US GREAT LAKES COASTAL RESILIENCE ASSESSMENT

2023

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Report cover images: Waves crashing on shores of Lake Michigan with Chicago skyline in background (top); spotted gar (bottom)

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GLOSSARY OF RELEVANT TERMS

The analysis was developed in adherence to the following terms and their definitions adapted from the U.S. Climate Resilience Toolkit and NFWF.

Term	Definition
Adaptive capacity	The ability of a person or system to adjust to a stressor, take advantage of new opportunities, or cope with change.
Ecosystem services	Benefits that humans receive from natural systems.
Exposure	The presence of people, assets, and ecosystems in places where they could be adversely affected by hazards.
Impacts	Effects on natural and human systems that result from hazards. Evaluating potential impacts is a critical step in assessing vulnerability.
Natural features	Landscape features that are created and evolve over time through the actions of physical, biological, geological, and chemical processes operating in nature (Bridges et al. 2014).
Nature-based features	Features that may mimic characteristics of natural features, but are created by human design, engineering, and construction to provide specific services such as coastal risk reduction (Bridges et al. 2014).
Nature-based solutions	Natural, engineered, and hybrid approaches that strategically protect, restore, sustainability manage, or mimic ecosystems to conserve or restore ecosystem functions and natural processes with the goal of reducing community exposure to natural hazards and climate stressors, and enhancing habitat for fish and wildlife.
Resilience	The capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption.
Risk	The potential total cost if something of value is damaged or lost, considered together with the likelihood of that loss occurring. Risk is often evaluated as the probability of a hazard occurring multiplied by the consequence that would result if it did happen.
Sensitivity	The degree to which a system, population, or resource is or might be affected by hazards.
Threat	An event or condition that may cause injury, illness, or death to people or damage to assets.
Vulnerability	The propensity or predisposition of assets to be adversely affected by hazards. Vulnerability encompasses exposure, sensitivity, potential impacts, and adaptive capacity.
Community Assets	Critical infrastructure and facilities important to the character and function of a community immediately following a major flood event, including populated areas and locations with high social vulnerability.

EXECUTIVE SUMMARY

Coastal communities throughout the United States face serious current and future coastal flood-related threats that are predicted to intensify over the short and long term. Coastal storms and heavy precipitation events have the potential to devastate both human communities and fish and wildlife habitats. As communities prepare, decision-makers need tools and resources that allow for data-driven decision support to maximize available funding opportunities and other planning needs.

The U.S. Great Lakes Coastal Resilience Assessment aims to support effective decision-making to help build resilience for coastal communities facing flood-related threats. The National Fish and Wildlife Foundation (NFWF), in partnership with the National Oceanic and Atmospheric Administration (NOAA), is committed to supporting programs and projects that improve resilience by reducing communities' vulnerability to coastal storms, sea level and lake level change, and flooding events by strengthening natural ecosystems and the fish and wildlife habitat they provide.

This Geographic Information System (GIS)-based Coastal Resilience Assessment combines spatial data related to land use, protected areas, human community assets, flooding threats, and fish and wildlife resources to identify and prioritize Resilience Hubs (see figure below). Resilience Hubs are areas of natural, open space or habitat where, if investments are made in habitat conservation or restoration, there is potential to provide benefits to fish and wildlife and help build human community resilience to flooding threats.

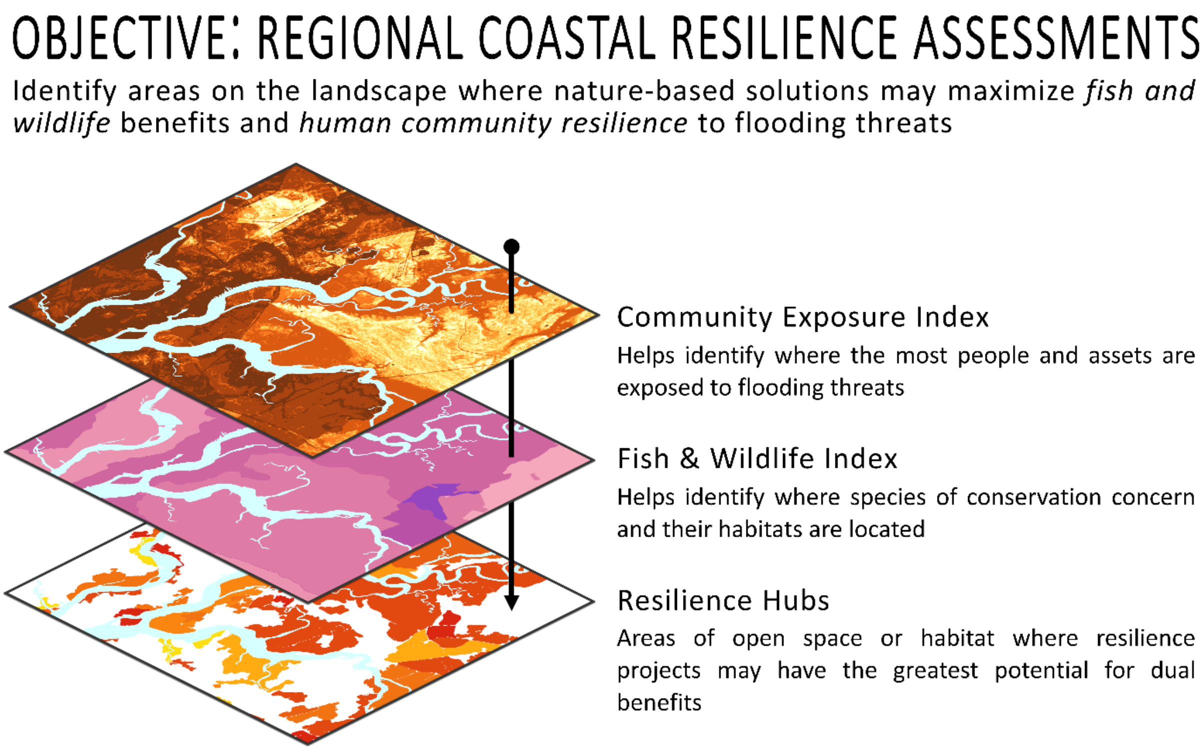
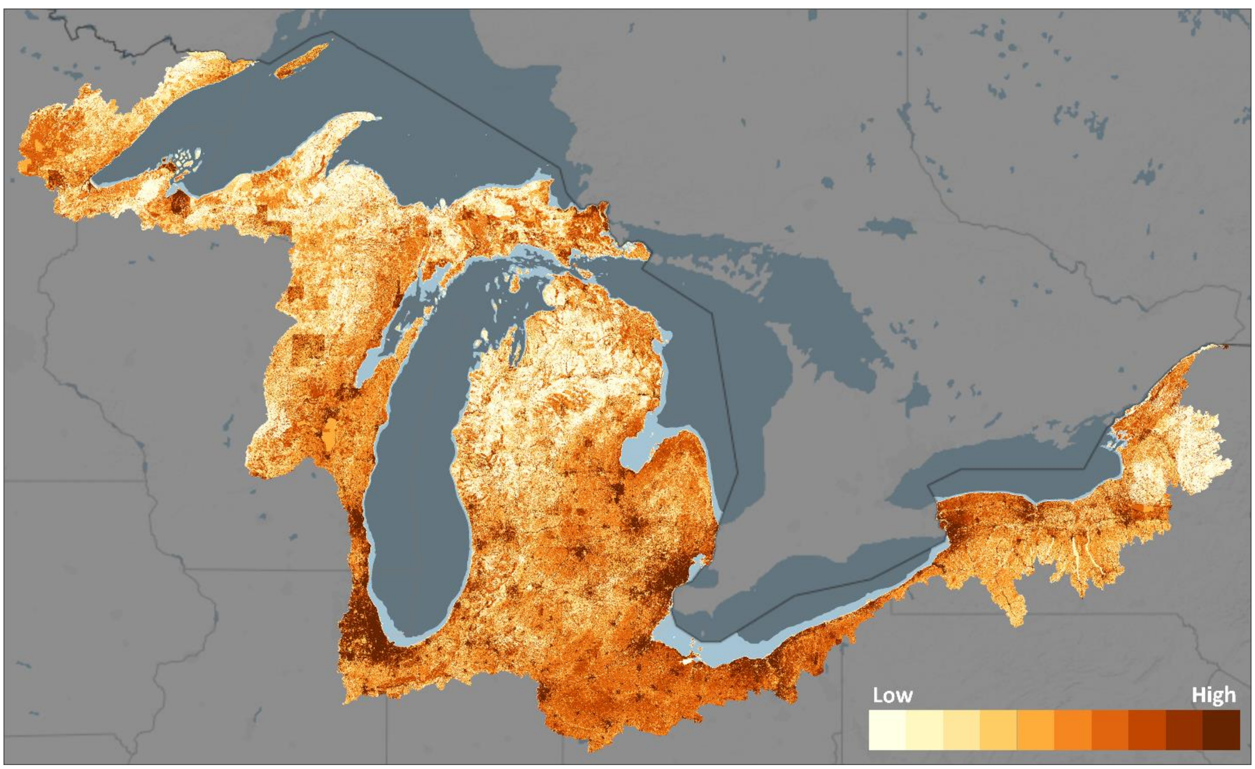


Figure outlines the objectives of the Regional Coastal Resilience Assessments, which combines a Community Exposure Index and Fish and Wildlife Index to create Resilience Hubs.

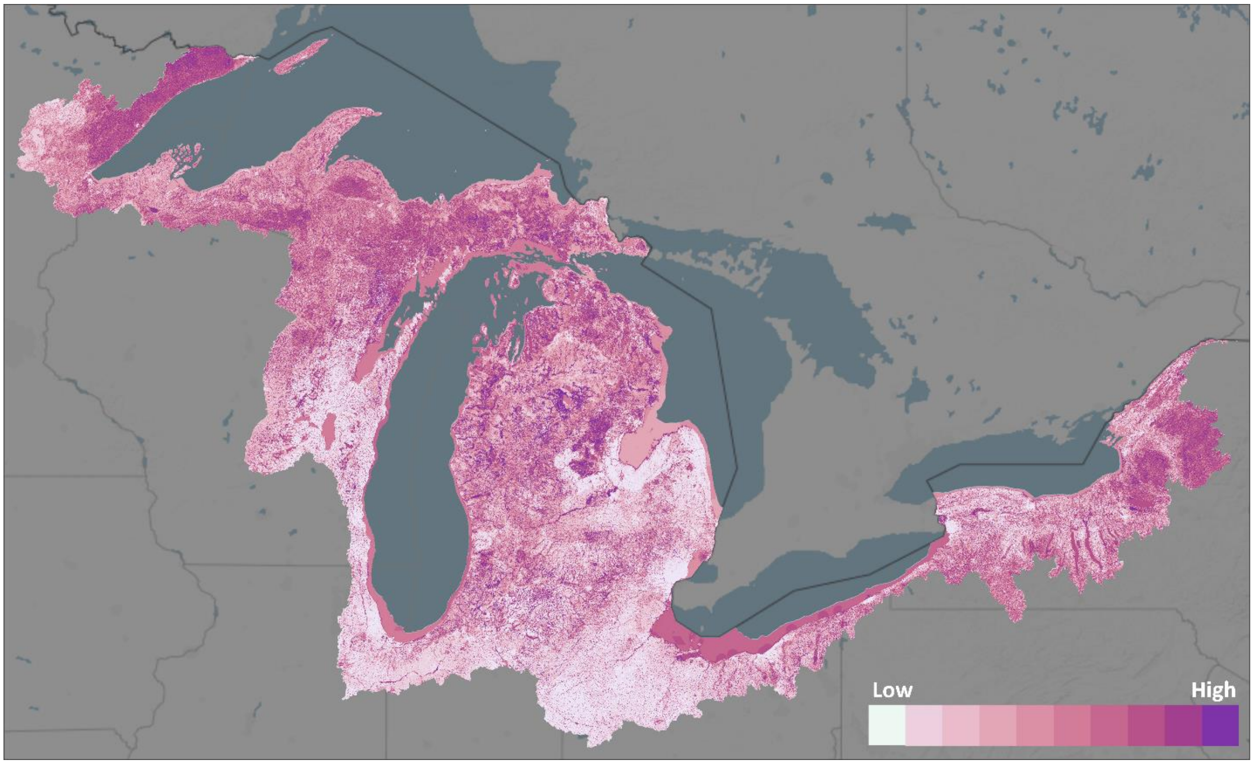
The Assessment identified areas throughout the U.S. Great Lakes region where human community assets are exposed to a range of coastal and inland flood-related threats. Importantly, the Assessment only considers a community's exposure to flooding threats and not a community's vulnerability or risk. In addition, the analysis identified terrestrial and aquatic areas important for species of conservation concern and other regionally important species. Together, the Assessment revealed natural areas of open space and habitat ideal for the implementation of resilience projects. The primary mapping products from the U.S. Great Lakes Assessment are shown below.

Local community planners, conservation specialists, and others can use the outputs of the U.S. Great Lakes Assessment to help make informed decisions about the potential of restoration, conservation, or resilience projects to support fish and wildlife while also helping to build human community resilience to flooding threats. The Assessment is intended to be used as a screening-level tool designed to help identify areas that may be well-suited for nature-based solutions and is not intended to identify all potential opportunities. The Assessment results are also limited by those data available at the time of analysis and by the underlying accuracy and precision of the original data sources; therefore, the Assessment may not capture all flood-related threats, community assets, fish and wildlife resources, or areas of open space. As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans.

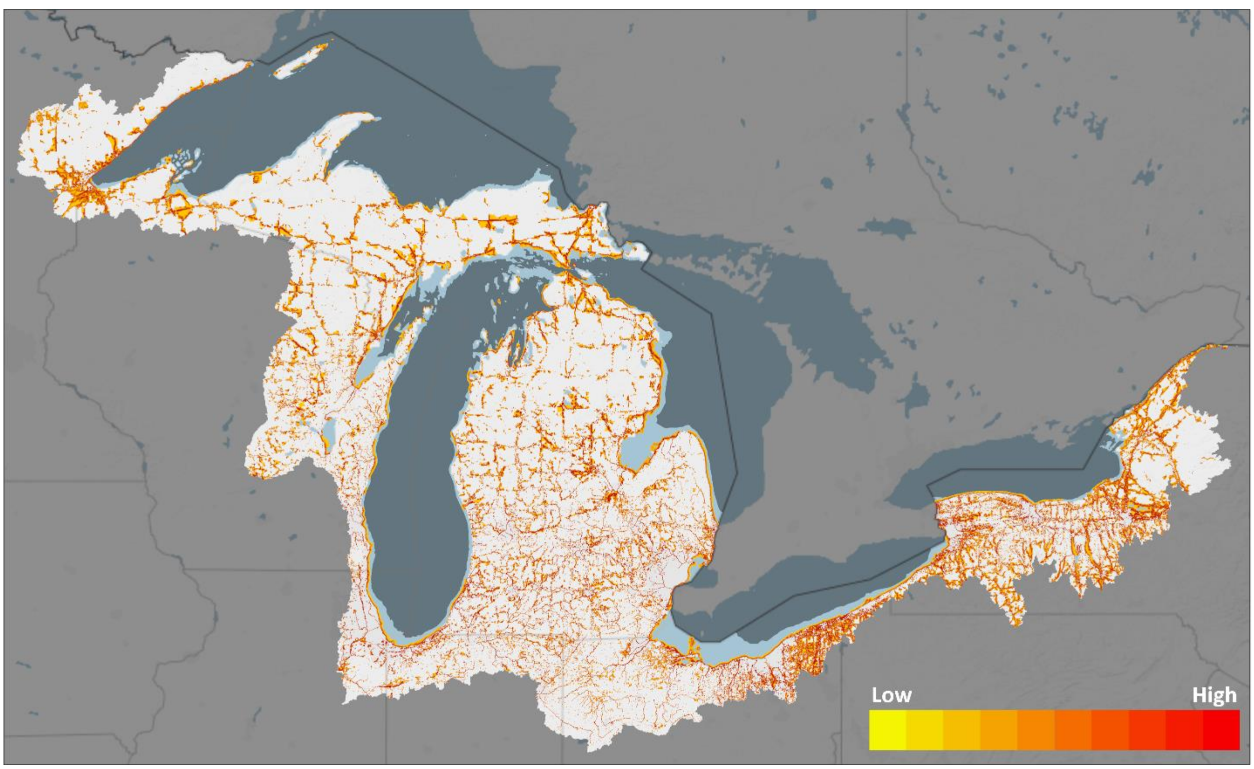
This U.S. Great Lakes Coastal Resilience Assessment report provides a detailed discussion of the data and methods used for the three primary analyses (Community Exposure, Fish and Wildlife, and Resilience Hubs), regional results, and case studies. In addition to the results presented in this report, NFWF has developed the Coastal Resilience Evaluation and Siting Tool (CREST), an accompanying GIS-based web tool that allows users to view, download, and interact with the inputs and results of the U.S. Great Lakes Assessment (available at resilientcoasts.org).



Community Exposure Index for the U.S. Great Lakes Coastal Resilience Assessment. Higher values represent areas where higher concentrations of community assets are exposed to multiple flooding threats.



Fish and Wildlife Index for the U.S. Great Lakes Coastal Resilience Assessment. Higher values represent areas where numerous species of conservation concern and their habitats are located.



Resilience Hubs for the U.S. Great Lakes Coastal Resilience Assessment. Higher values represent areas where resilience projects may have the greatest potential to benefit both human communities and wildlife.

INTRODUCTION

1.1 The Great Lakes Region

The Laurentian Great Lakes encompass the largest freshwater ecosystem on earth, spanning eight U.S. states and two Canadian provinces. Stretching over 94,000 square miles (240,000 square km), the Great Lakes Drainage Basin includes five major lakes connected by major rivers and canals including the St. Lawrence River and Seaway, Detroit River and Lake St. Clair, and the St. Marys River. Holding approximately one fifth of the world's supply of unfrozen surface fresh water, the Great Lakes provide drinking water and support livelihoods for over 35 million people (Angel et al. 2018). These abundant freshwater resources also help support manufacturing, transportation, farming, tourism, recreation, fishing, and other major industries important to the U.S. and Canadian economies.

The vast lakes vary in size and depth, contributing to diverse landscapes and ecosystems ranging from dense forest and bedrock bluffs in Lake Superior to sandy beaches and extensive dunes on Lake Michigan. The region's unique ecosystems support over 3,500 plant and wildlife species, including nearly 40 federally threatened and endangered species[5]. Expansive coastal wetlands fringing the lakes support waterfowl and provide nursery habitat for many ecologically and culturally important fish species. Coastal bluffs, dunes, and beaches offer important stopover habitat for many migratory shorebirds and bats, including critical habitat for threatened piping plovers (*Charadrius melodus*). Inland, extensive forests blanket the northern portion of the Basin, providing critical habitat for remnant gray wolf (*Canis lupus*) and Canada lynx (*Lynx canadensis*) populations.

While the northern portion of the Great Lakes Basin remains largely undeveloped, the southern portion is densely populated with far less natural land cover. Since the 1970s, the population has increased by 26% leading to a significant increase in the proportion of developed lands and hardened shorelines (ECCC & EPA 2022). In addition, widespread conversion of natural systems to agriculture has resulted in wetland loss throughout the region. As natural systems are lost or degraded, they lose their capacity to help filter nutrients, store excess water, and reduce flooding impacts (Mao & Cherkauer 2009).

Significant land use changes coupled with growing climate stressors leave human and wildlife communities throughout the Great Lakes vulnerable. The Great Lakes have experienced significant changes over the last century including stressors from pollution, nutrient inputs that contribute to harmful algal blooms, and the spread of invasive species. These threats are further compounded by projected increases in lake surface temperatures, precipitation, and evaporation, and decreases in lake ice cover (Angel et al. 2018). Extreme precipitation events can lead to coastal and inland flooding, overwhelming stormwater and other critical infrastructure. For example, in June 2018, seven inches of rain fell in one day on Michigan's upper peninsula, resulting in one death and a major federal disaster declaration due to widespread flooding and extensive and costly damage (FEMA 2018). Rising lake and air temperatures have contributed to a 71% average decrease in winter ice cover since the 1970s, leaving coastlines vulnerable to erosion during winter storm events (Wang et al. 2012).

The Great Lakes are also highly dynamic with naturally fluctuating water levels. From 1998 to 2013, the Great Lakes experienced historic low-water levels. From early 2013 through 2014, lake levels began to rise rapidly, by as much as 3.3 feet (1 m) in Lake Michigan-Huron (Gronewold et al. 2015). Sustained high

[5] For a list of threatened and endangered species in the Great Lakes listed under the U.S. Endangered Species Act, visit the U.S. Fish and Wildlife Service Environmental Conservation Online System (https://ecos.fws.gov/ecp/).

lake levels compounded storm-driven flooding and in 2018 alone, there were six major disaster declarations due to flooding in the coastal counties of the Great Lakes[6]. By 2020, levels in Lakes Superior, Michigan, and Huron were at or above record high-water levels. Extreme fluctuations in water levels not only impact coastal flooding, but also commercial navigation and hydropower management, among other impacts. In addition to affecting built infrastructure, changing water levels influence wetland migration and the availability of important habitat for fish and wildlife. While it is difficult to predict how water levels will change in the future, communities must prepare for extreme high- and low-lake levels combined with other climate-driven stressors.

