Strategies for Adapting Great Lakes Coastal Ecosystems to Climate Change

USDA Northern Forests Climate Hub
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Abstract

Natural resources practitioners working in Great Lakes coastal ecosystems face decisions about how to help coastal properties adapt to climate changes. Climate change can amplify existing stressors, interact with past coastal disturbance and management, and potentially increase the rate and magnitude of ongoing change. Practitioners can strengthen their long-term plans through proactive and intentional consideration of climate changes and by selecting adaptation options that address these changes while meeting management goals and objectives. In 2019-2021 the U.S. Fish and Wildlife Service and the Northern Institute of Applied Climate Science convened regional managers and scientists to develop a menu of climate adaptation strategies and approaches for Great Lakes coastal ecosystems. This menu can be used along with a structured decision-making framework to facilitate planning and implementation of climate-informed tactics. The menu was tested with several organizations in project-level planning in the Great Lakes watershed.

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Cover Photo: Empire Bluff Trail Overlook, Sleeping Bear Dunes National Lakeshore. National Park Service photo by Dennis Yockers.

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Sleeping Bear Dunes National Lakeshore. National Park Service photo.

Introduction

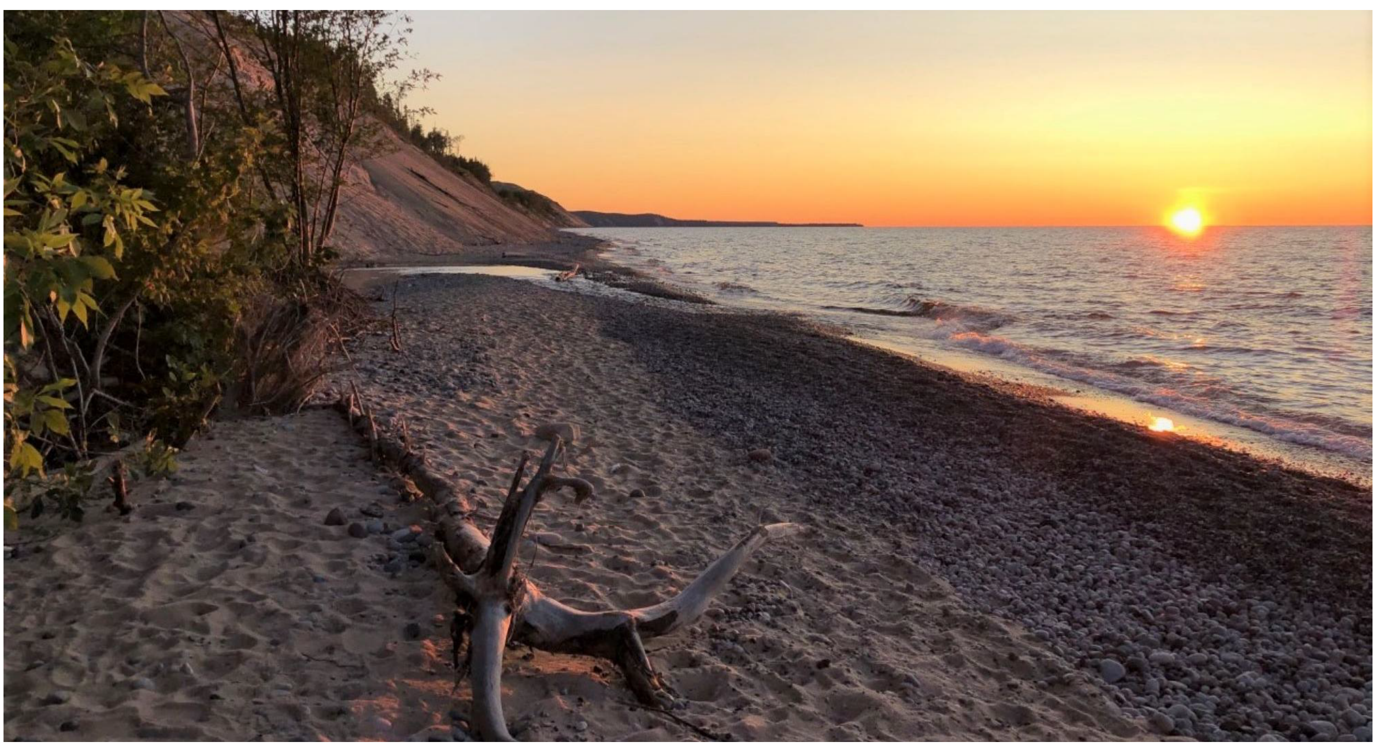
The Great Lakes contain nearly 20% of the earth's total surface fresh water and over 9,400 miles of coastline (Figure 1). Climate change has and will continue to impact the physical, chemical, and biological processes of the Great Lakes, and coastal ecosystems face a unique set of challenges due to these impacts. Across the broader Great Lakes region, ecosystems are experiencing changing thermal regimes, changing storm and precipitation patterns, and shifts in species assemblages (Duvenek et al. 2014, Bartolai et al. 2015, Angel et al. 2018, Wuebbles et al. 2019, Magee et al. 2021). In addition, coastal ecosystems face stressors that are specific to their proximity to the Great Lakes, including shrinking lake-ice cover, extent, and duration; increasing periods of wave action that accelerate erosion; and changing water levels that could exceed historical highs and lows as well as the pace of change (Mackey 2012, IUGLS 2012, Bartolai et al. 2015, Notaro et al. 2015, Angel et al. 2018, Magee et al. 2021).

Figure 1: *A map of the Great Lakes region and the coastal areas that are the focus of this menu. Source: Northern Institute of Applied Climate Science.*

Natural resources practitioners working in Great Lakes coastal ecosystems are often looking for ways to help coastal landscapes adapt to these changes. At the same time, practitioners may be working to restore coastal functions disrupted by past disturbance or management. Climate change becomes an added challenge that can amplify existing stressors and potentially increase the rate and magnitude of ongoing change (Shannon et al. 2019). Practitioners can strengthen their long-term plans through proactive and intentional consideration of climate changes and the inclusion of adaptation options that address these changes while meeting management goals and objectives. Along Great Lakes coasts, adapting ecosystems to climate change also helps them retain valuable ecosystem services, including carbon sequestration and shoreline protection, among others.

One of the major challenges of helping ecosystems adapt to climate change is translating broad concepts into specific, tangible actions. Existing adaptation literature and reports tend to cover broad coastal adaptation concepts (e.g., US EPA 2009, WICCI 2011, Murdock & Hart 2013, Mortsch 2018) or management practices relevant to a specific system or location (e.g., Keillor & White 2003, NRCS 2008, Powell et al. 2018). This document presents a menu of strategies and approaches to help natural resources practitioners move from general concepts to tangible, targeted adaptation tactics for their system. It can be applied to a variety of situations, accommodating diverse management goals, geographic settings, and site conditions (Swanston et al. 2016). The strategies, approaches, and example adaptation tactics are derived from a wide range of contemporary reports, expert input, and peer-reviewed publications. This resource is not intended to replicate existing resources nor to provide an overview of coastal dynamics or coastal climate vulnerabilities, which are covered well in other sources (see Box 1).

"In Great Lakes coasts, adapting ecosystems to climate change also helps them retain valuable ecosystem services, including carbon sequestration and shoreline protection, among others."



Sable Falls. Source: National Park Service photo.

Lincoln Creek. U.S. Geological Survey photo by Michelle A. Nott

This menu of coastal adaptation strategies and approaches, like other adaptation menus that have been developed, presents a diverse set of options for responding to climate change in Great Lakes coastal ecosystems. It draws from and complements previously published adaptation menus, including those for forested watersheds (Shannon et al. 2019), non-forested wetlands (Staffen et al. 2019), culturally relevant tribal perspectives (Tribal Adaptation Menu Team 2019), forests (Swanston et al. 2016), and others (see forestadaptation.org/strategies). However, given the unique climate challenges faced by coastal ecosystems throughout the Great Lakes, this menu focuses more specifically on coastal wetlands and estuaries; dunes and open beaches; rivers, deltas and riparian areas; stream channels; forested coasts and swamps; rock cliffs and bluffs; embayments; and nearshore habitats (Figure 2).

Intended users include those planning and implementing on-the-ground management actions, primarily natural resources practitioners, conservation planners, land or aquatic resources managers, tribal leaders and natural resources departments, and decision and policy makers, among others. Additional users may include those engaging with planning in some role, such as ecologists, consultants/contractors, landowners, and other stakeholders or indigenous rights holders.

The menu does not provide specific management recommendations or guidance, and instead outlines a broad range of potential responses. Some actions will be more appropriate than others in a given context. For example, some innovative or untested approaches may be desirable when conducting a restoration project in an already modified area but may have more risk associated with them when applied to an undisturbed coastal wetland. The text and references included for each strategy and approach will provide some context and additional considerations. Coastal professionals can use their expertise and judgement along with the adaptation strategies and approaches presented in this document to develop custom adaptation tactics based on their local conditions.

Although many of the strategies and approaches could apply to both plant and animal communities, most of the literature considered for this menu focused on vegetation and on physical and chemical processes. We recommend using the *Menu of Climate Change Adaptation Actions for Terrestrial Wildlife Management* for further ideas that explicitly consider animal communities (Handler et al. In Press).

Figure 2: *Great Lakes coastal ecosystems addressed in the menu of adaptation strategies and approaches.*

An Adaptation Planning Process

This menu was specifically designed to be used along with the *Adaptation Workbook* (Swanston et al. 2016). The *Adaptation Workbook* provides a structured, adaptive approach for integrating climate change considerations into planning, decision-making, and implementation (Figure 3). The *Adaptation Workbook* and growing suite of menus have been used together in hundreds of real-world natural resources management projects, many of which are described online as adaptation demonstrations at forestadaptation.org/demos. Other decision-making frameworks offer some similarities to the *Adaptation Workbook*, and this menu could be used with them as well (e.g., NOAA 2016).

This menu combined with a decision-making framework can be used to consider a variety of Great Lakes coastal management projects, from planning coastal reserves, to improving coastal habitat, to coastal wetland restoration. You will not see wetland restoration listed as a specific strategy or approach itself since wetland restoration projects could incorporate many of the strategies and approaches. The remainder of this document includes a brief introduction to a framework for climate adaptation, an overview of how to use the menu, the detailed menu, and a brief overview of case studies used to test the menu.

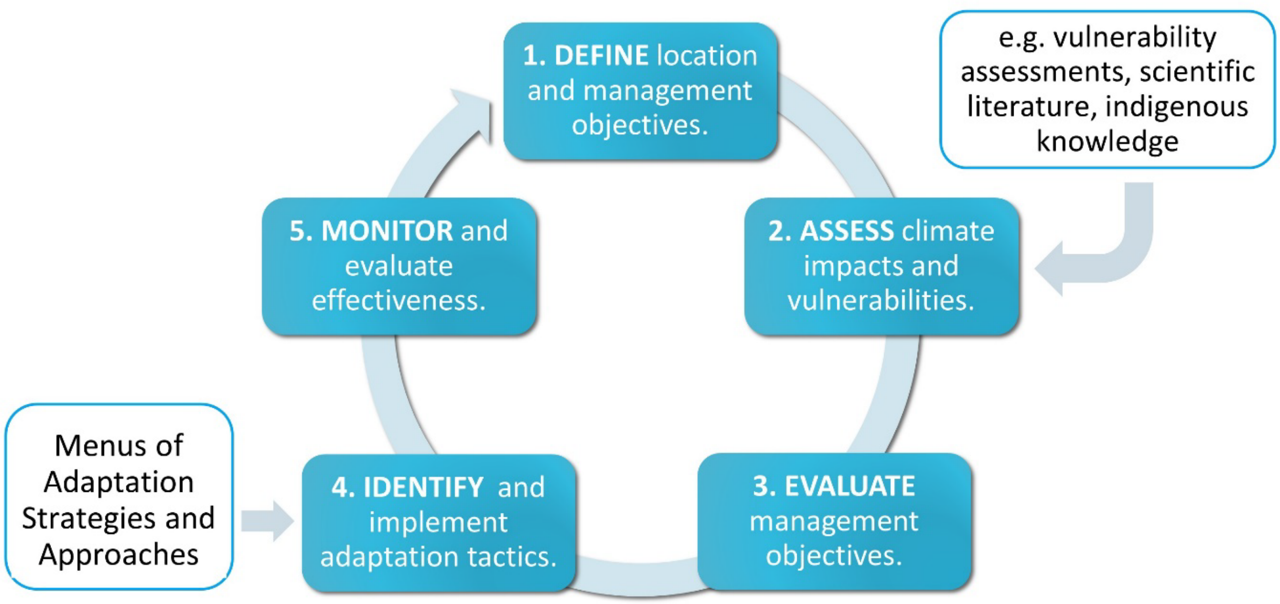


Figure 3: *The Adaptation Workbook is a structured process designed to be used in conjunction with vulnerability assessments and adaptation strategies menus to generate site-specific adaptation actions (Swanston et al. 2016, NIACS 2022).*

Box 1: Resources for Great Lakes Coastal Dynamics and Climate Change Impacts

These resources provide background and synthesis on climate change impacts and vulnerabilities on Great Lakes ecosystems and help to put the menu adaptation strategies and approaches in context. These and other local or regional impact and vulnerability resources can also be explicitly considered as part of the *Adaptation Workbook* process (Figure 3).

