's conditions farther southeast (Figure 1). In US states bordering the Great Lakes, annual average air temperatures from 1985-2016 were 1.4 °F greater than from 1901-1960, with the highest changes along Lake Superior.[2] The air temperature trends in the Great Lakes region are higher than those for the contiguous US and global trends over the same periods,[1] following the general pattern of greater warming at higher latitudes. The WICCI Climate Working Group showed that

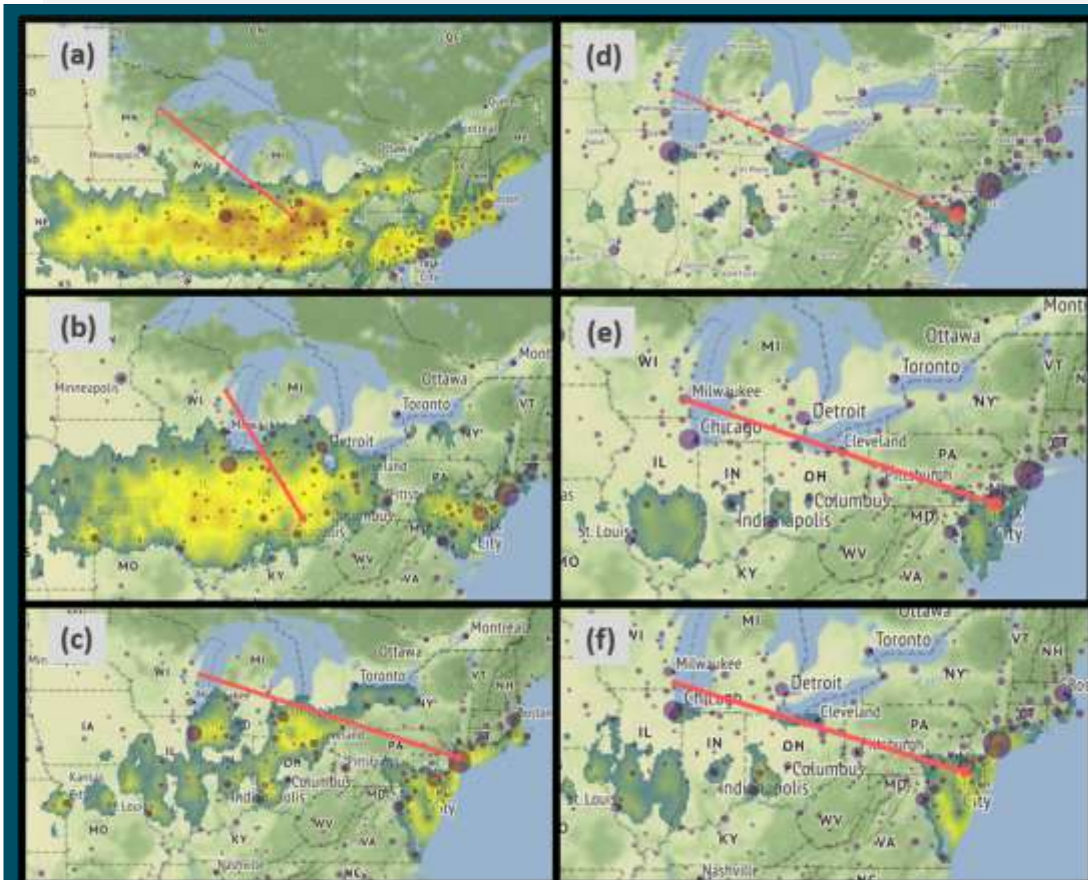


Figure 1. *Projected most likely future climates (2080's)for (a) Superior; (b) Green Bay; (c) Manitowoc; (d) Sheboygan; (e) Milwaukee; and (f) Racine. Red lines indicate the location with highest similarity, and colors indicate relative climate similarly with red showing high similarity and blue showing low similarity.*

Wisconsin has become 2.1 °F warmer since the 1950s, with winters warming more rapidly than summer.[17] Increased air temperatures are expected to continue through the next century.[17] Coastal areas on Lake Superior will experience a much warmer climate by the 2080's, with the Superior, WI area projected to feel more like current northwest Ohio, and Lake Michigan areas like Sheboygan and Milwaukee projected to be more similar to current southeastern Pennsylvania (Figure 1).[18] These air temperature increases will have significant ecological and social impacts on the Great Lakes and surrounding communities.

Increasing precipitation

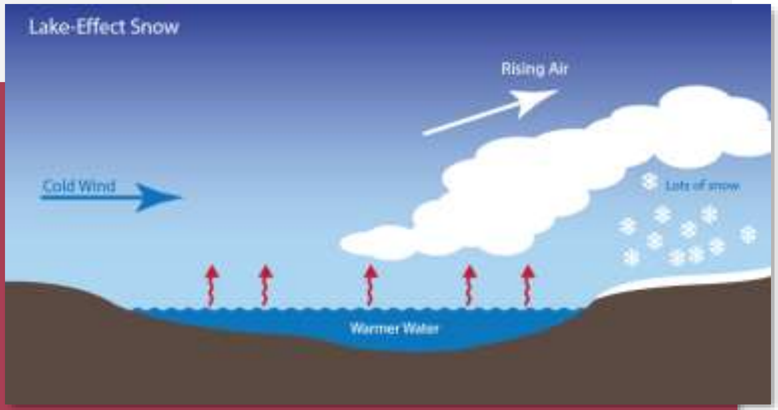
With climate change, precipitation is increasing, seasonal precipitation patterns are changing, and extreme events are becoming more frequent and severe. As air temperatures continue on their expected rise over the next century, annual precipitation throughout the Great Lakes basin is projected to increase[19] by approximately four percent for each degree Fahrenheit rise in average air temperature.[20] Seasonal precipitation patterns are also projected to change, with higher spring, fall and winter precipitation and an increase in frequency and intensity of storm events (2 inches or more).[20] All nine of Wisconsin's

Afloat in the middle of the storm near Saxon Harbor and Chequamegon Bay in Wisconsin. *Contributed by Deanna Erickson, Reserve Director, Lake Superior National Estuarine Research Reserve*

During the 2016 EPA CSMI on Lake Superior, educators joined researchers through a joint professional development opportunity coordinated by Sea Grant. Underway from Houghton, MI, lightning struck the radar system on this large Great Lakes research vessel, an early warning of the night to come. By nightfall, waves were cresting over the deck of the ship and lightening struck at a strobe light pace. Watching the weather radar, the crew watched the storm spin over the region, in a manner similar to a hurricane. The vessel rocked wildly through the night. Meanwhile very nearby on shore, the marina at Saxon Harbor was blowing apart under the force of floodwaters. In the morning, everyone onboard woke to dark chocolate milk colored waters and post-storm still winds. Pulling in to the Washburn marina, guest speakers arrived late and pale, shaken by the extreme damage to roads and infrastructure in their communities.

The 2016 storm had an intense and acute impact on the Mashkiziibi First Nation at the Bad River. Flooding blew out the roads and separated the community from medical services and businesses in Ashland.

Youth documented the flooding with video under the guidance of Patty Loew at Mashkiziibi (screenshot of video) climate divisions (regions within a state that are climatologically the same) reported their wettest decade in history from 2010 - 2020.[17] Very extreme precipitation events, such as those experienced in Northern Wisconsin along Lake Superior in 2012, 2016, and 2018,[21] are likely to occur more frequently in a warming climate. A warmer climate produces more frequent and intense storm events because warmer water evaporates faster and warmer air can hold more water.[22,23] Thus, it is likely that extreme precipitation will increase in Wisconsin in the future, with the most extreme precipitation events seeing larger increases than smaller rain events. Changes to precipitation will exacerbate flooding, particularly during winter months when declining snow-to-liquid ratios mean higher proportions of rainfall versus snow. Consequences include faster and more extreme flood pulses, and diminished snow cover to buffer overland flow and its associated pollutants.



Lake Effect Snow Diagram by NOAA SciJinks
https://scijinks.gov/lake-snow/

Great Lakes & regional climate feedback

Though the region is influenced by global climate change, the Great Lakes themselves influence regional weather and climate conditions. Lakes Michigan and Superior affect local and regional climates by moderating air temperatures in all seasons, increasing wintertime cloud cover and precipitation over and downwind of the lakes (lake-effect snow), decreasing summertime convective clouds and rainfall over the lakes, and creating the "lake breeze."[24–26] The temperature moderation of the lakes results in cooler temperatures during the summer and warmer temperatures in the winter along the shores compared to inland locations.[24] In the fall and early winter, the water in the Great Lakes cool slower than the air, creating large temperature differences between the water and near-lake air. These temperature differences cause greater convection in the atmospheric boundary layer that can increase winds over water, evaporation, lake effect snow, and wave action.[27] Climate-caused changes to the heat budget of the lakes may alter how Lakes Superior and Michigan impact the regional climate and intensify water level fluctuations. For example, warmer lake water temperatures could enhance lake-effect snow leading to larger snowfall events during ideal conditions, when cold air moves over the relatively warmer Great Lakes.[2]

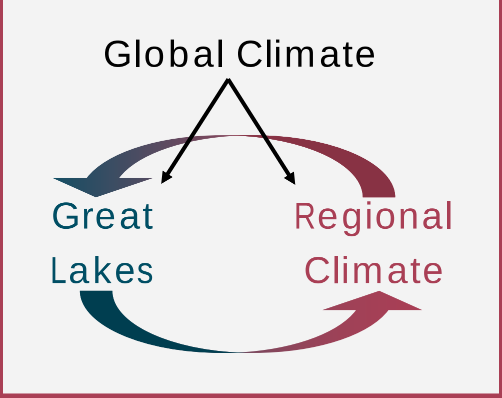


Photo: Shoves, 2016 Great Lakes Photo Contest, natural category by Ryan Pederson

3. Physical Changes to the Lakes

Water level fluctuations

The 2011 WICCI Report indicated the Great Lakes would experience lower water levels with climate change, however, it is now understood that the lakes are and will continue to experience more variable and extreme high and low water level conditions.[28–32] This new understanding is a result of both observations over the past decade and improved modeling approaches. For example, Lake Superior and Lake Michigan set new monthly high water level records in 2019 and 2020, though both lakes were at or near record low levels from 1999 through 2013.[28] The increased variability in water levels follow the pattern of increased precipitation variability and frequency of extreme weather events. Therefore, there will likely be an enhancement of the natural annual water level cycle in the Great Lakes resulting in a larger difference between yearly highs and yearly lows.[30–32]

Water levels in the Great Lakes are determined by the balance of over-lake precipitation, evaporation, inflows, and outflows from the lakes (Figure 2), all of which are expected to be influenced by climate change. Over the past two decades, over-lake precipitation has risen to very high levels, while over-lake evaporation has decreased rapidly.[28] Increased precipitation and more frequent and severe storms will alter tributary flow volume and timing into the Great Lakes.[28]

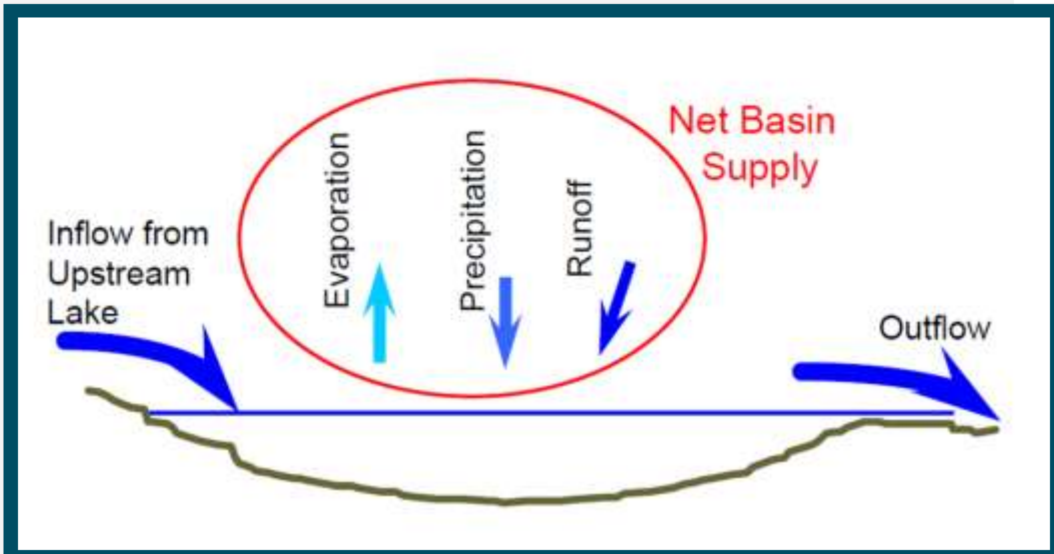


Figure 2. *Water levels in the Great Lakes are determined by the balance of over-lake precipitation, land runoff, and inflow entering the lake with evaporation and outflow leaving the lake. Image credit: Deanna Apps, US Army Corps of Engineers.*

Though water levels in the Great Lakes naturally fluctuate, the timescale and magnitude of the fluctuations are changing. Water levels change over minutes to hours (short term), annual, and multi-year (long term) time periods. Short-term water level changes are caused by waves, storm surges and seiches. Longer term water level change occurs annually due to seasonal weather patterns: typically higher during summer months (July-August) and lower during winter months (December-February). On average, water levels differ by about one foot between seasonal high and low water levels.[33] However, water level fluctuations are becoming more variable over shorter time frames (e.g., higher high and lower low water levels, with less time between extreme conditions) and coastal vegetation and habitat can be negatively impacted by hourly extremes[12] in addition to annual extremes.[34]

Photo: Mother's Day Storm, 2016 Great Lakes Photo Contest cultural category, by Philip Schwarz

Contrary to predictions a decade ago of lowering water levels due to climate change, water diversions, and dredging,[29,35] water levels across the Great Lakes have risen from 2013 to 2019.[29] Studies that predicted lower water levels with climate change over-relied on near-surface air temperatures as a predictor of evapotranspiration from the land surrounding the Great Lakes,[36] resulting in overestimated evapotranspiration and underestimated runoff in the models.[30,36] Now, ensemble trends show that net basin supply in the Great Lakes is expected to increase in winter and spring and decrease in summer due to increases in over-lake precipitation and runoff in winter and spring and increases in lake evaporation in summer.[32]

Great Lakes water levels are already experiencing greater variability over increasingly short timescales. Projecting effects from climate change is inherently difficult and uncertain.[37,38] Given this uncertainty, it is critical that observed patterns, climate change projection models, and resulting impacts on the Great Lakes and surrounding communities are regularly and iteratively revisited. Additionally, managers and coastal communities need to prepare for larger interannual variability in lake levels seen in the historical record, along with a potential increase in lake level variability and more extreme highs and lows.[32]

Working with wind, waves, and water at Maslowski Beach Chequamegon Bay of Lake Superior.

Contributed by Sara Hudson, Director, City of Ashland Parks and Recreation

Photo: Maslowski Beach Trip Advisor Review, Cathy S, United Kingdom, May 2019

Since 2012, the communities along the western shoreline of Lake Superior have been heavily impacted by intense storms, creating high winds, large waves, and above average rain falls. In 2016, a large storm hit destroyed a section of trail the connected the western most beach at Maslowski to the central beach. Then in 2018 another large storm hit and deposited 18" of new sand onto the beach. Making the pavilion, playground, sand volleyball court and beach unusable for almost 2 years.

