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Dynamic coasts, resilient futures: Navigating changes in the Great Lakes – Foreword to the special section☆,☆

Lorelle A. Meadows [a,*], Ethan Theuerkauf [b], Cary Troy [c], Pengfei Xue [a,d,e], Guy Meadows [a], Chin Wu [f]

[a] Great Lakes Research Center, Michigan Technological University, Houghton, MI, USA
[b] Department of Geography, Environment, and Spatial Sciences, Michigan State University, MI, USA
[c] Purdue University, Lyles School of Civil and Construction Engineering, West Lafayette, IN, USA
[d] Department of Civil, Environmental and Geospatial Engineering, Michigan Technological University, Houghton, MI, USA
[e] Environment Science Division, Argonne National Laboratory, Lemont, IL, USA
[f] Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI, USA

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ABSTRACT

Historically, research on coastal processes has largely been concentrated on oceanic environments which have much in common with the Great Lakes but also differ in significant ways. This is particularly true with respect to substantial and lasting water level fluctuations that occur on seasonal and decadal time scales that differ temporally from shorter term tidal fluctuations and greatly exceed long-term oceanic sea level rise. Since the late 1990s, the Great Lakes basin has experienced record-breaking high and low water levels as well as more frequent and intense storms. This combination of factors has led to changes to these nearshore environments and stimulated new and exciting coastal research characterizing and quantifying these changes and offering new insights into Great Lakes coastal processes. Studies in this special section address these unique coastal landscapes shaped by both natural forces (e.g., ice dynamics, waves, and fluctuating lake levels) and human influences (armoring, coastal structures, sediment nourishment, and policy interventions). The findings shared in this collection provide actionable knowledge for anticipating change, mitigating risk, and building long-term resilience while calling for adaptive management frameworks to foster proactive, equitable stewardship of the Great Lakes shorelines.

1. Introduction

Since the late 1990s, record-breaking water levels, both low and high, have led to widespread coastal changes throughout the Laurentian Great Lakes. The combination of extreme high water levels and more frequent and intense storms not only brought about changes to these nearshore environments but also stimulated new and exciting coastal research. Recently completed research has not only characterized and quantified these changes but has led to new insights associated with Great Lakes coastal processes, which are historically under-studied compared to ocean and estuarine environments. Understanding the current conditions, trends, and emerging threats to the Great Lakes from local to basin-wide scales contributes to proactive coastal management both now and into the future.

Historically, research on coastal processes has largely been concentrated on oceanic environments whose dynamics have much in common with the Great Lakes but also differ in significant ways. These differences mean that research approaches and models developed for oceanic coasts may not always be directly applicable to the Great Lakes. This is particularly true with respect to substantial and lasting water level fluctuations occurring on seasonal and decadal time scales that differ temporally from shorter term tidal fluctuations and greatly exceed long-term oceanic sea level rise. In addition, the resulting sedimentation patterns, impacts of seasonal ice cover, and the necessary strategies for

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* Corresponding author.
E-mail address: lameadows@mtu.edu (L.A. Meadows).

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addressing coastal resilience in the face of these challenges further set apart the Great Lakes as a unique coastal environment. This special section features recent findings relevant to these unique characteristics of Great Lakes coastlines and offers significant insights into approaches specifically designed to address these distinctive needs. This collection of new articles features a wide range of research, including local and regional studies, the development of cutting-edge regionally focused research and assessment tools, and well-documented best practices for management of Great Lakes coastlines and resources.

2. Research on Great Lakes coastal processes

While there are several natural mechanisms influencing sediment distribution along the Great Lakes coasts, human interventions play a dominant role in altering sediment pathways, particularly in response to shoreline erosion, habitat degradation, and infrastructure vulnerability. In this special section, authors study both natural and anthropogenic drivers of sediment transport, creating advances crucial to formulating integrated coastal management strategies.