Great Lakes Data and Climate Change Syntheses:

- An Assessment of the Impacts of Climate Change on the Great Lakes. (Wuebbles et al. 2019): elpc.org/wp-content/uploads/2020/04/2019-ELPCPublication-Great-Lakes-Climate-Change-Report.pdf
- Climate Change and Wisconsin's Great Lakes Ecosystem. (Magee et al. 2021): wicci.wisc.edu/great-lakes-working-group/. See also a presentation summarizing some of the findings from this report: https://www.youtube.com/watch?v=pACBAFpdX2o
- Great Lakes Water Level Dashboard: glerl.noaa.gov/data/dashboard/GLWLD.html
- Lake Superior Climate Change Impacts and Adaptation. (Huff & Thomas 2014): epa.gov/greatlakes/lake-superior-climate-change-impacts-report
- State of the Great Lakes 2019 Technical Report. (Environment and Climate Change Canada and the US EPA 2021). Pages 624-663 cover trends on watershed climate indicators such as precipitation, surface water temps, water levels, and ice cover. Available at binational.net: binational.net/wp-content/uploads/2021/02/SOGL-19-Technical-Reports-compiled-2021_02_10.pdf
- Sustained Assessment of the Great Lakes (GLISA): glisa.umich.edu/sustained-assessment/great-lakes/

Climate Change Impacts and Ecosystem Dynamics:

- A Review of Selected Ecosystem Services Provided by Coastal Wetlands of the Laurentian Great Lakes (Sierzen et al. 2012).
- Adapting to Climate Change: Solutions to Enhance Great Lakes Coastal Wetland Resilience (Mayne et al. 2021)
- WICCI Climate Change Vulnerability Assessments (CCVAs): Plants and Natural Communities (WICCI 2017): wicci.wisc.edu/plants-and-natural-communities-working-group/climate-change-vulnerability-assessments-ccvas/

Adaptation Concepts: Resistance, Resilience, and Transition

(modified from Swanston et al. 2016)

Adaptation strategies and approaches are part of a continuum of adaptation actions ranging from broad, conceptual application to practical implementation. This continuum builds upon the adaptation framework described by Millar et al. (2007). The concepts of Resistance, Resilience, and Transition serve as fundamental options for managers to consider when responding to climate change, and help to organize the strategies and approaches included in this menu (Figures 4,6). The ideas in this menu can also be used with other conceptual frameworks for climate adaptation, such as the Resist-Accept-Direct (RAD) framework (Schuurman et al. 2020).

Resistance actions improve the defenses of an ecosystem against anticipated changes or directly defend the ecosystem against disturbance to maintain relatively unchanged conditions. Although this option may be effective in the short term (mid-century or sooner), supporting the long-term persistence of an existing ecosystem may require greater resources and effort over the long term as the climate shifts further from historical norms. Resistance may be desired when there is a desire or mandate to maintain a resource with high cultural, ecological, or economic value. It may be most effective in ecosystems with low sensitivity to climate change or in areas that are buffered from severe climate change impacts (e.g., refugia). As an ecosystem persists into an unfavorable climate, the risk of the ecosystem undergoing irreversible change increases over time.

Resilience actions support the persistence of an existing ecosystem and enable it to recover following disturbance. This option can accommodate some degree of ecosystem change but encourages a return to a prior reference condition after a disturbance, either naturally or through management. Resilience actions enhance the ability of the system to bounce back from disturbance and tolerate changing environmental conditions, albeit with sometimes fluctuating populations (Holling 1973). Such actions may be most effective in systems that can already tolerate a wide range of environmental conditions and disturbances. Like the resistance option, this option may be most effective in the short term and may be subject to increasing risk over time. Resilience is effective until the degree of change exceeds the ability of a system to cope, resulting in transition to another state.

Transition actions intentionally anticipate and accommodate change to help ecosystems to adapt to new conditions. Transition actions intentionally facilitate the transformation of the current ecosystem into a different ecosystem with clearly different characteristics. These actions may be considered appropriate in ecosystems assessed as highly vulnerable across a range of plausible future climates such that the risk associated with resistance and resilience actions is judged to be too great. Transition actions are typically designed for long-term effectiveness. They are often phased into broader management plans that predominantly have a shorter-term focus on resilience actions.

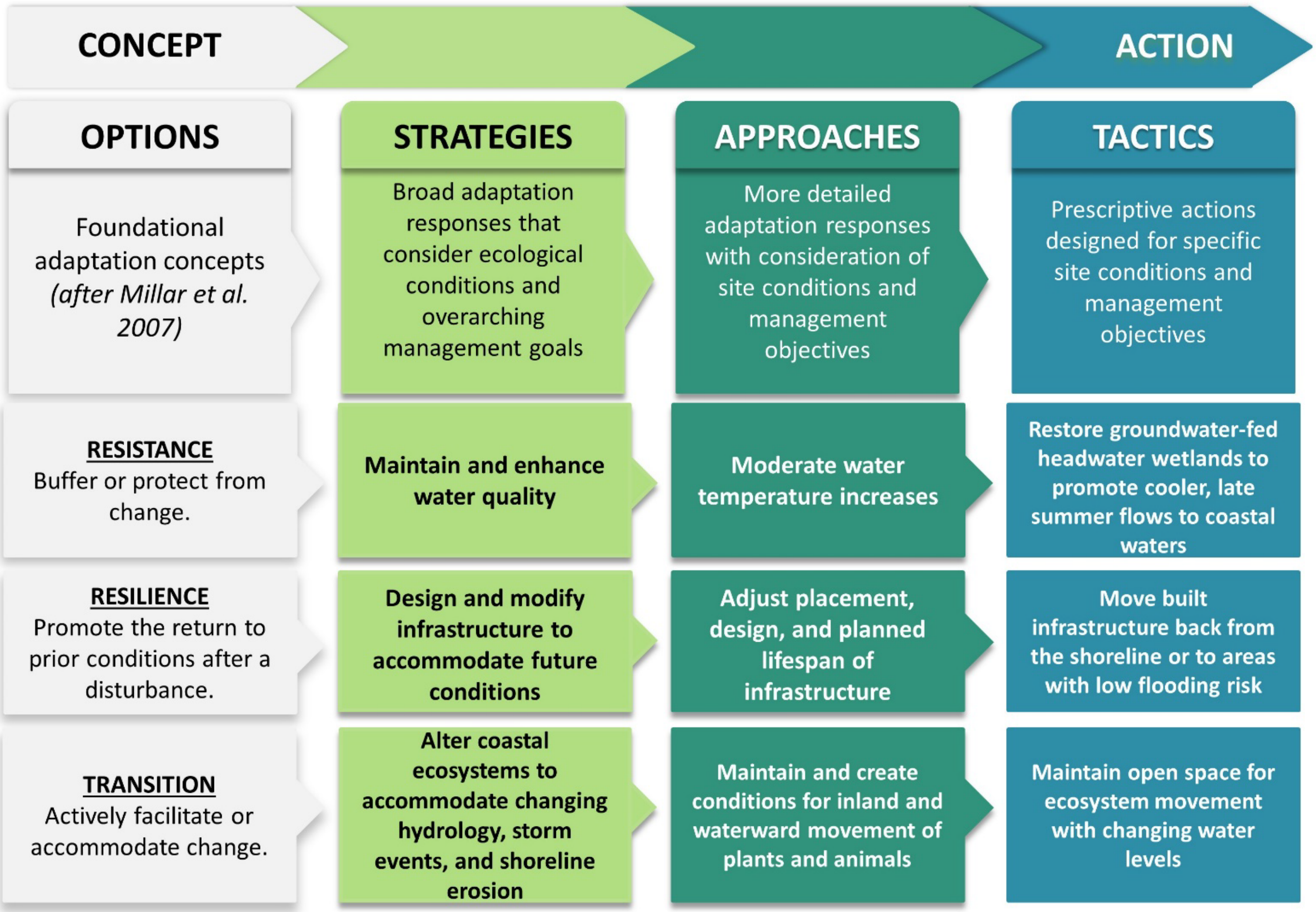


Figure 4: *Climate change adaptation actions work to achieve three broad adaptation options: Resistance, Resilience, and Transition. This figure shows examples of the level of specificity for adaptation strategies, approaches, and tactics included in this menu for Great Lakes coastal ecosystems.*

How to Use this Menu

The options of Resistance, Resilience, and Transition serve as the broadest level in a continuum of adaptation responses to climate change (Janowiak et al. 2011, Swanston & Janowiak 2012, Swanston et al. 2016). Along this continuum, actions for adaptation become increasingly specific (Figures 4, 5). Adaptation strategies are broad and help to describe how adaptation options could be employed across coastal ecosystems. The strategies within this menu are arranged roughly from Resistance-focused strategies to Transition-focused strategies. However, this is not a hard rule, as it depends on how each strategy is applied (Figure 6). The final strategy focuses on infrastructure and includes Resistance, Resilience, and Transition adaptation options. Many strategies could also align with Resist, Accept, and Direct (RAD) concepts (Schuurman et al. 2020).

The strategies, approaches, and tactics are derived from peer-reviewed research and evidence-based reports on climate change adaptation, Great Lakes coastal ecosystem management, and broader coastal adaptation examples. Strategies, approaches, and tactics are not mutually exclusive; a variety of different approaches and tactics can be selected to address climate concerns for a particular project.

Strategy: a broad adaptation response that is applicable across a variety of resources and sites, hydrologic and ecological conditions, and overarching management goals

Approach: a more detailed adaptation response specific to a resource issue or impact, site condition, or management objective. Adaptation approaches describe in greater detail how strategies could be employed.

Tactic: an action designed for specific site conditions and management objectives. Tactics are the most specific adaptation responses, providing direction about what, how, where, and when actions can be applied on the ground. Tactics can be developed specific to a species, the ecosystem type, site condition, management objective, or other factor.

Figure 5. *Adaptation menus help to make broad adaptation options more specific by linking to a strategy and approach; users customize on-the-ground actions.*

We have provided examples of tactics for each approach, but do not intend that they be implemented without due consideration of all relevant factors. The *Adaptation Workbook* process also provides a method to explicitly consider the benefits and drawbacks of potential adaptation tactics.

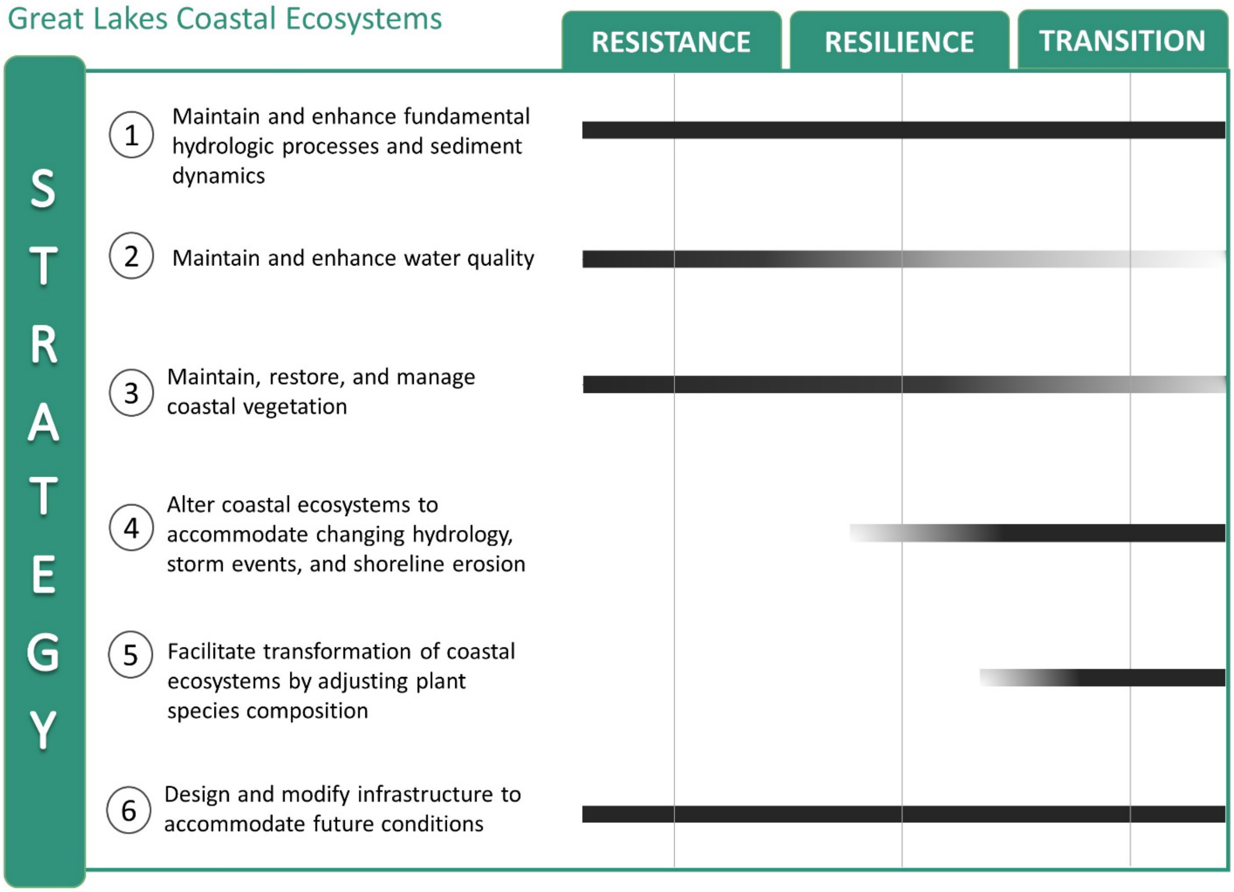


Figure 6: *Each strategy has a relationship to Resistance, Resilience, or Transition options. A solid line indicates a strong relationship between an option and a strategy, whereas fading indicates that the strategy relates to that option under some circumstances. Although a strategy may work under multiple options, the implementation is likely to be achieved through very different approaches and tactics.*

The adaptation strategies and approaches ***can provide:***

- A broad spectrum of possible adaptation actions that can help sustain healthy Great Lakes coastal ecosystems and achieve management goals in the face of climate change.
- A framework of adaptation actions from which managers select actions best suited to their specific management goals and objectives.
- Examples of tactics that could potentially be used to implement an approach, recognizing that specific tactics will be designed by those familiar with local conditions. A single tactic may also be designed that aligns with several different approaches.