Photo: City of Ashland, Parks and Recreation Comprehensive Outdoor Recreation Plan

Over the past three years , the City of Ashland has been working on resiliency measures to protect Maslowski Beach (park). Through grant funding, the City has installed 300' of extra heavy duty riprap along the shoreline to protect the park. The elevation of the entire site has been increased by 18" and stormwater is now encouraged to go into a drainage ditch south of the park which then conveyed into a bio swale. A concrete half wall was also installed on the north side of the pavilion to stop wave action from bringing in sand, 6' half wall wings were also placed on the sides to deter wave action and an additional 6' of concrete was laid down to raise the pavilion floor. The City also relocated the pedestrian trail to the south of the park. This new concrete sidewalk will connect the west and central beaches, pavilion and bathhouse. The playground will be reinstalled farther away from the shoreline and protected from wave action by the rip rap.

Learn more by clicking here or here.

Changes to water temperature and lake mixing

Warming lake water temperatures across the globe[39,40] and in the Great Lakes[41,42,39] have significant ecological impacts.[43,44] Climate change warms lakes through increased downward longwave radiation and prevention of heat loss from turbulent heat flux.[2] While warming trends are often strongest in deeper regions of lakes,[45,46] nearshore areas are also warming.[47] Nearshore warming may ultimately have more profound effects than warming deeper waters, given the high importance of nearshore areas to the overall lake ecosystem.[48] Even small changes in thermal characteristics of the Great Lakes may cause major shifts in the ecosystem, from plankton populations to ecosystem metabolic processes.[43,44,49,50]

Warming lake water temperature increases the strength and length of thermal stratification, a key physical lake process that drives whole-ecosystem conditions (Figure 3).[51] Both Lakes Superior and Michigan thermally stratify during the summer months, meaning warm water remains at the surface while cooler, more dense water remains in the bottom of the lake. Then, in the fall, as water temperatures drop to 39 °F (4 °C), the surface and bottom waters mix in a process called "turnover." The mixing during turnover is important as it carries oxygen from the lake surface to bottom waters and nutrients from the bottom to the surface waters. Warmer water temperatures with climate change promote *longer* periods of thermal stratification, where biotic processes may consume more bottom water oxygen before turnover, resulting in hypoxic or anoxic bottom water conditions.[52] Mild winter conditions, combined with increased solar radiation, and

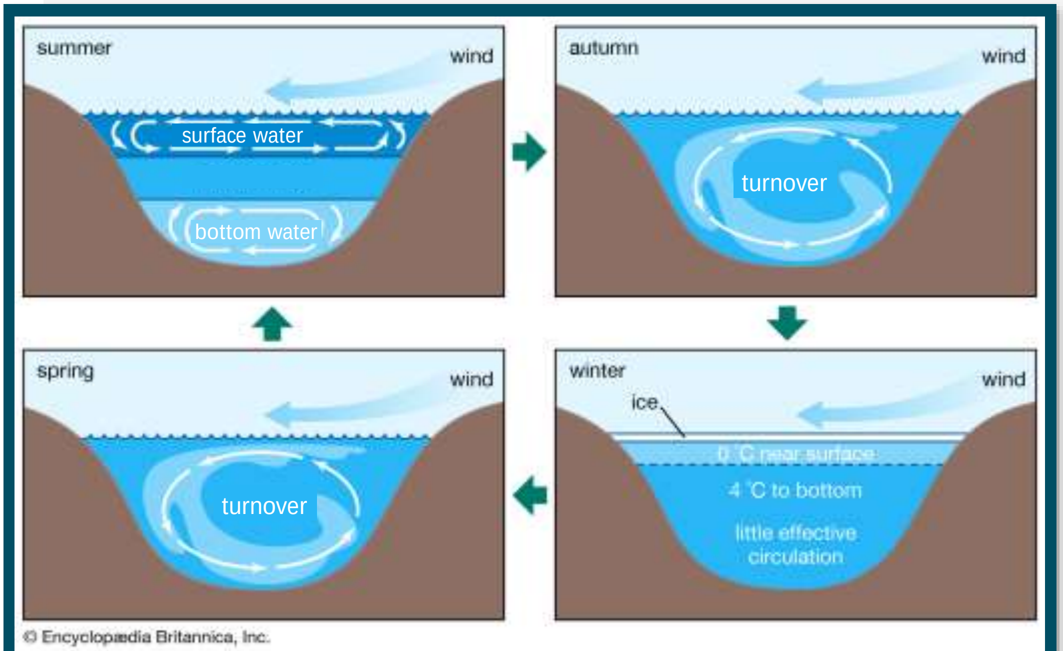


Figure 3. *Lake turnover and thermal stratification; In summer (upper left), warm surface water does not mix easily with cool, more dense bottom waters; In autumn (upper right) and spring (lower left), water temperatures from surface to bottom are similar and lake water mixes from surface to bottom; in winter (lower right). Figure modified from Encyclopedia Britannica, Inc.*

warmer spring air temperatures causes an increased *strength* of stratification (density difference from surface to bottom) in the lake.[49,50] Stronger thermal stratification promotes toxic cyanobacterial blooms due to the increased vertical stability of the water column.[53] Additionally, stronger thermal stratification requires more wind or thermal energy to induce mixing events, and alters the depth of mixed warm surface water, which affects nutrient availability throughout the water column.[51]

Lakes Superior and Michigan thermal stratification patterns have already shifted with climate change, and are expected to continue to change in the future.[41,42,54–56] Lake Michigan's increasing delay in fall turnover (and associated lengthening of the stratified period), loss of ice cover, shorter winter periods[54] may increase summertime phytoplankton and alter

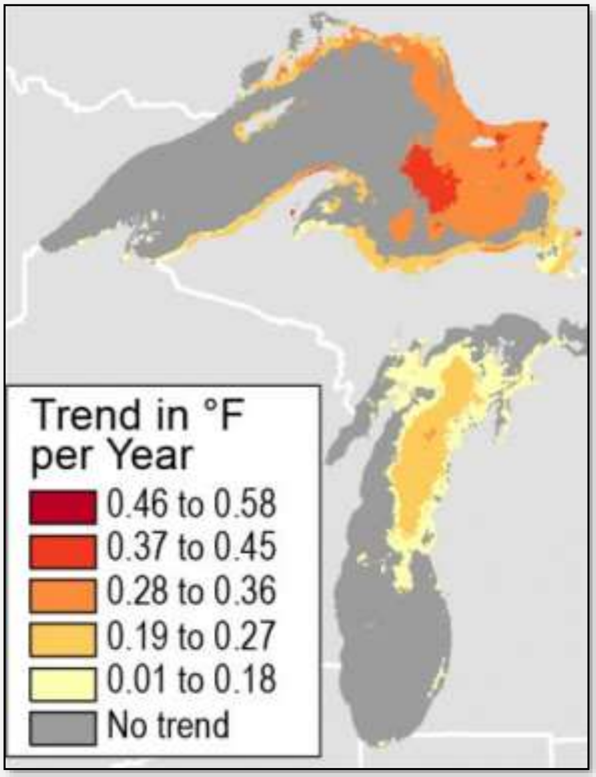


IMAGE: Summer Surface Water Temperature; US Climate Resilience Toolkit–GREAT LAKES

nutrient cycling with cascading ecosystem changes.[57] Lake Michigan in particular may be more susceptible to incomplete turnover events than some of the other Great lakes because of the combination of milder winter air temperatures and a lower steepness of bottom slope in the lake.[55] Modeling studies on Lake Superior suggest that climate changes may similarly delay turnover and cause a loss of ice cover by the mid-21st century.[56] Lack of water mixing during turnover events could contribute to low dissolved oxygen levels in bottom waters, with cascading effects on Great Lakes food webs.[1,54,58]

Lake Superior is the most rapidly warming Great Lake,[59] is one of the most rapidly warming lakes in the world,[39,41] and is projected to change more than any other Great Lake by the end of the 21st century.[58] Lake Superior's surface water is warming faster than surrounding air temperatures due to changes in the timing and strength of thermal stratification in the lake.[60] Lake Superior water temperatures are projected to increase between 8 and 12 °F throughout the 21st century.[24] While not changing as quickly as Lake Superior, Lake Michigan surface water temperatures are increasing as well,[61] and summer surface temperatures may exceed historical temperatures by over 5 ° F in the future.[62]

Warming in nearshore areas, specifically, may have more profound effects than warming deeper regions, given the disproportionately high importance of nearshore areas to the overall lake ecosystem,[48] and the fact that nearshore areas are where people generally interact with the Great Lakes. From 1994 to 2013, **Wisconsin's nearshore areas on** Lake Superior have warmed faster than open-water areas, though nearshore warming has been greater on the Canadian coastline.[45] Similarly, coastal Lake Michigan waters have warmed around Door County, though warming along the northern lower peninsula of Michigan was greater.[45] In Lake Superior, warming nearshore waters are associated with shifting phytoplankton community composition and higher primary production.[48] Warming in the nearshore area of Wisconsin's Lake Superior coast combined with increased nutrient delivery from precipitation events is likely driving the unprecedented recent cyanobacterial blooms[48] and increasing the likelihood of swimmer's itch and other waterborne disease.[63]

While there is a well-established pattern of surface water warming in Lake Superior and Lake Michigan, we know less about changes in subsurface water temperatures. However, subsurface temperature changes are important to understand because they affect stability, mixing, and stratification within the lakes.[64–66] From 1990 – 2020, deep water temperatures in Lake Michigan rose in the winter, and shorter winter seasons resulted in higher subsurface temperatures.[54] Earlier modeling investigations of Lake Michigan revealed that heat content in Lake Michigan increased in the late 1990s tied to changes in atmospheric conditions at the same time.[67] This modeling, showing increased heat content from air temperature warming, confirms that surface water warming is translated to deep water warming in Lake Michigan.[54]

Lake water temperature response to climate change

CHANGE IN TIMING:
Later Fall turnover — water column mixing that replenishes bottom water oxygen and increases surface nutrient availability

CHANGE IN DURATION:
Longer Summer Stratification—more favorable conditions for algae blooms

LOSS OF ICE COVER:
increased erosion potential, unknown ecological effects, warmer water temperature in spring

Ice cover changes

Ice cover is a "master variable" for many large lake limnological processes, so decreases in ice cover with climate change can significantly impact the Great Lakes ecosystem and shoreline stability. Since ice cover forms a physical barrier between the water and atmosphere, it regulates the transfer of light and wind energy to the water and exchange of heat and gases between the water and atmosphere.[68–70] Ice cover on the Great Lakes is sensitive to even small changes in air temperatures,[71] and warming air temperatures will delay ice formation and lead to some years with no or very limited ice cover.[70] Lack of ice cover affects water temperature in subsequent

The story behind the Arch of the Apostle (1st Place — 2019 Great Waters Photo Contest, natural features category): "*I took this image in February 2018. As Lake Superior began to freeze that winter, the conditions were perfect to create one of the most amazing natural phenomena I've ever witnessed in the Apostles. Big northeast seas, pounding at the exact angle necessary, blew ice into this small cove on Stockton Island and piled it 15-20 feet high. And there it froze into a petrified wall. Before the Lake could freeze over, the same wind blew waves into this cove again, hollowing out the massive ice wall into an incredible arch, some 12 feet high*." — Michael DeWitt

Photo taken at Stockton Island, Apostle Islands National Lakeshore seasons,[42,67] exacerbating the rising water temperature issues described in the previous section. Ice cover helps prevent shoreline damage from the large waves produced by storm events. Therefore, loss of ice cover can increase wintertime shoreline erosion, especially when combined with increased frequency and intensity of storm events that we expect in the future. Since ice cover is temporally and spatially variable in thickness and quality over a lake's surface,[66,68,72] the physical and biological results from loss of ice cover will be variable in space and time.

Remote sensing[73–75] and other studies[71] have shown that the extent and duration of Great Lakes ice cover has decreased since the 1970's (Figure 4). Lake Superior

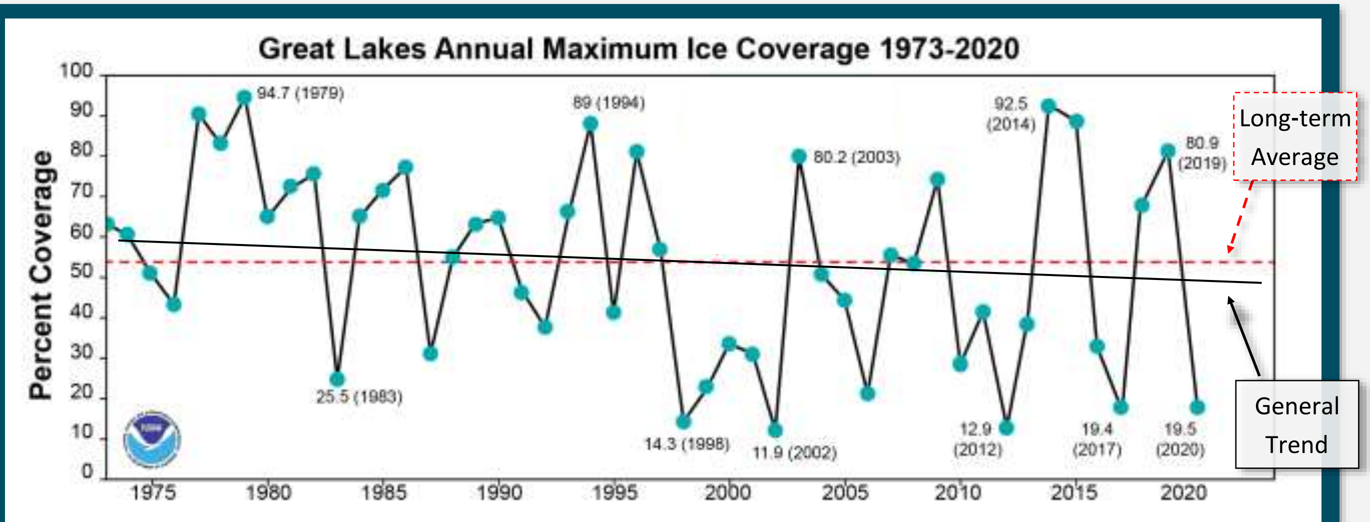


Figure 4. *Annual maximum ice cover across the Great Lakes from 1973 through 2020; Credit: NOAA GLERL, see current conditions here.* NOTE: Before 1998, the majority of years fall above the long-term average line, whereas in 1998 and later, the majority of years fall below the long-term average line, indicating a decreasing trend in ice cover.

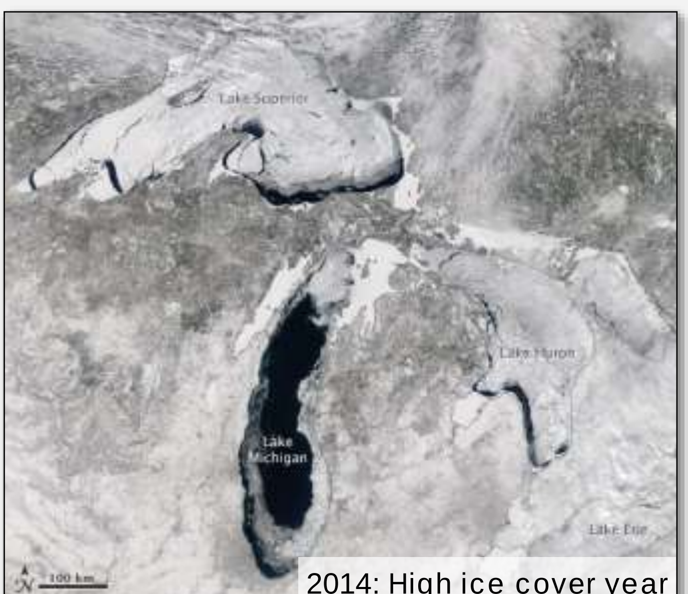


Photo: Ice cover on the Great Lakes in Feb. 19, 2014. Credit: Jeff Schmaltz, LANCE/EOSDIS MODIS Rapid Response TEAM at NASA GSFC

Photo: Ice cover on the Great Lakes in Feb. 14, 2020. Credit: Joshua Stevens, LANCE/EOSDIS and GIBS/Worldview, Suomi National Polar-orbiting Partnership, NOAA GLERL appears to have experienced a regime shift in ice cover in the 1990s.[42,76] Evidence of this ice cover shift can be observed in Figure 4, where most years before 1998 fall *above* the long-term average line and most years after 1998 fall *below* the long-term average line.