Although the interaction of ice with incident wave energy is well recognized as a factor in coastal evolution along both the Great Lakes and ocean coastlines, process-based insights into Great Lakes ice-sediment interactions are generally lacking and critically needed for modeling and managing coastlines in cold regions. In a comprehensive study of five Great Lakes beaches, Dodge et al. (2025) performed detailed ice core data analysis revealing the specific mechanisms by which sediment can be entrained into ice over a broad range of energetic nearshore environments. Findings suggest that while ice can transport sediment, its contribution to the overall sediment budget is often minor due to difficulties in offshore movement of ice-rafted debris. However, ice may still significantly impact sediment transport through processes like bed scour and presents an opportunity for future research into this phenomenon.

In addition to the unique dynamics of the winter environment on coastal change, it is important to cast current change in the context of historical natural processes and specific coastal environments. To do this, Nelson-Mercer et al. (2025) used historical shoreline imagery along the Indiana shoreline of Lake Michigan to determine the magnitude, rates, and spatial variability of shoreline changes, finding that shoreline erosion during recent high waters were large but consistent with other historical high water periods. However, the recent high waters were preceded by a prolonged period of low water levels and below-average wave energy, creating wide beaches that helped to buffer this erosion. Thus, by placing current erosion rates in the context of historical conditions, coastal managers and policymakers can more accurately assess the risks and potential future coastal changes more accurately. To further our ability to produce long hindcasts of wave conditions from which historical patterns and trends can be inferred, Abdelhady and Troy (2025) present a novel machine learning-based (ML) framework for simulating wave heights from wind observations. Because wind observations extend well beyond the first deployment of Great Lakes buoys in the late 1970s, this framework offers a unique avenue to develop long-term wave time series. The authors used this method to perform a 70-year ice-free hindcast of waves near Chicago, Illinois, in Lake Michigan.

The Great Lakes are home to a variety of unique coastal environments. By recognizing and acknowledging this, Mattheus and colleagues (Mattheus, 2025; Mattheus and Barklage, 2025; Mattheus and Theuerkauf, 2025; Mattheus et al., 2025) demonstrate the potential for development of more precise, site-specific strategies for coastal management. These studies present a thorough evaluation of the coastal dynamics of a fragmented littoral system, which, while unique to southwestern Lake Michigan, provide key insights into the value of robust studies of this nature in improving comprehensive knowledge of regional coastal processes and the effectiveness of coastal management policies and practices. Their work encompasses four robust examples of how detailed studies of geomorphic changes, ice dynamics, and sand-supply dynamics can provide significant insights into the development of site-specific management strategies to address coastal resilience.

Beach nourishments are a popular nature-based alternative to armoring for shoreline erosion mitigation, but they are often criticized due to perceived negative environmental impacts as well as their temporary nature, and monitoring is often nonexistent or insufficient to document effectiveness and impact. A study by Krafft et al. (2025) of dredge spoils placed at Fairport Harbor, Ohio, in Lake Erie targeted the perceived negative impact of increased turbidity on nearshore habitat during material placement. This timely study indicates that nearshore placement of dredged material aligns with natural sediment movement in the littoral zone, with minimal to negligible generation of turbidity beyond what occurs naturally. This provides important support for nourishment using nearshore dredge spoils as a cost-effective management solution that can offer shoreline protection and habitat restoration. In addition, a detailed study of the recent evolution of three opportunistic beach nourishment projects at Minnesota Point, Lake Superior (Roland et al., 2025), provides new insights into the influence of shoreline orientation, littoral sediment supply, and grain size compatibility in determining beach nourishment longevity, and suggests that short-term observations during storm events can provide valuable insights for future coastal management and resiliency efforts. This study provides a model for evaluation of these interventions as well as guidance for their future design and implementation.