The adaptation strategies and approaches ***do not:***

- Set guidelines for management decisions. It is up to the manager to decide how this information is used, potentially with the help of a decision-making framework like the *Adaptation Workbook*.
- Express preference for any strategies or approaches. Location-specific factors and practitioner expertise can inform the selection of specific strategies and approaches.
- Provide an exhaustive set of tactics. We encourage managers to consider additional actions that may be applicable to their projects.
- Recommend specific actions. Tactics included in the menu are examples of potential adaptation actions that fit within a strategy and approach. These tactics will not be appropriate in all situations. Further, not all tactics are vetted by research. Monitoring and adaptive management can be used to evaluate the success of actions at a given project site.

Black River Delta, Wisconsin. U.S. Geological Survey photo.

Box 2: Community Engagement and Coastal Planning

The Adaptation Strategies and Approaches have been designed primarily for those planning and implementing on-the-ground management actions. However, many coastal adaptation efforts may benefit from broad engagement that promotes coordinated planning and policy (Kraus & Klein 2009, Franks-Taylor et al. 2010, Pearsall et al. 2012a, Pearsall et al. 2012b). Coastal ecosystems often represent multiple community interests and interconnected ecosystem dynamics and planning can involve people and organizations beyond the coastal practitioners charged with executing treatments on the ground. Engaging with the community, tribes, policy makers, and different disciplines could help practitioners consider the range of possible outcomes of management actions and promote climate change adaptation across large scales (NOAA 2010). For example, coordinated planning could work to address issues like zoning, water quality, and sediment management at a broader scale.

Though community engagement, planning, and policy strategies are beyond the scope of this document, Appendix 2 includes some ideas from expert input and from documents that cover coastal adaptation through a planning and policy lens. These ideas are not recommendations but rather represent options that may be useful depending on a project's context. Many of these ideas could be incorporated into adaptation planning processes like the *Adaptation Workbook*.

Butterfly on plant. USDA Forest Service photo by Tammy Miller.

Menu of Strategies and Approaches for Coastal Ecosystems

Strategy 1: Maintain and enhance fundamental hydrologic processes and sediment dynamics.

Approach 1.1: Maintain and restore natural sediment transport processes.

Approach 1.2: Maintain and restore hydrological connectivity between hydrological features.

Approach 1.3: Maintain and enhance infiltration and water storage capacity of soils.

Strategy 2: Maintain and enhance water quality.

Approach 2.1: Moderate water temperature increases.

Approach 2.2: Reduce sediment deposition.

Approach 2.3: Reduce loading and export of nutrients and other pollutants.

Strategy 3: Maintain, restore, and manage coastal vegetation

Approach 3.1: Maintain the integrity of unique plant communities, coastal wetlands and estuaries, and their integral landforms.

Approach 3.2: Minimize non-climate physical damage to coastal ecosystems and habitats.

Approach 3.3: Establish living shorelines by maintaining and restoring coastal vegetation.

Approach 3.4: Maintain and enhance species and structural diversity in coastal ecosystems.

Approach 3.5: Prevent invasive plant and animal species establishment and minimize their impacts where they occur.

Approach 3.6: Maintain and establish refugia for plants and animals.

Approach 3.7: Maintain and increase connectivity of coastal habitats.

Strategy 4: Alter coastal ecosystems to accommodate changing hydrology, storm events, and shoreline erosion.

Approach 4.1: Manage coastal ecosystems to accommodate increased frequency and duration of low water levels.

Approach 4.2: Manage coastal ecosystems to accommodate increased frequency and duration of high water levels.

Approach 4.3: Promote features that reduce the impacts of wind and wave energy or damage from coastal erosion.

Approach 4.4: Manage sediment to respond to fluctuating water levels.

Approach 4.5: Reduce or manage surface water runoff.

Approach 4.6: Maintain and create conditions for inland and waterward movement of plants and animals.

Approach 4.7: Manage impounded wetlands to accommodate changes in hydrologic variability.

Strategy 5: Facilitate transformation of coastal ecosystems by adjusting plant species composition.

Approach 5.1: Favor or restore native species and genotypes with wide moisture and temperature tolerances.

Approach 5.2: Increase genetic diversity of seed and plant mixes.

Approach 5.3: Disfavor species that are distinctly maladapted.

Approach 5.4: Introduce species that are expected to be adapted to future conditions.

Approach 5.5: Move at-risk species to locations that are expected to provide more suitable habitat.

Strategy 6: Design and modify infrastructure to accommodate future conditions.

Approach 6.1: Reinforce infrastructure to meet expected conditions.

Approach 6.2: Design infrastructure with low-impact or ecologically friendly features.

Approach 6.3: Adjust the placement, design, and planned lifespan of infrastructure.

Approach 6.4: Remove infrastructure and readjust systems.

Strategy 1: Maintain and enhance fundamental hydrologic processes and sediment dynamics.

Great Lakes coastal ecosystems are and will continue to be affected by disruption of soil-water connections, both nearshore and at the watershed scale (Edsall & Charlton 1997, Kraus & Klein 2009, Lin & Wu 2014). Climate changes combined with land uses that have fragmented, altered, or obstructed water and sediment flow pathways can amplify existing ecosystem challenges. For example, shoreline hardening is common in the Great Lakes and can contribute to down-current coastal erosion by interfering with natural sediment movement and deposition (NOAA Office for Coastal Management et al. 2022). At the same time, climate changes can exacerbate erosion issues through more extreme water level fluctuations, increasing severity and frequency of storms, changing wave characteristics, and decreasing ice cover (Laurence & Nelson 1994, Mackey 2012, Wuebbles et al. 2019). At the watershed scale, dams and barriers have affected the hydrology and therefore the diversity and distribution of coastal wetlands, which are further threatened by climate changes (Keilor & White 2003, Kraus & Klein 2009, Wuebbles et al. 2019). This adaptation strategy encourages the holistic consideration of a project area and its surroundings, the recognition of interconnected water and sediment pathways, and the identification of how these pathways may be currently disrupted (Kraus & Klein 2009, Creed et al. 2011). It encompasses many fundamental ideas that may already be employed or under consideration by managers to restore more natural hydrologic processes and sediment movement and avoid further actions that impair them. For each of the approaches below, example adaptation tactics are presented for working at watershed scales and in nearshore project areas.

Approach 1.1: Maintain and restore natural sediment transport processes.

Throughout the Great Lakes, coastal land uses have interrupted or altered natural sediment transport. When sediment flow is interrupted by shoreline development or other factors, regular patterns of coastal erosion and deposition that support dynamic coastline features can be disrupted, and areas that either supply or rely on regular sediment deposits can be more quickly eroded or starved (Keilor & White 2003, Lin & Wu 2014, CT DEEP 2019). Changes in sediment transport can lead to shoreline recession, alteration of important features like bluffs and dunes, breached barrier beaches, and loss of wetland habitat, among other effects (Mayne et al. 2021). Climate changes that affect the pattern and intensity of waves and storms can amplify these losses (Mackey 2012).

At the watershed scale, streams and rivers can be important sources of sediment to river mouths and nearshore systems, and in some cases, it may be desirable to restore sediment supply from these waterways (Keilor & White 2003). However, in other situations, upland erosion and oversupply of sediment from tributaries could be a problem, and management might focus on reducing the volume of sediment transported to nearshore environments (see more on this in Approach 2.2). Each of these are potential adaptation responses, but each may have a different objective as it relates to the amount of sediment ultimately reaching the Great Lakes.

Example adaptation tactics for nearshore areas:

- Strategically remove shoreline hardening in identified sediment source areas to allow for natural sediment erosion and transport processes (Livchak & Mackey 2007, Zuzek 2020, Mayne et al. 2021).
- Seek natural shoreline stabilization techniques where feasible and avoid shoreline hardening (Mangham et al. 2018).
- Identify and acquire undeveloped shoreline properties that may provide a source of material for beaches and bar systems (Livchak & Mackey 2007).
- Bypass sand to the downdrift side of large shoreline structures that trap and prevent sediment drift (Livchak & Mackey 2007).

Example adaptation tactics for watersheds:

- Modify river discharge controls to increase sediment supply where sediment shortages exist, such as at the mouth of a river during high lake level conditions (Scavia et al. 2002, Wigand et al. 2017).
- Remove dams and barriers that prevent the natural transport of sand and sediment to river mouths and the nearshore ecosystem, where increased sediment supply is desirable (Mayne et al. 2021)

Approach 1.2: Maintain and restore hydrological connectivity between hydrological features.

Water level fluctuation is a natural feature in Great Lakes coastal ecosystems and contributes to habitat diversity and other critical ecological functions (IUGLS 2012, Mortsch 2018). Likewise, hydrologic connections between the lakes, coastal wetlands and fens, and tributaries help coastal ecosystems respond to short- and long-term hydrologic change and provide key habitat connectivity for different life stages of native species. Many of these hydrologic connections have been interrupted by dams and barriers, water level regulation, aquifer withdrawals, and various forms of shoreline development, which can lead to loss of coastal ecosystem biodiversity and function, particularly affecting coastal wetlands (Keilor & White 2003, Kraus & Klein 2009, IUGLS 2012). Changes in climate, including more variable and intense precipitation, can lead to fluctuating water levels that can cause both loss of hydrologic connectivity and periodic inundation (Mackey 2012, Wuebbles et al. 2019). Restoring hydrologic connectivity may be a first step in helping to restore coastal habitat diversity and the ability of ecosystems to cope with these changes.

Example adaptation tactics for nearshore areas:

- Remove existing dikes and avoid installing new dikes in shoreline wetlands to restore or maintain natural hydrologic regimes (NOAA 2010).
- Avoid dredging rivers or channels that disrupt hydrologic connections (Quinn 1985).
- Protect mineral-rich groundwater sources of fens from drainage or other alterations in hydrology.
- Avoid road construction through fens to prevent hydrologic alterations, impeded surface flows, and significant changes in species composition and structure. This often results from sustained flooding on one side of a road while the other side becomes drier and subject to increased shrub and tree encroachment (Mayne et al. 2021).

Example adaptation tactics for watersheds:

- Modify dams and weirs to manage water flow to mimic a more natural flow regime (i.e., frequency, magnitude, duration, and timing of flood pulses) at both high flows and low flows (Kraus & Klein 2009, Yochum 2017).
- Reconnect floodplains adjacent to incised river channels using stream restoration techniques to restore channel morphology and connectivity (Yochum & Reynolds, 2020).
- Rebuild or re-establish wider riparian zones and buffers along rivers and streams to handle greater flow variability (e.g., increase bank storage and riparian relief in high flows, increase baseflow conditions, re-adjust baseflow cross-section in low flows) (Dove-Thompson et al. 2011, Herb et al. 2016).
- Reroute streamflow from ditches to historic or reengineered channels (Perry et al. 2015).
- Protect base flows against significant water extraction at times when low flows are of concern (Herb et al. 2016).
- Replace causeways that limit water flow with bridges, or modify bridges and culverts to maximize water conveyance and hydrologic connectivity (Clarkin et al. 2006, Yochum 2017, Olson et al. 2017, Molina-Moctezuma et al. 2021).

Approach 1.3: Maintain and enhance infiltration and water storage capacity of soils.

Porous soils capture, absorb, and slowly release water to groundwater and downstream sources, protecting water quality, regulating flooding, and reducing coastal erosion (Keilor & White 2003, Smith et al. 2016, Abdallah et al. 2018). Climate change is expected to cause more frequent and intense rain events in the Great Lakes region, increasing rates of erosion, runoff, and soil losses (Wuebbles et al. 2019), which increases the benefits of actions that protect and restore soil properties to enhance water infiltration. Many existing guidelines and best management practices describe actions that can be used to enhance soil-water infiltration, and many of these actions are also likely to be beneficial in the context of climate adaptation, either in their current form or with modifications to address climate change impacts. This approach compliments and can be used in conjunction with many of the actions described in Approach 4.5, which focuses on reducing or managing surface water runoff.

Example adaptation tactics:

- Maintain vegetated buffers or plant buffer strips in agricultural fields adjacent to streams and wetlands, and incorporate grassed drainageways to slow runoff and bank erosion (Lucke et al. 2014, Faber-Langendoen et al. 2016)
- Minimize operation of heavy machinery (e.g., restrict to seasonal or conditional use), confine the use of heavy machinery (e.g., controlled traffic farming), or use lower impact tracked or autonomous vehicles to minimize soil compaction and impacts to vegetation (Raper 2005, Mariotti et al. 2020).
- Wait for suitable moisture conditions to use heavy machinery (University of Minnesota Extension 2018).