Future projections indicate that ice cover decreases will continue through the end of the 21st century.[77] On Lake Superior, the duration of ice cover is expected to decrease by 1 to 2 months by 2100.[24] Ice cover in Whitefish Bay, Lake Superior, is projected to decline by a factor of 3 by the end of the century under business-as-usual model simulation.[78]

Complex feedbacks between temperature, ice cover, and evaporation affect water levels

Since ice cover creates a barrier between the lake water and the atmosphere, decreased ice extent and duration increases the amount of time the lake water can evaporate in a given year.

However, decreased ice extent and duration alone will not necessarily increase evaporative losses of lake water.

Photo: Sea Smoke Sunrise, 2018 Great Lakes Photo Contest cultural historical category, by Howard Vrankin (example of wintertime evaporation scene)

Instead, the combination of less ice cover with larger air and water temperature differences in the autumn or spring can significantly increase evaporation rates.[79] To further complicate the interactions among temperature, ice, and evaporation: high ice cover years in Lake Superior have been observed following autumn periods with high evaporation rates,[76] likely due to the cooling effect of evaporation.

The complex interactions and feedbacks between ice cover, air and water temperature, and evaporation is an active area of research — see the Knowledge Gaps Section on Page 62 of this document, this research press release, and the Great Lakes Evaporation Network website to learn more.

Social and economic implications of physical lake changes

Physical changes to the lake are having significant impacts on coastal communities, and these impacts will continue and likely worsen in the future. Flooding events can directly damage infrastructure, cause loss of life, damage culturally significant human-built and natural features, and causes serious sociopsychological stress from shock and losses in catastrophic events.[80] Warmer temperatures will change recreation seasons and amenities,[81,82] and perceived environmental risks from climate change can affect tourist travel patterns.[83] Changes to lake mixing patterns may cause ecological cascades,[84] that could affect the economically and culturally significant fisheries, and water quality-based recreation (swimming, beaches, kayaking, etc). Shorter ice cover duration will lengthen the shipping season, but extreme low water levels require ships to carry smaller loads.[85,86] To ease the burden of these impacts, coastal communities need to build resiliency to climate change.

Coastal community resilience to physical changes in the lake can be achieved through diverse and novel approaches. Combined climate events (e.g., storm on storm; persistent rainfall) may become more common and are more likely to result in failing infrastructure,[87] but are often not considered in hydrological design.[88] Communities need to adopt and enforce more protective shoreland and floodplain zoning rules. Structures must be set back farther from the water's edge and there should be no structures in the floodplain.

In addition to direct infrastructure improvements, increasing community resilience requires fostering capacity building within vulnerable communities and recognizing the agency of these communities to build their own future.[89]

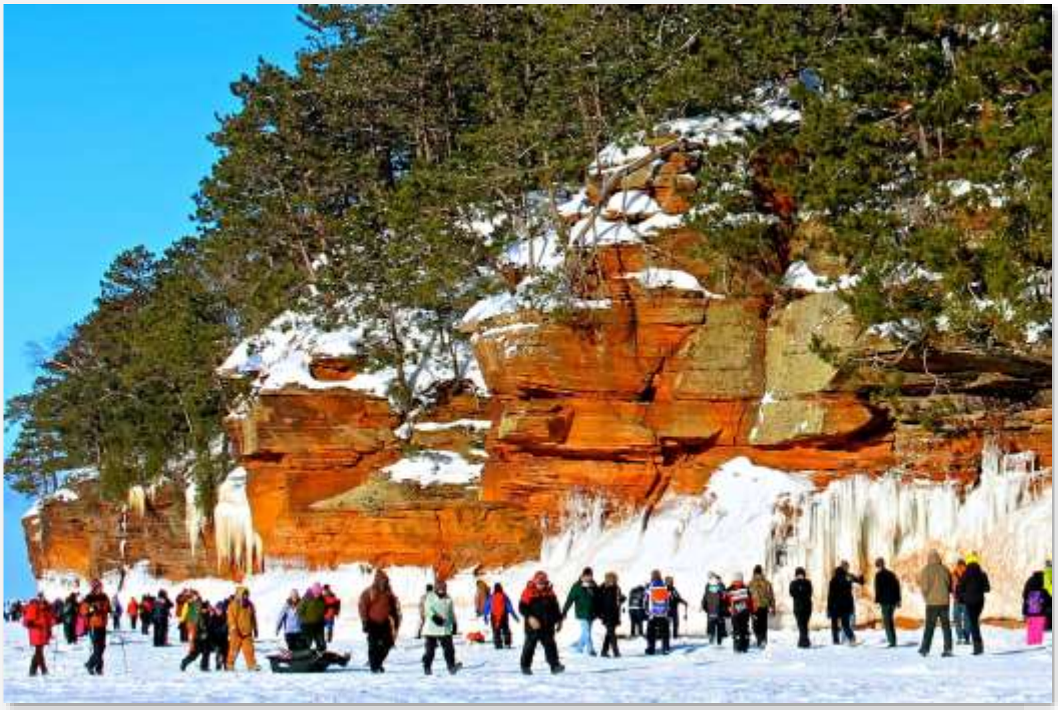


Photo: Ice Walk, 2015 Great Lakes Photo Contest people category, by Cheryl Barrett

Bottom-up, two-way flood risk communication, incorporating both the community perceived risk and data assessed risk,[90] increase likelihood of community buy-in to solutions[91] and builds the resilience needed in a changing world.[92] Further, risk communication and decision-making must directly address common cognitive biases. For example, wishful thinking and overconfidence are cognitive biases in risk assessment but can be overcome by including a third unaffected party and taking time to find reasons and circumstances under which a decision may be wrong, respectively.[88] **Incorporating surprises or "wildcards"** in decision-making increases the range of possible futures considered and fosters innovative solutions.[87,88,93]

Flooding Solutions in Packer Country

East River, tributary of the Fox River, which flows through Manitowoc, Calumet, and Brown counties and then into the bay of Green Bay.

Contributed by Julia Noordyk, Water Quality Outreach Specialist, Wisconsin Sea Grant

A 2019 flood resulted in dozens of displaced families and the condemnation of 50 homes after climate-change-induced weather resulted in early-March rainfall running off frozen ground. The area has clay soils with compacted land in the rural, upper watershed that promotes water runoff. The water then reaches paved surfaces in the city of Green Bay that have been developed in the floodplains, now dotted with aging stormwater infrastructure. Warmer winters are compounding flooding, as rainfall is occurring during times when the ground is frozen and infiltration is not possible.

Drone footage captures Fond du Lac, Wisconsin flooding CREDIT: Fond du Lac Police Department

In 2020, Wisconsin Sea Grant secured 18 months of funding from from the Fund for Lake Michigan and the Wisconsin Coastal Management Program to work with partners to develop flood mitigation strategies that include developing a hydrologic model of current and future watershed flood risk; development of interactive maps so that watershed residents and local officials can visualize the risk as well as effects of possible mitigation strategies; formation of a community of practice to connect residents, researchers local officials and nongovernmental agencies; and conceiving a resilience framework encompassing a vision, goals and near-term actions.

Along with Sea Grant, the other project partners are The Nature Conservancy; NEW Water; Brown, Calumet and Manitowoc counties; and the communities of Green Bay, De Pere, Allouez, Bellevue, Ledgeview, Rockland, Wrightstown and Holland.

Read more here and here.

Tackling water level CHAOS faced by coastal communities

Contributed by Karina Heim, Coastal Training Program Coordinator, Lake Superior National Estuarine Research Reserve

"Beach erosion and property damage." "Homes threatened." "Road and trail washouts." "Water quality impacts." "Fear in the community – change in sense of place." When Lake Superior coastal professionals gather to talk about the challenges posed by record-high water levels, these are just some of the impacts that they have experienced. Since 2014, an extended period of exceptionally high water year after year layered on top of large storm events has left communities scrambling to assess the resilience of waterfront investments and infrastructure in the face of such extremes. And yet, even while Great Lakes communities consider investments and regulatory adjustments to protect people and resources from water level impacts, there is collective acknowledgment that water levels are extremely dynamic and subject to fluctuate – particularly under an uncertain climate regime.

Life along the Great Lakes has always meant living with dynamic water conditions, with lake levels that rise and fall daily, with the season, and over the course of decades. But climate change threatens more extremes in water level conditions in the future.

Out of great challenges emerge new opportunities for partnership and collective learning. In 2020, anew community of practice known as Coastal Hazards of Superior (CHAOS) was formed to promote regional connection and knowledge sharing around Lake Superior coastal hazards challenges, with an immediate emphasis on high water and erosion impacts.

Supported by a steering committee of coastal outreach organizations, CHAOS is a voluntary gathering of western Lake Superior community leaders, local and tribal government staff, natural resource managers, coastal outreach liaisons, coastal engineers and designers, and land and property owners who have a stake in coastal resilience. In its first year, CHAOS has assembled 100 members and has held quarterly informational meetings. Timely and wide-reaching communities of practice such as CHAOS are a forum for building trust in relationships and can support regional solutions and coordination in response to climate challenges that are shared across jurisdictions.

High Water Spotter app, a water level photo collector app was developed in 2020 to encourage establishment of a visual record what water looks like, feels like, and is capable of when it is in an extreme condition:

Photo of Kilchis Meadow, mostly submerged, in the St. Louis River estuary. 9/23/2020

McQuade safe harbor (MN North shore) docks submerged, July 21, 2020

Check out the CHAOS landing page to learn more!

Photo: Cave Point Splash, 2015 Great Lakes Photo Contest, people category by Bill McClenahan

4. Impacts on Water Quality

Increasing nutrient loading

Climate change can have a major impact on water quality in the Great Lakes because extreme precipitation events result in runoff in carrying nutrients and contaminants into the lakes. The effects of precipitation, combined with air temperature and lake morphology accounts for a large portion of the variability in water quality trends for the Great Lakes,[94] indicating that climate change—both in terms of air temperature change and precipitation change—is likely an important driver of changing water quality.

Temperature increases will change how tributaries mix with the lake, in turn causing tributaries to enter the lake at different depths, affecting how inputs are delivered into the nearshore and

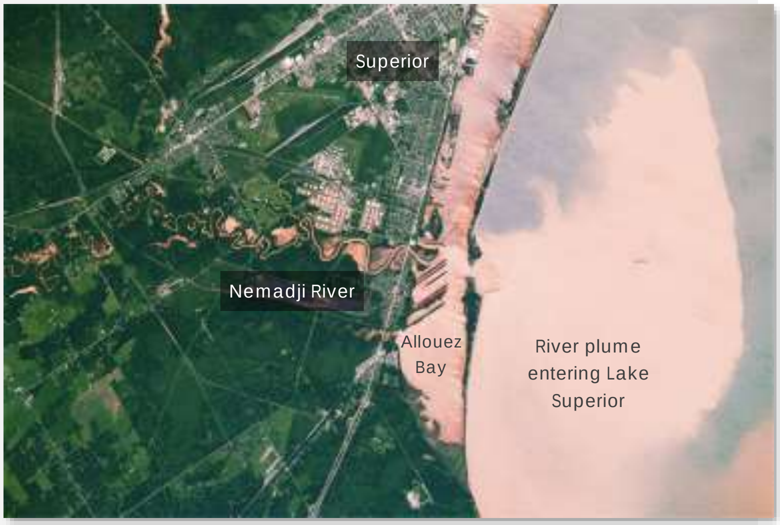


Photo: Astronaut (Expedition 56 Crew) photograph ISS056-E-21591 June 19, 2018, ISS Crew Earth Observations Facility and the Earth Science and Remote Sensing Unit, Johnson Space Center whether stream inputs are retained in the surface or transported to bottom waters.[95] Changes to how streams mix with the lake can impact cycling of nutrients, transport of river plumes, and water quality in the nearshore environment of the lake (Figure 5).[96–98] Extreme rainfall events have high potential for delivering more excess nutrients to the Lakes. For example, the extended 2012 rain event in Northern Wisconsin delivered a disproportionately large amount of phosphorus to Lake Superior's, greater than a 2016 storm with similarly high maximum rainfall but lower total rainfall.[99] The impacts from extreme rainfall events highlights the potential for increased precipitation events along the south shore to have a major impact on overall nutrient dynamics in Lake Superior.[99]

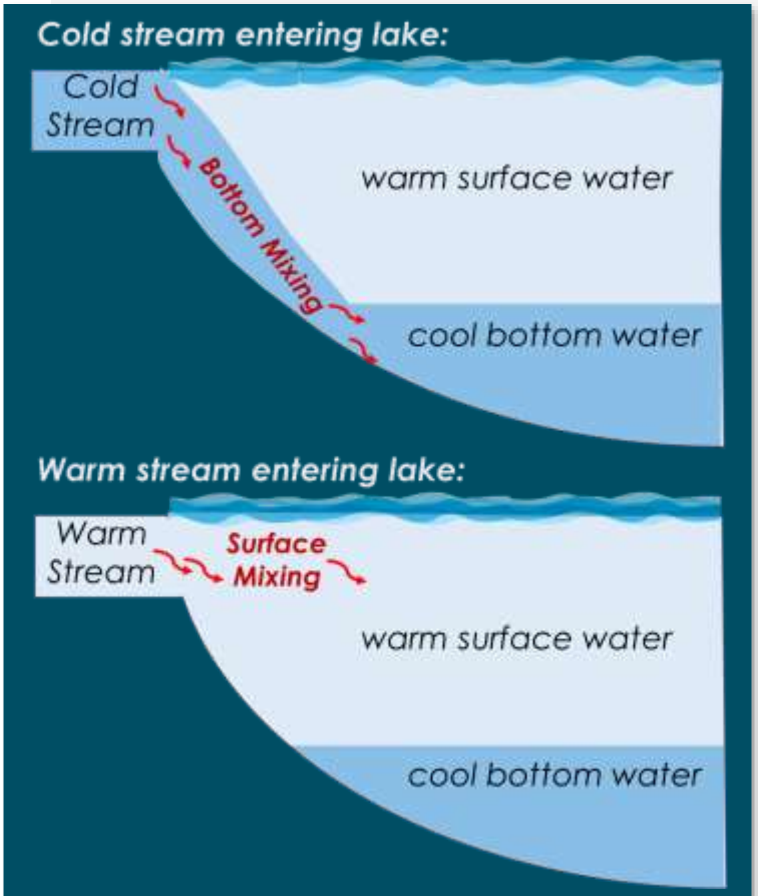


Figure 5. *Examples of mixing types between inflow streams and the receiving lake; TOP: streams that are colder (and therefore more dense) primarily mix with bottom waters; BOTTOM: streams that are a similar temperature to the lake surface readily mix with the surface waters.*

Worsening beach water quality

Beaches are very dynamic interfaces between the shore and water, and are where many people in Wisconsin primarily interact with our Great Lakes. Climate changes can negatively impact water quality at beaches, which can cause an increased health risk for recreational users.