Given the unique and dynamic flooding threats facing the Great Lakes region, flexible, partnership-driven adaptation planning efforts that integrate Indigenous knowledge and wisdom are critical to help communities plan, adapt, and build local resilience to climate threats. Many recent and ongoing efforts are helping communities in the Great Lakes understand flooding threats and mitigation strategies including, among many others, the U.S. Army Corps of Engineers' Great Lakes Coastal Resiliency Study (in progress), the Great Lakes Coastal Resilience Planning Guide (ASFPM 2021), the Great Lakes Integrated Sciences and Assessment efforts, and numerous state-, city-, and tribal-led efforts (Kaczmarek et al. 2022, Strouse et al. 2021, TAMT 2019). The U.S. Great Lakes Coastal Resilience Assessment intends to build on and complement these efforts.

As Great Lakes communities take steps to lower their exposure and plan for a more resilient future, resources such as this Coastal Resilience Assessment can equip decision-makers and stakeholders with valuable tools and information to help them better plan for future flood and storm events. The U.S. Great Lakes Coastal Resilience Assessment provides a framework that considers both fish and wildlife habitat and resilience for human communities facing growing flooding threats. By focusing on nature-based solutions that utilize natural habitats to reduce flooding threats to communities, this Assessment highlights one of numerous strategies needed to help build resilience in the Great Lakes.

[6] Federal Emergency Management Agency Major Disaster Declarations by state, January 1, 2018-May 2023. Available online: https://www.fema.gov.

1.2 Overview of the Regional Coastal Resilience Assessments

The National Fish and Wildlife Foundation (NFWF) and the National Oceanic and Atmospheric Administration (NOAA) are committed to supporting projects and programs[7] that improve resilience by reducing communities' vulnerability to coastal storms, sea level and lake level change, and flooding by strengthening natural ecosystems and the fish and wildlife habitat they provide. In response to growing coastal flooding threats, NFWF commissioned the University of North Carolina (UNC) Asheville's National Environmental Modeling and Analysis Center (NEMAC) to develop an assessment to identify coastal areas that are ideal for the implementation of nature-based solutions that build both human community resilience and fish and wildlife habitat. The resulting Regional Coastal Resilience Assessments (referred to from here forward as the Regional Assessments or Assessments) aim to identify and rank open space areas where targeted investments can implement resilience-building projects before devastating events occur and impact surrounding communities.

The U.S. Great Lakes Coastal Resilience Assessment is part of a broader effort that seeks to evaluate regional resilience for all U.S. coastlines. Regional Assessments are available for the U.S. Atlantic, Gulf of Mexico, and Pacific coastlines, Alaska, Hawai'i, Puerto Rico, the U.S. Virgin Islands, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands (Figure 1).

Figure 1. The geographic extent of the Regional Coastal Resilience Assessments in dark gray and the U.S. Great Lakes Assessment in orange. Map not shown to scale.

Strategically implementing resilience projects can increase the ability of surrounding communities and habitats to withstand and recover from the impacts of coastal storms and flooding events (Narayan et al. 2017). Efforts to build resilience begin by determining the exposure of a community's assets to a hazard or threat. The Regional Assessments use a GIS-based approach to model landscape characteristics and

[7] See the National Coastal Resilience Fund: https://www.nfwf.org/programs/national-coastal-resilience-fund.

their potential impacts to identify places throughout the coastal United States where assets are potentially exposed to flood threats. They combine human community assets, flooding threats, and fish and wildlife resource spatial data to identify and rank Resilience Hubs. Resilience Hubs are areas of natural, open space or habitat where, if investments are made in habitat conservation or restoration, there is potential to benefit fish and wildlife species while also helping to build human community resilience to flooding.

From a modeling standpoint, the Regional Assessments consist of three separate but interrelated analyses: (1) the Community Exposure Index, (2) the Fish and Wildlife Index, and (3) Resilience Hubs (Figure 2). These three components make the Regional Assessments unique as they look at resilience potential through the lens of both human and fish and wildlife communities. Specifically, the Community Exposure Index can guide land use and hazard mitigation planners in identifying potential development constraints and improve the understanding of possible risks to critical infrastructure and human populations. The Fish and Wildlife Index can inform where habitats important for species of conservation concern occur. The Resilience Hubs then identify open spaces and habitats suitable for the implementation of projects expected to build communities' resilience to flood events while also benefiting fish and wildlife.

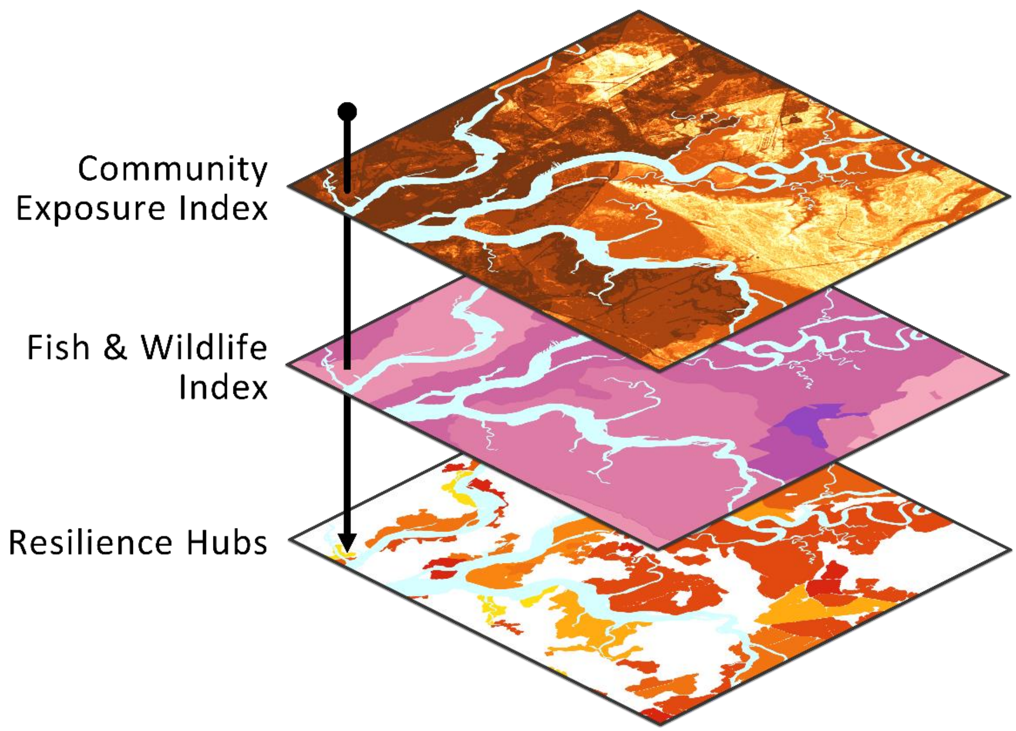


Figure 2. A conceptual model showing the separate, but interrelated components of the Regional Coastal Resilience Assessments.

While Resilience Hubs are the primary output of the Regional Assessments, each component can be used individually or in combination to help community planners, conservation specialists, funding applicants, and others make informed decisions about the ability of potential restoration, conservation, or resilience projects to achieve dual benefits for both human community resilience and fish and wildlife species and habitats. The Assessment is intended to be used as a screening-level tool designed to help identify areas that may be well suited for nature-based solutions. As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans.

METHODS

2.1 Introduction

The foundation of the Regional Coastal Resilience Assessments is based on the coastal vulnerability research outlined in Gornitz et al. (1994). In 2011, the New Jersey Office of Coastal Management and Department of Environmental Protection adapted that research to assess existing and future hazard vulnerabilities on a local scale (NJ-DEP 2011). This research was integral to structuring the inputs and methodology of this analysis.

The Regional Assessments use a Geographic Information System (GIS)-based approach to model landscape characteristics and their potential impacts through three primary analyses: (1) the Community Exposure Index, (2) the Fish and Wildlife Index, and (3) Resilience Hubs.

While both the Gornitz et al. (1994) and the New Jersey research (NJ-DEP 2011) focus on determining the magnitude of flood hazards on the landscape, the U.S. Great Lakes Assessment focuses on the exposure of community assets to flood threats. For example, the Community Exposure Index shows communities as highly exposed if they have critical facilities and/or infrastructure that also overlap with numerous flooding threats.

In addition to mapping human community assets and flooding threats across the landscape to determine exposure, habitats important for fish and wildlife were also identified. Habitat preferences for species of conservation concern and other regionally important species were incorporated into two indices: the Terrestrial Index and the Aquatic Index. Many habitats and species are vulnerable to flood-related stressors such as fluctuations in lake levels (Theuerkauf et al. 2019; Hohman et al. 2021). For example, flooding can impact water quality, which can have negative outcomes for sensitive populations of aquatic species (Georgakakos et al. 2014). Flooding can also upset ground-nesting birds and other species vulnerable to coastal inundation. However, neither the Community Exposure Index nor the Resilience Hubs are used to assess the exposure of fish and wildlife or species to flooding threats and should only be used to help identify areas of highly exposed human assets that coincide with areas that feature numerous fish and wildlife species.

The overarching goal of the Regional Assessments is to identify Resilience Hubs, which help locate natural, open spaces or habitats suitable for resilience-building conservation or restoration efforts capable of generating dual benefits for human communities and fish and wildlife. Hubs are determined first by the identification of undeveloped, natural landscapes or habitat cores, and then by the ranked combined averages of the Community Exposure and Fish and Wildlife Indices. The following sections describe the methods used in the U.S. Great Lakes Coastal Resilience Assessment.

2.2 Study Area

The U.S. Great Lakes Assessment was completed at a 30-meter resolution and includes the U.S. portion of the Great Lakes Basin, including all islands and nearshore areas to a 20-meter depth contour. The assessment boundary also includes several low-lying watersheds that may be impacted by flooding in the Great Lakes Basin. In addition to including the immediate coastline, the study area extends far inland to capture areas that influence or are influenced by coastal flood-related threats. For instance, intense rainfall and overland flow in poorly drained areas or areas with low slope can directly exacerbate storm-driven coastal flooding events.

Figure 3. The U.S. Great Lakes Coastal Resilience Assessment study area includes the U.S. portion of the Great Lakes Basin, including nearshore waters to a 20-meter depth contour.

2.3 Data Collection and Stakeholder Engagement

The Project Team began data collection efforts by compiling an initial set of publicly available data sets from multiple national and regional sources. In addition, the U.S. Great Lakes Assessment relied on significant input from local and regional stakeholders to identify and inform the use of additional data sets.

To help guide the Assessment process, the Project Team established a Technical Committee consisting of twelve members representing the Great Lakes Commission, the Great Lakes St. Lawrence Cities Initiative, the University of Michigan, the American Society of Adaptation Professionals, the U.S. Army Corps of Engineers, NOAA, and the U.S. Fish and Wildlife Service. The Technical Committee met regularly with the Project Team to:

1. Provide guidance to the Project Team at key decision points in the analyses, including recommendations on data to be included;

2. Help identify additional local stakeholders within federal, state, and tribal governments, universities, non-governmental organizations, and others to provide input into the development of the U.S. Great Lakes Assessment; and
3. Advise on final products and tools, including the effective dissemination of results.

During the initial development of the Assessment, the Project Team sought additional feedback from state and tribal governments throughout the region. The Project Team requested written feedback on a document outlining preliminary data sources and methods, which was used to inform the Assessment design. Comments were provided by state and tribal natural resource and coastal zone management agencies and organizations.

Building on initial data collection efforts with input from the Technical Committee and others, the Project Team hosted two workshops to allow and encourage regional stakeholders to review and provide input on preliminary Assessment products. A virtual Stakeholder Workshop was held on September 7-8, 2022 and included two sessions to introduce the Assessment and discuss preliminary results. An in-person workshop was held during the 2022 Great Lakes Coastal Symposium in Sault Ste. Marie, Michigan on September 21, 2022. All virtual and in-person participants had access to written materials and a temporary online GIS viewer to facilitate the review of draft models and provide comments during and after the workshop. The comment period remained open for over four weeks following the workshops.

Over 80 people attended the workshops, representing local, tribal, federal, non-government, and academic organizations. For a complete list of all organizations invited to the workshop, see Appendix J. Workshop participants helped the Project Team:

1. Identify geographic features, flooding threats, cultural and socio-economic factors, and additional considerations that are unique to the region;
2. Identify, collect, and appropriately use GIS datasets related to flooding threats, community assets, species, and habitats;
3. Provide references and contact information for additional experts that may be able to contribute data or knowledge to the effort; and
4. Obtain overall buy-in to the Assessment process and solicit ways in which it can be used by regional stakeholders in the U.S. Great Lakes region.

Participants reviewed draft maps and data sources during and after the workshops, providing important feedback and recommendations to improve the analyses. Following the stakeholder workshops, the Project Team reconvened with the Technical Committee to assess the feedback, comments, and suggestions provided during the workshops and to determine which data to incorporate into the revised products. Not all suggested data sources could be included in the Assessment. NEMAC then followed up individually with Committee members and other key stakeholders to further discuss changes to the data sources and methodology as needed. Results of the U.S. Great Lakes Assessment were reviewed by the Technical Committee and shared with local stakeholders via a public webinar.

2.4 Creating the Community Exposure Index

The Community Exposure Index was created by combining the Threat Index and Community Asset Index, depicting the spatial distribution of the potential exposure of assets to flooding threats (Figure 4). The following equation calculates exposure:

Threat Index × Community Asset Index = Community Exposure Index

While the methods used to create the Community Exposure Index are generally consistent among all Regional Coastal Resilience Assessments, the methods were modified for the U.S. Great Lakes Assessment to accommodate differences in data availability and incorporate flood-related threats due to the lake level variation, which differ from sea level rise and storm surge effects found in saltwater coastal regions. The following text describes the specific methods used for the U.S. Great Lakes Assessment; a complete list of datasets included can be found in Appendix A.

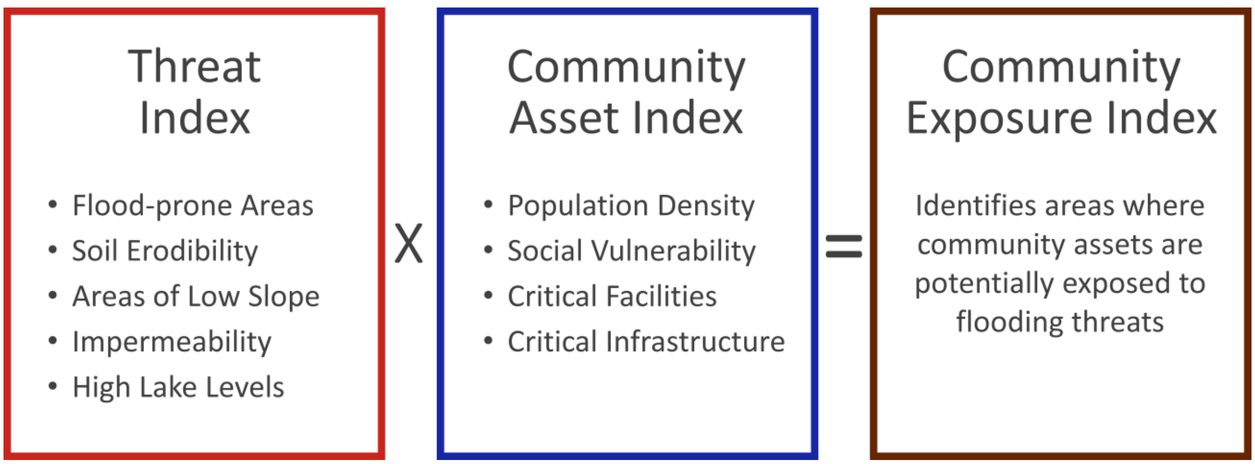


Figure 4. Elements of the Threat and Community Asset Indices used to create the Community Exposure Index.

2.4.1 Threat Index

Flood-related datasets are used to help communities understand which threats are potentially present in their area. While other threats may exist, for the purposes of this analysis only those threats relevant to coastal flooding-related impacts in the U.S. Great Lakes region were included. Threats are defined as datasets that show coastal flood, erosion, and severe storm hazards on the landscape. Using an ordinal combination method, all inputs were ranked numerically from low to high, representing the exposure—not the degree—of impact (MacDonald 2007; Gornitz et al. 1994; NJ-DEP 2011). Each ranked input is used to create the cumulative Threat Index (Ponce Manangan et al. 2014). The Threat Index is then reclassified into 10 classes using a percentile distribution. Additional details on those data used to create the Threat Index for the Great Lakes can be found in Appendix A.1 and Appendix C.

Flood-Prone Areas

Flood-prone areas were identified for the Great Lakes Assessment through a combination of the Federal Emergency Management Agency (FEMA) National Flood Hazard Layer and U.S. Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) Gridded Soil Survey Geographic (gSSURGO) Database & Gridded National Soil Survey Geographic Database (gNATSGO) flooding frequency classes. Whenever available, FEMA 100- and 500-year floodplains and the floodway were used because these data are the most accessible flood information available to municipal officials, non-government organizations, and communities. In areas outside the FEMA floodplains or floodway, soils identified as having very frequent to occasional flooding frequency were included. More details about the creation of this input can be found in Appendix C.1.

Soil Erodibility

Soil erosion resulting from flooding can drastically alter the landscape and impact human communities. To assess the erodibility of soils throughout coastal watersheds, the USDA NRCS gSSURGO Database & gNATSGO K Factor was used, which measures the susceptibility of soil particles to detachment by water. Soils high in clay have low K values and thus low soil erodibility values in the Assessment because they resist detachment. Conversely, the Assessment assigns high erodibility values to soils with high silt content, which are easily detached and capable of producing high rates of runoff (Renard et al. 2011). Sand beach, dune, and coastal bluff land cover classifications were incorporated with the NOAA Coastal Change Analysis Program (C-CAP) land cover and NOAA Office for Coastal Management U.S. Great Lakes Hardened Shorelines Classification and included throughout the Assessment. More details about the creation of this input can be found in Appendix C.2.

Areas of Low Slope

As a terrain's slope decreases, more land areas become prone to pooling water that can lead to prolonged periods of inundation. This threat input was developed with consideration of the Bruun Rule, which states that every foot rise in water can result in a 100-foot loss of sandy beach (NJ-DEP 2011). In this case, a one percent or less slope is likely to be inundated with a one-foot rise in water, helping to identify low-lying coastal areas that are more susceptible to inundation and changing coastal conditions. For the U.S. Great Lakes Assessment, slope was calculated from the U.S. Geological Survey (USGS) National Elevation Dataset (30m) and the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management 2016-2017 FEMA Lidar Digital Elevation Model data. More details about the creation of this input can be found in Appendix C.3.

Impermeability

The rate at which water flows through the soil or land influences the frequency and duration of time that lands are inundated. Slower rates of drainage can impede a community's ability to recover from a flood event since surfaces can remain flooded for longer periods of time. Where soils are impacted by development or infrastructure, they can become impervious. To account for water retention rates in soils, data from USDA-NRCS gSSURGO and gNATSGO drainage classes were used to classify a soil's ability to allow water to pool or drain (NRCS 2018). To identify the impervious land cover in urban areas—areas often lacking in comprehensive soil data—impervious land cover classifications were incorporated with the NOAA C-CAP land cover and included throughout the Assessment. Areas with impermeable soils within tile drainage agriculture were countered using the U.S. Environmental Protection Agency (EPA) EnviroAtlas - 2002 Edge-of-Field Simulated Nitrogen, Phosphorus and Water Quantity Loss by 12-digit HUC for the Conterminous United States and U.S. Department of Agriculture (USDA) National Agricultural Statistics Service Cropland Data Layer. See Appendix C.4 for details on this input and its ranking.

High Lake Levels

Water levels in the Great Lakes fluctuate naturally resulting in sustained periods of low and high lake levels both of which pose challenges for coastal communities. Low lake levels can disrupt commercial shipping, recreational opportunities, and hydropower generation. High lake levels can cause erosion, exacerbate storm-drive flooding, and cause property damage. The U.S. Great Lakes Assessment focuses on flooding threats and therefore, only high lake levels were included as an input to the Threat Index. High lake levels were estimated using the Global Surface Water Dataset curated by the European

Commission's Joint Research Centre (Pekel et al. 2016). This dataset uses global satellite imagery to map the location and temporal distribution of surface water from 1984-2020 with good coverage across the study area. The resulting high lake levels input represents intra- and inter-annual variation based on observed lake level changes. More details about the creation of this input can be found in Appendix C.5.

2.4.2 Community Asset Index

The Community Asset Index identifies human community assets that are important to help a community respond to and recover from a flooding event. The Index used datasets that quantify the number of assets present—not their magnitude of vulnerability or susceptibility to flood threats.

In the Great Lakes, the Community Asset Index incorporated data related to population density, social vulnerability, critical facilities, and critical infrastructure. All critical facilities and infrastructure were counted with equal weight in the Assessment, highlighting the importance of all community assets in emergency response. This approach is consistent with other existing methodologies to identify community assets that support recovery during an emergency, such as the FEMA Community Lifelines framework[8]. As with the Threat Index, the Community Asset Index was ultimately reclassified into 10 classes using a percentile distribution. A detailed list of datasets used for all Community Asset Index inputs included in the U.S. Great Lakes Assessment can be found in Appendix A.2. See Appendix D for a description of methods used to create the Community Asset Index.

Population Density

Population density is used to help identify densely populated areas throughout the U.S. Great Lakes region that may ultimately require more resources to respond to a flood event. The U.S. Census Bureau 2020 Decennial Census Total Population data were used at the census block scale where a single value was given to each census block according to a quantile distribution relative to the census blocks of highest population density in the U.S. Great Lakes study area. See Appendix D.1 for details on creating this input.