One method of shoreline armament commonly used in the Great Lakes is the shore-perpendicular groin field. Peterson and Wu (2025) report the results of a study of geomorphic changes along a high bluff shoreline within a groin field and along two pocket beaches under differing Lake Michigan water levels at Sheridan Park, Wisconsin. Distinct geomorphic responses unique to the high bluff coast were observed and suggest that under sustained high water level, groin fields are less effective at maintaining beach integrity, and induce severe end effects resulting in accelerated downdrift shoreline retreat and bluff erosion. These findings provide important insights for coastal management practices involving the installation of this type of structure in this vulnerable environment.

While driven by physical processes, Great Lakes coastal erosion caused by the most recent (2013–2020) rapid rise in water levels of nearly 2 m (in Lake Michigan) was also strongly influenced by coastal harbor structures. Prior to this event, little effort had been focused on understanding the specific role that large coastal structures, such as harbor jetties, have on regional sediment transport and coastal erosion processes. A detailed numerical study conducted by Zhu et al. (2025), focusing on the medium-sized harbor jetty impacts at South Haven, Michigan, provides a detailed description and quantification of the unique influence these common recreational harbor jetties have on nearshore. These findings will prove useful to coastal managers as they look to better understand and mitigate the effects of littoral barriers on coastal communities.

3. Development of research and assessment tools

The recent development of research and assessment tools for the improved management of Great Lakes coastal resources offer important alternatives to previously developed ocean-based approaches that neglect important aspects of local and regional dynamics. For example, Coastal Vulnerability Indices (CVI), which are used to quantify the vulnerability of coastal zones to threats such as shoreline erosion, sea-level rise, and storm surge impact, have been largely created for ocean coastlines. However, the Great Lakes encompass a unique set of dynamics for which the indices must be further tailored. Through the detailed geospatial and temporal evaluation of the Muskegon, Michigan, shoreline of Lake Michigan, Acheampong et al. (2025) have developed a CVI to provide coastal managers with valuable insights related to the reclassification and management of areas with high vulnerability to erosion as a result of increased shoreline armoring and climate change.

For the past several decades, significant pressure has been exerted along the shorelines of the Great Lakes to protect private and public lands from excessive erosion through hardened shoreline structures. During the most recent period of rising lake level, there was anecdotal evidence that the amount of shore armoring had increased throughout the Lake Michigan basin yet there was no formal quantification of this. Theuerkauf et al. (2025) compared the length of armored shoreline in 2021 (after the 2020 peak lake level) along the Michigan portion of the Lake Michigan coast to the armored length in 2014 and determined that in total the entire coast is around 5 times more armored. Southwestern Lower Michigan is now more than 35 percent armored yet was less than 10 percent armored prior to lake level rise. This armoring has important consequences: in a multi-decadal study of coastal erosion of sandy beach profiles in Lake Michigan, Penrod et al. (2025) developed a process-based model of nearshore sediment transport and geomorphic connectivity that reveals the negative influence of shoreline armoring on beach recovery processes and offers a simple and transferable method for predicting the likelihood of future beach recovery that can be used to help guide coastal management.

To gain a more thorough understanding of the variations in shoreline change that occur across the Great Lakes over time, Williams et al. (2025) demonstrate the use of historical snapshots dating back to 1938 to create the first comprehensive compilation of spatio-temporal shoreline change for a significant portion of Lakes Michigan, Huron, and Superior—mapping nearly 3300 km at sufficient fidelity to allow resolution at the individual property owner level. The resulting user-friendly, interactive web-GIS tool and database offers valuable insight into both short- and long-term shoreline dynamics. It also provides ancillary data to help place these changes in broader environmental contexts. This effort exemplifies the utility of a well-constructed spatio-temporal database—supporting scientific research, informing management decisions, and serving as a valuable educational resource.