Warmer sand and water temperature will likely increase the presence and persistence of microbial contamination at beaches.[100] Since waterfowl are a major source of *E. coli* to beaches, and climate change-induced impacts on bird abundance or migration may affect beach water quality.[100] At the same time, higher air temperatures may lead to increased crowds at beaches during the summer months. This could be especially true in Northern Wisconsin where fewer homes may have air conditioning, and in urban areas of the state where heat island effects can be particularly extreme and low-income urban populations may also lack air conditioning. The combined effect of having more people using the beaches and increased presence of microbial contamination on the beaches could lead to increased prevalence of people getting sick from beach contamination.

Photo: Splish, Splash, 2016 Great Lakes Photo Contest people category, by Shelby Chmielewski

Increased extreme precipitation events can increase contaminant and nutrient runoff to beaches (e.g., via stormwater runoff), including fecal pollution, resulting in beach closures. In particular, norovirus and rotavirus are predicted to have increased presence and persistence during extreme weather events.[100] In urban areas, extreme rainfall can stress sewer infrastructure and result in the release of untreated sewage to rivers and beaches.[101,102] Increased precipitation can lead to increased presence of species like *Cryptosporidium* and *Giardia*, while areas experiencing decreased precipitation may experience increased presence of *Candida* species.[100] Extreme events and lower ice cover can elevate *E. coli,* Enterococci, and other pathogens in sand and water.[100] Increased amount of time that sand is covered by water allows E. coli to remain active in the sand itself and enables easy transportation from sand to water. Additionally, increased wave activity may cause wider dispersal of microbes and release into the water.[100]

More nutrients, more harmful algal blooms (HABs)

Harmful algal blooms (HABs), characterized by high concentrations of algae or toxin-producing cyanobacteria,[103] are a significant threat to the water quality of the Great Lakes. HABs are likely to become more prevalent with climate change,[2,104,105] following global patterns of increasing HABs.[106] Cyanobacteria, also known as blue-green algae, can produce toxins, posing a direct human health threat. High concentrations of non-toxin producing algae cause

Why are HABs so bad?

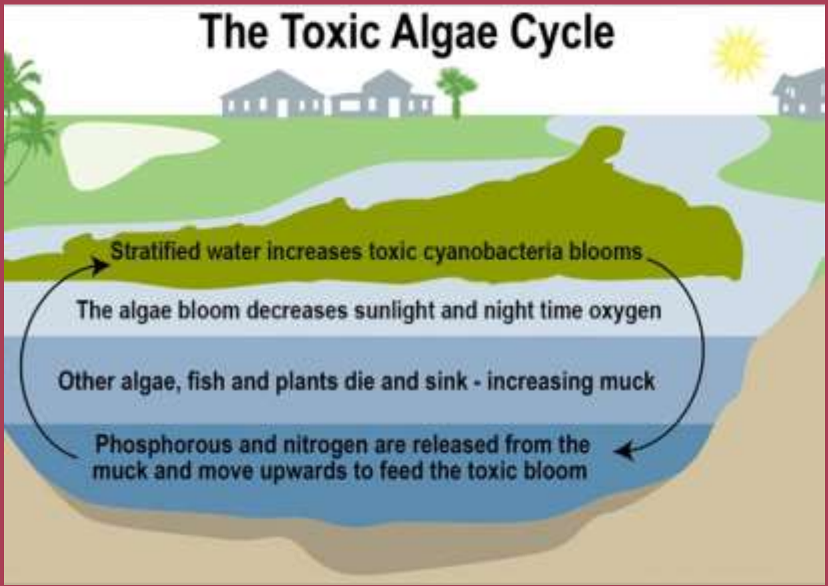


Image CREDIT: Vertez Aquatic Solutions, Control Harmful Algae https://vertexaquaticsolutions.com/control-harmful-algae/

ecological harm by blocking light in the water through the formation of surface scums, depleting oxygen concentrations during decomposition, and promoting wildlife botulism outbreaks,[107] which in turn harms recreation and fishery industries.[108]

The primary ways in which climate change may increase HABs is through warmer water temperatures, intensifying thermal stratification, increased carbon dioxide concentrations, changing timing of runoff events, and increases in nutrient loading.

Photo: An active algal bloom in Lower Green Bay from August 2019; *CREDIT*: NEW Water

Toxic cyanobacteria prefer warmer water, and high temperatures can preferentially favor growth of bloom-forming algae and cyanobacteria.[104,109] Stronger thermal stratification (greater temperature difference from surface to bottom waters) provides more vertical stability for HAB formation.[110,111] Carbon dioxide increases expected under changing climate can also favor cyanobacteria when compared to green algae species.[112]

Spring phosphorus loading will likely increase with increasing early spring precipitation combined with the greater erosion potential in the spring, when agricultural fields are fallow or crops are not yet mature.[43] The effects of warming waters and increased nutrient availability from extreme precipitation events likely combine to further enhance HABs.[48,109] All of these climate change impacts are likely to contribute to more severe and frequent HABs in Lakes Superior and Michigan.

HABs are a particular problem in the Bay of Green Bay, due to high phosphorus and other inputs from increasing runoff with climate change.[113] Though the Bay of Green Bay is only 7% of the surface of Lake Michigan, it receives 33% of the total nutrients delivered to the lake.[114] Increases in precipitation events with climate change could offset changes in cover crop and agricultural best management practices in the watershed. Though early spring phosphorus loading is expected to increase with extreme runoff events before crop maturity, summertime phosphorus loading may decrease with lower summertime precipitation.[43] Overall, the enhanced nutrient loading from the watershed during storm events may contribute to increases in harmful algal blooms within Green Bay[115] as well as exacerbating Green Bay's "dead zones."[116]

HABs are also an increasing concern in Lake Superior, which has experienced unprecedented blooms in recent years with rising water temperatures.[48,117] Wisconsin's Lake Superior shoreline has been subject to extreme precipitation in recent years, which have delivered large amounts of sediment and nutrients to the nearshore of the lake.[99] The resulting elevated nutrient levels may remain for months after major storm events. These large storm events have, in turn, coincided with major **algal blooms along Wisconsin's** Lake Superior shoreline.[48] An increase in the frequency and extent of algal blooms on Lake Superior may be caused in part by warmer waters.[24] Lake Superior cyanobacterial blooms generally occur in summers with the highest historically observed degree days.[48] The earlier warming of water temperatures and longer summer growing season, contributed to the major blooms in 2012 and 2018 on Lake Superior.[48]

There is likely a strong interactive effect between nutrient availability and water temperature in moderating the frequency and severity of HABs. Globally, lakes that have exhibited decreasing HABs also experience little warming, whereas lakes with nutrient management plans in place that are warming still exhibit increasing bloom formation.[106] Therefore, nutrient reduction goals may need to be even larger than previously thought to offset the effects of warming water temperatures and stronger thermal stratification.[53,118]

Photo: Jump, 2016 Great Lakes Photo Contest, by Melissa Cary

Social and economic implications of changing water quality

Decreased water quality in the Great Lakes has significant social and economic impacts, ranging from direct human health concerns, loss of tourism dollars, and detrimental effects on the fisheries industry. A major threat to water quality is harmful algal blooms,[119] which contain blue-green algae (cyanobacteria) that produce toxins causing human illness and death. HABs are difficult to predict in time and space because their formation depends on the right mix of temperature, water column stability, nutrients, and other conditions, and the amount of toxins produced in each bloom also varies with these interacting drivers.[120] Blue-green algae toxins can cause skin irritation, muscle cramps, gastrointestinal distress, paralysis, and cardiac or respiratory failure.[119] In addition to the health risks, HABs are also generally aesthetically displeasing, so can cause loss of tourism dollars[119] and decrease property values where HABS are frequent and severe.[121] Further, when HABs die, they sink towards the bottom of the water column and decompose, depleting oxygen in the water and causing major fish kills, harming commercial, recreational, and cultural fisheries.[119] HABs have been directly **implicated in economic losses in the 10's** of millions of dollars per year in New England, Florida, and the Pacific Northwest and could become a major issue in **Wisconsin's Great Lakes with climate** projections.[119] Within the Great Lakes, economic valuations of water quality suitable for boating can be over 40 dollars per person per day.[122] Beach and lakefront use is valued up to 50 dollars per person per day and the aesthetic value of higher water quality corresponds to 2-4 % higher housing prices.[122]

Managing decreased water quality generally, and HABs specifically, will require directly addressing human behavior and building institutional capacity and resilience (here "institution" refers to common behavior patterns between connected people and groups or organizations).[123–125] A major tool to manage water quality is to decrease nutrient loads with better land-use based practices. When environmental managers or outreach professionals aim to communicate the importance of alternative land-management practices, the receiver of the information needs to have confidence the practice will both achieve their individual goals (e.g., high crop production) and will achieve the environmental goals (e.g., improved water quality).[125] Careful pre-tested messaging and communication delivery of HAB risks within well-coordinated institutions can increase societal resilience to HABs by increasing public trust, understanding, and adoption of environmentally-friendly behavior.[123] HAB messaging about risks alone, without consideration of audience perception of those risks, familiarity and controllability of the risks, and without robust social science methods (e.g., well-designed and theory-based focus groups and field surveys), are unlikely to be sufficient.[123,126] Thus, embedding trained social scientists in management initiatives is crucial.[123] Increased institutional capacity requires effective messaging coordination between HAB-relevant entities, including but not limited to scientists, environmental managers, public health officials, business owners, lifeguards, media, anglers, recreationists, residents, and tourists.[123] These coordinated and well-grounded communication approaches are needed for both HAB risk assessment and HAB control and mitigation approaches.[123]

Photo: Urban Fishing, 2018 Great Lakes Photo Contest people enjoying Wisconsin's Waters category, by Katherine Murray

Photo: Cave Point Sunrise, 2016 Great Lakes Photo Contest, natural category by Dan Fearing

5. Impacts on Lake Habitats

Coastal habitats

Faster rates of water level change with climate change increases coastal erosion and results in coastal habitat loss in the Great Lakes.[127] Coastal habitat includes the nearshore terrestrial, aquatic, and transitional habitats: nearshore waters, coastal wetlands, sandy beaches, and vegetated dunes. Coastal habitats shrink and expand with natural water level changes, which drives changes species abundance and diversity, where intermediate levels of fluctuation increase diversity.[12,128] However, habitat loss occurs through the more extreme and rapid fluctuations due to climate change.[127]

Climate change alters habitat structure and function through increasing frequency and intensity of precipitation events, influencing water levels and wildlife usage patterns. Structural changes to habitat include upland or downland migration of vegetation with changing water levels. Coastal vegetation is adapted to respond to changing water levels, but may struggle to adapt to extreme changes over increasingly short timescales.[12,129] Changes to the structure of coastal habitat directly affects the species that use these habitats, including frogs, toads, and bird wildlife, where many species benefit from annual high-water levels,[34,130] but effects of shorter-term variation are less known. Functional changes can decrease or alter regulatory and supporting services such as stormwater storage and treatment, nutrient cycling, water quality, and erosion protection. Changes to ecosystem services affects public access, property values, recreation opportunities, and fisheries. For example, nutrient cycling is a key coastal wetland ecosystem function, and water level fluctuation alters the release of sediment phosphorus.[131] Diverse wetland and coastal habitats, accessible at high and low water levels are needed to provide species refugia from increasingly variable water levels.[130]

Shoreline habitats

Increasing storm magnitude and frequency will likely increase erosion rates along the Great Lakes coasts, regardless of higher or lower lake levels.[132] Shoreline habitats are directly at the interface between coastal terrestrial and coastal aquatic habitats including rocky shorelines and beaches. Here, shoreline habitats are the specific boundary between the lake and surrounding land, which is a subset of broader coastal habitats that encompass nearshore aquatic and terrestrial habitat. Shoreline erosion, including bluff recession, varies spatially, but is associated with changes to mean monthly and annual water levels.[133] Alterations to the shoreline to prepare for high and

Magnitude and duration of water level shapes shoreline aesthetics, habitats, and use. An extended below average water level period from 1999 to 2013 allowed for terrestrial establishment on the beach, which was rapidly eroded away when water levels quickly rose (2016) to near record highs (2019)

CREDIT: Wisconsin Sea Grant, Phil Moy and Titus Seilheimer

low water levels can exacerbate negative impacts of climate change to shoreline habitats. For example, during the recent record-high water levels, shoreline structures were installed along both the Lake Michigan and Lake Superiors coasts to protect homes and other coastal infrastructure from erosion damage. Structures that are installed to protect critical infrastructure can also eliminate or severely degrade important shoreline habitat for both aquatic and terrestrial species. Balancing the needs of wildlife and infrastructure during high water levels can be a point of conflict in resource management along the coasts.

Periods of higher water levels exacerbate conditions for flooding and erosion, resulting in the loss of land, damage to infrastructure, and associated loss of beneficial uses. During high water periods, there is even greater potential for storm-events to cause damage and erosion with increased wave run-up and seiches. Over half of the Apostle Islands National Lakeshore shoreline has high to very high potential for shoreline change, especially the gravel and sand beaches not immediately backed by bluffs.[24] Beaches may be more prone to coastal flooding because of wave run up under high water conditions. As lake water levels rise and storms become more intense, low-lying areas can become super saturated, reducing their infiltration capacity and leading to inundation. High water levels also cause waves to break closer to the shoreline, resulting in erosion. Frequent inundation, loss of erosion protection (e.g., habitat),

What benefits do coastal wetlands provide?

Benefits of coastal wetlands: 1) dissipate energy: during heavy rainfall wetlands reduce stream speed and act as natural sponges that absorb water; 2) improve water quality: wetlands purify water, filtering out sediments and contaminants; 3) control erosion: wetlands buffer shorelines against erosion and bind soil with their roots, 4) provide fish and wildlife habitat; 5) provide recreation, open space and aesthetic value: people hunt, fish, hike, boat, and photograph in wetlands; 6) supply groundwater flow: wetlands contribute to base flow of streams; 7) reduce flooding: wetlands soak up and store water and slowly release into streams, 8) protect coast from storms: coastal wetlands buffer wave energy. CREDIT: Green Planet Ethics and intense wave action can result in a cascade of negative impacts, including partial or complete loss of Great Lakes coastal beaches.

Falling water levels will expose additional beach face, which may seem attractive from a utility standpoint. However, exposed lakebed can become prime substrate for invasive species, such as Phragmites, if left unmanaged. Invasive species can quickly outcompete native vegetation, especially if not well established, altering habitat functionality (e.g., nutrient cycling,[134] loss of native species habitat).

Coastal wetlands

Coastal wetlands, as the interface between terrestrial and aquatic ecosystems, provide critical habitat in the Great Lakes and are sensitive to climate change impacts on both aquatic and terrestrial ecosystems. Coastal wetlands provide flood control, groundwater replenishment, water purification, and shoreline stabilization. Further, coastal wetlands are important reservoirs for biodiversity,[61] providing breeding or nursery habitats for many Great Lakes fish species.[135-138] Coastal wetlands are sensitive to terrestrial and aquatic changes due to climate change, including air temperature, precipitation, and winter period.[24]

Precipitation changes affect flow regimes and inundation periods in wetlands, which in turn impacts community composition and abundance of plant species within wetlands.[61] Extreme weather events can result in wetland infill, causing a total loss of habitat. Natural cycles of water level are important for maintaining healthy coastal wetlands.[24] Periodic high lake levels limit the expansion of trees, shrubs, and other terrestrial emergent plants, whereas periods of low water levels

Photo: Wetland Egret, 2018 Great Lakes Photo Contest, natural category by Reggie Gauger promote seed germination and limit the growth and spread of plants that require very wet conditions.[139,140] Though coastal wetlands are adapted to fluctuating water levels, more rapid and extreme decreases and increases in water level could be problematic, as slower rates of change allow for steady adaptation by vegetation and wildlife species. Additionally, persistent higher or low water levels lead to alteration of species composition within a wetland.