Social Vulnerability

The social vulnerability input is meant to identify areas in a community where an individual's ability to respond to and cope with the effects of threats may be more or less difficult as compared to other nearby areas. Disadvantaged households are typically found in areas of higher risk, leaving them vulnerable to flooding, disease, and other chronic stressors (EPA 2021). For the U.S. Great Lakes Assessment, the Demographic Index in the U.S. Environmental Protection Agency (EPA) Environmental Justice Screening and Mapping tool (EJScreen) was used to determine social vulnerability, which is the average of percent minority and percent low-income in each census block group (EPA 2022). To identify those communities with the highest social vulnerability, only those census block groups equal to or above the 50th percentile nationally were included in the assessment. More details about the creation of this input can be found in Appendix D.2.

Critical Facilities

The Assessment considered several different types of critical facilities including schools, medical facilities, government buildings, and fire and police stations identified using the U.S. Geological Survey (USGS) National Structures Dataset and Microsoft Building Footprints. It is important to emphasize that these critical facilities provide important services that support the operation of other types of critical infrastructure, such as residential, commercial, industrial, and public properties. These facilities are

[8] FEMA Community Lifeline: https://www.fema.gov/emergency-managers/practitioners/lifelines.

often prioritized in disaster planning since they may offer refuge to vulnerable populations. More details about the creation of this input can be found in Appendix D.3.

Critical Infrastructure

The Assessment considered several different types of critical infrastructure that may either help communities immediately respond to and recover from devastating flood events (*e.g.*, emergency evacuation routes) or assets that require protection during a flooding event (*e.g.*, hazardous waste sites). The Assessment included critical transportation infrastructure, waterways infrastructure, water treatment facilities, communications and energy infrastructure, and hazardous sites. More details about the creation of this input can be found in Appendix D.4.

2.4.3 Community Exposure Index

To create the Community Exposure Index, the Threat and Community Asset Indices were each given a value of 1 to 10 to indicate a low-to-high presence of threats or assets, respectively. Combination methods traditionally result in the summation of inputs to create a final land suitability index; however, the U.S. Great Lakes Assessment aims to understand exposure—the relationship between potential threats and the presence of community assets. Therefore, a multiplication function was used to understand this relationship. Areas with the highest prevalence of threats and the highest presence of community assets were calculated as having the highest levels of exposure. See Appendix E for a description of the methodology used to calculate the Community Exposure Index.

2.5 Creating the Fish and Wildlife Index

The Fish and Wildlife Index, which consists of terrestrial and aquatic components, allows for a greater understanding of important habitats and fish and wildlife resources where implementing nature-based solutions may support coastal resilience and ecosystem benefits (Figure 5). The Index attempts to identify areas on the landscape where terrestrial and aquatic species of conservation concern and their habitats are located. For the purposes of the U.S. Great Lakes Assessment, species of conservation concern include species with federal-level protection status, species of greatest conservation concern as identified through State Wildlife Action Plans (SWAPs), and species with off-reservation harvest regulations in the 1837 and 1842 Ceded Territories in Wisconsin and Minnesota[9]. A complete list of data can be found in Appendix A and a description of the methods used to create the Fish and Wildlife Index can be found in Appendix F and Appendix G.

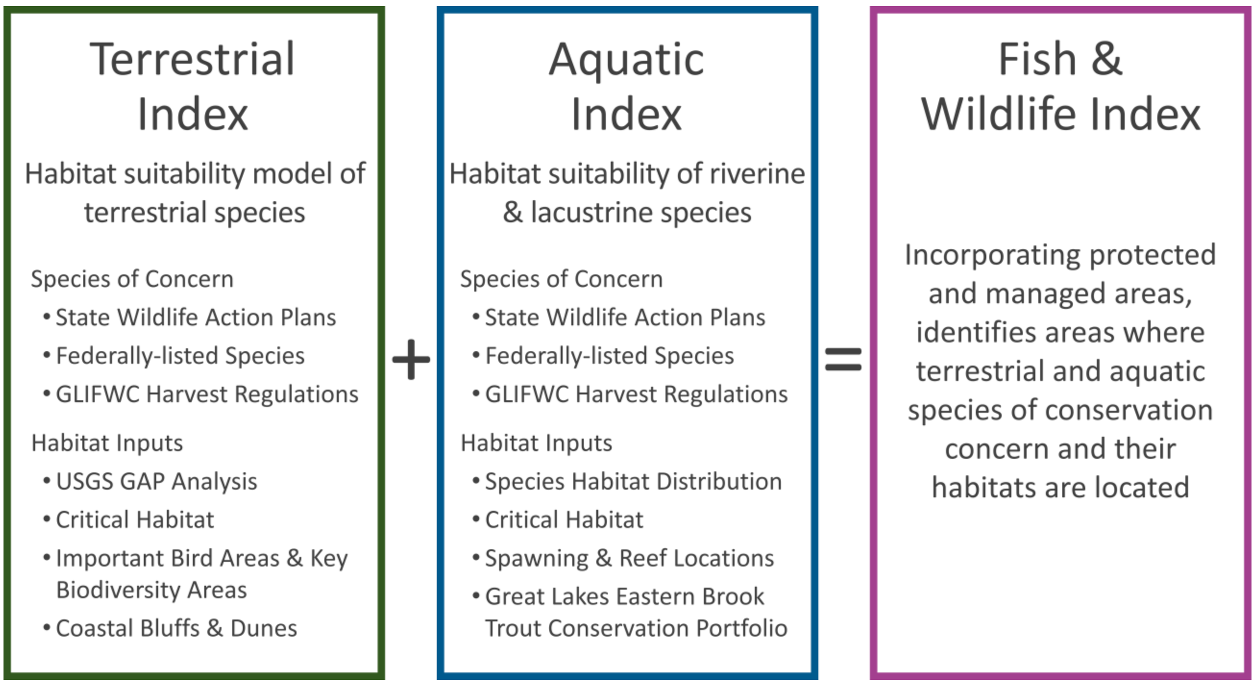


Figure 5. Elements of the Terrestrial and Aquatic Indices used to create the Fish and Wildlife Index.

2.5.1 Terrestrial Index

The Terrestrial Index aims to identify suitable habitats for species of conservation concern. Unlike approaches that rely on uneven species occurrence data, a habitat suitability approach provides the opportunity to model groups of species at a consistent regional scale (Rondini et al. 2011). To develop habitat suitability models, the Assessment first identified terrestrial wildlife species of greatest conservation need according to State Wildlife Action Plans (Derosier et al. 2015; IL DNR 2022; IN DNR 2015; MN DNR 2016; NY DEC 2015; OH DW 2015; PGC-PFBC 2015; WI DNR 2015), species listed as threatened or endangered under the U.S. Endangered Species Act, and terrestrial species with off-reservation harvest regulations. Focus was placed on terrestrial vertebrates, but invertebrates were included where critical habitat data were available. All species included in the Assessment were then combined into broad taxonomic groupings, including birds, amphibians, reptiles, and mammals. Finally, using the USGS Gap Analysis Project (GAP; USGS 2018), habitat preferences were identified for each

[9] For details see the Great Lakes Indian Fish and Wildlife Commission website: https://data.glifwc.org/regulations/.

species and summed by taxonomic group. Some species were excluded from the analysis if there were insufficient habitat suitability data available. All species listed in any of the eight relevant SWAPs were included across their entire range within the study area, regardless of the state or states in which a given species was listed. Coastal bluffs and dunes were used to supplement habitat suitability models, as through stakeholder engagement, these habitats were determined to be regionally important and not well-represented in the GAP models in this region.

In addition to modeling habitat suitability, the Assessment included designated critical habitat for species listed under the Endangered Species Act independent of the taxonomic groupings. Terrestrial species with critical habitat within the study area included piping plover (*Charadrius melodus*), Canada lynx (*Lynx canadensis*), gray wolf (*Canis lupus*), Hine's emerald dragonfly (*Somatochlora hineana*), and Poweshiek skipperling (*Oarisma poweshiek*). The Index also included BirdLife International Important Bird Areas (IBAs) and Key Biodiversity Areas (KBAs), which help to identify areas that support habitat conservation through acquisitions or easements or by encouraging the voluntary adoption of best management practices. Critical habitat, IBAs, and KBAs were combined with habitat suitability to create the Terrestrial Index.

Together, the analysis modeled areas with high species richness for terrestrial species of conservation concern based on existing distribution data for each species. A complete list of species (organized by taxonomic group) included in the U.S. Great Lakes Assessment is available in Appendix F.1.

2.5.2 Aquatic Index

Using similar methods to the Terrestrial Index, the Aquatic Index identifies habitat suitability for species of conservation concern that utilize riverine and lacustrine habitats. Calling on data from the State Wildlife Action Plans (SWAPs) (Derosier et al. 2015; IL DNR 2022; IN DNR 2015; MN DNR 2016; NY DEC 2015; OH DW 2015; PGC-PFBC 2015; WI DNR 2015), International Union for Conservation of Nature (IUCN) Red List of Threatened Species[10], NatureServe[11], U.S. Fish and Wildlife Service (FWS)[12], and NatureServe Explorer[13], the Index used existing species range and habitat preferences data for species of conservation concern to identify areas of high aquatic species richness. As with the Terrestrial Index, aquatic species included in the Assessment are those listed as species of greatest conservation need according to the SWAPs, species listed as threatened or endangered under the U.S. Endangered Species Act, and inland fishing and ricing species with off-reservation harvest regulations in the 1837 and 1842 Ceded Territories in Wisconsin and Minnesota.

For each aquatic species of conservation concern, habitat suitability layers were generated by coupling habitat preferences with land cover data to identify all areas of potentially suitable habitat within the species' range. Aquatic species were assigned to three major land cover types including riverine habitat (headwaters/creeks, small, medium, and large rivers excluding pipelines, underground conduits, and canals and ditches), lacustrine habitat (ponds, small, medium, large, and very large lakes), and wetland habitat (emergent, scrub/shrub, and forested wetlands). All aquatic species included in the Assessment were then combined into broad taxonomic groupings, including fishes, mollusks, and crayfishes. Some species were excluded from the analysis if there were insufficient data to determine habitat

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[10] International Union for Conservation of Nature (IUCN) Red List of Threatened Species: https://www.iucnredlist.org/.

[11] NatureServe (2010) Digital Distribution Maps of the Freshwater Fishes in the Conterminous United States (Version 3.0): https://www.natureserve.org/products/digital-distribution-native-us-fishes-watershed.

[12] U.S. Fish and Wildlife Service (FWS) Complete Current Range Vector Digital Data: https://ecos.fws.gov/ecp/.

[13] NatureServe Explorer: https://explorer.natureserve.org/.

preferences. All species listed in any of the eight relevant SWAPs were included across their entire range within the study area, regardless of the state or states in which a given species was listed.

In addition to modeling habitat suitability, the assessment included designated critical habitat for species listed under the Endangered Species Act independent of the taxonomic groupings, which in the U.S. Great Lakes region only includes the rabbitsfoot mussel (*Quadrula cylindrica cylindrica*). The Index also included nearshore reefs and fish spawning locations as well as Great Lakes Brook Trout Conservation Portfolio habitat patches[14], which served as a proxy for cool and cold-water habitat. A complete list of species and data sources included in the Aquatic Index is available in Appendix G.1.

2.5.3 Fish and Wildlife Index

To identify areas likely to support multiple species of conservation concern, the Terrestrial and Aquatic Indices were summed to create one combined Fish and Wildlife Index. In addition, protected and managed areas such as state and federally managed lands, National Marine Sanctuaries, and other protected areas were added directly to the Fish and Wildlife Index because they impact more than a single species group and are not distinctly aquatic or terrestrial in many cases. By combining the Terrestrial and Aquatic Indices with protected areas, it creates a continuous Fish and Wildlife Index that helps to identify areas where implementing a resilience or restoration project would likely benefit fish and wildlife communities of conservation concern. See Appendix H for more details on the creation of this combined Fish and Wildlife Index.

2.6 Creating the Resilience Hubs

Resilience Hubs are areas of natural, undeveloped space used to identify places that may be suitable for resilience-building conservation or restoration efforts with high potential to provide benefits to both human communities and fish and wildlife. Accounting for natural spaces on both terrestrial, riparian, and lacustrine environments, Resilience Hubs are formed based upon undeveloped landscapes and habitat types to create Habitat Cores (Figure 6). These Habitat Cores are then ranked according to the combined average values of the Community Exposure Index and the Fish and Wildlife Index, among other inputs described below. For a detailed description of data sources and methods, see Appendix A.6 and Appendix I, respectively.

2.6.1 Habitat Cores

To generate Resilience Hubs, the Assessment first identified Habitat Cores, or areas of intact, contiguous habitat where there may be sufficient natural land cover to support the implementation of nature-based solutions. All Habitat Cores are at least 4 hectares (10 acres) in size, regardless of ownership or preservation status. Three distinct methods were used to identify terrestrial, riparian, and lacustrine Habitat Cores. See Appendix I for details.

Terrestrial Habitat Cores

To generate terrestrial Habitat Cores, the Regional Assessments build upon methodology developed by the Green Infrastructure Center for the continental United States (Firehock & Walker 2019). The dataset is intended to guide local, regional, and community planners in identifying important places to conserve prior to planning development projects. The dataset also helps to prioritize which landscapes to protect and connect—such as natural systems that mitigate flooding, provide recreational or subsistence opportunities, and benefit air and water quality (Firehock & Walker 2019). Applying these methods to

[14] Trout Unlimited Great Lakes Brook Trout Conservation Portfolio: https://trout.maps.arcgis.com/apps/webappviewer/index.html?id=63870ecf17a14d1a9d11ba4328bcef3f.

the U.S. Great Lakes Assessment, fragmenting features such as roads, railways, and shoreline were used to break up natural, contiguous habitat features to identify individual Habitat Cores that were at least 4 hectares (10 acres) in size. Therefore, habitat cores represent relatively intact habitat that considers fragmenting features that may disrupt the movement of wildlife species. Developed and agricultural land cover types were excluded across the study with two notable exceptions: 1) hay and pasture land cover types were included due to their potential habitat benefits, and 2) former wetlands on agricultural land that are considered "potentially restorable" by the U.S. Environmental Protection Agency's EnviroAtlas were included to highlight potential restoration activities.[15]

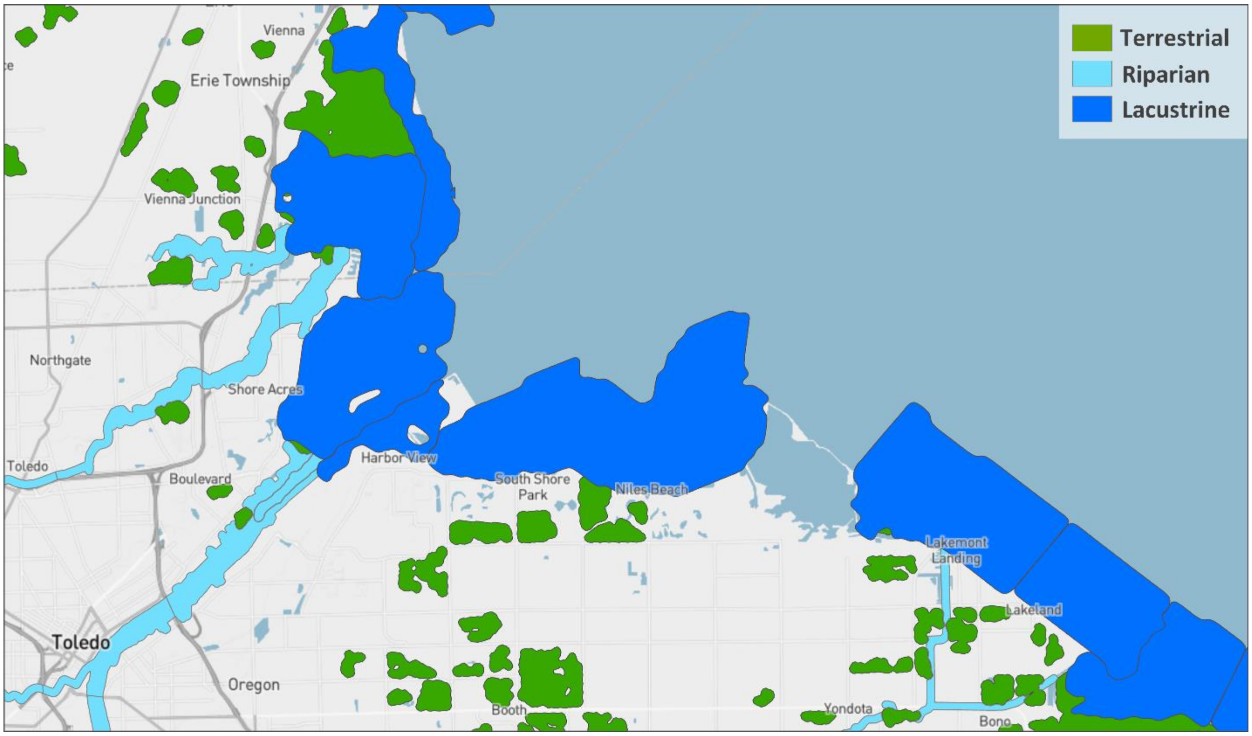

Figure 6. Unranked terrestrial (green), riparian (light blue), and lacustrine (dark blue) Habitat Cores in Toledo, Ohio.

Riparian Habitat Cores

When preparing the terrestrial Habitat Cores, many riparian corridors were inadvertently excluded from the analysis due to the minimum size threshold of 4 hectares (10 acres) and other topographical characteristics that are considered in the Green Infrastructure methodology. This was particularly pronounced in urban areas where riparian corridors along small rivers and streams were excluded despite their potential for stream connectivity and urban restoration projects. Therefore, the U.S. Geological Survey (USGS) National Hydrography Dataset Plus High Resolution (NHDPlus HR) "flowlines" and "area" feature classes were used to identify riparian Habitat Cores that would have otherwise been excluded from the analysis (Figure 6). Riparian features such as headwaters/creek, pipelines, underground conduit, and canal/ditches were not included. In all cases, riverine features were buffered by 100 meters. Additionally, dam locations and bridged roadways were used to fragment and separate long, contiguous riparian corridors. See Appendix I for details.

[15] EPA's EnviroAtlas - Percent Land Cover with Potentially Restorable Wetlands on Agricultural Land by 12-Digit HUC for the Conterminous United States; available at www.epa.gov/enviroatlas.

Lacustrine Habitat Cores

Many important nature-based solutions utilize shoreline and nearshore habitats to provide dual flood protection and habitat benefits such as offshore reefs, living shorelines, and beach and dune restoration projects. Therefore, the Assessment also identified lacustrine Habitat Cores with the nearshore waters of the Great Lakes and other large inland lakes. Using the Great Lakes Bathymetry Collection from NOAA's National Centers for Environmental Information, a depth boundary was extracted to include all lacustrine areas within a 20-meter depth boundary. To divide—or fragment—these open bodies of water, bathymetric data were then used to determine underwater sub-basins and define the geographic extent of the lacustrine Habitat Cores. In areas where bathymetric data were unavailable, a Thiessen polygon algorithm was used to fragment large, open bodies of water to delineate lacustrine Habitat Core boundaries (Figure 6).

2.6.2 Creating a Hexagonal Grid

Once the terrestrial, riparian, and lacustrine Habitat Cores were developed, they were combined into a single layer and all features were converted into a finer 4-hectare (10-acre) hexagonal grid (Figure 7). Due to the limited number of fragmenting features, many Habitat Cores can be thousands of acres in size. Therefore, a finer-scale hexagonal grid is important to show variation within a given Habitat Core and can help to facilitate local decision-making commensurate with the size of potential nature-based projects and solutions. See Appendix I for details.

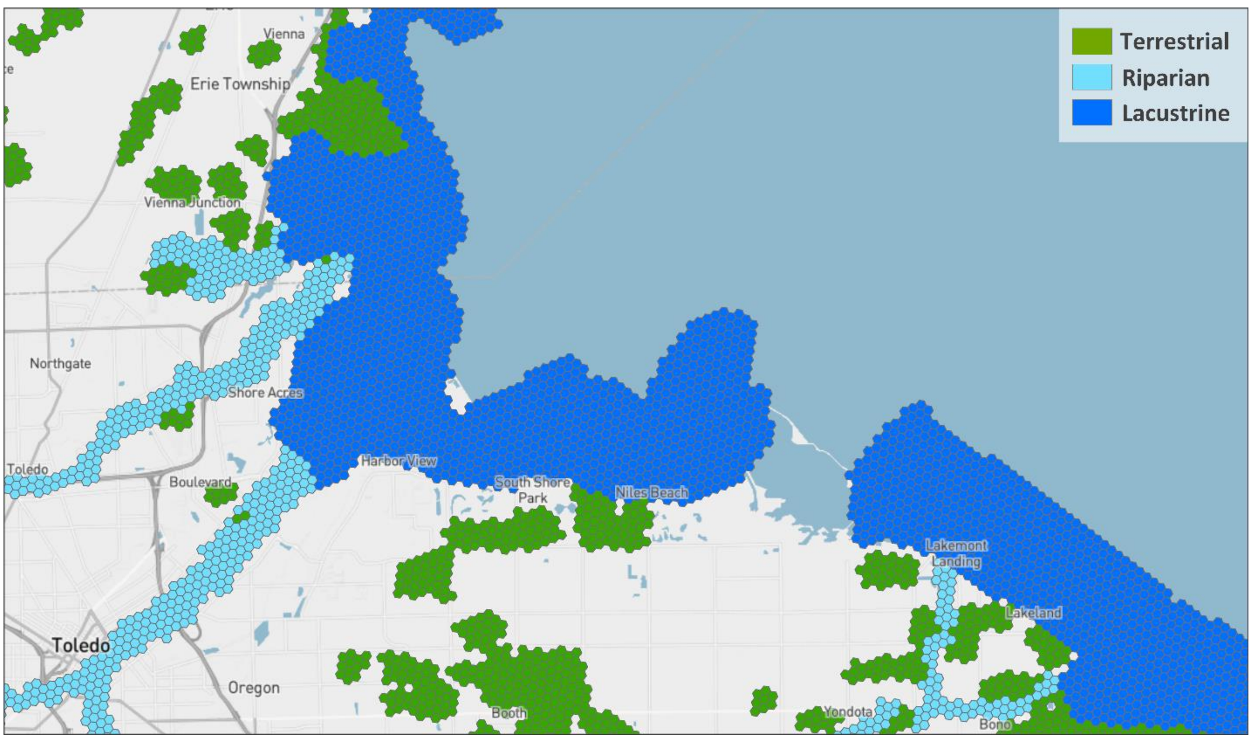

Figure 7. Unranked fine scale 4-hectare (10-acre) hexagonal grid of terrestrial (green), riparian (light blue), and lacustrine (dark blue) Habitat Cores in Toledo, Ohio.