- Restore or enhance headwater and mid-watershed wetlands using a range of techniques, including ditch plugs, ditch filling, drain tile removal, and shallow scrapes (NRCS 2008, NRCS 2011).
- Establish no-cut buffers around coastal fens and avoid road construction and complete canopy removal in stands immediately adjacent to fens to prevent increased surface flow.
- Maintain natural shorelines and pervious surfaces adjacent to the Great Lakes.

Strategy 2: Maintain and enhance water quality.

Natural resources managers may already implement actions to sustain or enhance coastal water quality, but climate changes such as warming temperatures and changing precipitation regimes may increase the potential for water quality impairments (Sinha et al. 2017, Wang et al. 2018, Wuebbles et al. 2019). For example, increases in the frequency and intensity of rain events can increase sediment and nutrient runoff into the Great Lakes. When combined with warmer temperatures, nutrient runoff can lead to harmful coastal impacts such as algal blooms and hypoxic conditions (Mackey 2012, Wuebbles et al. 2019, Magee et al. 2021). The emphasis of this strategy is on anticipating and preventing increased stresses before water quality impairment occurs. It may encompass “business as usual” actions that are currently well known in coastal management.

Approach 2.1: Moderate water temperature increases.

Warmer surface water temperatures can affect the thermal structure and chemistry of the Great Lakes, with several implications for coastal ecosystems (Mackey 2012). Warmer waters can cause changes in species assemblages, increases in primary productivity, more rapid decomposition and respiration, and lower dissolved oxygen levels (Dove-Thompson et al. 2011, Mackey 2012, Wuebbles et al. 2019). These changes can increase the potential for hypoxic (oxygen-deficient) conditions, particularly in shallow coastal areas and tributaries. Warmer water temperatures may also encourage the growth of harmful algal blooms, which could further increase the risk of hypoxic conditions and create public health risks (Dove-Thompson et al. 2011). As Great Lakes water temperatures continue to increase with climate change, finding ways to reduce warming from non-climate sources may help reduce or slow the overall extent and degree of warming.

Example adaptation tactics:

- Incorporate natural infrastructure and forested buffers to limit warm storm water runoff, particularly near high-quality or sensitive areas (Kaushal et al. 2010, Sutton-Grier et al. 2018).
- Identify major locations of thermal pollution in and adjacent to coastal wetlands, and modify or remove small dams and other barriers to improve thermal condition (Dove-Thompson et al. 2011).
- Maintain and restore groundwater-fed headwater wetlands to promote cooler, late-summer flows to coastal waters (Erwin 2008).
- Maintain and restore groundwater-fed coastal fens that act as stable temperature refugia (Krause & White 2009).

Approach 2.2: Reduce sediment deposition.

This approach emphasizes physical remediations that can reduce sedimentation in Great Lakes tributaries and nearshore coastal ecosystems. Sediment is a natural part of element cycling in aquatic ecosystems. However, excessive suspended sediments and their deposition can negatively influence watershed hydrology and flow pathways, decrease water clarity and photosynthesis, skew aquatic plant composition towards turbidity-tolerant species, and negatively affect aquatic organisms (Sierszen et al. 2012, Kjelland et al. 2015). Sedimentation can also increase nutrient availability in coastal ecosystems with deleterious effects on ecosystem function and quality (see also Approach 2.3). Climate change may increase sedimentation in the Great Lakes by increasing storms and wave energy and by changing patterns of precipitation, hard freeze, and snowmelt, all of which will interact with human activities and land use changes that cause sedimentation.

Example adaptation tactics:

- Increase in-stream sediment retention by introducing or re-establishing vegetation, woody debris, boulders, or beaver dams to aggrade the channel and raise the water table (Perry et al. 2015).
- Create upland buffers to reduce stormwater runoff and sediment transport to coastal areas (FFWCC 2016).
- Direct water into forested or densely vegetated areas with lead off ditches, broad based dips, bioswales, and water bars, in order to slow road surface drainage and reduce sedimentation (Keller & Ketcheson 2015, Strauch et al. 2015).
- Encourage adoption of agricultural best management practices to help mitigate erosion (Pearsall et al. 2012b).
- Restore stream morphology and meandering, and reconnect streams with their floodplain to help balance flow/sediment loads and provide long-term sediment capture. This type of restoration may have to be done at a large scale to provide a benefit (Thompson et al. 2018).
- Stabilize eroding streambanks by establishing vegetation, particularly at sites with sparse vegetative cover, sparse litter cover, or steep slopes.

Approach 2.3: Reduce loading and export of nutrients and other pollutants.

This approach emphasizes actions at multiple scales (site-level to watershed) to reduce delivery of nutrients and pollutants in coastal ecosystems. Climate change coupled with changing land uses are expected to influence the export and loading of nutrients and pollutants in Great Lakes waters. Nutrient exports from agricultural fertilizers, urban wastewater, and soil erosion heavily influence Great Lakes ecosystems; they are a primary cause of negative ecological impacts such as harmful algal blooms, low oxygen levels, and altered water chemistry and species composition (Kraus & Klein 2009, Wuebbles et al. 2019). Climate changes, including warmer waters and increased heavy precipitation events, are expected to exacerbate these ecological impacts (Mackey 2012, Wuebbles et al. 2019). Other chemical pollutants, such as salt, can also negatively influence coastal ecology. Actions that enhance the ability of the ecosystem to retain nutrients or intercept the export of pollutants to Great Lakes waters may become increasingly important to sustain water quality at or above critical thresholds. Many actions under Approach 4.5 (reduce or manage surface water runoff) can also be used to reduce nutrient loads.

Example adaptation tactics:

- Collaborate with agricultural landowners in the watershed to encourage best management practices that reduce nutrient loads, such as on-farm reductions in fertilizer application, removal of drain tile systems, use of cover crops, and use of riparian buffers (Pearsall et al. 2012a).
- Modify stormwater outfalls that affect nearshore habitats (FFWCC 2016).
- Identify and restore wetlands upstream in agricultural watersheds to help reduce the flow of nutrients and pollutants to nearshore waters, particularly in areas with high phosphorus surplus (Cheng et al. 2020).
- Create and enhance wetlands designed to increase the area and duration of soil saturation to improve reduction of nutrients. For example, "in-line" wetlands along ditches and small streams can be created to intercept and remove nutrients from flows before entering coastal waters (Staffen et al. 2019 following Hansen et al. 2018).
- Promote development of nutrient management plans to limit practices like manure spreading and fertilizer application on frozen surfaces and steep slopes and near Great Lakes tributaries or coasts.
- Encourage the use of voluntary certification programs that reduce nutrient runoff from agricultural lands, such as 4R certification (Right fertilizer source, at the Right rate, at the Right time, and with the Right placement - Kerr et al. 2016).

Sleeping Bear Dunes National Lakeshore. U.S Geological Survey Great Lakes Science Center photo by Joshua Miller.

Strategy 3: Maintain, restore, and manage coastal vegetation.

This strategy addresses coastal vegetation structure and composition as a key ecological building block in allowing coastal ecosystems to cope with a changing climate. Coastal plant communities have evolved in response to a range of natural disturbance regimes; however, they are currently subject to direct and indirect climate stressors including increased annual and seasonal temperatures, changing hydrology, changing habitat suitability for species, reduced ice cover, and increased wind and wave disturbances (Wuebbles et al. 2019). These stressors may lead to changes in plant community structure and composition, chemical processing, and habitat quality. At the same time, coastal vegetation can help buffer human and natural communities against climate-caused disturbances, such as wind and wave energy and flooding. Retaining existing healthy coastal vegetation and avoiding extensive manipulation and disruption to ecosystems such as coastal wetlands are components of this strategy. In addition, active management to increase structural and species diversity, control invasive species, and maintain connectivity and unique habitats may enhance coastal ecosystem resilience to climate pressures.

Approach 3.1: Maintain the integrity of unique plant communities, coastal wetlands and estuaries, and their integral landforms.

Coastal wetlands in the Great Lakes and the physical landforms that support them are particularly vulnerable to climate change, affected by changing water level regimes, increased storm frequency and intensity, and increased surface water temperatures (Wuebbles et al. 2019). In addition, healthy wetlands and estuaries are integral to helping Great Lakes coastal systems cope with climate changes; they stabilize shorelines, provide shelter for fish and wildlife, filter runoff to capture nutrients and sediments, and can buffer against flooding and wave damage (Sierszen et al. 2012, Cheng et al. 2020). These ecosystems may also support rare or unique plants that are of conservation interest. Many Great Lakes coastal wetlands are degraded or have been converted to other land uses. However, there are also high-quality wetlands and unique plant communities that can be prioritized for conservation efforts (Cvetokovic & Chow-Fraser 2011). This approach recognizes the importance of coastal wetlands and their integral landforms in overall climate change response and emphasizes conserving areas and rare communities that are unmanipulated before more extensive restoration is necessary. Restoring coastal wetlands may also be an important action and can be supported by many of the approaches and tactics included throughout this menu.

Example adaptation tactics:

- Avoid converting existing coastal wetlands to other landscape uses, such as draining wetlands for agriculture or converting wetlands to open beach.
- Reduce infilling and fragmentation of coastal wetlands and other coastal habitats.
- Avoid constraining coastal wetlands with built infrastructure (road embankments, commercial docks, channels, etc.), allowing vegetation to move dynamically.

- Focus land conservation and protection efforts on healthy coastal wetlands and estuaries (e.g., those with high biotic integrity, hydrologic connectivity, or high water quality), particularly in lakes where wetlands tend to be more degraded (Kraus & Klein 2009, Cvetokovic & Chow-Fraser 2011).
- Maintain the integrity of wetland basin landforms by restoring or enhancing native vegetation in locations where those landforms may be vulnerable to erosion.

Approach 3.2: Minimize non-climate physical damage to coastal ecosystems and habitats.

Climate change is expected to cause physical stress to coastal landforms and ecosystems, such as through increased wind and wave energy and shorter periods of protective ice cover (Mackey 2012). This approach focuses on limiting or eliminating non-climate impacts from recreation, visitation, and other human uses that may physically degrade coastal landforms, vegetation, or animal habitat (McLachlan et al. 2013, Klein & Dodds 2017). Reducing this direct physical damage could help improve the health and integrity of coastal vegetation and landforms and their ability to cope with added climate pressures. Built infrastructure represents a particular category of physical disturbance and is addressed more specifically in Strategy 6: Design and modify infrastructure to accommodate future conditions.

Example adaptation tactics:

- Establish no-wake zones to reduce physical damage to sensitive nearshore habitats due from recreational or commercial use.
- Install paths and boardwalks to minimize impacts of informal social trails and trampling on vegetation (NOAA 2010, WSP 2022)
- Restrict the location or timing of beach access in sensitive habitat areas to accommodate species life cycles and facilitate ecosystem recovery (McLachlan et al. 2013). For example, piping plover breeding habitat on Montrose Beach, Chicago.
- Redirect recreation or physical access away from areas where coastal vegetation and features might be negatively impacted (e.g., fens, swales, coastal mineral marshes, dunes/banks) (McLachlan et al. 2013).
- Limit foot traffic and climbing on sensitive coastal cliffs and rock ledges or on less stable coastal bluffs and banks to protect vegetation and reduce erosion.
- Prevent off-road vehicle access to sensitive coastal fens to prevent deep ruts in the loose soils, altered surface flows, altered species composition, and invasive plants.
- Reduce human threats to wetland basin landforms, especially along perimeters (e.g., berms between wetlands and adjacent lakes, basins near hilly terrain subject to runoff).

Approach 3.3: Establish living shorelines by maintaining and restoring coastal vegetation.

Living or vegetated shorelines (sometimes called nature-based shorelines) have many advantages from an adaptation standpoint. Coastal vegetation can reduce wave energy, coastal erosion, and flood hazards that may increase as a result of climate change while providing co-benefits such as runoff filtration, aesthetic value, and habitat value for species that may be vulnerable to climate pressures (Keilor & White 2003, NOAA 2015, Sutton-Grier et al. 2015, Sutton-Grier et al. 2018, SAGE 2019, Shea et al. 2021). Living shorelines may cost less to establish and maintain compared to built infrastructure and be better able to respond dynamically to fluctuating water levels. Built infrastructure and shoreline hardening can help prevent erosion but may also cause problems elsewhere by interrupting sediment movement. In addition, hardened features often lack the ecological co-benefits and adaptability of living shorelines (Keilor & White 2003, NOAA 2015). Living shorelines may include other elements in addition to vegetation, such as coir logs, rocks, netting, and erosion control blankets (NOAA 2015, Shea et al. 2021). Increasingly, hybrid strategies that combine natural coastal infrastructure and built elements are being recognized as important coastal adaptation options (Sutton-Grier et al. 2018). In this approach, the timing of planning and establishing a living shoreline is key; it is generally much more difficult to effectively implement this approach when high water or erosion are already causing problems. Many of these actions can be supported by Approach 3.2 (minimize non-climate physical damage to coastal ecosystems and habitats).

Example adaptation tactics:

- Restore vegetated shorelines or add fronting vegetation to dampen wave action (Hanley et al. 2020).
- Plant native vegetation on disturbed dunes to anchor sand (SAGE 2019).
- Manage herbivory to promote the regeneration of desired vegetation in coastal systems.
- Where shorelines have been artificially steepened (e.g., with previous hardening measures), grade the bank and densely plant with vegetation (Erdle et al. 2006).
- Use removable seawalls to protect planted vegetation in its early stages of growth (Sutton-Grier et al. 2015), or use biodegradable toe protection like coir logs for slopes (Shea et al. 2021).
- Establish vegetation and other habitat elements in areas where shoreline infrastructure provides low energy wave environments, such as harbors or behind breakwaters.
- Reverse wetland losses by restoring converted wetlands, such as areas that have been drained and used for agricultural use (Crooks et al. 2011, WI DNR 2015b, WICCI 2017b, Magyera et al. 2018).
- Directly seed or transplant desired wetland vegetation in areas where coastal wetlands are being restored. This may follow other restoration actions, such as ensuring that hydrologic conditions can support wetland vegetation (Wilcox & Whillans 1999, Crooks et al. 2011).