Social and economic implications of lake habitat change

Damages to coastal habitat have significant social and economic impacts, ranging from loss of migratory and wetland bird recreation and tourism, damage to fisheries, and physical loss of shoreline areas and buildings from erosion.[141] Fisheries implications of changing lake habitats are covered in following section.

Managing shoreline erosion often requires assessing tradeoffs of protecting current infrastructure or managing loss of habitat. However, novel nature-based solutions that work with the variability in nature, including installation of living shorelines and wave attenuation structures may help address both infrastructure and nature protection.[142] Implementation of these nature-based solutions requires localities to overcome political, institutional, and knowledge barriers to increased adoption.[143] Nature-based solutions to shoreline management that enhance coastal habitat are more resilient to extreme events, both in terms of ability to withstand extreme events and recover from disturbance, and will significantly decrease the property damage from extreme storms.[144]

The WICCI Coastal Resilience working group webpage and report provide a detailed assessment of changing coastlines.

Photo: Concert on the City Dock in Downtown Green Bay, 2015 Great Lakes Photo Contest, people category by Christopher Rand

Photo: A Sucker For Color, 2016 Great Lakes Photo Contest, natural category by Colleen McCarty

6. Impacts on Species

Plankton shifts

Climate change affects both phyto- and zooplankton species in the Great Lakes, altering aquatic food webs. Warmer water temperatures and less ice cover leads to longer growing seasons and stronger thermal stratification, corresponding to increases in primary productivity[53,61,104,109] and changes to plankton community composition.[145] Different trophic levels often have differing responses to changing temperatures, which restructures food webs.[84] Warming lake water causes some phytoplankton taxa to increase in size and others to decrease: diatoms in Lake Superior have become smaller whereas diatoms in Lake Michigan have become larger,[146] which can have cascading effects on the food web. Changes to lake mixing patterns and depth of the thermocline causes a change in the vertical distribution of phytoplankton in the water column and seasonal succession patterns.[147]

In Lake Superior, rapid increases in primary productivity are attributed to increasing surface water temperatures and a longer growing season.[48,148] Lake-wide annual primary production in Lake Superior is expected to increase through the mid-21st century. Additionally, a phenological shift is occurring, such that the highest daily primary production in the lake is expected to peak between 14 and 25 days earlier than in the 1990s.[56] Changing water levels affect the surface area of substrate available for periphyton communities,[149] and climate impacts could result in a shift in species composition and altered structure of aquatic food webs in the lake.

Climate can influence zooplankton dynamics by altering the timing of peak production.[43] In other temperate lakes, earlier spring warming leads to earlier phytoplankton blooms, but not always earlier peaks of herbivorous zooplankton.[150,151] A changing climate could influence zooplankton community composition by favoring species that can maximize productivity under expected changes in temperature.[43] Warmer surface waters on Lake Superior may also cause copepods to become smaller and more abundant, but cascading effects on the ecosystem and food web are unknown.[24]

Invasive species facilitation

One of the greatest potential threats to ecosystems with climate change is the facilitation of species redistribution and introduction of non-local species to the region.[2] Additionally, species will shift their ranges, so new invasive species may have a competitive advantage in the Great Lakes,[152] and native species may shift their range northward.[153] Warmer conditions may lead to increases in invasion success and may increase the impacts of invasive species that are already present in the region.[1] For example, in Lake Michigan, warmer water and increased nutrient run-off with climate change boosts invasive carp populations by increasing their food sources.[154] During lower water levels, phragmites may become more favored along the Lake Superior shoreline, in part because of warmer water temperatures.[24] Dreissenid mussels have not had a major impact on Lake Superior yet, mainly because northward expansion has been limited by the lake's cold water temperatures. However, as Lake Superior becomes warmer, dreissenid expansion will increase, and could present a major threat to the lake.[24]

White perch and alewife are currently rare in Lake Superior, but their distributions are expected to expand with a warming climate.[155] Distribution expansion is likely because of reduced overwinter mortality as lake water warms.[156] The invasive round goby[157] and flathead catfish[158] are both expected to gain additional habitat with continued warming.

Climate change has the potential to both produce more favorable conditions for sea lamprey and reduce the effectiveness of control efforts in the Great Lakes. In Lake Superior, longer growing seasons for lamprey and their hosts increase feeding and growth, resulting in larger lamprey sizes before spawning.[159] Large lamprey will have greater feeding rates, causing increased mortality to host fish because of increased attack rates, wounding rates, and indirect mortality from infection.[159] Large lamprey may also have increased fecundity, fueling an increase in the overall sea lamprey population.[159] Lake trout, which are key hosts to sea lamprey in Lake Superior will likely experience higher mortality rates as water temperatures increase in the future.[3] Additionally, warmer waters can increase larval sea lamprey's tolerance of lampricides.[160] This could increase costs of lampricide application and potentially result in lowered effectiveness of lampricides in controlling populations as water temperatures continue to warm.

Fish and fisheries

Understanding how Lake Michigan and Lake Superior fish populations will be affected by climate change is crucial because those fish populations have significant ecological and social importance. Ojibwe people have a strong subsistence, cultural, and spiritual relationship with fish[161] and Hmong subsistence anglers in Sheboygan, Green Bay, and Milwaukee rely on Great Lakes fish. However, the impact of climate change on fish populations and contaminant transport through the food web is a complex issue with many unknowns, requiring further research and monitoring. Fish in Lake Michigan and Lake Superior will be affected by increasing water temperatures, increases in storm intensity, and shifting phenological patterns. Most of the studies looking at impact of Great Lakes fishes to climate change have used empirical approaches to link observed (past) changes in growth or recruitment to variables believed to be driven by climate changes, but fewer studies have examined potential future responses of fish populations to climate change.[43]

Photo: Home from the Fishing Grounds, 2017 Great Lakes Photo Contest, cultural category by Ruth Harker

Habitat

Changes in air temperature and precipitation directly influence physical (temperature, ice cover, water level, clarity) and chemical variables (phosphorus, oxygen) associated with fish habitat.[43] Warm-, cool-, and cold-water fish are expected to have increased thermal habitat within the lakes, but likely in different areas of the lake than they currently occupy.[44] Cold-water fish habitat will extend toward northern and deeper portions of the lake, while warmer water fish habitat will extend toward southern and nearshore areas of the lakes.[44] From 1979 to 2006, preferred thermal habitat in Lake Superior for lean lake trout, Chinook salmon, and walleye increased at a rate of 5 - 7 days per decade.[162] However, siscowet lake trout saw a decrease of 3 days per decade in preferred thermal habitat. As a result, spatial extent of preferred habitat increased for lean lake trout, Chinook salmon, and walleye, but decreased for siscowet lake trout. Increased primary production rates with warmer water and longer summer thermal stratification could stimulate more biomass decomposition in bottom waters, leading to hypoxia in the summer.[43] This may be particularly problematic in Green Bay, where there is already persistent, recurring summertime hypoxia.[116] In highly productive coastal wetlands, coastal wetlands can experience diurnal oxygen cycles with nighttime hypoxia, and warmer temperatures could increase the potential for nighttime hypoxia.[43]

Growth

Climate change can affect fish growth directly through changes in water temperature and indirectly through impacts on prey availability. Increases in water temperature will likely lead to increased fish growth in warm-water fishes and reduced fish growth in cool- and cold-water fishes. However, the net change in fish growth will also be limited by prey availability, habitat, and local conditions.[43] Bioenergetics modeling for multiple species projects that fish growth should increase with warmer thermal habitats because fish are able to behaviorally thermoregulate, assuming prey is not limiting. If prey is limiting, however, growth is expected to decrease with warmer temperatures.[43] Fishes in all three thermal guilds, with the exception of siscowet lake trout, are likely to have an increase in the duration and extent of optimal growth temperatures in all of the Great Lakes.[43] Warmwater fishes are expected to have smaller changes in growth because they do not have the same ability as other thermal guilds of finding and consuming sufficient prey to balance larger metabolic costs at higher temperatures.[62]

Recruitment

Climate change alters physical and thermal habitat during spawning and early developmental processes, which may increase or decrease fish recruitment depending on the species and driver of interest. For example, nearshore-spawning species have shown higher recruitment during higher lake levels in Lake Michigan because high water levels may increase spawning and nursery habitat in the nearshore and adjacent tributaries.[163] Additionally, spring and summer nearshore-spawning fishes have higher recruitment with warmer water temperatures,[43] including yellow perch, alewife, and walleye.[163,164] However, warm winters may reduce egg quality and hatching success for yellow perch,[165] lake whitefish,[166] and other species because reduced ice cover may expose fish eggs to damaging wave action in shallow areas.[43]

More frequent and severe storms may increase or decrease fish recruitment through increased stream inputs and wind-driven displacement and temperature changes.[167] Large stream flow events increase nearshore turbidity, which can increase larval fish survival by providing refuge from visual predators, as has been observed for Yellow Perch in Lake Erie.[168,169] However, larval cisco survival in Lake Superior may be hindered by increased turbidity because their predator, smelt, has less predation pressure themselves in turbid conditions.[170] Wind from springtime storms can physically displace eggs and cause rapid temperature drops from upwelling, causing mortality in nearshore spawning fish such as walleye and lake whitefish.[163,167,171]

Since fish recruitment impacts from climate change are so mixed, more research is needed to understand lake- and location-specific effects on individual species. Additionally, the interactive effects of increasing water temperature, wind, and high streamflow events with decreased ice cover and changing thermal stratification patterns are largely unknown.[167]

Phenology

Faster warming in the spring and longer summer stratification can alter reproductive phenology of Great Lakes fishes, but the effects will vary among species because of different life-history strategies, physiology, and environmental cues.[43] Some potential shifts include earlier spawning for warm and cool-water fish because of earlier stratification onset and later spawning for cold-water fish because of later turnover and later arrival of cooler water temperatures.[43,165,172] In Lake Michigan, yellow perch have been observed spawning earlier in both Milwaukee and Green Bay.[172] The earlier spawning appears to be aligned with maintaining a consistent spawning temperature, as warming begins earlier in the spring.[172] However, there is thus far no clear relationship between climate change and spawning for lake trout in Lake Michigan or Lake Superior.[172] Warming affects spawning success, which may have detrimental consequences to native fish species in the lakes. Warming can also cause a mismatch between spawning timing and food availability. Changes in spawning time can lead to mismatches between larvae and planktonic prey species both because spawning occurs too early or too late compared to peaks in planktonic production.[43,165]

Photo: Morning Colors, 2015 Great Lakes Photo Contest, cultural natural category by Chris Gaziano

Risks to Species of Interest

WALLEYE

Walleye, which have high economic and cultural value in Wisconsin, are threatened by warming water temperatures and changing precipitation patterns due to climate change. Walleye are an important fish species to Ojibwe peoples across northern Wisconsin,[161] and a valuable species to recreational anglers and the tourism industry in the state. Though warmer water temperatures in Lake Superior has expanded suitable thermal habitat for walleye, the warmer water may result in increased competition for food, lowering growth rates.[161] Alterations to the timing and amount of precipitation decrease walleye recruitment in stream tributaries.[3] During extreme precipitation events, large flows can prevent fish passage to spawning grounds, increase organic matter, which can smother eggs, and carry eggs downstream to unsuitable habitat.[161] Conversely, during periods of drought, low stream flows and low water levels can prevent walleye from reaching spawning areas or leave rearing habitat too warm and shallow.[161]

Illustration by Virgil Beck

LAKE STURGEON

Lake sturgeon are a long-lived and slow-growing species, with females living over 100 years and not reaching sexual maturity until about 25 years. Lake sturgeon are an important species culturally, as an original Ojibwe head clan.[161] Overall, Great Lakes lake sturgeon populations are reduced in comparison to their historical presence across Ojibwe ceded territory[161] largely due to overfishing and habitat degradation and fragmentation.[173] Lake sturgeon recovery is slow due to their long time to maturity, migration, and protracted spawning.[173] Lake sturgeon have a medium vulnerability to climate change driven largely by a high sensitivity to climate changes, but with some ability for the species to adapt to new conditions and potential for population stimulation with warmer water and a longer growing season.[161] Lake sturgeon recovery efforts are focused on water quality and spawning habitat.[161]

Illustration by Virgil Beck

BROOK TROUT

Brook trout are one of two trout species that are native to the Great Lakes Basin. This cold-water species was once prevalent but is no longer highly abundant in the region. Because of brook trout temperature preferences, they are generally restricted to cold, fast flowing streams and tributaries in the Lake Superior basin. Warming in streams and tributaries negatively affects their habitat, and low flows during drought conditions

Illustration by Virgil Beck

can lead to more sporadic recruitment,[161] creating compounding harm with climate change. Brook trout have a high sensitivity to climate change and low ability to adapt, making them highly vulnerable to climate change.[161]

CISCO

Cisco are a cold-water pelagic fish found in the Great Lakes basin. Cisco were historically threatened because of commercial harvesting and impacts from invasive species like the rainbow smelt.


Illustration by Joseph R. Tomelleri

Populations in Lake Superior may be rebounding thanks to management efforts; however, recruitment of cisco has been variable in Lake Superior and the fishery is mostly supported by a few strong year classes.[161] With warming conditions, the timing of larval cisco hatch is variable, which may lead to differences between when cisco hatch and when prey species are available.[161] Changes in the timing and amount of ice cover is also expected to affect survivability of larval fish.[161] The 1854 Treaty Authority classifies cisco as being highly vulnerable to climate change.[161] The loss of diversity of the cisco suite of species has made them less able to recover from changes in the environment and future changes in climate could make ongoing recovery efforts more difficult.

LAKE TROUT

Great Lakes lake trout populations **collapsed in the mid 1900's** primarily from overfishing and sea lamprey predation.[174–177] Protection of spawning populations, stocking programs and sea lamprey control have improved populations in the Great Lakes, although population recovery is highly variable across management units in each lake.[3,178,179] Water temperatures and decreasing ice cover are impacting lake trout populations in Lake Superior.[161] Warmer water temperatures will cause early onset of lake stratification, which means that trout fry have fewer days to feed on prey species before surface waters warm considerably and push fish to deeper, cooler waters. Increased storm activity in the fall and winter combined with less ice cover on the Great Lakes could cause high egg mortality and failed year classes.[161] Wind and wave action during these storm events in winter might damage or displace eggs, especially on relatively shallow reefs.[3] Larger runoff events during high precipitation years could increase siltation on spawning grounds and impact reproduction.[161] Both GLIFWC and the 1854 Treaty Authority have assessed lake trout as being highly vulnerable to climate change[3,161] because they are sensitive to impacts from climate change and have a limited ability to adapt.