2.6.3 Scoring Habitat Cores and Hexagons

The final Habitat Cores and hexagonal grid are each scored separately using the average values of the Community Exposure and Fish and Wildlife Indices and other key inputs. As the final product of the Assessment, the Resilience Hubs identify areas of open space where implementing a nature-based solution has potential to benefit fish and wildlife while building community resilience to flooding threats. Resilience Hubs are presented in two ways: 1) Resilience Hub Cores provide a coarse-scale view that assigns a single average rank to each Habitat Core, and 2) a Resilience Hub Grid provides a fine-scale view that assigns an average rank to each individual 4-hectare (10-acre) hexagon.

The Resilience Hub Cores and Grid are both scored using the same methods. Using a zonal statistics geoprocessing technique common to many GIS analyses, average values from the Community Exposure Index were calculated for each Habitat Core and hexagon, including the surrounding areas within one kilometer. Incorporating the buffer area was necessary because Habitat Cores and associated hexagons are natural, open landscapes containing few to no exposed community assets. The buffer was determined in consultation with technical experts. Next, the average Fish and Wildlife Index value was calculated for each Core and hexagon without applying a buffer.

The analysis also considered important habitat types that are most likely to provide flood protection benefits to nearby human community assets. For instance, nature-based solutions for flood mitigation are commonly implemented within emergent and forested wetlands, floodplains, beach and dune habitat, and nearshore reef structures. Similarly, aquatic connectivity projects that remove barriers or retrofit undersized culverts can in many cases also help reduce flooding to transportation infrastructure and other nearby community assets. Therefore, when ranking the Habitat Cores and hexagons, the Assessment considered the proportion of these habitat types within a Core or hexagon and the proximity of these habitat types to one another (within 1.5km). For lacustrine Habitat Cores and hexagons, depth was also considered, giving higher ranks to features in shallower depths where nature-based solutions are more likely to provide coastal protection benefits through wave attenuation.

Finally, because Resilience Hubs are intended to identify areas where resilience-building efforts could simultaneously mitigate flooding *and* benefit fish and wildlife, rankings also considered the average distance from critical facilities and infrastructure. Using a zonal calculation, Habitat Cores and hexagons within 1.5 km of one or more critical facilities or types of critical infrastructure received a higher rank. The final Resilience Hubs and hexagons ranks were calculated using the following equations:

Terrestrial and Riparian Habitat Cores and hexagons
*Resilience Hub score = (proportional area of each habitat within each Habitat Core) + (distance value from each habitat to a Habitat Core) + ((average Community Exposure Index value * average Fish and Wildlife Index score) * average distance to Critical Facilities & Infrastructure))*

Lacustrine Habitat Cores and hexagons
*Resilience Hub score = ((proportional area of each habitat within each Habitat Core) + (distance value from each habitat to a Habitat Core) * average water depth)) + ((average Community Exposure Index value * average Fish and Wildlife Index score) * average distance to Critical Facilities & Infrastructure))*

Using a quantile distribution, the values for the scored Habitat Cores were then classified into a 10-class ranking scale; the scored hexagons were classified into a 10-class ranking scale separately. After classifying the scored Cores and hexagons, the lowest 50% of the classification was dropped from the Assessment. The remaining top 50% was reclassified into 10 classes and ranked from 1 (low) to 10 (high). This 1 to 10 ranking results in the final Resilience Hubs presented as Resilience Hub Cores and a Resilience Hub Grid. See Appendix I for details.

When considering the Resilience Hubs that result from the U.S. Great Lakes Assessment, the following will generally be true:

(1) Hubs with the highest Community Exposure Index and Fish and Wildlife Index values will receive a higher ranking;
(2) Hubs containing more fish and wildlife assets will receive higher average Fish and Wildlife Index values, compared to areas unlikely to support numerous species of conservation concern;
(3) Hubs near critical infrastructure assets will receive higher average Community Exposure Index values than areas not near significant densities of critical infrastructure assets; and
(4) Hubs near habitats most likely to provide flood protection benefits will receive higher overall scores, whereas those farther from these habitats will generally receive lower scores.

In summary, the Resilience Hub approach—in determining both Habitat Cores and their subsequent hexagons—identifies contiguous natural landscapes composed of similar landscape characteristics that are nearest to community assets and significant habitats. Lands identified have the potential to be of higher ecological integrity and thus may offer improved potential for both human and wildlife benefit.

RESULTS

The U.S. Great Lakes Coastal Resilience Assessment reveals abundant opportunities to use nature-based solutions to help build human community resilience while supporting fish and wildlife habitats and species. Nature-based solutions include actions that sustainably manage and utilize natural systems to address societal challenges such as flooding and erosion while benefiting biodiversity and human well-being. Implementing nature-based solutions, such as habitat restoration and conservation, can provide tremendous co-benefits to people and wildlife as described in the case studies outlined below (see Section 4). To explore the findings of the U.S. Great Lakes Assessment, results for the Community Exposure Index, Fish and Wildlife Index, and Resilience Hubs are presented regionally. A single model was used across the U.S. portion of the Great Lakes Basin, allowing results to be directly compared within and among states.

3.1 Community Exposure Index

The U.S. Great Lakes region features the longest shoreline in the continental U.S. with over 4,500 miles of coastline. This vast shoreline is regularly exposed to crashing waves, steady erosion, and ever fluctuating lake levels. With climate change projected to increase temperatures and precipitation while decreasing ice cover, the region is expected to face growing flooding hazards from more frequent and severe storm events (Angel et al. 2018). As these hazards are magnified, more communities will be affected throughout this densely populated region.

The results of the U.S. Great Lakes Assessment highlight the extent of coastal and inland flooding hazards throughout the study area. The Community Exposure Index reveals areas throughout the region where dense concentrations of human community assets are exposed to numerous flooding threats, as indicated by the darkest shades of brown (Figure 8). With the region's largest cities located along the lakeshores, it is unsurprising that these populated areas are most exposed to flooding threats. High exposure values are particularly evident in major metropolitan areas such as Chicago, Milwaukee, Detroit, and Cleveland. These cities and surrounding communities consistently received the highest exposure rankings in the region (10). While the highest exposure values are most frequently observed in urban areas, areas of high exposure are also seen in the agricultural belt of Indiana and northwest Ohio, where extensive former wetlands create soil conditions that may contribute to inland flooding during precipitation events. Although such exceptions exist throughout the study area, exposure values are generally lower in the more rural northern and extreme eastern portions of the region. For instance, the high elevation and sparse infrastructure within the Adirondack Park contribute to consistently low exposure values. By exploring the Threat and Community Asset Indices individually, many of the patterns observed in the Community Exposure Index become clear.

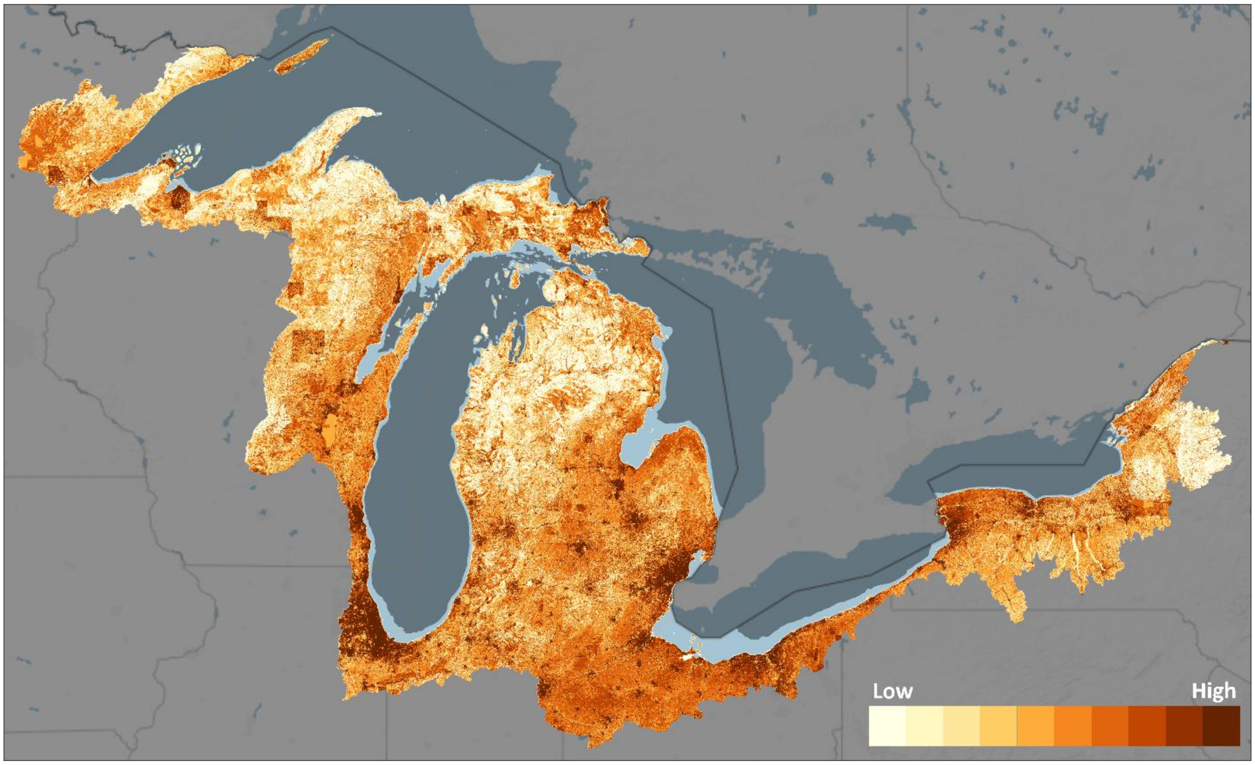

Figure 8. Community Exposure Index for the U.S. Great Lakes Coastal Resilience Assessment study area. The Threat and Community Asset Indices are multiplied to produce the Community Exposure Index, which shows areas where assets overlap with flood threats. To view results in detail, see CREST.

3.1.1 Threat Index

The Threat Index combines regional datasets that explore a range of flood-related hazards, including soil conditions, slope, flood-prone areas, and observed changes in lake levels. Information related to seiches, fetch, and other wave-driven flooding hazards were not available across the study area and while these hazards are indirectly captured through historical records of high lake level inundation, the Assessment presents a conservative estimate of the severity and extent of coastal hazards observed throughout the study area. Despite these limitations, there are many areas across the region facing numerous flood-related threats as indicated by the darkest shades of red (Figure 9).

Throughout the study area, many of the areas with the highest Threat Index values are seen along low-lying shorelines with moderately-high to high soil impermeability. For instance, major metropolitan areas around Chicago, Milwaukee, Detroit, Cleveland, and Buffalo feature highly impermeable soil (mostly impervious surfaces associated with development), low slopes, and moderately high to high soil erodibility, all of which contribute to high Threat Index values. In contrast, shorelines protected by extensive, high elevation dunes and bluffs generally received lower Threat Index values despite high soil erodibility. This is evident along the eastern Lake Michigan and Lake Superior shorelines. Areas particularly prone to flooding within the 100- and 500-year floodplains are also evident in the model results, including flood-prone areas around Saginaw Bay, Toledo, and the Kankakee River in northwest Indiana. High Threat Index values are also visible in large existing and former wetland complexes, which generally contain low elevations and high soil impermeability. This leaves areas in eastern Michigan's upper peninsula, agricultural areas in northwestern Ohio, and flood-prone wetland complexes around Lake Winnebago in Wisconsin threatened.

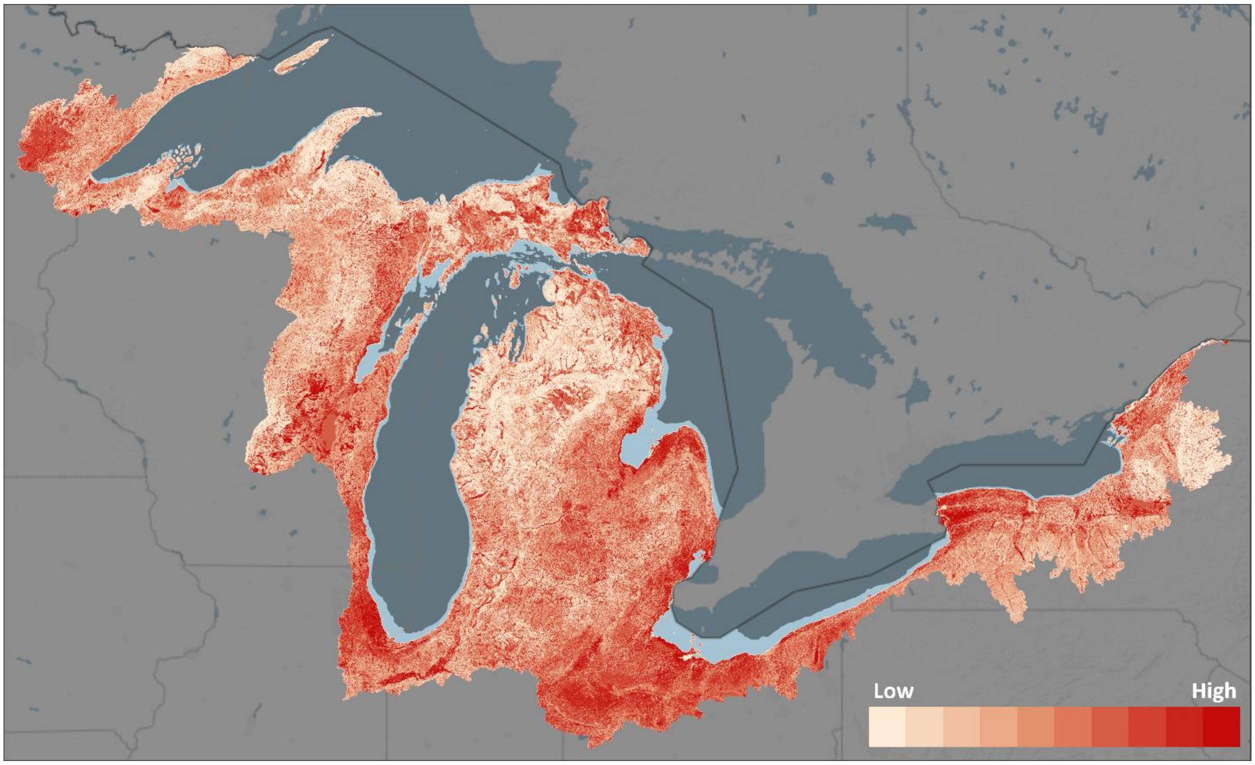

Figure 9. Threat Index for the U.S. Great Lakes Coastal Resilience Assessment study area. To view results in detail, see CREST.

3.1.2 Community Asset Index

While flooding threats are evident throughout the study area, the Community Asset Index identifies concentrations of community assets around the most highly developed and populated coastal areas. Most of the population within the study area lives along highly exposed coastlines. The five most densely populated counties in the region are located directly on the coast, leaving residential, commercial, and critical infrastructure potentially vulnerable to flooding hazards. The social vulnerability input further highlights high exposure among many of the impoverished urban communities. Although the Community Asset Index does reveal the highest values within urban areas, rural communities are also evident, particularly when zoomed into more localized scales. In fact, important community assets can be seen throughout the region, including roads, bridges, communication infrastructure, and airports, all of which are critical for effective emergency response in the event of major flooding events. High social vulnerability also contributes to high Community Asset Index values in rural areas such as the Menominee Reservation in Wisconsin, the Fond du Lac Reservation in Minnesota, Cattaraugus Reservation in New York, and townships within Menominee and Gogebic Counties in Michigan.

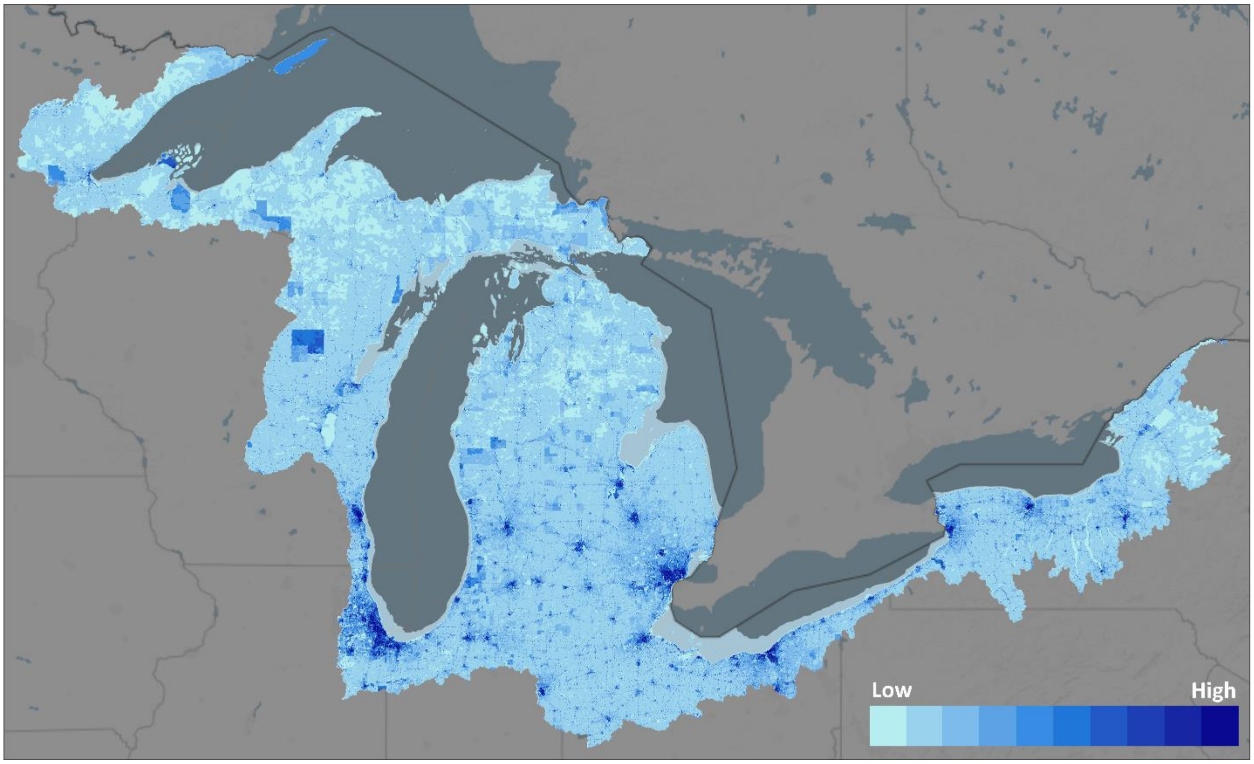

Figure 10. Community Asset Index for the U.S. Great Lakes Coastal Resilience Assessment study area. To view results in detail, see [CREST](#).

3.1.3 Combining Flooding Threats and Community Assets

Duluth, Minnesota and Superior, Wisconsin provide good examples of how a combination of high Threat and Community Asset Index values equate to high values in the Community Exposure Index (Figure 11). Particularly high Threat Index values occur around the City of Superior, where the low slope of the terrain and high impermeability of the soils combine to increase the overall threat. While Duluth also has many impervious surfaces contributing to high soil impermeability, Superior has high overall threat values because the city is surrounded by flood-prone areas. In the Community Asset Index, concentrations of critical infrastructure and critical facilities combine with areas of dense population and social vulnerability to create the highest values in Duluth. Main transportation corridors in and out of the cities are also evident in the Community Asset Index. The combination of flooding threats and dense community assets create the patterns observed in the Community Exposure Index. Here both Duluth and Superior have similarly high exposure, and while Superior faces greater threats overall, the threats facing Duluth may impact more community assets. To explore the results of the analysis in more detail for any area of interest throughout the study area, visit the Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to Section 3.4 below.