Approach 3.4: Maintain and enhance species and structural diversity in coastal ecosystems.

Climate change may create conditions that are less suitable for some plant species and that provide challenges to seed germination and growth, such as through temperature changes, early spring warming, changing precipitation patterns, and prolonged inundation (Walck et al. 2011, Duveneck et al. 2014). Diverse ecological communities may be less vulnerable to climate change impacts because risk is distributed among multiple species (Engelhardt & Kadlec 2001, Duveneck et al. 2014). Similarly, maintaining a diversity of size and age classes may reduce risk, as species' vulnerability to climate change may vary with life stage. In some coastal ecosystems, another measure of diversity may be "functional redundancy," where important plant traits and roles are represented by multiple species (Brotherton & Joyce 2015). Active management may be applied to enhance these various aspects of species, structural, and functional diversity. Caution is warranted to avoid introducing species that may damage native plant communities. In fact, controlling the spread of non-native *Typha* spp. and *Phragmites* spp. can be among the most effective ways to maintain and enhance species diversity in coastal wetlands (see Approach 3.5: Prevent invasive plant and animal species establishment and minimize their impacts where they occur). Additional examples of actions to increase diversity in wetlands can be found in Climate Adaptation Strategies and Approaches for Conservation and Management of Non-Forested Wetlands (Staffen et al. 2019).

Example adaptation tactics:

- Use diverse species mixes for planting or seeding in restoration projects, using native species where possible and avoiding invasive species.
- Promote landform heterogeneity in coastal restoration projects to help achieve species and structural diversity.
- Create openings in dense wetland vegetation (e.g., cattails) to allow new species to establish.
- Use silvicultural practices (e.g., canopy gap creation, understory thinning, underplanting) in coastal forests to promote a diversity of tree species (Fahey 2014, WI DNR 2015a).
- Develop off-site seed banks and living repositories for native plants that are vulnerable to climate change to maintain wild populations of rare plant species. Work with indigenous communities to identify and store culturally important species in a culturally appropriate way (Tribal Adaptation Menu Team 2019).
- Retain forest cover following loss of ash from emerald ash borer in hardwood swamps and floodplain forests, such as through interplanting, reforestation, and control of invasive plants (WICCI 2017b, D'Amato et al. 2018).

Approach 3.5: Prevent invasive plant and animal species establishment and minimize their impacts where they occur.

Climate change may alter the distribution, abundance, and impact of invasive species (Hellmann et al. 2008). In some coastal ecosystems, climate change might produce conditions that favor invasives like reed canary grass *(Phalaris arundinacea*) which may benefit from warmer temperatures, longer growing seasons, and higher nutrients (Zedler 2007). Similarly, warmer water temperatures, reduced ice cover, and greater nutrient runoff may benefit some aquatic invasive species, with potential consequences for native biodiversity (Rahel & Olden 2008). In coastal ecosystems, invasive species may severely reduce plant diversity and other ecological functions that might help those ecosystems adapt to new climate conditions (Lishawa et al. 2015). Climate change may demand new ways to prevent invasions or prioritize control efforts. It may also offer opportunities for controlling invasions, such as through seasonal drying or poorer conditions for coldwater invasives (Hellmann 2008, Rahel & Olden 2008).

Example adaptation tactics:

- Prevent the introduction of invasive species by following best management practices, such as wood and plant material quarantines, equipment cleaning and inspection (e.g., of boats, construction sites, shoes), and providing education at sites (Poff et al. 2002, WICCI 2017b).
- Incentivize the harvest and use of invasive species for food, medicine, or other personal uses at the edge of invasion to prevent the expansion of invasives into new areas (Magee et al. 2019).
- Remove invasive cattails in younger stands to encourage greater native plant recovery (Lishawa et al. 2015).
- Continue with chemical and biological control efforts to slow the spread of invasive species, such as hemlock woolly adelgid (McAvoy et al. 2017).
- Establish early detection and rapid response protocols and support networks across jurisdictions to identify and control new species infestations in a coordinated manner (Hellmann et al. 2008).
- Prioritize high-quality sites and potential seed sources (e.g., upstream sites) for eradicating invasive plants through physical or chemical treatments (Boos et al. 2010, Hazelton et al. 2014).
- Actively monitor for and control new invasions, such as *Phragmites* spp. and reed canary grass establishment, following extreme storm events or wave disturbance (WICCI 2017a).
- Engage with existing networks on best practices for monitoring and managing invasive species, such as the Great Lakes Phragmites Collaborative (Great Lakes Phragmites Collaborative 2022).
- If invasive plant species are providing stabilization benefits for coastal slopes, plan for quick revegetation after invasive species removal to reduce risks of soil erosion.

Approach 3.6: Maintain and establish refugia for plants and animals.

Within a broader coastal landscape, there may be variation that creates unique sites with the right characteristics to act as refugia. Climate refugia are areas that remain relatively buffered from contemporary climate change over time and enable desired species to persist (Morelli et al. 2016). In coastal ecosystems, refugia may be tied to specific hydrologic settings (Galatowitsch et al. 2009, Sherwood & Greening 2013). For example, certain areas may be sheltered from more extreme water level fluctuations or less exposed to nutrient runoff. Focused management actions may help to identify refugia, maintain their unique site conditions, and protect them from additional stressors. Managing for potential refugia along an inland to waterward gradient may also help species adjust to changing water levels and compliment actions that maintain and create conditions for inland and waterward movement of plants and animals (Approach 4.6).

Example adaptation tactics:

- Preserve areas where unique combinations of microtopography and coastal processes create diversity or provide a buffer from climate stressors.
- Preserve or enhance topographic and bathymetric heterogeneity within coastal wetland habitats to provide high- and low-water refugia (Beller et al. 2019).
- Increase the size of refugia to include a variety of microhabitats, such as a range of moisture and temperature gradients (Powell et al. 2018).
- Modify canopy thinning operations to maintain shade that sustains vernal pools as refugia areas for amphibians (Powell et al. 2018).
- During periods with unfavorable conditions, support and create habitat for key species. For example, remove herbaceous and woody vegetation and redistribute cobble/gravel on beaches to create open beach conditions for the endangered piping plover during prolonged periods low ice scour (US FWS 2013).
- Promote sites that support species and habitats culturally important to tribes (e.g., wild rice in coastal wetlands, paper birch in maritime forests, blueberries in coastal pine and barrens habitats).
- Limit foot traffic and climbing on sensitive coastal cliffs and rock ledges that support at-risk species.
- Where possible, retain or create connectivity among refugia to allow species movement and mixing.

Approach 3.7: Maintain and increase connectivity of coastal habitats.

This approach is focused on increasing connectivity between coastal habitats to enable species to respond more easily to disturbances or changing conditions. Managing coastal landscapes and waterways for connectivity may enhance the flow of genetic material, allow for easier species movement, and reduce lags in migration. Connectivity at multiple scales (local to regional) will be important in responding to climate pressures (Hilty et al. 2020, Albright et al. 2021). For example, in coastal ecosystems, it may be important to maintain connections between habitat types that support species at different life stages, such as vernal pools and larger coastal wetland complexes. The ideas here are focused on general habitat connectivity. Related tactics in Approach 4.6 (maintain and create conditions for inland and waterward movement of plants and animals) include helping species to respond to changing water levels by improving connectivity along an inland to waterward gradient.

Example adaptation tactics:

- Select restoration sites that maximize connectivity between riparian habitats in order to facilitate species range shifts (Perry et al. 2015 following Seavy et al. 2009).
- Provide for terrestrial and aquatic habitat connectivity across roadways or other barriers that divide important habitat, such as fences, dams, or energy infrastructure (Albright et al. 2021).
- Acquire property for preserves or create easements on private landholdings adjacent or close to existing natural areas (Swanston et al. 2016).
- Restore and enhance migration routes that protect species access to important habitats, such as spawning and nursery areas (Dove-Thompson et al. 2011).
- Develop wide movement corridors (> 0.6 mile), because they tend to offer more diverse microclimates and provide live-in habitat for slow dispersers (Albright et al. 2021).
- Manage natural areas or riparian corridors that act as migration corridors to promote their maximum habitat value, and prioritize management in those locations (Swanston et al. 2016, Albright et al. 2021).
- Identify, map, and manage the connectivity of aquatic habitats in the vicinity of coastal wetlands, such as vernal pools, their drainage connections, and pool networks that serve as travel corridors to larger coastal wetland complexes (Wenning 2015).

Strategy 4: Alter coastal ecosystems to accommodate changing hydrology, storm events, and shoreline erosion.

Climate change may contribute to periods of both low and high water levels, and the challenge for many coastal managers will be considering and preparing for both, as well as potentially faster shifts from one state to the other (IUGLS 2012, Notaro et al. 2015, Wuebbles et al. 2019, Magee et al. 2021). It is uncertain whether these fluctuations will be outside of the historic range of variability or not. Climate factors that contribute to periods of low water levels include periods of drought, decreased inputs from tributaries, and increased evaporation caused by higher temperatures and decreased ice cover (IUGLS 2012, Wuebbles et al. 2019). Higher average precipitation in the Great Lakes region and increased heavy precipitation events leading to increased stream inputs, may contribute to high lake level periods (Cherkauer & Sinha 2010, IUGLS 2012, Gotkowitz et al. 2014, Wuebbles et al. 2019, Gronewold et al. 2021). Climate change may also cause more intense and frequent storm events, which are associated with higher wind speeds, increased waves, and storm surges (Mackey 2012, Magee et al. 2021). When combined with high water levels, increasing waves and storm surges have the potential to cause substantial coastal impacts, including coastal erosion, bluff failure, and flooding (Wuebbles et al. 2019, Magee et al. 2021). Proactive consideration of hydrologic change in the Great Lakes can help managers reduce future risks and take advantage of opportunities to sustain ecosystem functions (Erwin 2009).

Approach 4.1: Manage coastal ecosystems to accommodate increased frequency and duration of low water levels.

Climate change may lead to periods of low water in the Great Lakes through decreased ice cover and increased periods of evaporation and late season drought. Water level fluctuations are a natural feature of hydrology in the Great Lakes; however, low water levels that exceed historic lows or occur for longer durations could cause significant concerns for coastal systems, particularly as human communities seek to maintain access and proximity to the water. Low lake levels could reduce hydrologic connectivity between tributaries and the lakes (Wuebbles et al. 2019) and expose or eliminate productive nearshore zones and coastal wetlands that serve important ecological functions (Poff et al. 2002, Taylor et al. 2006). Coastal wetlands could become isolated, reducing habitat for species that require them for spawning and nursery habitat (Poff 2002). This approach seeks to both maintain ecosystem function during low water levels, while considering and preparing for eventual increases in water levels.

Example adaptation tactics:

- Help plants become established further lakeward by protecting new plantings (Poff et al. 2002) and disallowing mowing of wetland plants to favor open beaches.
- In sites with open wetlands that are drying, inter-seed with native wet meadow species tolerant of lower water levels and suitable for the region, such as species with ratings of FACW and FAC that can occur in both wetlands and non-wetlands (Staffen et al. 2019 following Galatowitsch et al. 2009). Consider in advance how these species may respond when water levels increase.
- Where diverse open wetland or beach communities are desired, manage woody species encroachment.
- Promptly control colonizations by non-native wetland species (e.g., *Typha* spp.) that are known to invade coastal wetlands at greater rates during low water periods (Lishawa et al. 2015).
- In coastal wetlands, fill in ditches, block them at their outlets, and re-direct flow away from them to prevent low water tables at higher elevations during low water years (Wilcox & Whillans 1999).
- Prioritize shoreline restoration efforts during periods of low water (with the exception of coastal wetlands), particularly those that restore habitat types that can help reduce risk during high water levels (Keilor & White 2003).
- Remove infrastructure and hard measures that restrict water flow to and through coastal wetlands (Shannon et al. 2019).

Approach 4.2: Manage coastal ecosystems to accommodate increased frequency and duration of high water levels.

Recent years, particularly 2017 into 2021, provide an example of what periods of high Great Lakes water levels might look like and their effects on coastal areas. Climate change may contribute to increased periods of high water in the Great Lakes through greater annual precipitation and intense rainfall events in the Great Lakes Basin (Cherkauer & Sinha 2010, Wuebbles et al. 2019, Gallagher et al. 2020). This approach focuses on managing and helping coastal ecosystems cope with flooding and inundation as a result of high water levels.

However, ideas that may help meet management goals under high water periods are also found in several other approaches within Strategy 4: Alter coastal ecosystems to accommodate changing hydrology, storm events, and shoreline erosion (see Approaches 4.3-4.6). These approaches focus on reducing damage from wind, waves and coastal erosion, reducing or managing surface water runoff, and creating conditions for plant and animal movement in response to increased lake levels. Similarly, tactics related specifically to coastal built infrastructure are found in Strategy 6: Design and modify infrastructure to accommodate future conditions. It is important to note that any tactics undertaken during high water levels should consider and prepare for potential return to low water levels.