Illustration by Virgil Beck

LAKE WHITEFISH

Lake whitefish are the most harvested fish in the Great Lakes and are highly sensitive to climate change with a minimal ability to adapt.[161] Like other native Salmonidae fishes in the Great Lakes, lake whitefish spawn in the fall, and their eggs overwinter before hatching in the spring. Wind and waves during storm events before the onset of ice cover have been linked to lower survival and hatching rates.[180] Ice cover protects these overwintering eggs in sub-optimal spawning habitat, so reductions in ice cover would lower lake whitefish survival in these habitats.[161,180] However, an overall analysis on climate change projections indicated that there may be potential for increased lake whitefish recruitment in portions of Lakes Michigan and Superior assuming no negative impact from food web dynamics, invasive species, disease, and other external factors.[180]

Illustration by Ellen Edmonson and Hugh Chris

Manoomin (Wild Rice)

Manoomin, or wild rice, has had significant cultural significance for Wisconsin tribes for thousands of years[181–183] and is an important part of the Great Lakes ecosystem. Manoomin is a sacred food to the Lake Superior Ojibwe.[181,184] Ojibwe prophecy led the people to the Great Lakes region, where the food, manoomin, grew on water during their migration from the eastern part of the continent.[182] Manoomin is also an important part of the Great Lakes ecosystem. Many species of wildlife use manoomin habitat for reproduction, foraging, or as nursery areas and it can play a role in maintaining ecosystem quality.[185]

Factors such as weather, water and nutrient levels, and presence of pests can all influence manoomin abundance, and may contribute to substantial year-to-year variability in abundance.[3] But climate change may be one of the biggest threats to manoomin because of changing water levels, warmer air temperatures, and increase impact of invasive species.[182] Surveys from the early 1900s show that some areas of the Great Lakes produced 200 pounds of rice per family, which was enough to sustain them through the long winter. However, due to today's lower abundance of this important species, families are

Photo: Manoomin seeding efforts in the St. Louis River Estuary, WI by Matt Steiger, WDNR only able to harvest 80 pounds or less.[186]

Manoomin is an annual plant that grows in shallow waters of lakes, streams, and rivers, and it grows best in places with some moving water.[3,177] The plant has three life stages: a submergent stage, where the plant develops under the water; a floating leaf stage, where one or two leaves float on the water's surface; and an emergent stage where the plant grows out of the water.[3] In Wisconsin, manoomin is found primarily in the northern third of the state.[3,182]

Manoomin may be a highly vulnerable species because there are potential climate effects in each stage of its life cycle.[3] For example, manoomin is adapted to annual water level fluctuations, and depends on some level of fluctuations, but multiple years of low or high water level from extended periods of wet or try years can prevent it from growing in a given location.[3] Low Lake Superior water levels in 2007 and resulting manoomin crop reductions forced the Bad River Band of the Lake Superior Tribe of Chippewa to cancel its annual manoomin harvest, and a 2012 flood caused near total wild rice crop failure on the Fond du Lac Reservation.[181] Manoomin is sensitive to extreme high water levels during the floating leaf stage,[182] which can drown or uproot the plant before seeds are able to develop.[3,184]

Manoomin is also sensitive to temperatures[3] and adapted to cold conditions in northern Wisconsin.[182] Lower ice cover conditions and warming winters within the Great Lakes basin will likely have negative impacts on manoomin in the future, and warmer winters are associated with lower seed germination rates in the spring.[3] Manoomin depends on ice cover during winter to create low oxygen conditions that help seeds emerge from dormancy in the spring, and thicker and longer-lasting ice prevents other species from outcompeting manoomin.[3] Warmer temperatures can also create conditions for disease (e.g. brown spot disease) and invasive species (e.g. common carp and rice worms) that can negatively impact manoomin populations in Wisconsin and throughout the rest of the Ceded Territories.[3] The unusually warm years of 2005 and 2010 affected the manoomin harvest because of disease.[182,184]

Manoomin has been listed as highly to extremely vulnerable to climate change because of changes in water levels, stronger and more frequent storm events, and pollution.[3,161] GLIFWC's abundance data show observed reductions that are consistent with expected climate effects.[3]

Projections of future climate change show that warming could lead to a shift of wild rice outside of the Great Lakes region.[185]

More manoomin information:

- Manoomin: Food That Grows on the Water Video
- First, We Should Consider Manoomin (Wild Rice) Video
- GLIFWC's manoomin Information Page
- Manoomin-Wild Rice: The Good Berry Brochure
- Wild Rice: Ecology, Harvest, Management Brochure
- Gikinoo'wizhiwe Onji Waaban (Guiding for Tomorrow) "G-WOW" Changing Climate, Changing Culture Resource
- Lake Superior Manoomin Cultural and Ecosystem Characterization Study, Final Report
- Restoring Wild Rice in the St. Louis River Estuary Video
- University of Wisconsin Sea Grant Resources

Tribal gathering rights are restricted to lands ceded in treaties, which are already at the southern edge of the species' range, meaning that any northward range shifts will greatly impact tribal members in Wisconsin.[182]

Social and economic implications of impacts on species

Climate-induced changes to Great Lakes physical characteristics, water temperature patterns, and water quality all interact to affect species in the Great Lakes basin, with impacts on recreation, cultural, aesthetic, and identity-based values in addition to commercial fisheries and the tourism industry. The water in the Great Lakes basin is key to the traditional Anishinaabe creation and migration story, where the Creator instructed the Anishinaabeg to find "the place where food grows on water" in reference to the manoomin (wild rice) prevalent in the basin.[187] The six Ojibwe tribes in Wisconsin are successors in interest to the Ojibwe bands that negotiated the treaties of 1836, 1837, 1842, and 1854.[188] In all of those treaties, the Ojibwe reserved their pre-existing rights to hunt, fish, and gather in the lands and waters that were ceded to the United States government.[188] Further, the Red Cliff and Bad River Bands have the right to continue commercial and subsistence fishing in Lake Superior.[189] Ojibwe ways of life, guaranteed by treaty rights, related to numerous species are threatened by climate change, as species ranges (including many fish species and manoomin) may shift out of their Ceded Territory or go extinct.[3] Almost all Great Lakes fisheries depend on coastal wetlands for supporting fish populations at various life stages.[190] The high bird diversity and abundance at healthy coastal wetland sites across the Great Lakes provides a major benefit through direct recreation opportunities and increased tourism dollars in the region.[190] Direct use of Wisconsin's fisheries (sport and commercial) is over 150 million dollars per year, and the indirect value and cultural value to Indigenous groups is much more.[122]

Species management to address social and economic impacts need to work across diverse stakeholder groups and connect and empower community organizations and Anishinaabe community leaders.[191] Great Lakes fisheries management requires understanding the fish population dynamics and angler behavior in addition to influences of one fishery on another.[192] Species-specific recreation management (e.g., birding, wildlife viewing) should consider both the direct value of the recreation industries and the indirect relational value that recreationists hold.[193] For example, species-based recreationists may hold protection of those species as a moral responsibility and as part of their own identity.[193] The future of Great Lakes species and communities of people (residents, business owners, recreationists, etc.) are interlinked, requiring holistic management.[194]

Protecting the Lake Superior Watershed: A stormwater story

Contributed by Megan Högfeldt, Water Resources Specialist, City of Superior. St. Louis River Estuary —Effective management of stormwater reduces flooding and fosters resilient ecosystems for many species to thrive.

THE SETTING: The St. Louis River runs between the cities of Duluth and Superior opening into Lake Superior, creating one of the largest freshwater estuaries in the Great Lakes—The seven streams flowing through the landscape offer reactional opportunities for residents and tourists. The area contains the Superior Municipal Forest—4,400 acres of boreal forest—the third-largest city forest in the US. This area has a unique overlapping zone between Canadian and southern boreal forest types where diversity of tree species is high! Wild rice grows in Pokegama Bay that feeds Pokegama River into the St. Louis Estuary and Allouez Bay, a coastal wetland located on the inland side of Wisconsin Point.

CLIMATE CHALLENGE: The naturally wet soils here, combined with the seven streams that run through the landscape, make the area prone to flooding. Since 2012, frequent high flow (rainstorms) events have damaged streets, culverts, ditches, and underground pipes. The storm runoff introduces sediments and pollutants into the estuary system.

WHAT IS BEING DONE: Given the legacy wastewater infrastructure in Superior of combined sewer conveyance systems, the city is gradually implementing separated stormwater conveyance systems that direct stormwater flow to constructed wetlands. This decreases the amount of water flowing to the waste water treatment plant during storm events, reducing the chance of treatment plant overflow, deterring untreated wastewater from entering Lake Superior, reducing sewer backups in homes and businesses, and minimizing flooding.

- Stormwater is directed to the Poplar Wetland Basin, Billings Park Stormwater Basin, or South End Stormwater Basin
- These basins provide environmental and social benefits: Poplar Wetland Basin has plants and designs to create a park-like setting for public use in an urban setting; the wetlands provide homes for hundreds of animals, insects, and plants
- Another constructed wetland is being built on Barker's Island to increase stormwater infiltration and settling
- Wet ponds and dry ponds: Wet ponds are simply intended to capture runoff and let its sediments settle out while the water remains in the pond. Dry ponds are designed to hold water during high-flow events temporarily and then dry up afterward

Before COVID restrictions, Poplar Wetland Basin Tours were available for the public and students. Hopefully, these events will resume in the near future.

Constructed wetland basins described above are intended to create a more natural treatment system for SW. While these can vary significantly in design, they can use engineered media and designed channels and slow flow areas that help treat stormwater.

Poplar Wetland Basin, CREDIT: City of Superior

Learn more about this work here and see a virtual tour of the Poplar Wetland Basin

Photo: Red Superior, 2016 Great Lakes Photo Contest, cultural category by Brian Wolf

7. Climate Change Interactions

Impacts of climate change in the Great Lakes occur alongside multiple stressors, such as pollution, nutrient and sediment increases from land-use change, invasive species, and other human influences. Separating these issues from one another is difficult, and many have an additive or even multiplicative effect on one another.

Land-use Change & Habitat Loss

Land-use change in the basin may exacerbate habitat loss due to climate change. Habitat destruction – including dams, natural resource extraction, loss of coastal wetlands, and hardening shorelines – in the Great Lakes has a major impact on fish species.[43] The basin is projected to see large increases in both urbanized areas and agricultural areas, likely resulting in increases in nutrient loading to the lakes by the mid-21st century.[195] Increases in urbanization along the coasts creates additional conflict as it relates to infrastructure management during high and low water levels. Infrastructure protection and shoreline hardening projects often cause degraded shoreline and nearshore habitat.

Land-use Change & Nutrient Runoff

Many impacts of climate change alone (e.g harmful algal blooms, changes in primary productivity, reductions in water quality, etc.) can be exacerbated by, and in turn exacerbate, the impacts of nutrient runoff in the Great Lakes basin. For example, significant degradation of the Green Bay ecosystem has resulted as a product of extensive agricultural runoff into the Fox River and bay of Green Bay.[115] Climate change-induced increases in precipitation can increase nutrient runoff, further harming water quality. These precipitation events and longer growing seasons can offset water quality improvements made through implementation of agricultural best management practices. Warming air temperatures may also exacerbate impacts of nutrient loading to water because warming conditions combined with increased nutrient availability leads to increased likelihood of phytoplankton blooms and preference for toxin-producing species.[106] Over the last four decades, the few large lakes across the globe that have seen decreases in bloom severity were those that warmed less than other lakes, suggesting that lake warming may also be counteracting nutrient management efforts in lakes experiencing worsening bloom conditions.[106] The influence of nutrient runoff and climate change as exacerbating issues may be very important in the case of Green Bay, where nutrient runoff, increasing water temperatures, and altered mixing regimes may make the Green Bay "dead zone" worse in coming years.

Invasive species impacts may amplify climate impacts

Though invasive species spread and infestation may be facilitated by climate change itself, as discussed in the invasive species subsection of Chapter 6 Impacts on Species, here we consider the interacting ecosystem consequences of invasive species-induced impacts and climate change-induced impacts.

Photo: A Paddle on Riebolts Creek, 2016 Great Lakes Photo Contest, by Chuck Germain

Invasive species have had a major impact on the Great Lakes ecosystem, and these changes can be amplified by climate changes. For example, sea lamprey and alewives had major negative impacts on the Great Lakes fishery.[43] Warmer water with climate changes allows for greater growth of invasives and allows for increased spread to new areas. Dreissenid mussel (zebra and quagga mussels) colonization in the Great Lakes has greatly altered fate and transport of nutrients in the lakes.[43] Dreissenid's ability to sequester nutrients and primary production in nearshore benthic environments prevents nutrients from being used by higher trophic levels in offshore areas.[196,197] These changes can disrupt aquatic food webs, making it more likely that food sources will be unable to meet increased growth of offshore fish species. Additionally, selective filtration by Dreissenid mussels promotes toxic, harmful algal blooms (HABs),[198] which could exacerbate the climate-induced increases in HAB formation. The interactive effects of nutrient loading, invasive mussels, and climate change may be one of the biggest impacts on the Great Lakes.[199]

Contamination

Toxic pollution from industry is a major issue across the Great Lakes, but specifically in Areas of Concern. Wisconsin has four Areas of Concern – one on Lake Superior and three on Lake Michigan – with all four having significant impacts from sediments contaminated with legacy pollutants. One unknown is the impact that climate change could have on contaminated sediments in the environment. Increases in precipitation could alter flow and hydrology in such a way that sediment resuspension into the water column could increase or increased flow could bring in contaminated sediments from higher in the watershed to new areas along the Great Lakes nearshore.[200] This is especially problematic in areas such as Sheboygan, Green Bay, and Milwaukee which have high populations of Hmong subsistence anglers who are already at risk of high contaminant burdens.[201]

Climate migration

Tribes in Wisconsin reserved the rights to fish, hunt, and gather in off-reservation areas.[188] These place-based rights may become geographically mismatched with species distributions, as in the case of potential manoomin and fish species range shifts due to climate change.[181] Historically, tribes were able to adapt to changes in water resources and movement of species through traditional migration practices but current treaties and court decisions restrict these practices to the geographic region of the Ceded Territories. This can limit tribal abilities to adapt to climate change and maintain their cultural and spiritual practices and food sources if tribal members are unable to access important species as they shift northward outside the bounds of the Ceded Territories.[181]

Migration may also become an issue as people move from areas with greater climate risk and impact on the Great Lakes.[202] Increased population and strain in resources could amplify climate impacts. For example, larger populations coming to the Great Lakes could increase urban sprawl, changing forests and wetlands to suburban or urban land uses, increasing runoff into the lakes and reducing water quality.

Nothing gets your attention better than Mother Nature nearly killing you: A climate change story only slightly longer than this title

Contributed by Andrew Teal, Town of Barnes AIS Committee.

U.S. Highway 63 northbound, at the Twentymile Creek road/stream crossing, July 11, 2016 — In 2016 I had few demands on my personal time, so I would meet volunteers just about whenever and wherever they needed me. Nights, weekends, the other end of the county, whatever. Well, I was returning home from a Town of Barnes AIS Committee meeting in Barnes, and passed through Grand View at about 8:45 p.m. That was the approximate halfway point between the Barnes Town Hall and my apartment. The torrential rain had been falling for at least two hours at this point, so even in that relatively sandy area, the water had begun to rise, and road visibility was diminished. Every few seconds I heard the whooshing of the tires ever-so-briefly hydroplaning on that leg of the drive. Passing over what I would later discover was the Twentymile Creek stream crossing, I saw too late that water had begun to pool in the northbound lane. With no time to react, I hit the water at speed. Fortunately, my Pontiac Grand Am did not stall, despite the rapid deceleration and the no-doubt enormous wave that it generated. I kept a close eye out after that, but not even Bibon Swamp had water over the road during the remainder of the drive home.

The next day, news stories, town road maintenance personnel reports, and social media posts poured in. That's when I saw photos of the exposed concrete box culvert and fifty-foot vertical drop between it and the surface of U.S. Highway 63. That's when I heard about the Sheriff's deputy that had to radio for help halfway through his shift, escape his patrol vehicle in a flood, and cling to a tree for hours before being rescued. Both of those events happened in the same place I hit the pool of water mere hours earlier. Questions swirled through my mind like the floodwaters around the road I nearly witnessed blowing out. What if I had driven through there even an hour later and the washout had already occurred? Would I have been able to stop in time, or would I have fallen through the road? If I did fall, would I have been as lucky as that Sheriff's deputy, clinging to a tree until help arrived? Or would my car have turned into a four-wheeled casket and floated me off to the hereafter? People might think my recounting of this story is overblown, but I remind them that people died because of that storm. For everyone else, the Northland was essentially closed and cut off from the rest of the region due to the number of roads that got damaged or flooded.