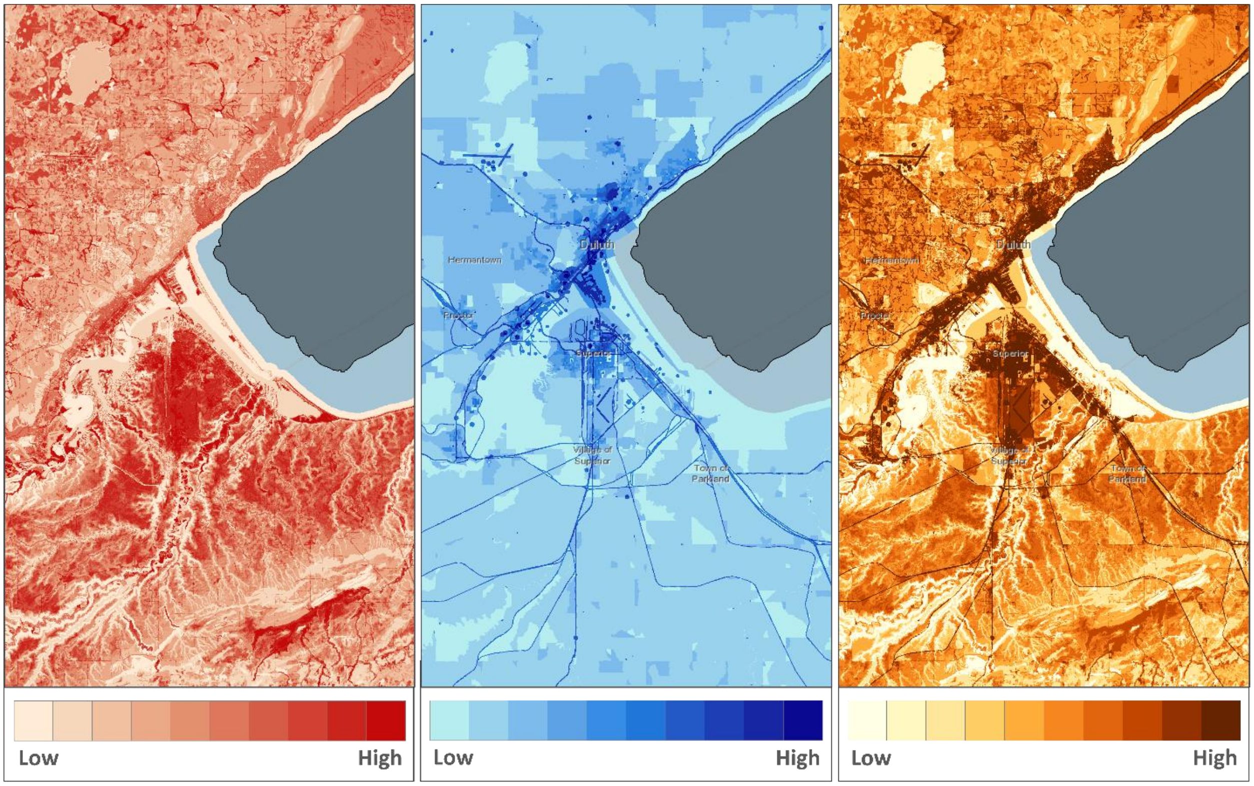

Figure 11. Threat Index (left), Asset Index (middle), and Community Exposure Index (right) for the Duluth metropolitan area in Minnesota along the western Lake Superior shoreline. Results show multiple flooding threats in areas of high community asset density, resulting in high Community Exposure Index values. The study area extends to a 20-meter depth contour as shown by the black boundary. To view results in detail, see CREST.

3.2 Fish and Wildlife Index

The Great Lakes are home to many unique ecosystems that support diverse fish and wildlife populations. As the largest freshwater ecosystem in the world, the region boasts globally significant waterfowl and shorebird populations, rare freshwater mussel species, and species endemic to the deep waters of the Great Lakes. The northern portion of the region is largely undeveloped, contributing to dense forests, healthy rivers and streams, and many undisturbed wetlands. In contrast, the densely populated southern portion of the Great Lakes region has been heavily modified, where many wetlands, forests, and native prairies have been converted for agricultural use and urban development. A recent study exploring land cover from 2015 revealed nearly 97 percent natural land cover within the Lake Superior Basin compared to just 21 percent natural cover in the Lake Erie Basin (ECCC & EPA 2022). These striking differences contribute to significant variation in the presence and condition of wildlife habitat throughout the region.

In addition to habitat loss, urban development, agriculture, and industry have long contributed to significant nutrient and sediment pollution across the Great Lakes region. Natural systems are further threatened by the spread of non-native and invasive species, including European common reed (*Phragmites*), zebra and quagga mussels, and sea lamprey among some 188 aquatic non-native species identified in the region (ECCC & EPA 2022). Climate change further threatens native species at risk from rising temperatures, species range shifts, and changes in the timing of seasonal events (Angel et al. 2018). While other studies describe species' climate vulnerability, spread of invasive species, and the impacts of pollution and poor water quality (Angel et al. 2018), this assessment aims to identify habitat that may be suitable for species of conservation concern and does not consider a species' vulnerability or adaptability to flooding or other threats. The Fish and Wildlife Index relies on habitat suitability models and does not include current or historical species occurrence data.

The results from the Fish and Wildlife Index focus on terrestrial, riverine, and lacustrine species of conservation concern as identified by the SWAPs (Derosier et al. 2015; IL DNR 2022; IN DNR 2015; MN DNR 2016; NY DEC 2015; OH DW 2015; PGC-PFBC 2015; WI DNR 2015), species listed as threatened or endangered under the U.S. Endangered Species Act, and species with off-reservation harvest regulations (see Appendix F.1 and Appendix G.1 for a full list of all species included in the Fish and Wildlife Index.) By assessing habitat preferences across various taxonomic groups, the Fish and Wildlife Index combines separate Terrestrial and Aquatic Indices to identify areas expected to support numerous species of conservation concern, with the highest values representing the highest relative species richness.

The Fish and Wildlife Index reveals particularly high values (shown as darker shades of purple) along large rivers, within dense forests, and among coastal and inland wetlands (Figure 12). At a regional scale, consistently low values are seen throughout the region's most densely populated and agricultural areas; however, when viewed at more localized scales, even the most densely populated cities reveal large rivers and remnant wetlands capable of potentially supporting numerous species of conservation concern. In contrast, the more undeveloped northern and eastern portions of the study area show consistently high Fish and Wildlife Index values at a regional scale, owing to large tracts of intact habitat such as the Adirondack Mountains in New York and the Superior, Chequamegon-Nicolet, Ottawa, and Hiawatha National Forests in Minnesota, Wisconsin, and the upper peninsula of Michigan. Also evident are high values in north central Michigan including the Shiawassee River and Shiawassee National Wildlife Refuge southwest of Saginaw Bay, which boast large inland wetlands and deciduous forests. When zoomed into local scales, extensive coastal habitat including forests, wetlands, dunes, and bluffs associated with migratory birds and bats, is also visible throughout much of the Wisconsin lakeshore. To better understand the patterns visible in the Fish and Wildlife Index, it is helpful to also explore results within the Terrestrial and Aquatic Indices.

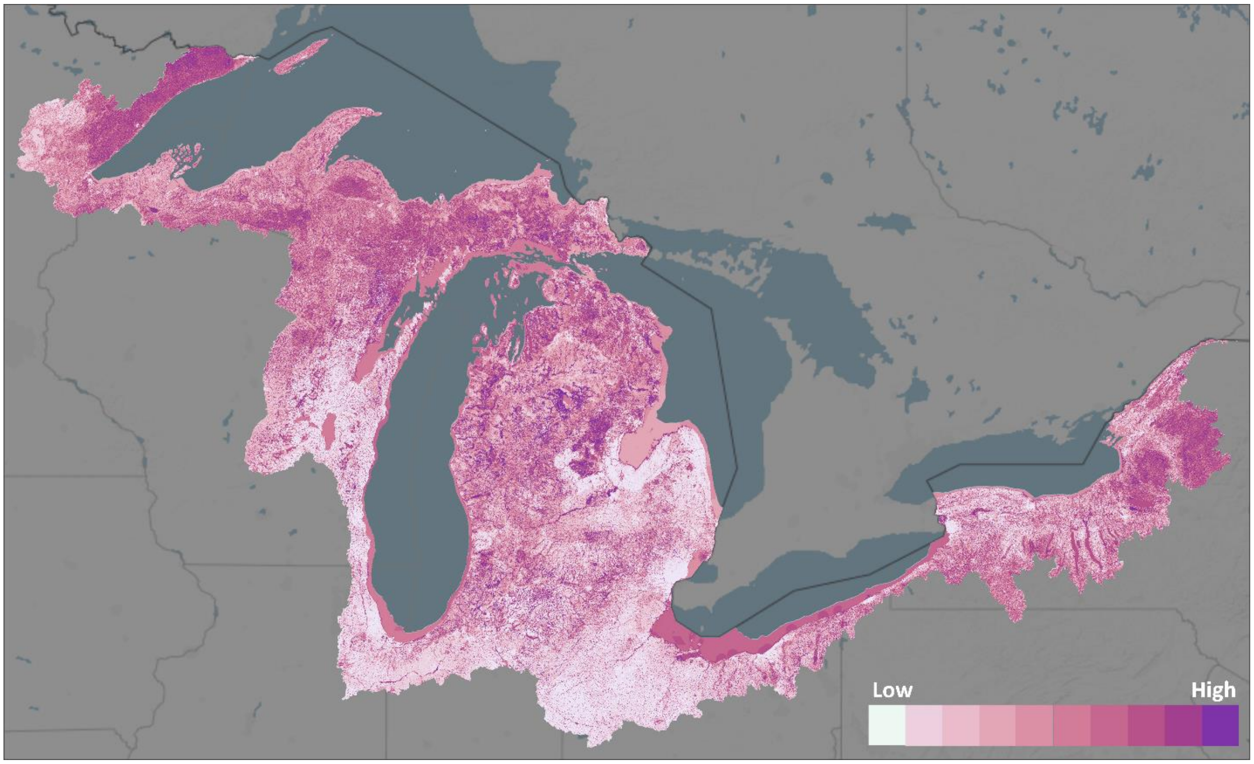

Figure 12. Fish and Wildlife Index values for the U.S. Great Lakes study area. Darker shades identify areas likely to support numerous terrestrial and aquatic species of conservation concern. To view results in detail, see CREST.

3.2.1 Terrestrial Index

The U.S. Great Lakes Assessment compiled habitat suitability data from 289 terrestrial species of conservation concern that when combined with critical habitat, Important Birds Areas and Key Biodiversity Areas, and coastal bluffs and dunes, reveals areas of high terrestrial species richness throughout the study area. The highest Terrestrial Index values (shown as darker shades of green) are evident along Minnesota's Superior lakeshore, in central Michigan, and within the Adirondack Mountains of New York (Figure 13). In the Superior National Forest in Minnesota, the high Terrestrial Index values are driven by a combination of high mammal diversity–including critical habitat for both Canada lynx (*Lynx canadensis*) and gray wolf (*Canis lupus*)–and a globally significant Important Bird Area known to support over 160 breeding bird species. Similarly, in central Michigan the high Terrestrial Index values west of Saginaw Bay reflect areas such as the Michigan Department of Natural Resources Gladwin Lake Plain Management Area and Important Bird Area, which features aspen and lowland shrub habitat ideal for golden-winged warbler (*Vermivora chrysoptera*). The area supports many other species of conservation concern including the eastern massasauga rattlesnake (*Sistrurus catenatus*), red-shouldered hawk (*Buteo lineatus*), and numerous amphibians including species associated with forested and scrub/shrub wetlands and vernal pools such as the wood frog (*Lithobates sylvaticus*) and blue-spotted salamander (*Ambystoma laterale*).

Figure 13. Terrestrial Index for the U.S. Great Lakes Coastal Resilience Assessment study area. To view results in detail, see CREST.

Additional patterns are revealed when the Terrestrial Index is viewed at a more localized scale. For instance, the Indiana Dunes National Park and State Park offer unique and regionally important habitat for many migratory and nesting birds despite its relatively urban surroundings. The parks feature a high-quality dune system along with marsh, swamp, and upland forest habitat that together offer important nesting habitat for willow flycatcher (*Empidonax traillii*), wood thrush (*Hylocichla mustelina*), cerulean warbler (*Setophaga cerulea*), and prothonotary warbler (*Protonotaria citrea*). Although Terrestrial Index values are significantly lower in urban and agricultural areas overall, habitats important for numerous species of conservation concern remain along many riparian corridors and vegetated floodplains, such as the Maumee River flowing through Toledo or the Des Plaines River in the greater Chicago area. Grand Island in Buffalo, New York represents another urban area featuring high Terrestrial Index values owing to globally significant concentrations of gulls and a wide diversity of waterfowl that use the Niagara River corridor. These areas and others suggest the region includes a wide diversity of habitat capable of supporting numerous species of conservation concern.

3.2.2 Aquatic Index

The Aquatic Index reveals more subtle patterns when viewed at a regional scale, where the highest values (shown as darker shades of blue) occur predominantly along nearshore lake habitat and within the northern portion of the study area (Figure 14). Darker shades are evident throughout Minnesota, northern Wisconsin and Michigan, and the mountains of New York, where extensive cold-water habitat is important for a wide range of fishes, mollusks, and crayfishes. Many of the highest values in the Aquatic Index are seen in the nearshore waters of the Great Lakes and large inland lakes. While data limitations restrict variation in these habitat types, these lakes provide important habitat for over 128 species of conservation concern, including cisco (*Coregonus artedi*), deepwater sculpin (*Myoxocephalus thompsonii*), and longnose sucker (*Catostomus catostomus*). Despite well-documented water quality concerns in Lake Erie, the shallow lake hosts impressive aquatic species richness.

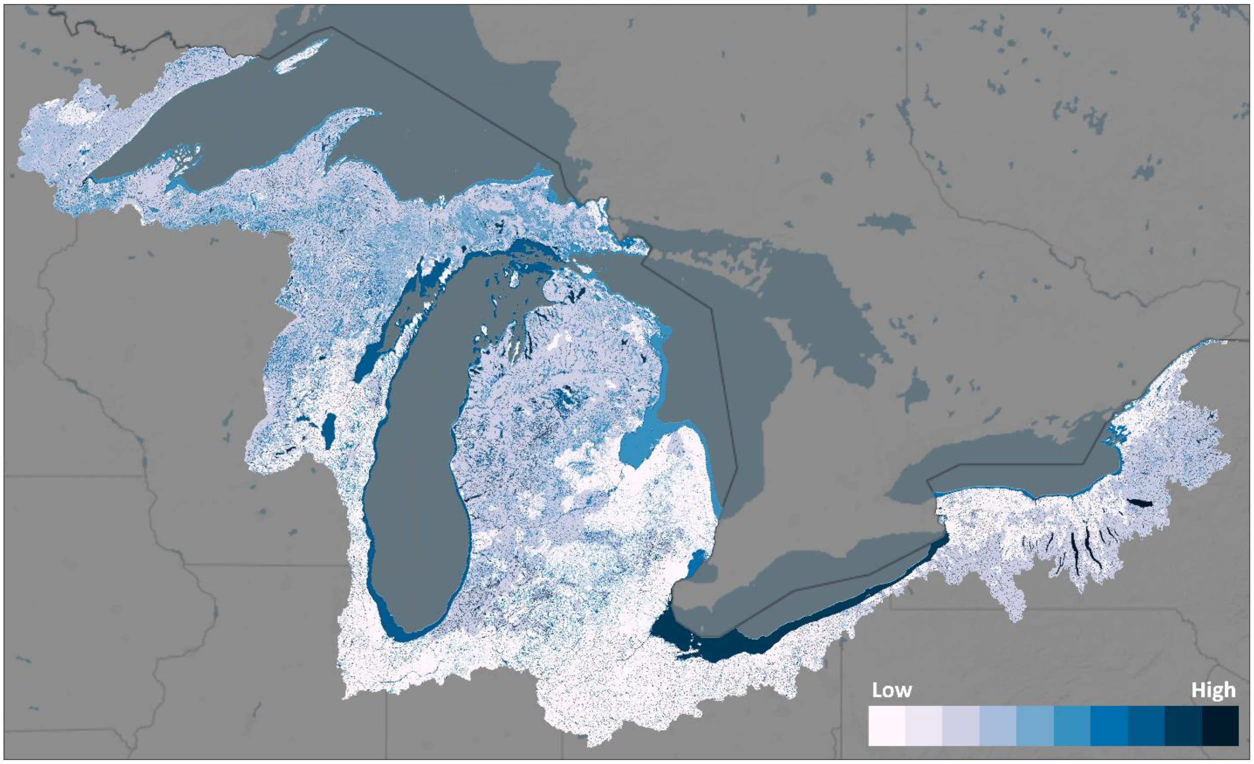

Figure 14. Aquatic Index for the U.S. Great Lakes Coastal Resilience Assessment study area. To view results in detail, see CREST.

When results are viewed locally, high Aquatic Index values within individual rivers, streams, and wetlands become apparent. For instance, large inland wetlands in north-central Michigan offer important habitat for brassy minnow (*Hybognathus hankinsoni*), lake chubsucker (*Erimyzon sucetta*), and spotted sucker (*Minytrema melanops*). Similarly, riparian corridors and vegetated floodplains provide habitat even in more urbanized and agricultural locations, including the Kankakee River flowing through Indiana and Illinois, which has particularly high Aquatic Index values. One of the more diverse and high-quality streams in the most southern portion of the study area, the river supports sensitive species such as the ironcolor shiner (*Notropis chalybaeus*), river redhorse (*Moxostoma carinatum*), and starhead topminnow (*Fundulus dispar*). The assessments also highlight the unique freshwater estuary at the mouth of the St. Louis River in Duluth, Minnesota, home to extensive wetland and aquatic habitat important for lake sturgeon (*Acipenser fulvescens*), walleye (*Sander vitreus*), northern pike (*Esox lucius*), wild rice (*Zizania* sp.), creek heelsplitter mussels (*Lasmigona compressa*), and many other aquatic species. Throughout the U.S. Great Lakes, the assessment identifies extensive aquatic habitat supporting many species of conservation concern.

3.2.3 Combining Terrestrial and Aquatic Indices

Particularly high Terrestrial, Aquatic, and combined Fish and Wildlife values are found along the eastern Lake Ontario shoreline southwest of Watertown, New York (Figure 15). This stretch of coastline supports one of the largest inland dune systems in the eastern Great Lakes and the only major freshwater dune system in the eastern U.S. The extensive sandy beaches and dunes serve as critical habitat for federally endangered piping plover (*Charadrius melodus*). Behind the dunes, high-quality freshwater marshes support migratory and breeding birds including American black duck (*Anas rubripes*), pied-billed grebe (*Podilymbus podiceps*), least bittern (*Ixobrychus exilis*), and breeding populations of the New York state-endangered black tern (*Chlidonias niger*). Together, this unique barrier beach system represents an

Important Bird Area, several state Wildlife Management Areas, and two state parks. These features contribute to high Terrestrial and Fish and Wildlife Index values. The large emergent marshes and ponds also generate high Aquatic Index values, providing important nursery habitat for spawning fishes while cold-water inland streams support a diversity of resident fishes, crayfishes, and mollusks. In combination, the numerous diverse and unique habitat types highlight the importance of this area for a broad suite of regional species of conservation concern. To explore the results of the analysis in more detail for any area of interest throughout the study area, visit the Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to Section 3.4 below.

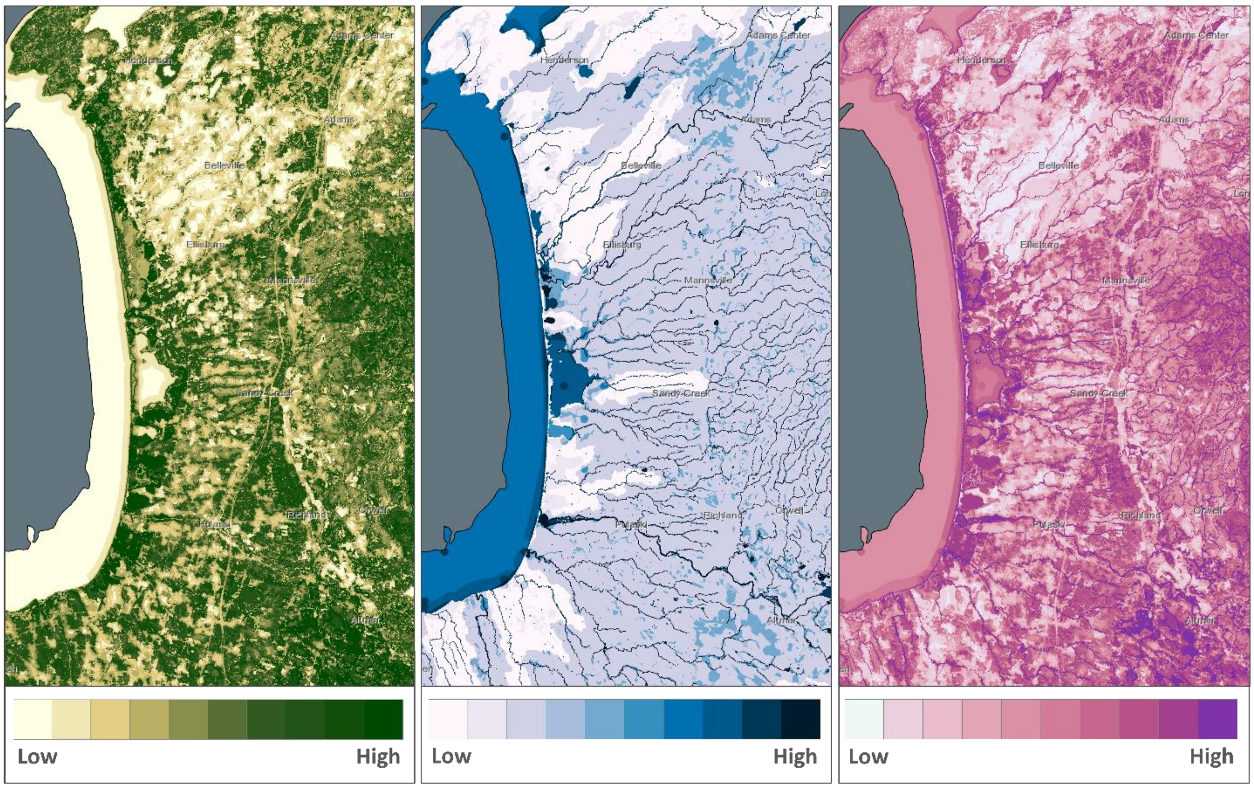

Figure 15. Terrestrial Index (left), Aquatic Index (middle), and Fish and Wildlife Index (left) for the Eastern Lake Ontario shoreline, including the Southwick Beach and Sandy Island Beach State Parks in New York. Results show high values in both the Terrestrial and Aquatic Indices, resulting in many areas with high Fish and Wildlife Index values. The study area extends to a 20-meter depth contour as shown by the black boundary. To view results in detail, see CREST.