In addition to coastal vulnerability to erosion, coastal flood risk plays a significant role in low-lying Great Lakes coastal environments. To address the needs of rural communities where data on coastal conditions is scarce, Thomas et al. (2025) describe the development of a web application that incorporates multiple modeling tools within Google Earth Engine (GEE) for flood risk assessment. This application is currently operational across five counties in the Western Upper Peninsula of Michigan, offering an accessible platform for understanding rural flood risk and aiding in management decision-making. Additional work employing high resolution numerical models of wave propagation, runup, overtopping, and flooding on the Canadian shore of Lake Ontario provides insight into the importance of local factors and conditions on the relationship between flood severity, rising water levels, and wave heights (Cornett et al., 2025). Results of this study show that wave action plays a significant role in initiating flooding at water levels below the threshold required to cause flooding under calm conditions and in exacerbating flooding at water levels above this threshold, and it offers an opportunity for expansion of this tool beyond its existing extent to other locations through validation and evaluation.

4. Best practices for coastal management

In addition to increasing our understanding of coastal processes and tools for coastal change and process assessment, it is important to translate this information into the hands of coastal stakeholders so that they are better equipped to make informed decisions that protect Great Lakes coastal resources. To effectively address the needs of coastal managers, it is essential to translate research that is specifically tailored to the region's unique environmental conditions and develop collaborations between researchers, policymakers, and local stakeholders. With a data-centered approach, Bunting et al. (2025) surveyed over 100 coastal stakeholders across six communities on Lake Michigan. They found that there is an overwhelming agreement among decision-makers that while data are valuable, it is critically important to provide resources to boost data comprehension and understanding of the methods involved in producing key data products so that those data are employed in effective ways.

Although not connected to the Bunting et al. (2025) study, Shriberg et al. (2025) propose a framework that could address the data knowledge gap that is a barrier to data-driven coastal management. They conducted a workshop and briefing with over 50 coastal managers and experts that identified the need for creation of a coastal resilience resource hub based on five unique "pillars" of support as well as the development of communities of practice to improve coordination and resource development and increase a community's ability to respond and plan for their changing coasts.

Finally, Salus et al. (2025) describe the development of four regional communities of practice in Wisconsin and Minnesota offering a robust model for reducing coastal hazard risk across boundaries, navigating complex coastal hazard issues, and improving planning through enhanced mapping capabilities, and collective identification of priority coastal management practices.

5. Conclusion

Together, these studies underscore the interconnected physical, ecological, and human dimensions of Great Lakes coastal systems. They reveal a coastal landscape shaped by both natural forces—such as ice dynamics, waves, and fluctuating lake levels—and human responses, including armoring, coastal structures, nourishment, and policy interventions. Across the collection, there is a strong emphasis on multi-scale and interdisciplinary methodologies, from drone imagery and sediment cores to multi-decadal shoreline profiles, machine learning, as well as the critical role of community-engaged research and adaptive management frameworks.

Importantly from a broader perspective, this special section also advances the science of process-based and integrated numerical modeling for coastal systems, with studies leveraging tools such as XBeach, SWAN, FVCOM, CSTMS, and Google Earth Engine to simulate wave-driven flooding, sediment budgets, harbor effects, and flood risks under variable climate conditions. These modeling frameworks not only provide mechanistic understanding but also support scenario-based planning and decision-making at regional and site-specific scales.

As climate variability continues to amplify coastal hazards across the Great Lakes basin, the findings in this collection provide actionable knowledge for anticipating change, mitigating risk, and building long-term resilience. They collectively call for integrative coastal governance approaches that align scientific insight with local needs, emphasizing the critical role of community-engaged research and adaptive management frameworks to foster proactive, equitable stewardship of the Great Lakes shorelines.

CRediT authorship contribution statement

Lorelle A. Meadows: Writing – review & editing, Project administration, Conceptualization. **Ethan Theuerkauf:** Writing – review & editing, Project administration, Conceptualization. **Cary Troy:** Writing – review & editing, Project administration, Conceptualization. **Pengfei Xue:** Writing – review & editing, Project administration, Conceptualization. **Guy Meadows:** Writing – review & editing, Project administration, Conceptualization. **Chin Wu:** Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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