Example adaptation tactics:

- Move built infrastructure back from the shoreline and allow native vegetation to grow between infrastructure and the shoreline (Sutton-Grier et al. 2015, Mangham et al. 2017).
- Assess wave energy and identify the extent to which living shorelines are feasible in high water conditions (Gallagher et al. 2020).
- Protect and restore protective barrier beaches ("beach ridges") and sand spits that historically protected coastal wetlands (Wilcox & Whillans 1999); this can potentially be done by reusing dredge spoils to create these types of barriers.
- For coastal restoration projects that include planting and seeding, select native species that can tolerate periods of inundation.

Approach 4.3: Promote features that reduce the impacts of wind and wave energy or damage from coastal erosion.

More frequent storms and increased wind and wave energy in the Great Lakes are expected to worsen shoreline erosion, particularly when these coincide with periods of high water or low winter ice cover (Mangham et al. 2017, Wuebbles et al. 2019). Climate change may also be shifting the direction of storms, causing wind damage or erosion concerns in new areas (Mackey 2012). Increased intensity of wind and wave events can make it more difficult to establish vegetation or maintain desired vegetation composition in coastal ecosystems. Conventional methods of managing storm surge, coastal erosion, and flooding have focused on shoreline hardening; however, it is now apparent that these techniques can have consequences that include erosion and damage of adjacent sites, elimination of important shallow water habitat, and disruption of the hydrologic connections that enable coastal ecosystems to respond to change (Erdle et al. 2006, Lin & Wu 2014, Sutton-Grier et al. 2015, 2018). This approach includes tactics that may help respond to wind, wave energy, or coastal erosion, but not necessarily all three of those impacts simultaneously. Tactics can be designed to account for the type of shoreline (e.g., cohesive bluff vs. sandy shoreline) and other local conditions and risk factors. Taking action before erosion becomes problematic may greatly increase chances of success (see also Approach 3.3: Establish living shorelines by maintaining and restoring coastal vegetation).

Example adaptation tactics:

- Install offshore reef and breakwater structures to protect coastline habitats (SAGE 2019) while considering nearshore processes that should be maintained. The use of submerged reefs at Illinois Beach State Park is an example of such a project (Healthy Port Futures 2022).
- Install underwater barriers to dissipate or disrupt wave energy (Tulaikova 2018).
- Retain or plant vegetation on the top and face of shoreline bluffs to slow erosion and improve stability (Mangham et al. 2017).
- Retain dense wetland vegetation where it might help protect emergent vegetation from increased wind and wave energy.
- Frame lake views through areas of low-growing and selectively pruned vegetation rather than removing vegetation.
- Plant a vegetated buffer of deep-rooted native plants at bluff-top edges and maintain a no-mow buffer of at least 10 feet from bluff-top edges.
- Physically alter the shape of a bluff to make the slope more gradual or include terraces to increase bluff stability (Keilor & White 2003, Mangham et al. 2017).
- Install sand fences to capture shifting and blowing sands and stabilize dunes (NOAA 2010).
- Install hard infrastructure to prevent localized flooding and erosion, where necessary, and with full understanding of potential downsides (EPA 2009, Mangham et al. 2017, Gallagher et al. 2020).
- Restore or enhance native vegetation to protect wetland basin landforms from erosion and wave breaching.

Approach 4.4: Manage sediment to respond to fluctuating water levels.

Climate change is expected to cause prolonged periods of both low and high water levels in the Great Lakes and rapid fluctuations between extremes (IUGLS 2012, Notaro et al. 2015, Wuebbles et al. 2019, Magee et al. 2021). Supporting and restoring natural sediment transport processes (see Approach 1.1) can help coastal ecosystems respond to these fluctuations. However, in some cases, more active and deliberate sediment management may be warranted. For example, managers can plan for low and high water by using sediment dredged during low water periods to proactively nourish or protect areas that might be affected by high water. Some of these tactics should be approached with caution, as they may have effects on disturbance-dependent coastal species, may have downstream consequences, or may require consideration of sediment contamination issues (Brown et al. 2016).

Example adaptation tactics:

- Add or stabilize sediment along shorelines (beach nourishment) (Carmo 2018, SAGE 2019).
- Replace groin fields with riverfront restoration and artificial sand nourishment in river delta and beach areas (Sherwood & Greening 2013, Carmo 2018).
- Use a combination of beach nourishment, sand traps, and planting to establish sand dunes to provide storm protection to coastal infrastructure (Keilor & White 2003, Hanley et al. 2020).

- Strategically use and recycle dredged sediment to create islands or shoals for wildlife, prevent erosion, and recreate wetland protective features. Take advantage of accelerated dredging during low lake level periods for the Great Lakes (Mayne et al. 2021).
- Conduct large-scale beach nourishment by constructing a “sand engine” or other supply that distributes sediment via natural currents over longer (decadal) time periods (de Schipper et al. 2016, Brown et al. 2016, Carmo 2018).

Approach 4.5: Reduce or manage surface water runoff.

The Great Lakes region is projected to receive increased annual precipitation, with increases likely concentrated in winter and spring and with more precipitation falling in heavy rain events (Cherkauer & Sinha 2010, Wuebbles et al. 2019). Even modest changes in precipitation can amplify the magnitude and volume of surface runoff and cause higher peak flows and flashiness in Great Lakes tributaries, increased flooding, and increased duration and frequency of soil saturation and inundation (Magyera et al. 2018). In addition, increased runoff from agricultural and urban areas may compromise Great Lakes water quality (Wuebbles et al. 2019). In bluff systems, runoff can erode the top and face of the bluff, significantly decreasing bluff stability (Mangham et al. 2017). Actions for reducing surface runoff and overland flow may include actions to increase surface roughness, maintain soil porosity, and otherwise disperse concentrated or fast-moving flows of water. These actions may be particularly important in areas prone to erosion or bluff collapse, adjacent to built infrastructure, and subject to early and rapid snowmelt over frozen soils (Shannon et al. 2019). Actions in this approach compliment Approach 1.3: Maintain and enhance infiltration and water storage capacity of soils.

Example adaptation tactics:

- Strategically place downed wood to deflect, slow, and pool overland flow water as snow melts over saturated soils and frozen soils.
- Add retention or detention structures to slow runoff to streams (Perry et al. 2015, WI DNR 2015a).
- On bluffs, direct runoff away from the bluff-top edge, potentially toward a storm sewer or other drainage system (WICCI 2011, Mangham et al. 2017). Minimize water inputs from sources like lawn watering and septic systems.
- Where concentrated flow enters a wetland, such as at a culvert or a storm sewer outfall, install energy dissipation features to limit negative impacts of extreme runoff events on wetlands (Minnesota Stormwater Manual 2019).
- Reduce impervious surface area (Perry et al 2015).
- Use green infrastructure practices that retain water on the landscape or release it slowly, such as permeable pavement, green and blue roofs, and bioretention features. For bluff systems, limit use of rain gardens or other infiltration features near the bluff-top edge to avoid contributing to groundwater issues.
- If shoreline access is desired, use pervious, switchback pathways down the bluff to avoid creating channels for runoff to concentrate.
- Restore or construct wetlands to store water on the landscape.

Approach 4.6: Maintain and create conditions for inland and waterward movement of plants and animals.

Coastal development and land use can often restrict or complicate the ability of coastal ecosystems to shift dynamically in response to changing water levels. Since both high and low water levels are expected in the Great Lakes under future climates, maintaining and improving the ability of species to move inland and waterward according to their hydrologic requirements will be crucial (Kraus & Klein 2009). For example, providing opportunities for movement inland could allow coastal forests, beaches, wetlands, and other ecosystems to persist where high water or coastal erosion are affecting current habitat. In the case of coastal wetlands, providing inland areas that can be inundated could help that ecosystem move in response to high water, while protecting nearshore conditions could help support waterward movement during periods of low water (Mayne et al. 2021). This approach focuses on removing barriers, addressing geomorphic constraints, and actively preparing areas for species' inland and waterward movement.

Example adaptation tactics:

- Remove man-made structures or alter geomorphic conditions to allow wetlands to migrate in response to new water level conditions (Mortsch 1998).
- Maintain open space for ecosystem movement with changing water levels, for example, by using conservation easements (Murdock & Hart 2013).
- Manage invasive species on inland properties that can act as critical corridors and habitat areas under high water to improve the ability of native coastal habitats to establish inland (Morelli et al. 2016, Mayne et al. 2021).
- Preserve and restore habitat corridors along river systems, including both wetland and uplands. This could support linear movement of species along the river corridor and lateral movement to/from upland and wetland to the river (Perry et al. 2015, WI DNR 2015a).
- Regrade slopes to remove elevation barriers to allow ecosystem migration.
- Use a GIS-based approach to identify, map, and prioritize refugia areas for unimpeded upland wetland migration under sustained high-water level scenarios (Morelli et al. 2016, Zuzek 2020).

Approach 4.7: Manage impounded wetlands to accommodate changes in hydrologic variability.

In many Great Lakes coastal areas, wetland communities are maintained through impoundments where water level and flow are controlled by dikes or other structures. Impoundments have been used to sustain wetlands for a variety of reasons (Doka et al. 2006). For example, development and land use constraints on the upslope edge of a wetland or flat topography coupled with high water periods can make it difficult or impossible for wetlands to persist without water control structures. In some cases, a diked wetland with managed water levels may provide an opportunity to preserve specific wetland functions where they might otherwise be lost (Doka et al. 2006, Audubon Great Lakes 2019). However, impounded wetlands have several downsides that can inhibit some of the ecological functions that may be important under future climates. For example, diked wetlands may be less able to tolerate changing water levels or help absorb sediment and nutrient runoff (Doka et al. 2006) and may be at greater risk of invasive species establishment (Herrick & Wolf 2005). In some cases, impounded wetlands may no longer be viable or desirable given current or anticipated changes; in these cases, actions like strategic breaching or restoring connectivity to adjacent waters may be considered and evaluated through risk assessments.

Example adaptation tactics:

- Rehabilitate impoundment structures to be more resilient to changing water levels, where feasible.
- Install selective fish passage structures to promote aquatic connectivity while preventing undesirable fish (e.g., common carp) from entering impounded wetlands (Wilcox & Whillans 1999).
- Where diked wetlands should be preserved, maintain high plant and structural diversity by creating well interspersed vegetation communities (Doka et al. 2006) and removing or reducing invasive and nonnative plants (Herrick & Wolf 2005).
- Mechanically manage water levels to meet restoration goals; for example, mimic more natural lake level fluctuations to support desired species (Audubon Great Lakes 2019).
- Create and maintain deep water areas and channels to create a refuge for fish and wildlife during winter draw-downs and extended periods of ice cover and low oxygen in winter (Mayne et al. 2021).
- Where temporary isolation of wetlands from open waters is desired (e.g., for restoration), consider the use of temporary dikes using aquadams (Wilcox & Whillans 1999).
- Reestablish hydrologic connections and natural water level fluctuations through portable cofferdams, dewatering to allow wetland plants to grow from the seed bank (Kowalski et al. 2009).
- Discourage the construction of new permanent dikes, unless mimicking the protective function of a lost barrier beach, and include water control structure placement that allows hydrological connection similar to the original wetland (Wilcox & Whillans, 1999).
- Where dikes are degraded and costly to repair, strategically breach dikes to recouple coastal wetland processes with the open waters.

Strategy 5: Facilitate transformation of coastal ecosystems by adjusting plant species composition.

Climate change may drive alterations in coastal community composition. Climate parameters are changing at a rapid and unprecedented pace, setting up conditions where local plants may no longer be ideally suited to local conditions (Breed et al. 2013, Prasad et al. 2014, Staffen et al. 2019). Climate change has already altered the range distributions of species, leading to the introduction of novel species into ecosystems (Wuebbles et al. 2019). As species move in response to climate change, it is expected that new communities will form, invasive species will create concerns in new areas, and ecosystem functions will be altered (Mortsch 2018). For example, changes in phenology may create timing mismatches between interdependent events, leading to changes in community composition and ecosystem functioning (Mortsch 2018). Managers may determine that maintaining current conditions or restoring ecosystems to a previous condition is not feasible at some sites and that managing for a range of acceptable trajectories is more practical. This strategy seeks to maintain overall ecosystem function, health, and habitat value by enabling and assisting transitions of species and communities in suitable locations. Many of these actions may be most suitable for, and pose less risk to, ecosystems that are already disturbed, as opposed to intact systems. Though this strategy is focused primarily on plants, please see A Menu of Climate Change Adaptation Actions for Terrestrial Wildlife Management (Handler et al. In Press) for more on facilitating the transition of animal communities.

Approach 5.1: Favor or restore native species and genotypes with wide moisture and temperature tolerances.

Some native and locally occurring species may be more adapted to anticipated site conditions or stressors associated with climate change, such as greater periods of inundation and drought. Promoting the establishment of these species could help to transform more vulnerable coastal communities into sustainable and functional systems. In coastal forests, using management to favor native species with wide ecological amplitude and tolerance to a wide variety of climate and site conditions may help facilitate a gradual shift in forest composition (Shannon et al. 2019). This approach does carry some risk; it may favor generalist species and may run counter to goals that are focused on conservation of culturally important, rare, or threatened species.