3.3 Resilience Hubs

The U.S. Great Lakes Assessment identified many Resilience Hubs throughout the study area. While the highest-ranking Resilience Hubs are scattered across the landscape, the Assessment revealed ample opportunities throughout the study area to implement nature-based solutions to help build human community resilience while also benefiting habitat and the species and ecosystem services they support.

The final Resilience Hub rankings identify areas of contiguous open space that are of a sufficient size to provide fish and wildlife and flood risk reduction benefits. As described in the Methods section above, the boundaries of the Resilience Hubs are formed by identifying terrestrial, riparian, and lacustrine Habitat Cores at least 4 hectares (10 acres) in size. Once the boundaries of the Habitat Cores are determined, a single average rank is applied based on the product of the Community Exposure and Fish and Wildlife Index values, and other key inputs. For additional detail, results are also presented as a Resilience Hub Grid, where Habitat Cores are converted into 4-hectare (10-acre) hexagons. Each hexagon also receives a single average rank based on the values from the Community Exposure Index, Fish and Wildlife Index, and other factors.

Resilience Hub results are presented as both coarse-scale Resilience Hub Cores and a fine-scale Resilience Hub Grid. When viewing the Resilience Hub Cores, large tracts of contiguous open space are helpful to identify connected landscapes, but because each Core receives a single average rank, it can obscure variation within the Core. Therefore, the Resilience Hub Grid is helpful to visualize variation, where the highest-ranking hexagons will occur in those areas in closest proximity to human community assets exposed to flooding threats. In all cases, only the highest-ranking Resilience Hubs represent areas with the greatest potential to implement nature-based solutions capable of achieving dual benefits.

Due to the large scale of the U.S. Great Lakes region, differences among the Resilience Hub Cores or the hexagonal Grid are not easily distinguishable at a state or even regional level. Therefore, readers are encouraged to view the results in more detail for any area of interest by visiting the Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to Section 3.4 below.

As an example of the distinction between the Resilience Hub Cores and Grid, Figure 16 zooms into the broader Green Bay, Wisconsin area to provide a side-by-side comparison. The Resilience Hub Cores help to visualize connected watersheds and contiguous habitat; however, the rankings are based on the average values assigning a single score regardless of the size or features within the Core (Figure 16a). By viewing the Resilience Hub Grid, the variation within a given Core becomes visible (Figure 16b). For instance, around the Bay itself, nearly all nearshore waters represent similar moderate rankings when viewing the Resilience Hub Cores; however, the Grid clearly shows significantly higher Hub values closer to shore and adjacent to dense community assets. These shallower areas may therefore represent better opportunities for offshore rock reefs or other nature-based solutions that seek to reduce wave energy and reduce coastal erosion. Similarly, in the western portion of Figure 16, large tracts of contiguous open space receive a single, average score when viewing the Resilience Hub Cores whereas the Grid shows the highest values concentrated along rail and highway infrastructure. Both the Resilience Hub Cores and Grid highlight numerous opportunities for resilience-building projects within the city of Green Bay, the Oneida Reservation, and many other communities in the area.

For the purposes of this report, the regional results are shown as the Resilience Hub Grid only. At a regional scale, Resilience Hubs are seen across most of the study area (Figure 17). This is in part due to the large number of fragmenting features, even in some of the most remote areas, that break up the landscape into many, relatively small Resilience Hubs.

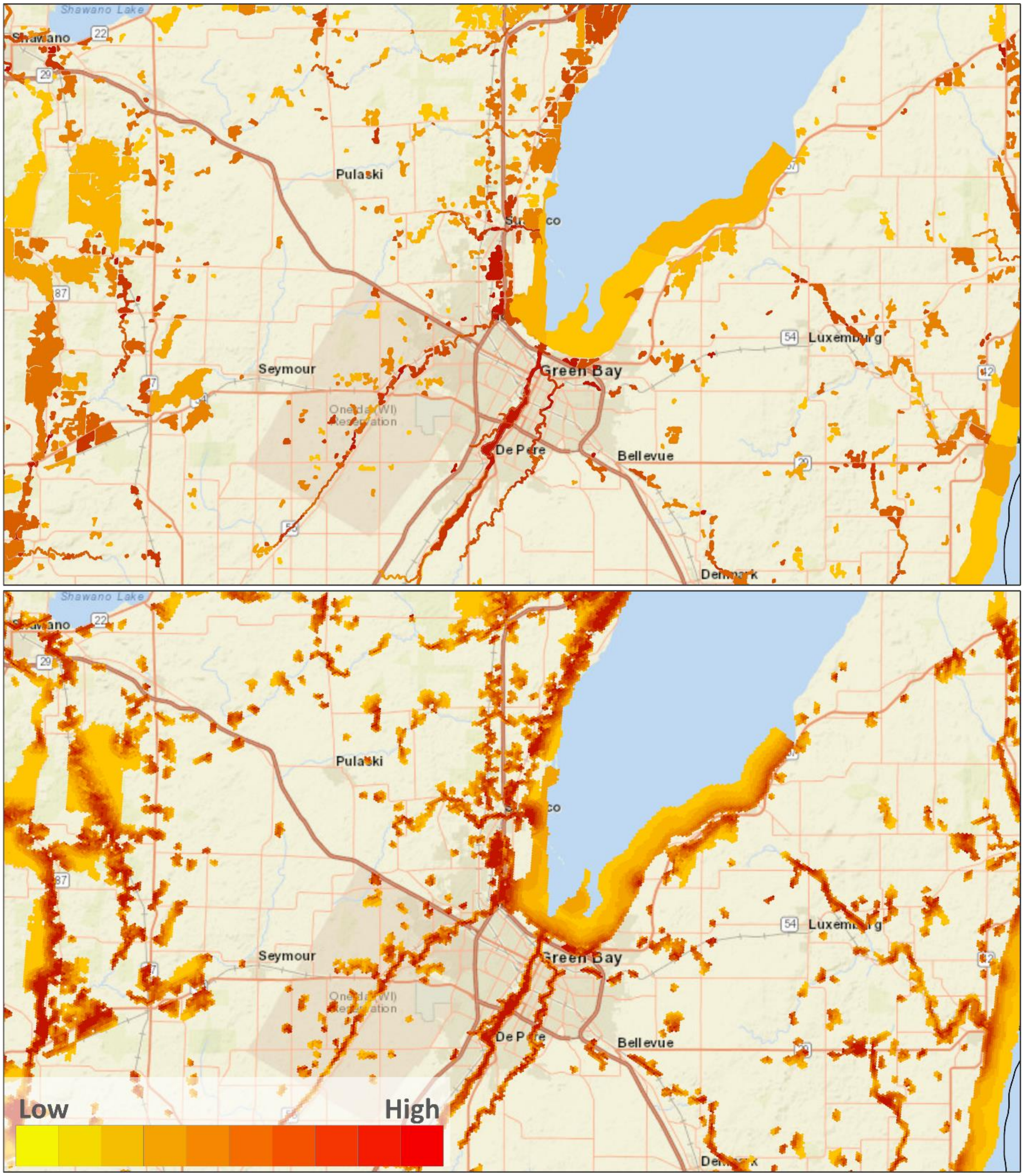

Figure 16. Resilience Hub Cores (top) and Resilience Hub Grid (bottom) in the Green Bay, Wisconsin metropolitan area. When viewed at this scale, the difference between the Cores and Grid becomes apparent. To view results in detail for other communities, see [CREST](#).

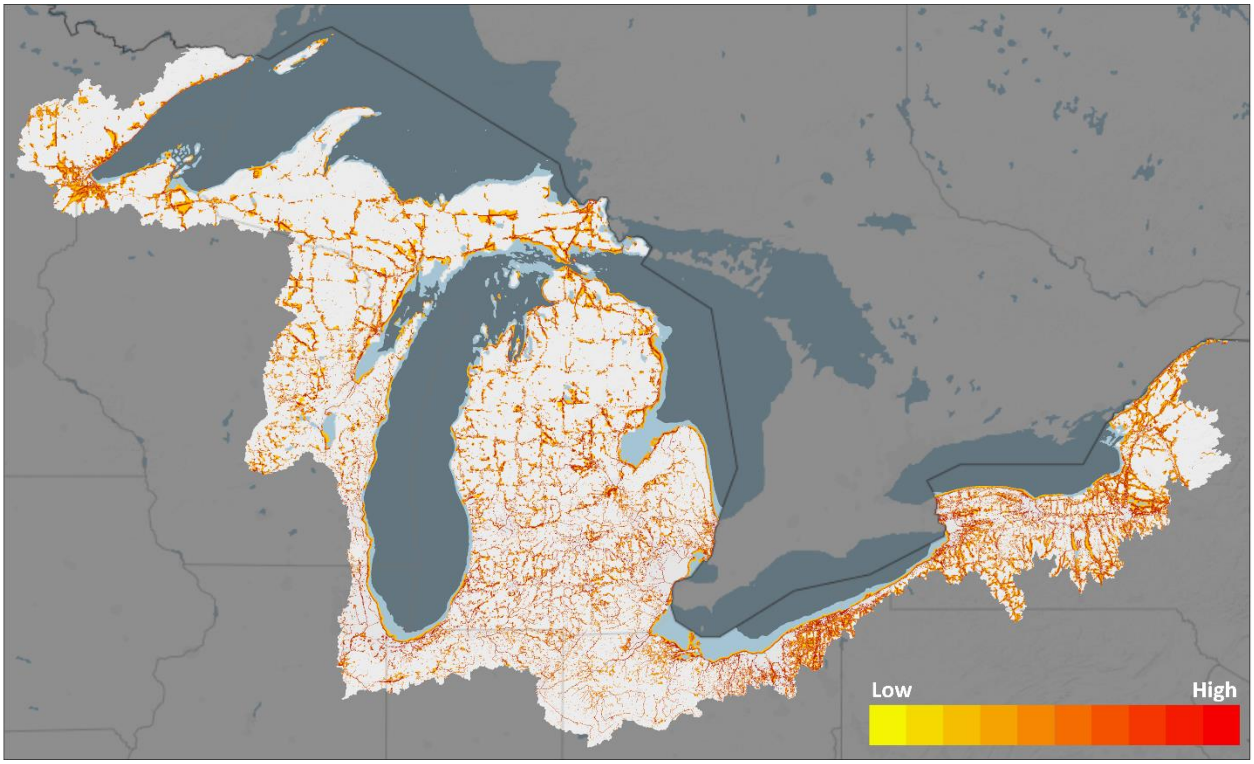

Figure 17. Resilience Hub Grid for the U.S. Great Lakes Coastal Resilience Assessment study area. High ranking Resilience Hubs (darker reds) represent areas well suited for the implementation of nature-based solutions that may benefit both species of conservation concern and human community resilience to flooding threats. To view results in detail, see CREST.

Zooming into the most northern, largely undeveloped portion of the study area (Figure 18), the region's transportation infrastructure is particularly visible where large tracts of open space are fragmented by critical infrastructure. Population centers around Duluth, Marquette, and Sault Ste. Marie also feature large concentrations of high-scoring Resilience Hubs. While the large tracts of undeveloped land offer excellent fish and wildlife habitat and many opportunities for wildlife-focused restoration and conservation projects (see Section 3.2), this Assessment focuses on identifying areas where nature-based solutions can simultaneously provide flood protection and ecosystem benefits. Therefore, Resilience Hubs are concentrated in areas with nearby human community assets.

In the central portion of the study area, high ranking Resilience Hubs are also evident along major transportation infrastructure (Figure 19). While high ranking Hubs are visible in the region's largest cities, limited natural open space in Milwaukee, Chicago, and Detroit generally focus resilience-building opportunities around riverine and coastal habitats. Therefore, generally more Hubs are present in the broader metropolitan areas, smaller cities, and towns where human community assets more frequently intersect with open spaces. Many of the highest-ranking areas occur along the coasts and in areas with remnant emergent wetlands.

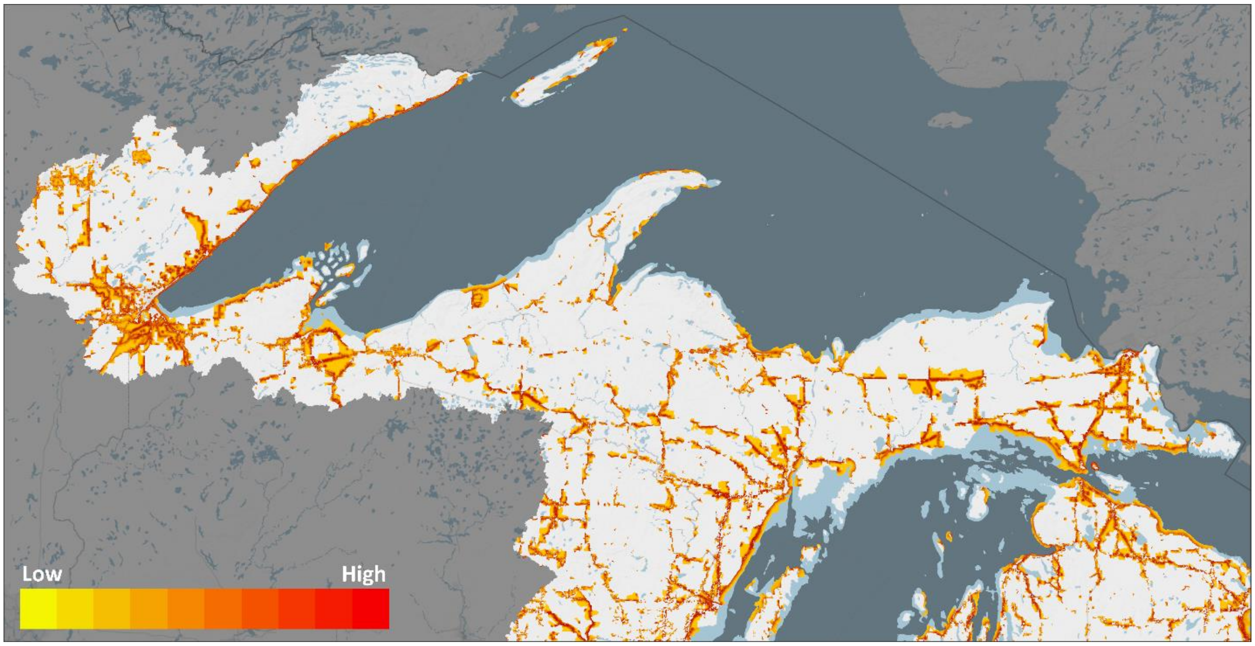

Figure 18. Resilience Hub Grid for the northern region of the study area in Minnesota, northern Wisconsin, and Michigan's upper peninsula around Lakes Superior, Michigan, and Huron. To view results in detail, see CREST.

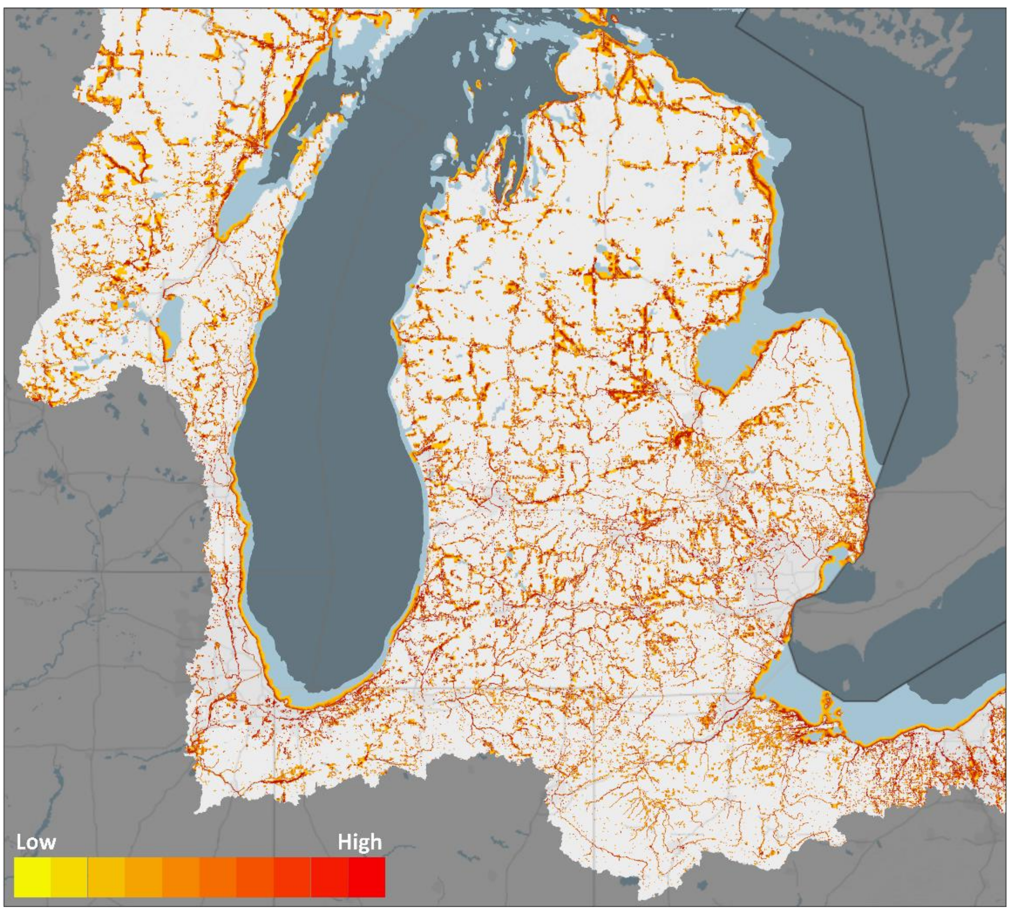

Figure 19. Resilience Hub Grid for the central region of the study area in eastern Wisconsin, Illinois, Indiana, Michigan's lower peninsula, and western Ohio around Lakes Michigan, Huron, and Erie. To view results in detail, see CREST.

Resilience Hubs are particularly prevalent in the eastern portion of the study area around Lake Erie and Lake Ontario (Figure 20). With a mosaic of deciduous forest, woody wetlands, and pasture/hay fragmented by roads and other infrastructure, areas east of Cleveland show one of the study area's large concentrations of high-ranking Hubs. Similarly, large wetland complexes around Oneida Lake north of Syracuse show many high values. In contrast, there are relatively few hubs within the undeveloped Adirondack Mountains. To explore the results in more detail for any area of interest throughout the study area, visit the Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to Section 3.4 below.

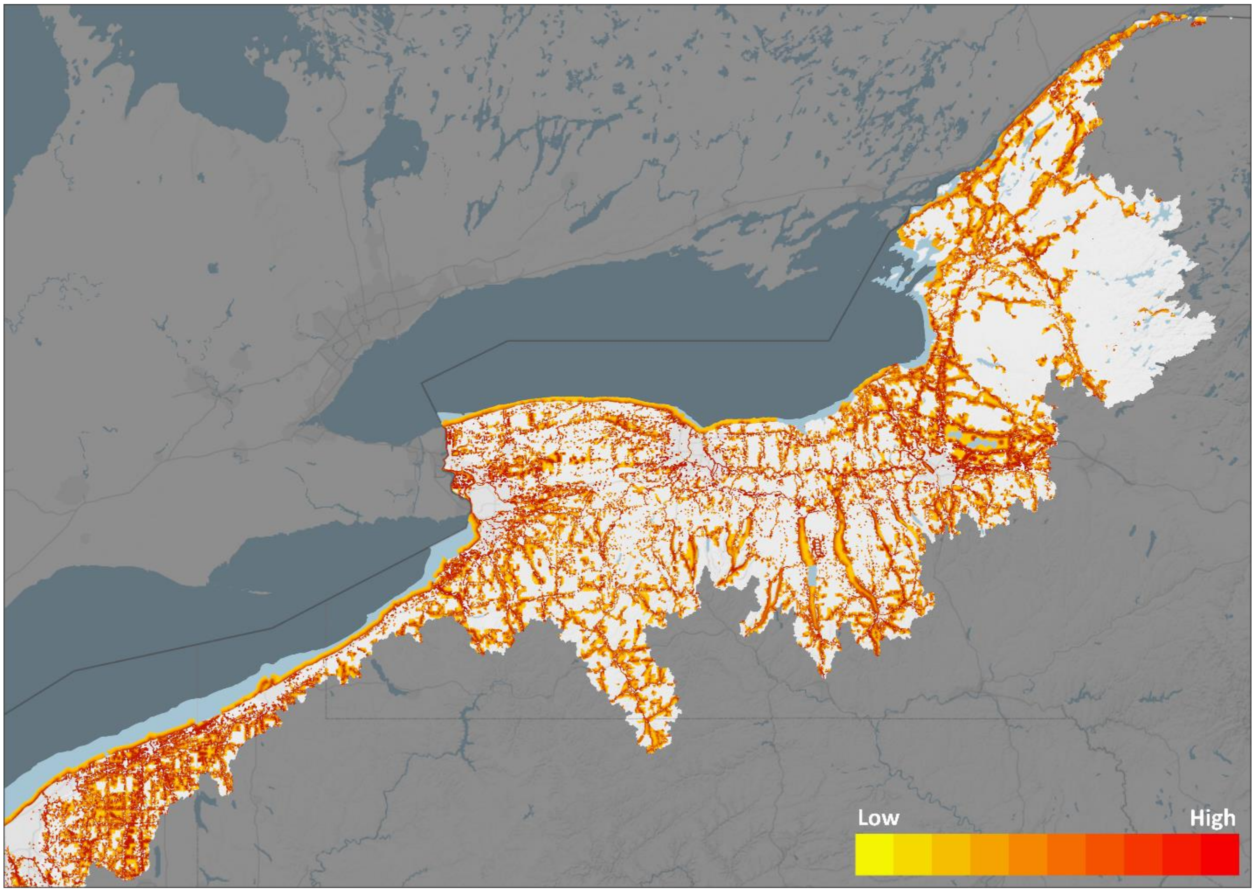

Figure 20. Resilience Hub Grid for the eastern region of the study area in Ohio, Pennsylvania, and New York around Lakes Erie and Ontario and the St. Lawrence River and Seaway. To view results in detail, see CREST.