CLIMATE CHALLENGE: Infrastructure resiliency and wetland restoration (among other ideas) are now hot topics of conversation and funding up here because of the 2016 and 2018 floods. Much of the infrastructure that was damaged or destroyed during those floods has since been rebuilt. Many of the affected communities operated on budgets that could not handle the necessary repairs though, so the disaster declaration that was finally issued was critical to moving forward with the process. This is still true to some extent, both regarding the budgets and the need for disaster declarations to obtain needed funding for repairs. It would be helpful to have larger pots of money available before disaster strikes, without too much bureaucracy attached, so communities can restore wetlands on their properties and appropriately upsize culverts to handle more intense storms and heavier precipitation events. Paying a little for it now so we can properly prepare makes far more sense than paying a lot later to repair the damage, on top of the economic loss due to road closures and resulting environmental damage from washouts.

EQUITY AND JUSTICE: Underserved and rural communities are often limited by lower tax base and revenue in preparing for climate disasters. When disaster strikes, if the affected area is not damaged enough to qualify for disaster aid and has to pay out of pocket, (or it does qualify, and the local/county government has to cover a percentage), this can leave communities hurting for funds to prepare for the next disaster.

Photo: Cave Point Sunrise, 2016 Great Lakes Photo Contest, natural category by Karen Alesch

8. Solutions

Addressing ongoing climate change requires diverse adaptive management approaches to develop and implement resilient and sustainable strategies. Management approaches generally fall into four categories: actions that resist change, actions that build resilience, actions that facilitate change, and (often non-) actions that accept change:[52,203,204]

Resisting change. these adaptation actions work to armor against negative consequences of climate changes and attempts to maintain historical conditions. Resistance actions may be effective in the short-term, but might not be feasible over the long term as they will require greater resources and effort.[204] These options may be most appropriate for ecosystems with low sensitivity to change or those that have high economic, cultural, or ecological value.

Building resilience. these adaptation actions reduce stress, minimize vulnerability in the system, and promote return of normal or historic functions to systems after disturbances. These actions might be most effective in areas that already tolerate a wide range of conditions.[204]

Facilitating change. these adaptation actions direct, facilitate, or accommodate ecosystem change through active measures to move toward a desired new condition. These actions are long-term solutions where resistance or resilience is not feasible.

Accepting change. this adaptation concept includes accepting changes that will happen and choosing to not intervene or alter the outcomes of climate changes.

Within these concepts, adaptation actions can take a variety of approaches including communication and outreach, changing policy or regulation, and implementing practices on the ground. From the literature and professional judgement, the working group has developed the following list of climate adaptation actions for Wisconsin's Great Lakes ecosystem. Some actions can fall into multiple categories, so may be listed more than once.

Actions that resist change

Habitat protection and management

* Prioritize and maintain sensitive or at-risk species and habitats
* Maintain or create refugia habitats
* Protect remaining populations of wild rice
* Wetland protection and restoration — *See Solutions Case Study 2 on Page 53 and Solutions Case Study 3 on Page 57 for example*
* Increase and/or reconnect floodplain habitat to streams and rivers — *See Solutions Case Study 3 on Page 57 for example*
* Enhance fish habitat by creating off-channel or wetland fed streams that provide higher water flows and lower temperatures during the summer
* Implement spawning habitat improvement projects for fish
* Protect watershed landcover types that facilitate high groundwater recharge
* Reduce fragmentation to promote

Photo: Prevailing Waters, 2016 Great Lakes Photo Contest, natural category by Shelby Chmielewski continuous natural ecosystems

* Restore native vegetation — *See Solutions Case Study 2 on Page 53 for example*
* Strategically acquire lands to connect key habitats and protected areas
* Establish ecological buffer zones around natural features

Increase invasive species control efforts

* Target invasive species control efforts to high priority areas
* Increase invasive species control efforts
* Continue invasive species management and monitoring

Protect water quality

* Advocate for and enforce water quality standards that are protective of wild rice
* Incentivize nutrient runoff reductions in the watershed
* Implementation of TMDL programs
* Enhance or restore riparian vegetation
* Implement slow the flow and structural storage capacity projects to protect against extreme runoff events — *See Solutions Case Study 1 on Page 51 for example*

Photo: Nature Preserve, 2017 Great Lakes Photo Contest, cultural and historical features category by Katherine Murray

* Stabilize stream banks
* Limit soil erosion
* Maintain soil quality and nutrient cycling in soil

Actions that build resilience

Protect water quality

* Wetland protection and restoration
* Increase implementation of green infrastructure practices — *See Solutions Case Study 2 on Page 53 for example*
* Incentivize nutrient runoff reductions in the watershed
* Implementation of TMDL programs
* Enhance or restore riparian vegetation
* Implement slow the flow and structural storage capacity projects to protect against extreme runoff events — *See Solutions Case Study 1 on Page 51 for example*

Habitat and infrastructure protection and management

* Promote sustainable wild rice management techniques
* Adopt and enforce more protective shoreland and floodplain zoning ordinances (e.g., structure set-backs farther from water's edge and no structures in floodplains)
* Increase and/or reconnect floodplain habitat to streams and rivers, focused upstream of at-risk infrastructure — *See Solutions Case Study 3 on Page 57 for example*
* Education and outreach about importance of critical habitat and species in Wisconsin's Great Lakes and the Great Lakes coastlines
* Wetland protection and restoration
* Restore native vegetation

- Encourage native shoreline vegetation in new areas to increase water retention, dissipate wave energy, and reduce erosion
- Use wind-resistant vegetation to minimize blow-downs and erosion along coastal shorelines

Prevent introduction of invasive species

- Education and outreach on invasive species control and prevention efforts
- Improved or increased ballast water treatment
- Fish passage barriers

Reduce non-climate stressors

- Reduce pollution
- Reduce fishing pressure
- Sustainably manage fish harvest
- Increase tree canopy shading around rivers and streams to keep water cool as long as possible
- Enhance the ability of the ecosystem to retain water on the landscape

Actions that facilitate change

Facilitate species transitions

- Introduce species that are likely to be more adapted to future conditions
- Evaluate fish stocking programs with a climate lens and stock species and genetic strains that may be more climate adapted.
- Plant seeds or seedlings originating from seed zones that resemble the expected future conditions of the planting site and/or are better adapted to a warming climate and can maintain a more resilient habitat
- Conserve and restore ecological connections to facilitate migrations and other transitions caused by climate change
- Maintain and enhance connectivity in aquatic and terrestrial ecosystems for the purpose of species migration

Actions that accept outcomes

Maintain ecosystem services through managed efforts

- Maintain beach usage through enclosed swimming areas
- Increase stocking of fish species that may not be well-adapted to change
- Implement beach grooming practices to reduce pathogen contamination at beaches

Monitor impact of climate change, but do not direct change

- Establish monitoring programs

Great Lakes Region Adaptation Resources

Climate Change Vulnerability Assessment and Adaptation Plan: 1854 Ceded Territory Including the Bois Forte, Fond du Lac, and Grand Portage Reservations

Resist-Accept-Direct framework

NIACS adaptation workbook

A Tribal Climate Adaptation Menu

Freshwater Coast Adaptation Menu

Climate Vulnerability Assessment for Great lakes Shorelines

Watershed-based Midwest Climate Vulnerability Assessment Tool

Spur Lake State Natural Area adaptation planning demonstration project

Restoring Wild Rice in the St. Louis River Estuary

Solutions Case Study 1: Example actions to increase resilience and resist change with Slow the Flow approaches

Review and Recommendations for Slow the Flow Practices in **Wisconsin's Lake Superior Basin**

Contributors: Michele Wheeler[1], Molly Wick[1,2,3], Tom Hollenhorst[2], Ellen Cooney[1], Jason Fischbach[4], Nichol Marten[1], Tom Bernthal[1], Karen Gran[3]

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The precipitation regime for the Mid-West of the United States of America is anticipated to change as climate change effects take place, altering the delivery of nutrients and sediments from watersheds to lake systems. Since 1991 the average annual precipitation for the Mid-West has increased by approximately 9% when compared to a baseline average (1901-1960).[205] Most of the United States has also experienced an increase in intensity and frequency of heavy precipitation events.[205-207] Lake systems depend on nutrients, carbon and sediments from the landscape to maintain their ecosystem. Runoff from rivers, overland flow and bank erosion are the conduits for how nutrients, carbon, and sediments enter a lake system. Changes in hydrology influence sediment delivery, with corresponding effects on water quality, instream and riparian habitat and biotic composition,[208,209] the overall impact these changes will have on a system are not well understood. We have experienced changes in the nearshore of Lake Superior with the occurrence of algal blooms starting in 2012, which may be linked to nutrients bound to sediments that are entering the lake system at a larger amount that previously experienced. These blooms also seem to be associated with extreme rain events.[48]

Agencies in Wisconsin's Lake Superior basin began conservation efforts to improve watershed quality over 60 years ago. These efforts have focused on restoring and protecting hydrology of the area **using the "Slow the Flow" technique**. The Slow the Flow approach seeks to reduce peak flows of rivers and streams by using landscape-scale watershed restoration approaches that increase in-channel roughness, upland roughness, upland retention, and infiltration. Recent strategic Slow the Flow efforts have sought to improve implementation of Slow the Flow across jurisdictions, agencies, land use, and land ownership and to identify and priorities for conservation efforts across the basin.

The variety of different interests, landowners, and land uses makes realistic regional watershed-planning for both public and private lands challenging. Therefore, a strategic and targeted watershed approach is recommended to effectively reduce the accelerated runoff and corresponding habitat and water quality problems experienced in the Lake Superior clay plain region.

Solutions Case Study 1: Example actions to increase resilience and resist change with Slow the Flow approaches

Summary of recommended parameters to consider for prioritization of Slow the Flow effort locations in the Lake Superior Basin. Parameters are listed in three groups: primary metrics can be used to identify priority subwatersheds. Within those priority subwatersheds, they can be ranked further by using secondary ranking criteria. Tertiary considerations may help narrow priorities further based on land use type considerations.

Primary metrics

* Percent storage by subwatershed
* Percent wetland are lost by subwatershed (potentially restorable wetlands)
* Peak discharge/subwatershed ratio
* Percent open lands by subwatershed

Secondary ranking metrics

* Percent of wetland area with surface water attenuation by subwatershed OR percent of total wetland area with surface water attenuation function
* Proportion of riparian area not mapped as wetland by subwatershed
* Proportion of forest by subwatershed

Tertiary considerations

* Inactive farmland
* Transitional Zone and soil permeability
* Downstream coastal ecosystem/ habitat type

What does "slow the flow" mean?

Vegetation and wetlands slow the flow of water across the land, increasing infiltration and evaporation, decreasing runoff volume

Paved surfaces and drained land quickens water flow across the land, decreasing infiltration and evaporation, increasing runoff volume and erosion potential of flow

Incorporation of natural features in developed areas SLOWS THE FLOW of water, increasing infiltration and evaporation, decreasing the volume of runoff and erosion potential

Diagram credit: SlowTheFlow.net, General principles of urban SuDS (Sustainable Drainage Systems)

Solutions Case Study 2: Example actions to increase resilience and resist change with Green and Grey infrastructure

Coastal Resiliency: Actualizing Co-benefits through Incorporation of Nature-based Solutions

Contributors: Julie Kinzelman and Adrian Koski, City of Racine

Background

In response to intensifying climate change threats to the Great Lakes region, coastal communities are working to increase coastal resilience,[210] or the capacity for interlinked coastal physical, ecological, and social systems to withstand and recover from disturbances.[211] Globally, efforts to increase coastal resilience commonly include governance and community-based approaches, environmental vulnerability assessments, education and communication.[210,212-214] Even with ongoing efforts to increase resiliency, coastal communities remain vulnerable to extreme climate events, as evidenced by recurring major storm and flood damage.[215] However, one key component to resilient coastlines is the integration of classic engineering approaches with nature-**based solutions, or "green"** infrastructure.[216,217] Incorporating well-designed green infrastructure produces co-benefits where both ecosystem functions and social benefits are improved, fostering interlinked physical, ecological, and social resiliency.[217,218]

The Samuel Myers Restoration Project combined green (nature based) and grey (human-made structure based) mitigation measures to improve coastal resiliency, by enhancing both ecosystem function (e.g., the capacity of the ecosystem to adequately accommodate large volumes of precipitation and remove nutrients associated with runoff and recreation opportunities (e.g., swimming and birding).

Photo: Samuel Myers Park—Restored Coastal Wetlands and Dunes, 2017 Great Lakes Photo Contest, stewardship category by Julie Kinzelman

Solutions Case Study 2: Example actions to increase resilience and resist change with Green and Grey infrastructure

Samuel Myers Park

Samuel Myers Park is located on the Lake Michigan shore in Racine, WI. In the 1930's, the area that would become Samuel Myers Park was Lake Michigan water within a series of rubble mound breakwater structures. The middle breakwater structure was connected to land in the 1970's to create a protected small craft boat launch. Two key legacies of this history: prior to 2015, 1) the low-profile breakwater was frequently overtopped due to climate-change induced storm surges, and 2) the accreted sand and sediment that formed the shoreline of Samuel Myers Park lacked elevational gradient to effectively transport water across the site (e.g., stormwater runoff), contributing to water quality impairment, and creating favorable conditions for invasive species to persist.

Photo: Samuel Myers Park—Swim Ban from the 1990's to 2016. By Julie Kinzelman

From the 1990's to the start of the Samuel Myers restoration in 2014, the park was providing ecosystem *dis*services, which negatively affect human well-being.[219] A permanent swim ban was instated at the park in the 1990's because of poor recreational water quality. This ban was revisited in 2007 but remained in place due to persistent poor water quality conditions. Additionally, the original small boat launch was no longer useable as the water's edge had receded with accreted sediments and falling lake levels (2011—2013). Much of the shoreline area of the park was heavily invested with Phragmites and black locust, invasive species that exacerbate hydrologic issues and nutrient pollution transport.[220]

Solutions Case Study 2: Example actions to increase resilience and resist change with Green and Grey infrastructure

Restoration Project Approach

Restoring Samuel Myers Park provided ecosystem services such as recreation, habitat, and storm water management rather than the *dis*services of degraded water quality, prolific invasive species (e.g., Phragmites), and poor stormwater drainage. The collaborative approach to restoration included an intensive pre-restoration study, development of a conceptual plan, construction, and monitoring (Table 1).

The restoration of Samuel Myers Park established connected green infrastructure around the park, including two engineered wetlands with native vegetation, a dry prairie, a rain garden, bioswales, a wet meadow, numerous stormwater trees, and dune features.