Example adaptation tactics:

- Favor genotypes or species that are better adapted to frequent or severe fluvial disturbance and higher water availability, and locate plantings on surfaces that are both suitable under current conditions and protected from increased disturbance (Perry et al. 2015).
- Favor plant species in wetlands that are resistant to desiccation, such as perennial species that spread by runners and those with deep tap roots (Shannon et al. 2019).
- Establish plant species that can survive in high-energy coastal habitats and tolerate increased wave action, such as common threesquare (*Schoenoplectus pungens*) (Albert et al. 2013).
- Plant native, flood-tolerant species in coastal areas that are vulnerable to flooding and inundation but that currently do not support such species. Look to nature for candidates, such as native species associated with emergent and submergent marsh communities (Epstein 2017).
- In coastal forests, underplant a variety of native species on a site to increase overall species richness and provide more options for future management.
- Consult planting guides to understand what types of vegetation might be suited to current and future conditions, for example, see Carter et al. (2021) for a planting guide for bluff systems in Southeastern Wisconsin.

Approach 5.2: Increase genetic diversity of seed and plant mixes.

In many coastal areas, natural gene flow has been limited or interrupted due to habitat fragmentation and loss. In addition, local seed sources commonly used in restoration projects may be poorly adapted to future climate conditions (Broadhurst et al. 2008, Prober et al. 2015, Berrang 2019). Increasing genetic diversity of plant and seed mixes in restoration projects could mimic more natural gene flow, potentially increasing population fitness and adaptive capacity. Introducing genotypes from new areas has associated risks, including the potential for outbreeding depression, maladaptation, and inadvertent introduction of aggressive genotypes (Broadhurst et al. 2008). These risks may be lessened by carefully delineating seed transfer zones and avoiding longer-distance introductions.

Example adaptation tactics:

- Consider different seed sourcing or "provenancing" methods to enhance diversity while reducing risk of negative consequences. For example, employ "regional admixture provenancing," which encourages seed collection from several wild sources within a defined seed transfer zone (Bucharova et al. 2019).
- Collect seed from large populations rather than small, fragmented ones to help limit the introduction of undesirable traits associated with inbreeding depression (Breed et al. 2013).
- Plant seeds or seedlings originating from seed zones that resemble the expected future conditions of the planting site (Huff & Thomas 2014, Berrang 2019).
- Use small amounts of seed collected from seed source locations that have been updated to align with future climate conditions, and use these to establish seed production areas for restoration projects. This may be particularly important for long-lived plants such as trees. Note that it can take 30 or more years for some tree species to start producing useful amounts of seed (Berrang 2019).
- Employ "climate-adjusted provenancing" by supplementing locally collected seed with seed collected along a linear climate gradient that aligns with climate change projections (Prober et al. 2015).

Approach 5.3: Disfavor species that are distinctly maladapted.

Climate change may alter coastal environments beyond a species' ability to adapt. For example, a species at the southern edge of its range may face more pressures as conditions change (Duveneck et al. 2014). Models that incorporate climate change and species' life history characteristics can help to identify species that are likely to decline (Prasad et al. 2014). Management can be used to maintain vegetation and ecosystem function in response to species declines and during periods of transition. This may include shifting management focus and effort away from declining species or restoration efforts with low probability of success. It could also mean actively promoting new species assemblages in ecosystems where the dominant species are declining or likely to disappear (Shannon et al. 2019). This approach should be used with caution; for example, if a species is of cultural importance to tribes, it may be worth extra time and effort to retain that species on the landscape as long as possible and to seek out refugia where supporting that species might be more successful. In addition, many species endemic to the Great Lakes are located in coastal areas, so efforts to retain these species may be warranted.

Example adaptation tactics:

- Remove unhealthy individuals of a declining species in order to promote other species expected to fare better. This does not imply that all individuals should be removed, and healthy individuals of declining species can be retained as legacies (Swanston et al. 2016).
- Anticipate and manage rapid decline of species with negative prognoses in both the short and long term (e.g., hemlock, ash) by having adequate seed stock of a desired replacement species expected to do well under future climate conditions (Swanston et al. 2016).
- Retain species of cultural importance as long as possible, and make an effort to locate and protect refugia for these species (Tribal Adaptation Menu Team 2019).
- Avoid establishing plant species or stocking fish species where local conditions are no longer favorable for their survival.

Approach 5.4: Introduce species that are expected to be adapted to future conditions.

Maintaining ecosystem function may involve the active introduction of species or genotypes to areas that they have not historically occupied, an action known as assisted migration or assisted colonization (Hoegh-Guldberg et al. 2008, Handler et al. 2017). Different forms of assisted migration carry different levels of risk that need to be carefully considered in each management context. Assisted migration may be more appropriate in severely fragmented ecosystems or when rehabilitating disturbed areas where there are minimal risks to existing species (Hoegh-Guldberg et al. 2008, Handler et al. 2017). Confining the movement of species within their current or historic range or slightly beyond is considered a more conservative approach (Havens et al. 2015). An example would be including common or widespread species in a restoration project from nearby southerly or drier locales (Galatowisch et al. 2009). It may also be appropriate to focus efforts on species for which there is ample information on their life histories and less chance of them posing an invasion risk (Hoegh-Guldberg et al. 2008, Havens et al. 2015).

Example adaptation tactics:

- Shift tree species mixes to include species less vulnerable to climate change, such as in ecosystems already impacted by ash mortality that require reforestation (WICCI 2017c).
- Plant flood-tolerant species, such as swamp white oak and silver maple, on sites that are expected to become more prone to flooding and that are currently not occupied by flood-tolerant species (Shannon et al. 2019).
- Plant drought-tolerant species in sites that are expected to experience more frequent dry conditions throughout the growing season (e.g., due to soil or hydrological characteristics) (Staffen et al. 2019).
- Consult planting guides to understand what types of vegetation might be suited to current and future conditions, for example, see Carter et al. (2021) for a planting guide for bluff systems in Southeastern Wisconsin.

Approach 5.5: Move at-risk species to locations that are expected to provide more suitable habitat.

A subset of assisted migration, sometimes called species-rescue assisted migration, focuses on avoiding extinction of species threatened by climate change (Pedlar et al. 2012, Handler et al. 2017). This may be an approach to consider for species that are culturally significant, rare, threatened, or restricted in movement by highly fragmented landscapes. Considerable uncertainty surrounds the likelihood for success in longer-distance relocations, and a high failure rate for establishment is common (Godefroid et al. 2011). Risks include potentially invasive behavior of a translocated species, alteration of ecological processes (e.g., nutrient cycling), transport of diseases and parasites, and hybridization with closely related species (Maschinski & Albrecht 2017, Staffen et al. 2019). In the case of species that are culturally significant to tribes, access can be provided for Tribal members to continue to harvest or otherwise maintain relationships with these species once they are moved.

Example adaptation tactics:

- Plant or seed a rare or threatened plant species that is at risk for extinction to a newly suitable habitat outside its current range, targeting multiple locations to build redundancy (Powell et al. 2018, Shannon et al. 2019).
- Store seeds of vulnerable plant species for establishment at a suitable location in the future (Powell et al. 2018).
- Assist the migration of aquatic or terrestrial wildlife around barriers by trapping and releasing in newly suitable locations.
- Employ resources such as the NatureServe Climate Vulnerability Index or U.S. Fish and Wildlife Service's Risk Assessment and Mapping Program to identify species that are vulnerable to climate change as well as areas where habitat is projected to be suitable for them (Staffen et al. 2019).

Strategy 6: Design and modify infrastructure to accommodate future conditions.

Climate-driven changes like fluctuating water levels, increased wind and wave action, warmer winters and less ice cover, extreme rainfall, and altered coastal visitor use will all affect coastal infrastructure including docks, piers, shoreline protection structures, bridges, roads, trails, water treatment facilities, coastal residences, and more (Keilor & White 2003, Wuebbles et al. 2019, Gallagher et al. 2020). In some cases, coastal infrastructure may be maladaptive; for example, infrastructure can alter the sediment transport dynamics that supply sand to dynamic beaches, bars, and spits that protect coastal ecosystems (Livchak & Mackey 2007). In other cases, infrastructure may pose safety hazards if it is unable to withstand flooding or extreme events (Sutton-Grier at al. 2018). Coastal infrastructure design can consider the potential effects on local landforms, hydrology, and shoreline vegetation to help support coastal habitat and human safety as the climate changes. For example, built infrastructure could offer wave protection for vegetation or human communities (Sutton-Grier et al. 2018, SAGE 2019). Changing conditions present new considerations of how infrastructure design and placement can harm or support ecosystems, coastal safety, and accessibility of coastal areas for multiple user groups.

Approach 6.1: Reinforce infrastructure to meet expected conditions.

In some cases, it may be necessary to improve and update built infrastructure to respond to climate pressures, particularly when that infrastructure serves a high-value or critical purpose. For example, high-energy or working waterfronts may need upgraded shoreline structures to account for increased wave energy or changing wind direction (SAGE 2019). Built infrastructure can also play a role in supporting goals for managing various natural resources. For example, updating water treatment infrastructure to eliminate combined sewer overflows may help improve the water quality of the Great Lakes while accommodating increasing heavy rainfall (Wuebbles et al. 2019). This approach should be employed with caution and with a full understanding of potential drawbacks or maladaptive characteristics of reinforced infrastructure (Livchak & Mackey 2007).

Example adaptation tactics:

- Enhance existing breakwaters to attenuate wave impact on wildlife habitat (EPA 2009, SAGE 2019).
- Upgrade shore protection structures to accommodate increasing wave energy (Mangham et al. 2017).
- Update and maintain urban water treatment infrastructure to account for increasing runoff and sedimentation (Wuebbles et al. 2019).
- Improve dikes or other impoundment structures to be more resilient to changing water levels.
- Enhance bottom-scour protection at the base of coastal protection structures and infrastructure to protect against undermining at low water levels.
- Routinely inspect shore protection infrastructure to identify damage early so repair or replacement can be made before damage worsens and severely threatens facility assets and operations.
- Conduct vulnerability assessments to identify priority assets to protect or repair.

Approach 6.2: Design infrastructure with low-impact or ecologically friendly features.

In coastal areas, there may be ways to design and build infrastructure that is supportive of coastal ecosystem health and processes. For example, combining natural and built infrastructure may meet goals for coastal protection while also supporting coastal ecosystem habitats (Sutton-Grier et al. 2015, 2018). In some cases, infrastructure can be designed to include habitat-friendly features or even to support habitat goals for desired species. At the watershed scale, actions that use natural materials (e.g., soils and plants) and that enable the landscape to distribute water rather than concentrate it may minimize impacts on vulnerable downstream and coastal sites (Ahiablame et al. 2012). Approach 3.3: Establish living shorelines by maintaining and restoring coastal vegetation and Approach 4.7: Manage impounded wetlands to accommodate changes in hydrologic variability, also include actions that may use built infrastructure to support natural resources.

Example adaptation tactics:

- Where seawalls may be necessary, construct lower seawalls by enhancing and maintaining natural vegetated foreshores that reduce wave impact (Hanley et al. 2020).
- Design or retrofit bulkheads to provide habitat features for aquatic species (Cuyahoga County Planning Commission).
- Modify coastal structures with textured surfaces or additional smaller cobble stones that can provide surfaces for aquatic species that are unavailable on smooth concrete (Shea et al. 2021).
- Divert and disperse stormwater from impervious surfaces (such as walkways, roofs, roads, and trails) to forests, densely vegetated areas, swales, and filter strips to increase water retention on site and enhance filtering of water (Ahiablame et al. 2012).
- Use pervious pavement for new walkways, roads, or trails.
- Where concentrated flow enters a wetland, such as at a culvert or a storm sewer outfall, install energy dissipation features to reduce negative impacts of extreme runoff events (Minnesota Stormwater Manual 2019).

Approach 6.3: Adjust the placement, design, and planned lifespan of infrastructure.

While climate change projections and impacts were likely not considered in infrastructure design processes until recently, such considerations are vital now, particularly for infrastructure located in coastal areas prone to flooding or with highly erodible soils and for high-traffic areas such as roads, bridges, and trails (Strauch et al. 2015, Staffen et al. 2019). Since Great Lakes water levels are expected to include periods of both high and low water, infrastructure can be designed to creatively accommodate both conditions or a shorter period of use. Using infrastructure with a shorter planned lifespan (e.g., temporary boardwalks, bridges) can minimize long-term risks associated with permanent structures while still meeting near-term goals. While initially costly, the relocation or rerouting of vulnerable infrastructure to less vulnerable areas may reduce long-term maintenance costs and limit structural losses (Keller & Ketcheson 2015, Strauch et al. 2015, Staffen et al. 2019).

Example adaptation tactics:

- Construct docks to accommodate greater water level fluctuations (Krumenaker, 2014).
- Reroute road and trail infrastructure out of areas at risk for flooding or storm damage (Strauch et al. 2015). For example, see Marquette's Lakeshore Boulevard relocation project (Superior Watershed Partnership and Land Conservancy 2018).
- Adopt setback regulations for new building development based on anticipated erosion over the useful life of the structure to increase opportunities for natural shorelines (Luloff & Keillor 2016).
- Move built infrastructure (e.g., boardwalks, buildings, visitor facilities) back from the shoreline or to areas with low flooding risk (Strauch et al. 2015).
- Relocate existing buildings away from the shoreline, particularly in bluff areas where shoreline stability is complex and erosion is difficult to control (Keilor & White 2003).

- Design trails, boardwalks, or other visitor accommodations with a planned lifespan, and re-evaluate their placement and necessity at the end of a planned period of use.
- Promote relocation of homes and other assets as an alternative to shoreline hardening to protect properties (Mangham et al. 2018).
- Adopt long-lot formats for new coastal subdivisions that can make future home relocation easier (Mangham et al. 2018).