3.4 Coastal Resilience Evaluation and Siting Tool

To provide an online interface to allow users to interact with key Assessment data, including input data and final models for the Community Exposure Index, Fish and Wildlife Index, and the Resilience Hubs, the Coastal Resilience Evaluation and Siting Tool (CREST) was developed as an accompanying GIS-based web tool (available at resilientcoasts.org). CREST helps users make informed decisions about proposed project sites and address other key questions about how to build resilience within their community. It also allows users full access to the U.S. Great Lakes Assessment data so they may incorporate them into their own GIS applications or other planning processes. Additionally, CREST provides access to the Assessment results even if the user does not have a GIS background or access to GIS software.

Users can directly access results of the U.S. Great Lakes Assessment straight from the CREST homepage. In addition to simply exploring the results of the Regional Assessments, CREST allows users to analyze results for specific areas of interest. For instance, if a user has already identified a potential project location, they can draw or upload the project boundary within the tool to view site-specific results for the Resilience Hubs, Community Exposure Index, Fish and Wildlife Index, and the results for each of the model inputs. Alternatively, if a user does not have a specific project location in mind but is interested in evaluating opportunities within a particular region, they can draw a broad area of interest to view results. In both cases, the user can view the results in CREST or download the results in tabular or GIS formats for additional analysis.

CREST is intended to be used as a screening-level tool designed to help identify areas that may be well suited for nature-based solutions. As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans.

CASE STUDIES

Communities throughout the Great Lakes region face growing threats from erosion and storm-driven flooding, with storm events predicted to increase in frequency and intensity in the coming decades. To help mitigate these hazards, shorelines across the region have been hardened with traditional protective infrastructure such as revetments, seawalls, and levees. While these traditional gray options are often effective at dissipating wave energy and reducing flooding risk, many are in disrepair, require expensive maintenance, and fail to provide the ecological co-benefits provided by nature-based solutions. Therefore, a growing number of communities throughout the Great Lakes region are seeking innovative solutions that use nature-based alternatives, often in concert with traditional gray infrastructure, to help meet the challenges ahead.

Nature-based solutions are natural, engineered, and hybrid approaches that strategically protect, restore, sustainability manage, or mimic ecosystems to conserve or restore ecosystem functions and natural processes with the goal of reducing community exposure to natural hazards and climate stressors and enhancing habitat for fish and wildlife. Efforts that work to restore coastal wetlands, rebuild dunes or natural buffers, or install living shorelines, among other approaches, are all strategies that reduce climate risks to communities while enhancing habitats.

The Great Lakes Coastal Resilience Assessment aims to identify opportunities to implement nature-based solutions that not only provide habitat, fish, and wildlife benefits, but also help build community resilience to flooding threats and other coastal hazards. The following case studies describe several recent and ongoing projects throughout the region[16], using the U.S. Great Lakes Assessment to demonstrate how results can be used to identify potential locations to implement or help advance nature-based solutions.

4.1 Coastal Protection through Habitat Restoration in Lake Superior

The City of Marquette, Michigan is one of many communities working to implement hybrid approaches that integrate natural habitat features into existing gray infrastructure. Situated along the southern shore of Lake Superior, Marquette is the largest city in Michigan's upper peninsula with over 21,000 residents. The developed lakeshore was once dominated by sandy beaches featuring a dune and swale complex with intermittent wetlands. Today, much of the shoreline is protected by a combination of rock revetments and nearshore breakwaters, leaving little natural shoreline habitat within the city.

Recently there has been growing interest in modifying hardened shorelines in Marquette to allow for more natural sediment dynamics and inland migration of important coastal habitats (City of Marquette 2015). To address this need, Superior Watershed Partnership (SWP), in coordination with the City of Marquette and other local partners, launched a project in 2018 to implement a green-gray hybrid infrastructure project in northern Marquette. With funding from the National Coastal Resilience Fund[17] and other sources, the project will help reduce impacts from coastal storms, protect public infrastructure, restore public access to the shoreline, and create 38 acres of coastal habitat.

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[16] The case studies described in this report are meant to be illustrative and are not meant to highlight the types of projects that may be competitive for National Coastal Resilience Fund or National Fish and Wildlife Foundation funding.
[17] https://www.nfwf.org/programs/national-coastal-resilience-fund

The project area is situated along a relatively undeveloped stretch of shoreline and is bisected by a multi-use walking trail and Lake Shore Boulevard, a major thoroughfare along Marquette's lakeshore (Figure 21). The area is currently protected by a continuous stone and concrete revetment that was built in 1939. In disrepair, the revetment leaves the shoreline vulnerable to erosion and frequent overtopping during storm events (Figure 22). Exposed to the pounding waves that build over Lake Superior, Marquette has recently experienced unprecedented coastal flooding and storm damage. In October 2017, the city suffered millions of dollars in damages after an historic storm brought record 28.8-foot waves and extreme winds reaching 77 miles per hour. The impacts of the storm were further compounded by near-record high lake levels. While this event was extreme, the Assessment confirms that Marquette is regularly exposed to numerous flood-related threats that leave its coastal infrastructure vulnerable (Figure 23). The results of the Asset Index further highlight the importance of the project location in helping to protect and provide improved recreational access to nearby socially vulnerable communities (Figure 24).

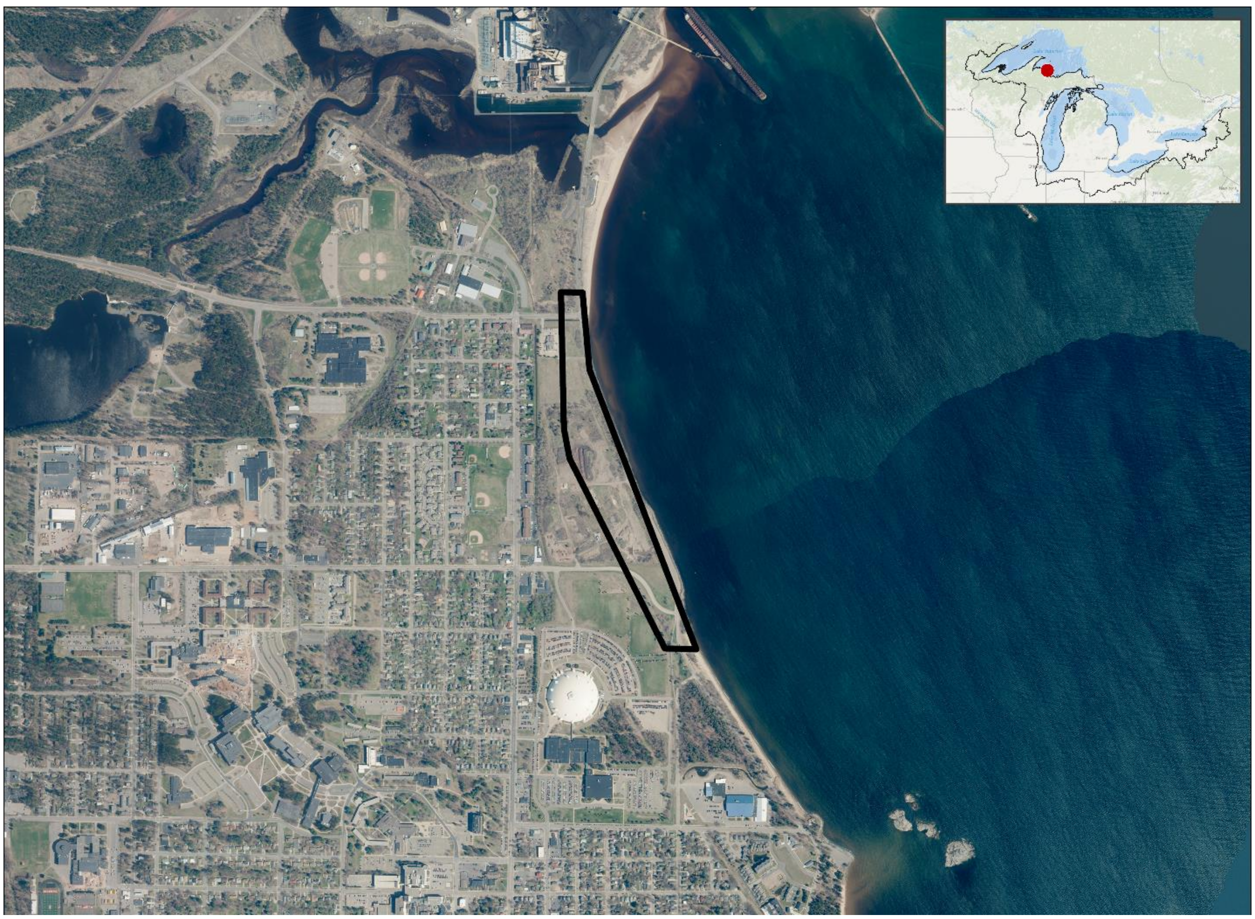

Figure 21. Approximate location of the green-gray hybrid infrastructure project in Marquette, Michigan (black polygon).

Figure 22. Lake Shore Boulevard during a large storm event. Waves are seen overtopping the existing revetment, scattering debris over the road. Image credit: Geraldine Grant, Superior Watershed Partnership.

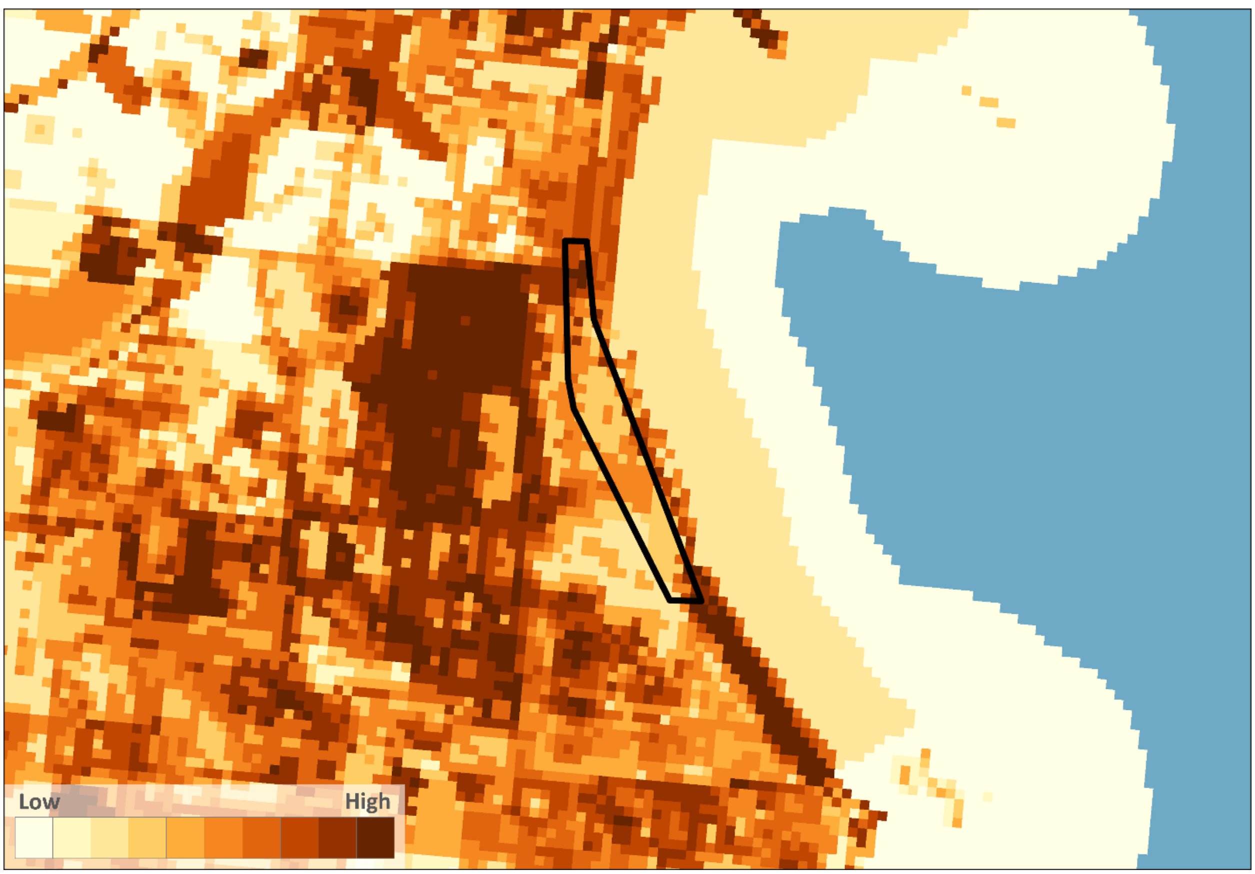

Figure 23. Community Exposure Index results reveal high values where human community assets are exposed to flooding threats both within and adjacent to the project area (black polygon).

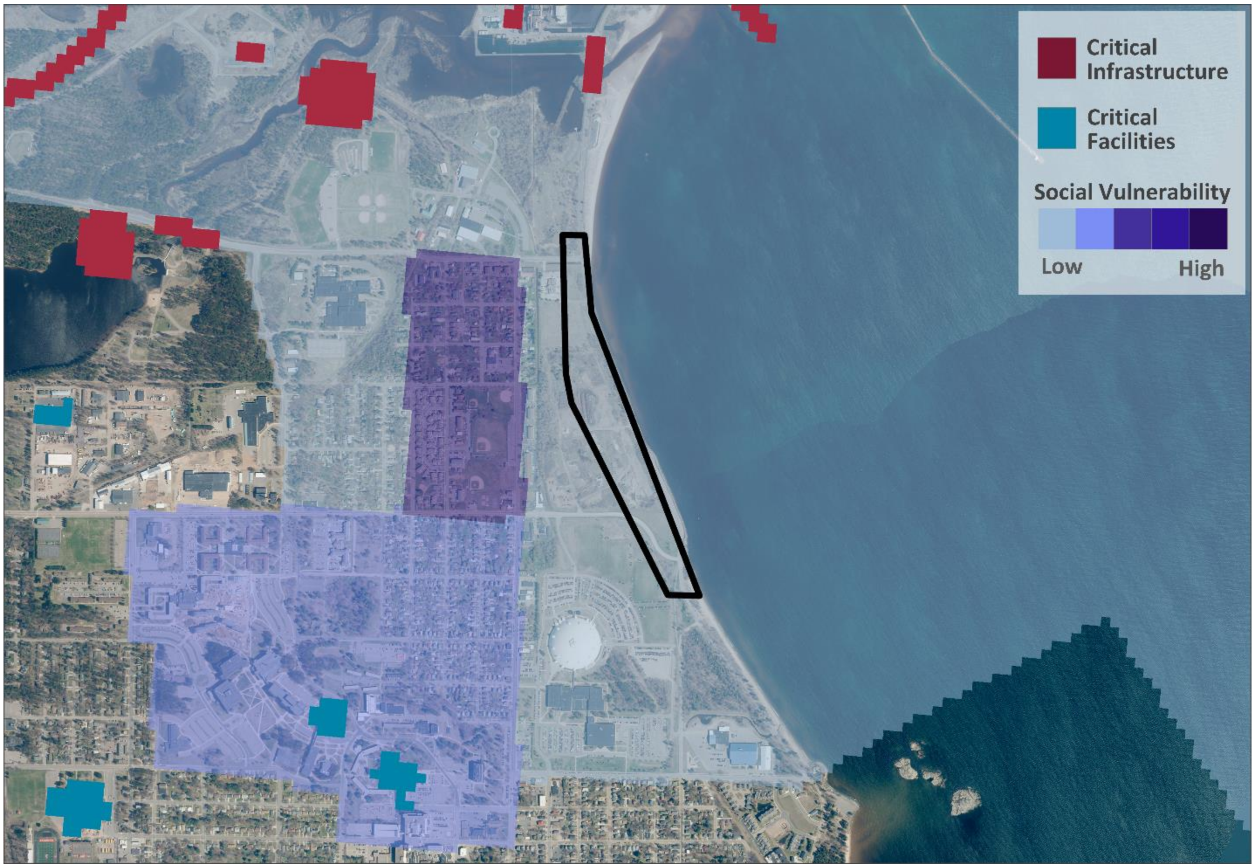

Figure 24. The project area (black polygon) is adjacent to socially vulnerable communities, critical facilities, and critical infrastructure.

The project will implement several strategies that will help build local resilience to flooding threats while simultaneously creating habitat for fish and wildlife species (Figure 25). In 2020, the City of Marquette coordinated with SWP to move Lake Shore Boulevard about 300 feet further inland to a higher elevation. By relocating the road, the project team is working to restore the surrounding habitat by creating dune swales and wetlands with sufficient room to allow natural dune migration over time. In total, the project will restore three acres of sand beach habitat, 16 acres of dune swales, three acres of coastal wetlands, 16 acres of upland terrestrial habitat, and 1.6 acres of nearshore aquatic habitat at the mouth of the Dead River. By integrating a living shoreline design that will replicate a natural cobble beach, the project will also provide public access to this mile-long stretch of the Lake Superior shoreline for the first time in nearly a century. Together, the restored habitat will provide public access, help reduce flooding through improved stormwater infiltration and flood water storage capacity and provide important ecosystem benefits for native species. The results from the Assessment show moderate to high Fish and Wildlife Index values within and around the study area (Figure 26). By restoring a range of habitat types, the project is expected to provide improved habitat conditions for a broad suite of species including an estimated 33 species of fishes and dozens of resident and migratory bird species.

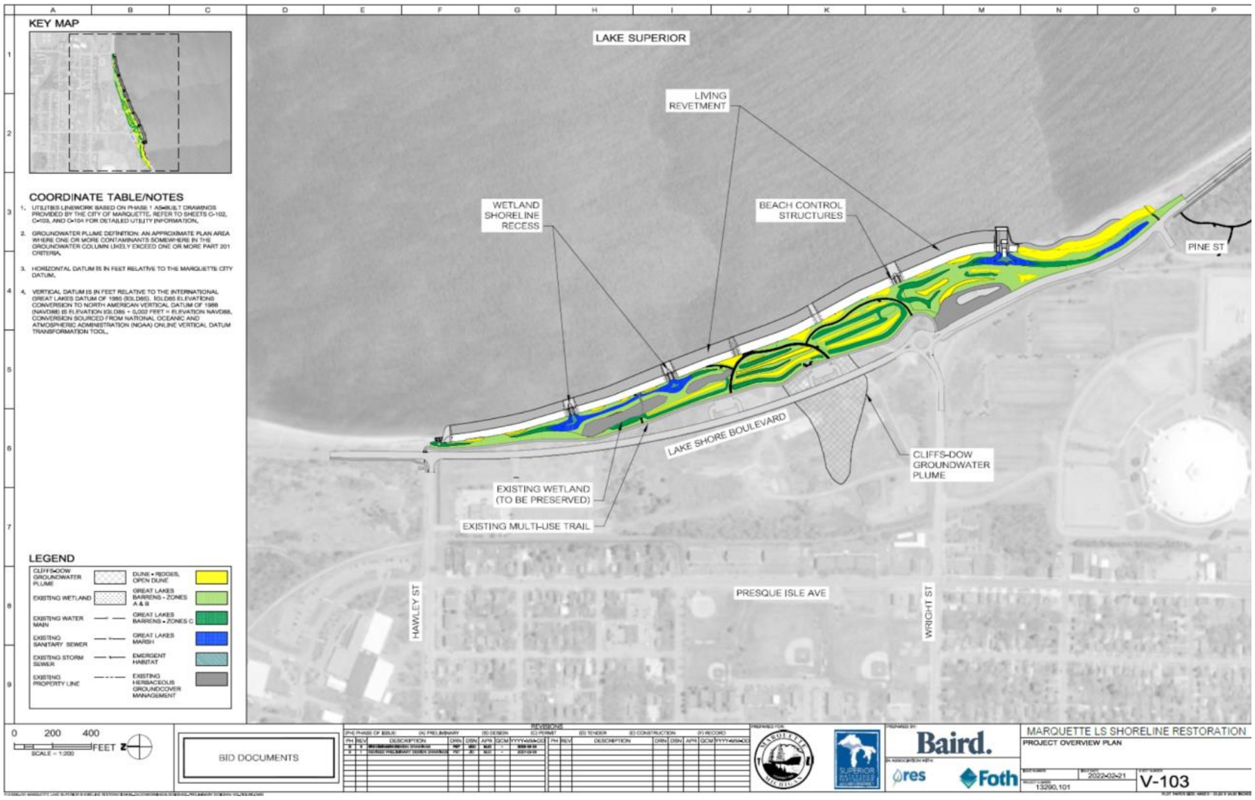

Figure 25. Project overview plan for the Marquette Shoreline Restoration. Plans show the new location of Lakeshore Boulevard, existing wetlands (gray), and planned habitat restoration activities including dunes (yellow), barrens (light and dark green), and marsh (blue). Thick black lines show public access trails to the shoreline. Plan prepared by Baird.