These green infrastructure features were embedded within modifications to grey infrastructure, including parking lot and access drive drainage modifications and increasing the height of the breakwater. The restoration project increased carbon sequestration and stormwater infiltration

Table 1. Samuel Myers Park Restoration approach components and outcomes

Component	Details	Outcome
Cooperative project	Government and non-profit partners: Multiple City of Racine departments, the Root-Pike Watershed Initiative Network, Friends of Myers Park, Lakeside Curative Services, the Great Lake Community Conservation Corps, Americorps NCCC, the Ozaukee Washington Land Trust, community organization volunteers	Build on resources of multiple groups, access diverse funding sources, foster desired outcomes for different stakeholders
Pre-restoration study	4-year intensive study: using US EPA Beach Sanitary Survey Tool; stormwater outfall assessments, mapping, water quality monitoring, hydrodynamic studies, wetland delineation, vegetation survey, archaeological investigation	Identify primary environmental & social concerns: water pooling on shore, then transferring bird fecal matter and other debris to surface water; Phragmites infestation; stagnation along breakwater; lack of public access and amenities
Develop Conceptual Plan	with Miller Engineers and Scientists (Sheboygan, WI)	Plan to address impairments to water quality and storm water management issues, manage invasive species, create habitat for migratory birds, promote better uptake of nutrients on park land, create public access
11-phase plan	Conceptual plan divided into 11 phases of construction to facilitate funding while incrementally adding environmental and social benefits	Smaller, easier to achieve phases enabled use of diverse funding sources and incremental improvements
Restoration Implementation & Construction	3 yrs of construction (2014 – 2017)	increased breakwater height; native vegetation, canoe launch, ADA compliant paths, gazebo & benches, educational signage, pollinator gardens, re-grading, bioswales, rain gardens, dunes, constructed wetlands

Solutions Case Study 2: Example actions to increase resilience and resist change with Green and Grey infrastructure

on the property (via newly planted and growing trees), increased sightings of migratory bird species in addition to fish, reptiles, amphibians, and mammals. From a public use perspective, the most notable improvement post-restoration was the removal of the swim ban in 2017 and establishment of an offshore swimming area for use by boaters.

Looking ahead

This project has been largely successful thus far, particularly for prompting the removal of the decades long swim ban. However, the continued threat of climate change-induced changes to lake water levels and more frequent and intense storms are a continued threat. In fact, a Jan 10 – 12, 2020 storm event occurring under near historic high-water levels, damaged portions of green and grey infrastructure in the park. The storm breached a revetment north of the park, causing greater surface flow than the capacity the park was designed to withstand. Project managers are taking an adaptive management approach to the problem and will be working on creating greater resilience to coastal storms and erosion throughout the park. The capacity of the green infrastructure is anticipated to meet climate change projections.

The Samuel Myers Park project provides an ongoing example of how to increase coastal resilience by integrating environmental and social benefits in restoration and highlights the importance of an adaptive management approach in the face of climate change uncertainty.

Photo: Samuel Myers Park—Sand Prairie in Bloom, 2017 Great Lakes Photo Contest, natural category by Julie Kinzelman

Solutions Case Study 3: Example actions to increase resilience and resist change with Natural Flood Management

Adapting to Climate Change with Natural Flood Management in the Lake Superior Basin

Contributors: Jennifer Western Hauser; Kyle Magyera, Wisconsin Wetlands Association

Overview

Watersheds within Ashland County have been the subject of many studies related to natural geology and hydrologic features, land use alterations, and problems like flooding, erosion, and water quality concerns. Climate change, with more frequent and extreme precipitation events, is making these problems more urgent.

Ashland County is at the forefront of a collaborative effort to integrate natural flood management (NFM) into strategies to build a more climate-resilient landscape. NFM emphasizes strategic hydrologic restoration practices within a catchment area to restore the landscape's natural ability to capture, infiltrate, and slowly release runoff. It often focuses on restoring upper watershed wetlands and reconnecting floodplains to reestablish natural functions, like water storage and slowing flow to reduce downstream erosion and infrastructure failures.

> Natural flood management (NFM) emphasizes work along stream reaches, in multiple locations and with multiple landowners, to help restore more natural hydrologic conditions in the catchment
>
> Recovering hydrologic processes on reach scales allows the landscape to transition to handle and cope with the unpredictable or varying hydrologic conditions expected to be amplified by climate change
>
> NFM practices in the upper watershed that repair wetland drainage and increase floodplain connectivity can improve the landscape's ability to endure and recover after extreme precipitation

The current project in Ashland County seeks to gather data on degraded conditions and prioritize where NFM projects such as headwater wetland restoration and floodplain reconnection can occur upstream of at-risk infrastructure. The effort received a first-of-its-kind Pre-Disaster Mitigation Grant from FEMA, an appropriation from the State of Wisconsin to construct NFM demonstration projects (2019 Act 157) and has attracted other investments to support integrating NFM into local climate adaptation strategies. The collaboration is led by Ashland County, with the Wisconsin Wetlands Association as project manager and technical advisor, and the assistance and support of many state and federal agencies listed in the Consultation Section of this brief.

Solutions Case Study 3: Example actions to increase resilience and resist change with Natural Flood Management

Issue

The hydrologic and geologic characteristics of Ashland County watersheds, such as the steep terrain and highly erodible soils, make the area naturally prone to flashy flows and erosion. Over time, altered hydrology from urbanization, logging, conversion to agriculture, and undersized road-stream crossings have compounded water flow challenges. An increase in extreme rainfall events, expected with climate change, is making these issues more urgent for local governments. While there are many challenges associated with these issues, the focus of the initiative in Ashland County is cost-effectively mitigating risks to public infrastructure like roads, culverts, and bridges. To tackle this issue, Ashland County is focusing on strategic NFM practices that restore upper watershed wetlands and floodplains to mitigate damage to downstream infrastructure.

Ashland County has plentiful upper watershed wetlands, but many are degraded by incising streams, gullies, ditches, and eroding ravines that compromise their ability to capture water. These conditions exacerbate flooding and can cause wetlands to dry or convert to uplands as they get cut off from their water source. Floodplain disconnection further increases the velocity and energy of flows, sending debris and sediment downstream to vulnerable culverts.

The collaboration in Ashland County successfully pursued a first-of-its-kind FEMA grant for the project, *Rebuilding Natural Infrastructure in Ashland County*. This joint project explores how degraded upstream conditions can amplify damage to downstream transportation infrastructure and prioritizes restoration opportunities. As part of this grant, Ashland County is:

* Identifying vulnerable public infrastructure and upstream erosion hazards using FEMA-approved methods for assessing flood risk factors.
* Identifying and prioritizing upper watershed wetland and floodplain restoration opportunities using FEMA-approved cost-benefit analysis.
* Updating Ashland County's Hazard Mitigation Plan to include wetland and floodplain restoration strategies for building resilience.

Building upon this initiative, the State of Wisconsin appropriated $150,000 toward the construction of up to three NFM demonstration projects (2019 Act 157). State agencies like the Wisconsin Department of Natural Resources and Wisconsin Emergency Management will be involved in summarizing the results of the demonstration projects and suggesting recommendations on policy changes and funding streams to create incentives to protect and restore natural

Solutions Case Study 3: Example actions to increase resilience and resist change with Natural Flood Management

infrastructure and reduce floods. The data being collected through these initiatives gives Ashland County a wealth of opportunities to pursue NFM restoration practices to build resilience and set an example for other flood-prone communities.

Why is this a concern

Climate change is exposing vulnerabilities that have long existed and worsened since the late 1800s. Like many areas of Wisconsin, Ashland County is facing the difficult task of protecting public safety, transportation infrastructure, businesses, homes, and farms from frequent and occasionally catastrophic floods. From an economic perspective, flooding has the potential to devastate local government budgets and the local economy. Extreme flooding also causes untold ecological damage by wiping out fish & wildlife habitat, accelerating erosion, and sending sediment to Lake Superior. These effects are compelling local governments to explore and integrate untapped strategies and approaches like NFM.

Strategy

NFM to address flooding and provide added benefits - As a climate adaptation tool, NFM can help reduce damages to downstream infrastructure, as demonstrated in Ashland County. These same strategies yield additional benefits like preserving cold-water trout fisheries, maintaining high-quality fish and wildlife habitat, improving water quality, and arresting erosion on agricultural lands—all threats associated with climate change.

Program evaluation - For NFM to become part of the regular mix of climate adaptation strategies in Wisconsin communities, we need to align and expand our federal, state, and local programs to encourage the assessment and restoration of upper watershed wetlands and floodplains. State agencies with programming that touches this area include the Division of Emergency Management within the Department of Military Affairs, Department of Agriculture, Trade and Consumer Protection, Department of Natural Resources, Department of Transportation, and Department of Administration.

Photo: Bluff failure on the Brunsweiler River caused by an extreme storm event in 2016 and altered hydrology in the upper watershed. By WI Wetlands Association, Kyle Magyera

Solutions Case Study 3: Example actions to increase resilience and resist change with Natural Flood Management

More demonstration and pilot projects – More NFM demonstration projects help communities observe the process of building a partnership, identifying similar problems, and possible pathways to NFM solutions. Doing this work requires partners to collaborate with local, state, and federal agencies, and identify sources of support to fund projects. Beyond this, demonstration projects also serve to help communities visualize what NFM practices look like on the ground and the project costs and benefits, which can be useful for other communities in FEMA grant applications or FEMA's benefit-cost analysis toolkit.

Hazard mitigation plans – State and federal programs should support hazard mitigation planning efforts by local communities affected by repetitive or catastrophic flooding and grow the base of knowledge about NFM as a strategy to address flooding and improve hydrologic health. Communities that undertake this thorough and comprehensive process should receive cost-sharing and technical support for implementing the disaster recovery and flood risk reduction strategies identified in these plans.

Hydrologic assessment data - To improve understanding of how water moves across the landscape, Wisconsin needs investments in statewide LiDAR data completed according to the USGS 3DEP standards and hydro-conditioned digital elevation models derived from 3DEP LiDAR. These baseline data can improve flood elevation models (i.e., HEC-RAS, HAZUS, etc.) to help planners and engineers determine the sizing of culverts,

Photo: USGS completing a geomorphic assessment that will help Ashland County and partners prioritize where hydrologic restoration can reduce flood risks. By WI Wetlands Association, Kyle Magyera

Photo: Technical experts explore solutions to erosion hazards and the degradation of hydrologic processes in a headwater wetland. By WI Wetlands Association, Kyle Magyera

Solutions Case Study 3: Example actions to increase resilience and resist change with Natural Flood Management

where to reestablish wetland storage and reconnect floodplains, and how those actions reduce risks. The data also has applications across many sectors, including transportation planning, emergency management, agricultural and urban non-point runoff management, and more.

How we came to this conclusion

The collaboration in Ashland County developed following a case study (*Exploring the Relationship Between Wetlands and Flood Hazards in Wisconsin's Lake Superior Basin (2018)*, in which the Wisconsin Wetlands Association found that the loss of upper watershed wetland and floodplain storage is widespread and contributing to downstream infrastructure damages in extreme rain events. The 2018 Case Study also highlighted many opportunities to restore and reestablish the water storage and 'slow the flow' functions provided by wetlands and floodplains.

After the case study, partners convened to discuss these degraded conditions and associated problems for infrastructure and began implementing a plan for further action. That plan has involved partnership development, field-based observation, spatial analysis, data collection, and policy analysis to understand the problems and potential solutions.

Place-based work, observation, study, and consult with other states

WWA routinely consults and collaborates with local, state, and national partners on our place-based work, watershed restoration projects, field-based learning, and other science-based outreach and education.

The comprehensive list of collaborators in the Ashland County NFM initiative includes the Wisconsin Wetland Association, Federal Emergency Management Agency, Environmental Protection Agency, US Geological Survey, Wisconsin Departments of Natural Resources and Division of Emergency Management, Northwest Regional Planning Commission, DATCP, Northland College, Inter-Fluve, WCMP, NOAA, St. Mary's GeoSpatial Services, NRCS, USFS, and Trout Unlimited.

The collaboration engaged hydrology and engineering experts at a 2020 design charette exploring potential restoration sites and NFM practices. Mike Kline of Fluvial Matters in Vermont also provided feedback and consultation on watershed conditions and methods for mapping and characterizing erosion hazards and assessing hydrologic restoration potential on reach and catchment scales.

Photo: Stony Shore Before Sunrise, 2016 Great Lakes Photo Contest, natural category by Cameron Cech

9. Knowledge Gaps

The following knowledge gaps highlight resources to dig deeper into Great Lakes research needs.

Of particular note is that climate change is already affecting directly and indirectly valued ecosystem services. However, our understanding of the current and historical indirect value (cultural, identity, regulating services, etc.) and the spatial distribution of the Great Lakes ecosystem services remains understudied.[4,221] Preserving and adapting Ojibwe lifeways and treaty rights as the region becomes increasingly impacted by climate change will be a major challenge and requires novel approaches.[161] Additionally, key basic functions of the Great Lakes are largely unknown, including the role of pelagic (open-water) habitats in food webs, the current state and spatially variability in ecosystem processes.[221]

Often climate change knowledge and information go unused in local to regional planning and management.[222] Though providing broadly applicable information and incorporating climate adaptation actions within broader sustainability approaches can overcome this barrier to information use, more research is needed to improve the use of climate change knowledge.[222]

Climate change predictions

Since the Great Lakes both affect regional climate and are affected by climate change, an integrated land-lake

-atmosphere modeling approach would improve predictions of climate change effects in the region.[223] Such a modeling approach would improve the efficacy of climate change planning, from individual municipalities to international agreements. Interactions between climate change stressors and other stressors (e.g., invasive species, land use change, contaminants) are inadequately known, in addition to characteristics of resilient Great Lakes ecosystems to these multiple stressors.[200,221]

Photo: Danger Thin Ice, 2015 Great Lakes Photo Contest natural category, by Edward Deiro

Ice cover

Ice formation, ice cover, and under-ice ecology in the Great Lakes is severely understudied due largely to the risks associated with sampling in wintertime on the Great Lakes.[68] We know that ice processes in the Great Lakes are more similar to ocean ice processes than smaller lake ice, but the interaction between ice formation, cover, and drift with surface wind and wave energy remains largely unknown (e.g., how much surface waves delay ice formation and how ice cover lowers wave energy).[68] Further, the feedbacks between air temperature, water temperature, and evaporation with winter ice cover extent and duration are highly complex.[224] Researchers are just beginning to unravel how all these interactions result in observed changes in Great Lakes ice cover and water levels.[77,78]

Ice thickness, clarity, and snow cover are important for determining light penetration below the ice, which drives under-ice primary productivity. In general, Great Lakes ice accumulates less snow than ice on smaller lakes, due to wind carrying the snow elsewhere, and thus more light may be available under-ice driving more photosynthetic activity than is commonly assumed to occur in the winter. However, our knowledge of historical and current ice transparency and under-ice photosynthesis is lacking and the climate change effects on these ecosystem processes remain unknown.[68]

Biogeochemical processes, including transformations of nitrogen and phosphorus, are moderated by ice cover and resulting water temperature, and it is unknown how decreased ice cover or loss of ice cover may alter these processes in the Great Lakes.[68] Understanding changes to biogeochemical processes is essential for understanding cascading effects in the food web (i.e. phytoplankton, fish).

Nutrient loading, HABs, and water quality

Since climate change effects on water quality are mediated through physical and biogeochemical processes, the direct connection of climate drivers and water quality response is complex and not well understood.[225] Further, model projections for phosphorus loading to the lakes can be mixed. Simulated streamflow and phosphorus loading to all of Lake Michigan under future climate models range from a 30% decrease in phosphorus loading to a 25% increase in phosphorus loading to the lake, with significant spatial variability across the basin.[195] Improved understanding of the connection between changes in tributary flow volume and timing with lake ecosystem processes is key for predicting lake response.[95] In particular, the spatial distribution and sub-basin context is important for understanding how a storm event will be mediated by a tributary and ultimately affect the receiving lake.[99]

Fish and Fisheries

Predicting fish response to climate change will require a much better understanding of the interacting effects of multiple physical and biological changes in the lake.[167] Key gaps in basic fish ecology include how different life history stages respond to stressors.[226] Additionally, fisheries management will require a better understanding of how populations respond and adapt to invasive species in the Great Lakes (e.g., diet shifts of native species following invasion).[224] Promoting resilience in Great Lakes fisheries will require integrating differing spatial and temporal resolution of natural and social science research,[227] and considering alternative management approaches.[226]

Photo: Summer Fun, 2016 Great Lakes Photo Contest people category, by Carol Toepke

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