Approach 6.4: Remove infrastructure and readjust systems.

Roads, trails, levees, breakwaters, and other forms of infrastructure may become increasingly difficult to maintain as the climate changes. Impacts such as more severe storms, fluctuating lake levels, and higher flow events exert greater and more frequent stress on coastal infrastructure and may even jeopardize human safety. In some situations, removing or decommissioning infrastructure may represent the most practical and cost-effective approach. Such actions may also be leveraged to improve quality and functionality of coastal ecosystems. For example, reducing impervious surfaces may result in decreased overland flow and stormwater velocity, thus reducing runoff and erosion and improving water quality. Infrastructure removal may present opportunities to restore natural hydrologic fluctuations to coastal wetlands or other ecosystems (NOAA 2010). Finally, removing hard shoreline infrastructure and allowing it to be replaced by natural infrastructure and vegetation can improve habitat value, water filtration, and carbon storage, among other ecosystem services (Sutton-Grier at al. 2015).

Example adaptation tactics:

- Remove shoreline hardening structures such as bulkheads, dikes, and other engineered structures to allow for shoreline migration (EPA 2009).
- Decommission and revegetate unnecessary roads or trails (Shannon et al. 2019).
- Strategically remove shoreline hardening in sediment source areas to allow for natural erosion and transport processes.
- Strategically breach dikes to recouple coastal wetland processes with the open waters, especially where dikes are degraded and costly to repair.
- Remove hard structures that restrict flow such as undersized culverts, dams, concrete armoring, and weirs (Shannon et al. 2019, Yochum & Reynolds 2020).

Applying the Menu: Adaptation Demonstration Projects

We released a draft menu of adaptation strategies and approaches in May, 2021. We used this draft to test the application of the menu with three real-world coastal management projects: coastal wetland adaptation at Apostle Islands National Lakeshore (WI); a shoreline and coastal restoration project at Ford Cove on Lake St. Clair (MI); and a marsh bird habitat improvement project in Allouez Bay on Lake Superior (WI). We used the menu in conjunction with the *Adaptation Workbook* (Swanston et al. 2016) in facilitated virtual workshop sessions with each project team. Project teams used the *Adaptation Workbook* to: (1) describe their goals and objectives; (2) assess vulnerability; (3) evaluate their objectives in light of climate change; (4) select adaptation strategies, approaches, and tactics using the draft menu; and (5) develop monitoring metrics to evaluate the effectiveness of the proposed adaptation actions. We gathered feedback from project teams and workshop facilitators on the organization, wording, and utility of the menu to refine the strategies and approaches. This published version reflects those suggested changes.

Ford Cove Shoreline and Coastal Restoration Project

Ford House and partners are planning for the restoration of 1 mile of currently hardened Lake St. Clair coastline and over 17 acres of adjacent marsh, nearshore habitat, and forested wetlands. The team considered climate change impacts and vulnerabilities that were important for this project area, including the potential for more rapid and extreme water level fluctuations and increased wave heights. To help meet their restoration goals, the project team considered a variety of adaptation actions, including reshaping parts of the restoration area to provide habitat diversity and transitional zones for flora and fauna (Approach 3.4) and providing floating habitat that can cope with changing water levels (Approaches 4.1 & 4.2). See more at forestadaptation.org/ford-cove.

Ford Cove. Photo courtesy of Ford House.

Apostle Islands National Lakeshore; Coastal Wetland Vulnerability and Adaptation

Coastal wetlands in the Apostle Islands National Lakeshore are managed in part for preservation. A project team considered how climate change might affect their ability to maintain a stable number and distribution of wetland communities with high florisitic quality over time. They used the Great Lakes coastal ecosystems menu to consider where management interventions might be appropriate. For example, actions could include continuing early detection and rapid response for invasive species and removing invasive cattail litter from wetlands to minimize structural and chemical changes (Approach 3.5). Additionally, carefully considering placement of new docks could avoid altering sediment transport that supports wetland landforms and protective barriers (Approach 1.1). See more at forestadaptation.org/APIS-coastal-wetlands.

Apostle Islands coastal wetland. National Park Service photo.

Allouez Bay Marsh Bird Habitat Improvement Project

This highly collaborative project focuses on increasing marsh bird habitat quality by managing invasive plant species, maintaining and enriching native plants, and increasing hemi-marsh conditions at Allouez Bay. Climate challenges for this project include the potential for increasing high-energy storm events and rapid, high magnitude water level changes. These climate impacts could favor invasive cattails in the Bay and challenge the ability to establish and maintain desirable native vegetation, as well as make conditions challenging for nesting marsh birds. Some of the adaptation actions the group considered included creating features to buffer the effects of wind and wave energy (Approach 4.3) and maintaining dense vegetation in strategic locations to protect emergent vegetation from wind and waves (Approaches 3.4 and 4.3). Adaptation actions are directly impacting the scope and timing of the project. The group is planning management actions in several different phases, in part to provide wind and wave protection before undertaking certain vegetation restoration actions. See more at forestadaptation.org/Allouez-Bay

Allouez Bay workshop participants. Photo courtesy of Kristen Schmitt.

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Appendix

The following pages feature:

- Appendix 1: Menu of Adaptation Strategies and Approaches for Great Lakes Coastal Ecosystems – Summary for Printing (1 page)
- Appendix 2: Community Engagement and Coastal Planning Options (2 pages)

Menu of Adaptation Strategies and Approaches for Great Lakes Coastal Ecosystems

Strategy 1: Maintain and enhance fundamental hydrologic processes and sediment dynamics.
Approach 1.1: Maintain and restore natural sediment transport processes.
Approach 1.2: Maintain and restore hydrological connectivity between hydrological features.
Approach 1.3: Maintain and enhance infiltration and water storage capacity of soils.

Strategy 2: Maintain and enhance water quality.
Approach 2.1: Moderate water temperature increases.
Approach 2.2: Reduce sediment deposition.
Approach 2.3: Reduce loading and export of nutrients and other pollutants.

Strategy 3: Maintain, restore, and manage coastal vegetation
Approach 3.1: Maintain the integrity of unique plant communities, coastal wetlands and estuaries, and their integral landforms.
Approach 3.2: Minimize non-climate physical damage to coastal ecosystems and habitats.
Approach 3.3: Establish living shorelines by maintaining and restoring coastal vegetation.
Approach 3.4: Maintain and enhance species and structural diversity in coastal ecosystems.
Approach 3.5: Prevent invasive plant and animal species establishment and minimize their impacts where they occur.
Approach 3.6: Maintain and establish refugia for plants and animals.
Approach 3.7: Maintain and increase connectivity of coastal habitats.

Strategy 4: Alter coastal ecosystems to accommodate changing hydrology, storm events, and shoreline erosion.
Approach 4.1: Manage coastal ecosystems to accommodate increased frequency and duration of low water levels.
Approach 4.2: Manage coastal ecosystems to accommodate increased frequency and duration of high water levels.
Approach 4.3: Promote features that reduce the impacts of wind and wave energy or damage from coastal erosion.
Approach 4.4: Manage sediment to respond to fluctuating water levels.
Approach 4.5: Reduce or manage surface water runoff.
Approach 4.6: Maintain and create conditions for inland and waterward movement of plants and animals.
Approach 4.7: Manage impounded wetlands to accommodate changes in hydrologic variability.

Strategy 5: Facilitate transformation of coastal ecosystems by adjusting plant species composition.
Approach 5.1: Favor or restore native species and genotypes with wide moisture and temperature tolerances.
Approach 5.2: Increase genetic diversity of seed and plant mixes.
Approach 5.3: Disfavor species that are distinctly maladapted.
Approach 5.4: Introduce species that are expected to be adapted to future conditions.
Approach 5.5: Move at-risk species to locations that are expected to provide more suitable habitat.

Strategy 6: Design and modify infrastructure to accommodate future conditions.
Approach 6.1: Reinforce infrastructure to meet expected conditions.
Approach 6.2: Design infrastructure with low-impact or ecologically friendly features.
Approach 6.3: Adjust the placement, design, and planned lifespan of infrastructure.
Approach 6.4: Remove infrastructure and readjust systems.

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Appendix 2: Community Engagement and Coastal Planning Options

The adaptation strategies and approaches presented in this document have been designed primarily for those planning and implementing on-the-ground management actions. However, many coastal adaptation actions may benefit greatly from broad engagement that promotes coordinated planning and policy (Kraus & Klein 2009, Franks-Taylor et al. 2010, Pearsall et al. 2012a, Pearsall et al. 2012b). Coastal ecosystems often represent multiple community interests and interconnected ecosystem dynamics, so this level of planning may involve people and organizations beyond the coastal practitioners charged with executing treatments on the ground. Engaging with the community, tribes, policy makers, and different disciplines could help practitioners consider the range of possible outcomes from management actions and promote climate change adaptation across large scales (NOAA 2010). For example, coordinated planning could work to address issues like zoning, water quality, and sediment management at a broader scale.

Forest trail. Photo courtesy of Danielle Shannon.

Though community engagement, planning, and policy strategies are beyond the scope of this document, we have provided some ideas below based on expert input and gathered from documents that cover coastal adaptation through a planning and policy lens. These actions are not recommendations but rather illustrate a broader set of options that may be useful for some projects. Ideas like these could be incorporated into adaptation planning processes like the *Adaptation Workbook*. See more ideas in (Mangham et al. 2018) and the Lake Biodiversity Conservation Strategies (Kraus & Klein 2009, Franks-Taylor et al. 2010, Pearsall et al. 2012a, Pearsall et al. 2012b). For more on funding, see (Mangham et al. 2018, NOAA 2021).

Community engagement, planning, and policy options:

- Promote community engagement in coastal management decisions.
- Revise ordinances and permitting to be more responsive to coastal ecosystem changes.
- Coordinate planning across ownership and scales to respond to coastal ecosystem vulnerabilities.
- Employ incentives to minimize coastal ecosystem vulnerabilities.

Promote community engagement in coastal management decisions.

- Carefully consider how and when to collect input or conduct outreach on project goals, climate vulnerabilities, and adaptation responses.
- Gather input from community members with a diverse range of perspectives, such as historically marginalized and underrepresented groups, indigenous communities, landowners, recreational users, policy makers, and others.
- Respect and consider values of indigenous communities in management decisions.
- Support facilitated visioning exercises or other processes to lay out and identify shared values (Mangham et al. 2018).
- Support public-private partnerships that can help achieve goals, such as coastal hazard mitigation (Mangham et al. 2018).
- Explicitly consider socioeconomic and community benefits when weighing pros and cons of adaptation actions, such as the impacts to frontline communities.
- Enhance knowledge, technical skills, and information exchange with local policy makers and land use planning authorities to build capacity (Franks-Taylor et al. 2010).
- Develop new coastal homeowner tutorials to highlight appropriate erosion solutions, methods, and materials (Mangham et al. 2018).

Revise ordinances and permitting to be more responsive to coastal ecosystem changes.

- Revise rules and permitting processes to allow breakwater structures that can lower wave energy and allow the installation of living shorelines (Mangham et al. 2018).
- Add fees to coastal structures that would restrict or trap sediment and use the proceeds for beach nourishment or other sediment management activities (Mangham et al. 2018).
- Develop a review and response mechanism for municipal ordinances. Review policies and make changes either periodically or after certain criteria are met (e.g., coastal erosion reaches a certain threshold) (Mangham et al. 2018).
- Develop flexible county ordinances to implement greater setbacks for developments where risks are high. Fund coastal erosion studies to identify risk (e.g., erosion rates vary with substrate, elevation, and slope).
- Conduct risk assessments for coastal properties prior to sale (Mangham et al. 2018).

Coordinate planning across ownership and scales to respond to coastal ecosystem vulnerabilities.

- Coordinate coastal ordinances among municipalities (e.g., bluff vegetation ordinances) (Mangham et al. 2018).
- Create a regional sediment management plan (Pearsall et al. 2012b).
- Develop and implement collaborative watershed plans that integrate green infrastructure principles (Pearsall et al. 2012b).
- Promote policies and programs that reduce nutrient losses in agricultural areas and nutrient delivery into waterways (Pearsall et al. 2012a).
- Promote ecosystem-based watershed planning to foster closer cooperation between local towns and higher levels of government (e.g., County and State governments) (Kraus & Klein 2009).
- Modify zoning and restrict development in sensitive areas.
- Map and prioritize areas for unimpeded upland wetland migration under sustained high-water level scenarios (Morelli et al. 2016).
- Protect coastal sediment feeder areas and prohibit armoring of those areas to promote sediment movement (Mangham et al. 2018).

Employ incentives to minimize coastal ecosystem vulnerabilities.

- Employ rolling easements that can help coastal ecosystems respond to fluctuating water levels (EPA 2009).
- Employ easements (or transfer of development rights) to promote undeveloped shoreline (Mangham et al. 2018).
- Purchase land that is at risk of flooding, storm damage, erosion, or bluff collapse, and use it for conservation.
- Employ land exchange programs, in which owners can exchange property in a flood risk area for other land, allowing ecosystems to adapt to changes.
- Establish payments to farmers to implement BMPs to reduce sediment, phosphorous, and nitrogen pollution in priority watersheds (Franks-Taylor et al. 2010).
- Promote certification programs for nutrient management that help increase farmers' profits while reducing agricultural nutrient runoff. One example is 4R certification (Right fertilizer source, at the Right rate, at the Right time, and with the Right placement), which certifies crop advisors and nutrient service providers (Kerr et al. 2016).

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