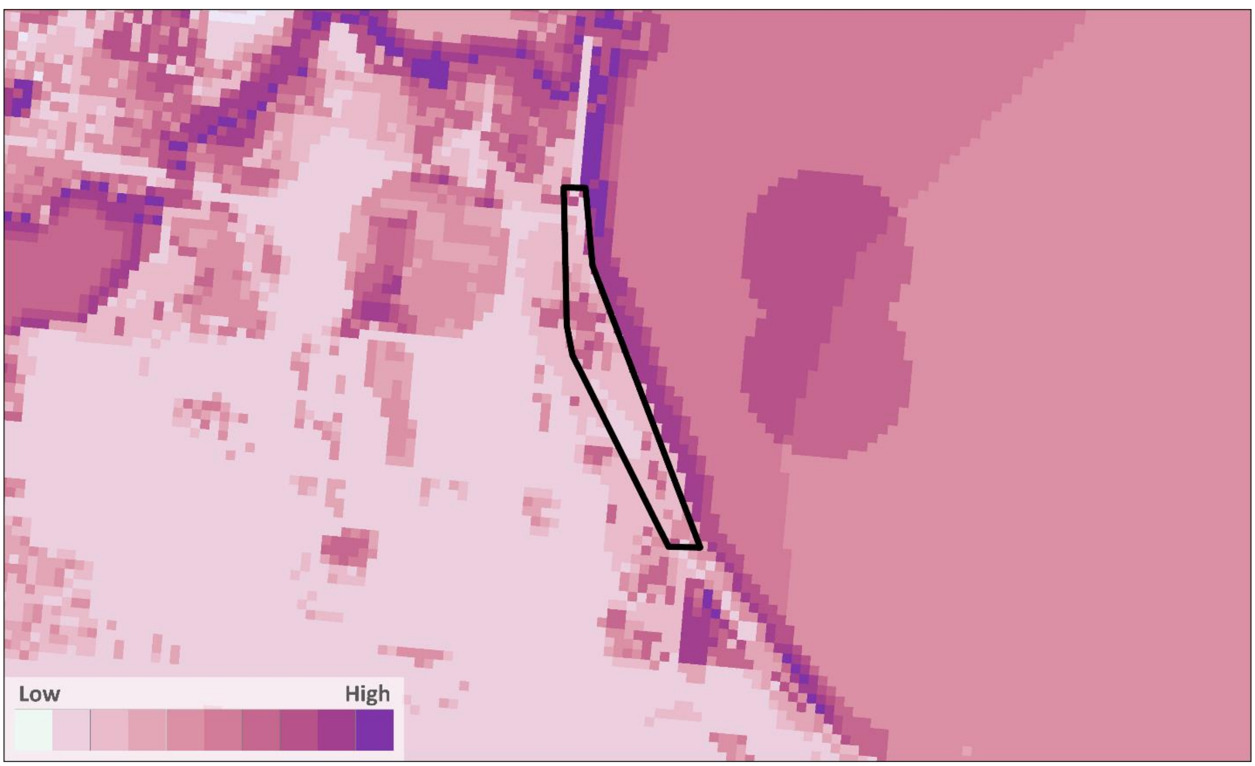

Figure 26. Fish and Wildlife Index results show areas important for species of conservation concern within and adjacent to the project area (black polygon).

With concentrations of coastal community assets and wildlife habitat facing significant flooding threats, this hybrid design demonstrates the potential for achieving multiple resilience-building benefits. The project site is surrounded by Resilience Hubs, highlighting the suitability and benefits of implementing nature-based, resilience-building interventions in this location (Figure 27). Innovative projects like this can serve as important models for other communities interested in exploring how nature-based solutions can be seamlessly integrated with traditional flood control measures to maximize benefits for people and wildlife alike. Using zonal statistics, the Assessment results allow users to calculate the average Resilience Hub score within the project polygon. In this case, the project area received a moderate Hub score of 5.4 out of 10. The Coastal Resilience Evaluation and Siting Tool (CREST) allows users to upload proposed or actual project polygons to quickly calculate scores for all Assessment inputs and outputs.

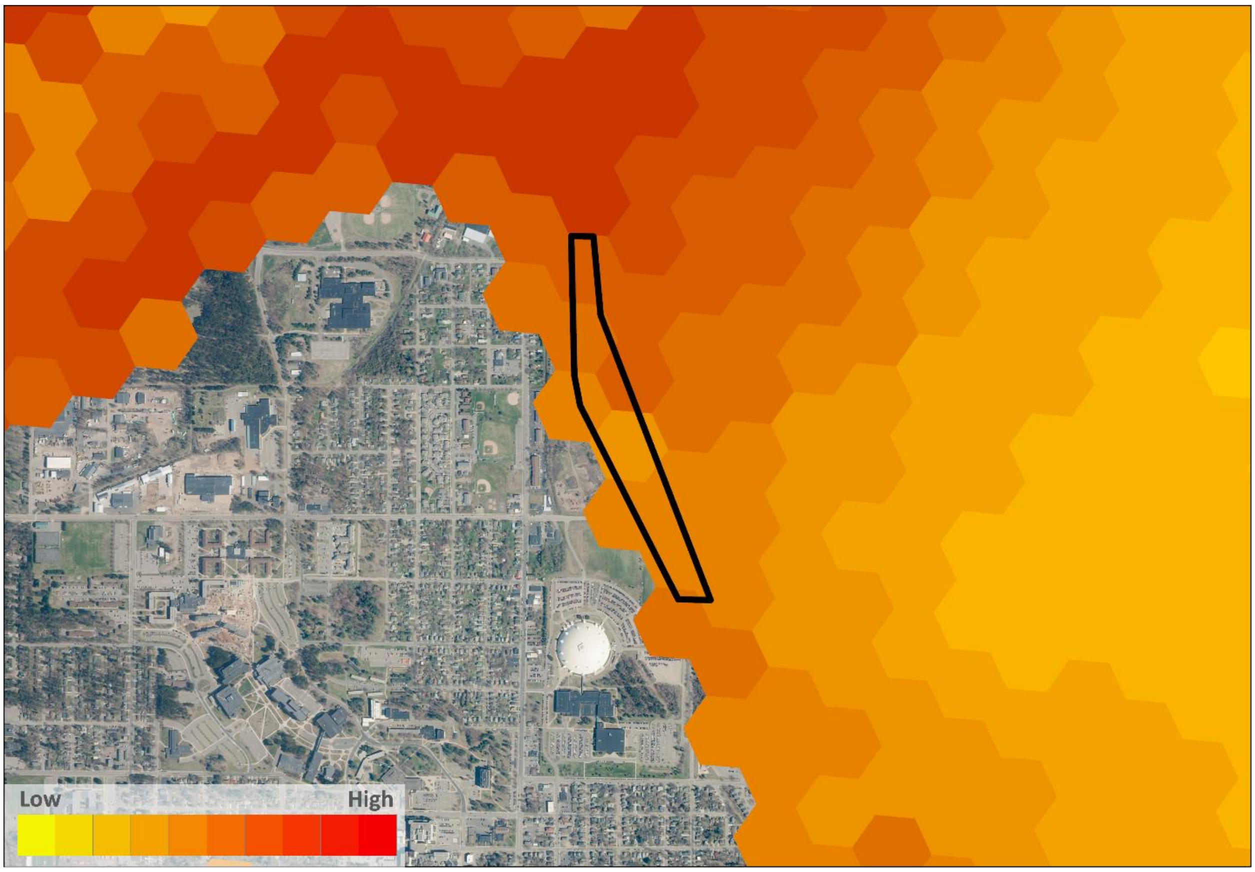

Figure 27. The project area (black polygon) is within and adjacent to high scoring Resilience Hubs, highlighting the suitability of this area for nature-based resilience projects with potential to benefit fish and wildlife and help build community resilience to flooding threats. The average Resilience Hub score within the project site is a 5.4 out of 10. The Resilience Hub Grid shows 4-hectare (10-acre) hexagons covering areas of open space.

4.2 Reducing Flood Risk through Floodplain Reconnection in the Lake Erie Basin

In response to recent extreme weather events that contributed to devastating flooding, the State of New York launched the Resilient New York Initiative. Through the Initiative, 48 high-priority watersheds were selected throughout the state based on the severity and frequency of recent flooding and ice jams, flood damage, and projected susceptibility to future hazards (OBG 2020). Eleven of these flood-prone watersheds occur within the greater Buffalo, NY area within the Lake Erie Basin[18], including Buffalo Creek Watershed in West Seneca, NY.

Buffalo Creek is one of three major tributaries flowing into the Buffalo River. The Town of West Seneca, a suburb of Buffalo, was built on and around these floodplains, leaving much of the community at risk from ice jam flooding and increasingly severe precipitation events. Previous flood mitigation efforts excavated a portion of the Buffalo Creek to create a straight, narrow channel designed to reduce ice formation and ultimately ice jam flooding. This effort removed natural river meanders, cut off oxbow wetlands, and degraded in-stream habitat. Unfortunately, downstream communities, including the Lexington Green neighborhood that was built on top of the former Buffalo Creek channel, continue to experience significant seasonal ice jam flooding (Figure 28). The Assessment results demonstrate significant flooding threats along Buffalo Creek, with nearly the entire Lexington Green neighborhood within a highly flood-prone area (Figure 29).

Figure 28. Aerial photo of recent ice jam flooding in West Seneca, New York. Photo credit: West Seneca Police Department.

[18] See Department of Environmental Conservation website for details: https://www.dec.ny.gov/lands/121102.html#:~:text=The%20Resilient%20NY%20program%20will,watersheds%20throughout%20New%20York%20State.

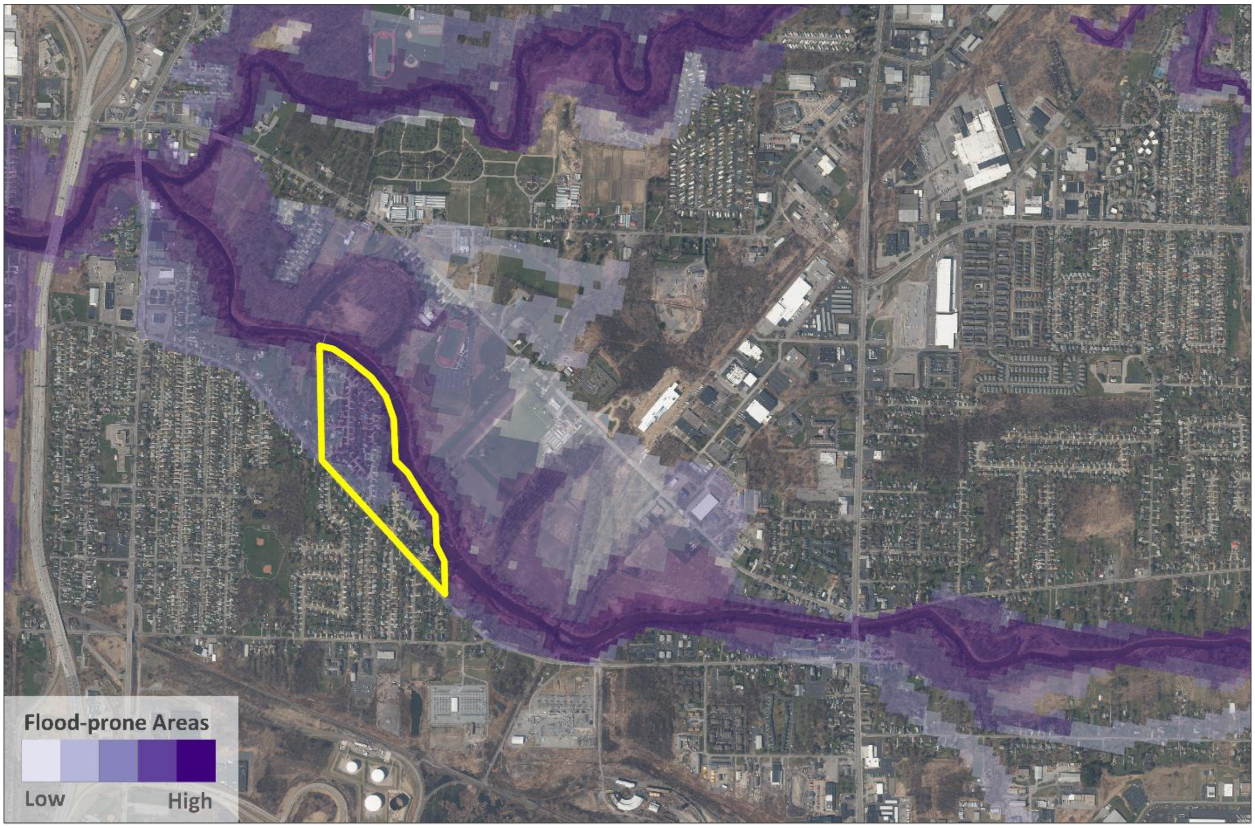

Figure 29. Flood-prone areas within the Buffalo Creek floodplain in West Seneca, New York. Lexington Green (yellow polygon) and other neighborhoods in the area are located within areas highly prone to flooding.

In response, Buffalo Niagara Waterkeeper (BNW) and partners have begun exploring nature-based options to help mitigate flooding in the Lexington Green neighborhood. With funding from the National Coastal Resilience Fund and other sources, the project will explore feasibility and develop design plans needed to reconnect Buffalo Creek to its historic floodplain. The project will explore creating a floodplain bench upstream of Lexington Green to add natural storage capacity during times of high flow to help reduce flooding to 90 homes in the neighborhood (Figure 30). Initial studies suggest a floodplain bench could reduce flooding by over two feet during a 100-year storm event[19].

[19] For more details about the project, visit the Buffalo Niagara Waterkeepers website: https://bnwaterkeeper.org/buffalo-creek-floodplain-reconnection-project-in-west-seneca/.

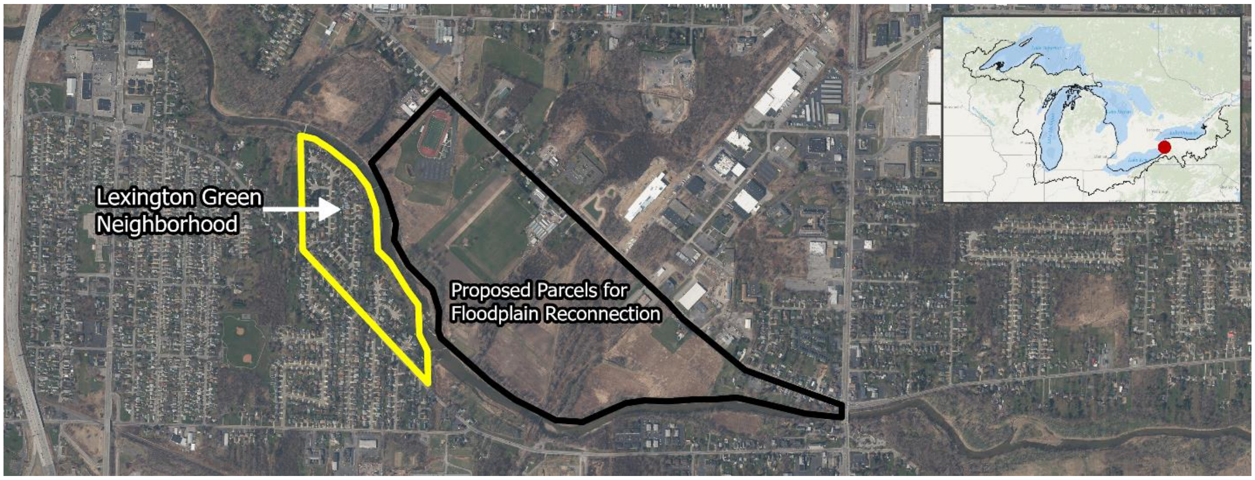

Figure 30. Map showing the boundary of the proposed floodplain reconnection (black polygon) in West Seneca, New York. The proposed project will benefit the Lexington Green neighborhood (yellow polygon).

In addition to offering vital flood protection to the community, the project will restore the creek's natural floodplain and provide important ecosystem benefits. Once implemented, the project aims to protect the site from future development, sustaining important riparian and upland habitat. By integrating native vegetation, wetland features, and nesting and foraging habitat into the design, the project team hopes to bolster wildlife populations in the area. The Fish and Wildlife Index, and its component Terrestrial and Aquatic Indices, demonstrate the potential wildlife benefits within and around the stream (Figure 31).

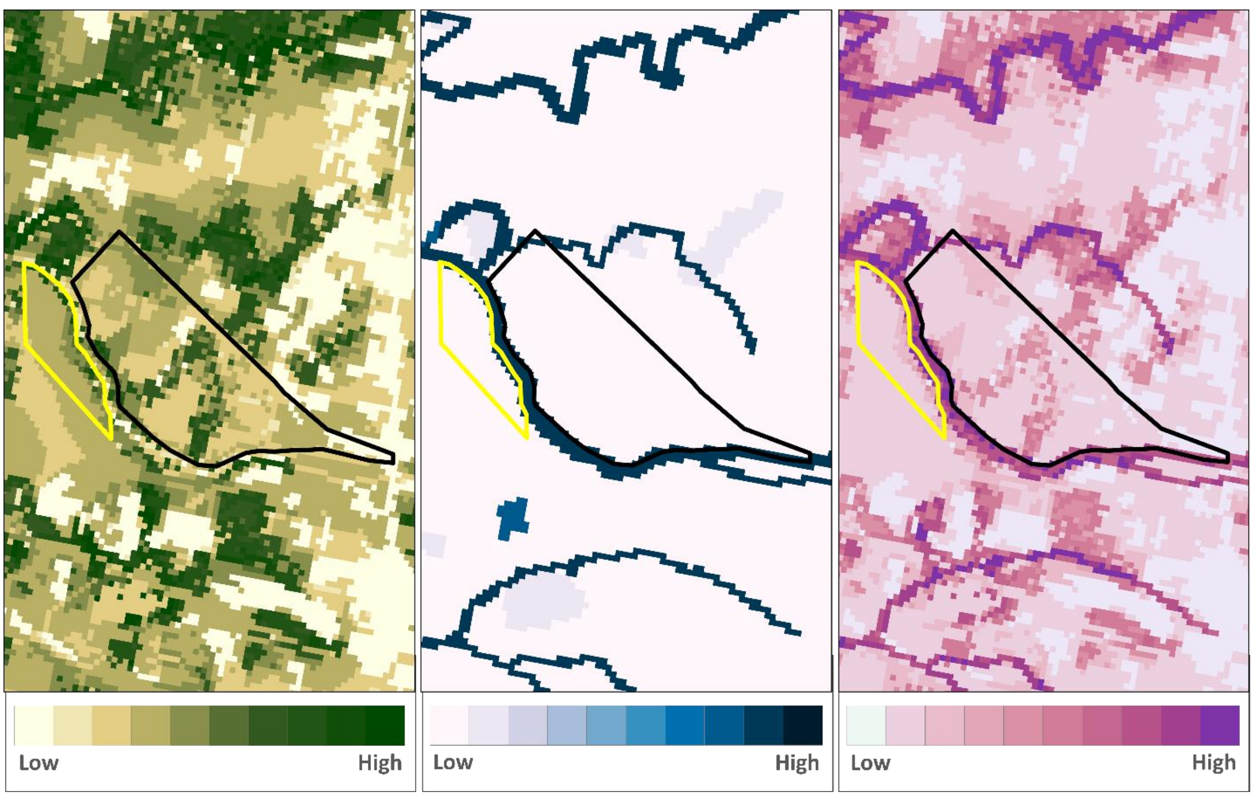

Figure 31. Terrestrial Index (left), Aquatic Index (middle), and Fish and Wildlife Index (right) results along Buffalo Creek and floodplain show high values surrounding the proposed floodplain reconnection project area (black polygon) and Lexington Green neighborhood (yellow polygon).

Over 10 years ago, BNW worked to restore the West Seneca oxbow wetland located just downstream of Lexington Green. This important project helped to protect now rare wetlands in the lower Buffalo River watershed and is visible in the Assessment results as an important location for species of conservation concern (Figure 31). Buffalo Creek, the restored oxbow wetland, and areas within the floodplain all represent high ranking Resilience Hubs demonstrating the potential of resilience building efforts, alone and in combination, that can provide dual flood protection and habitat benefits (Figure 32). Using zonal statistics, the average Resilience Hub score within the project polygon is a 5.7 out of 10; the average score is lower due to the presence of developed areas not covered by a Resilience Hub, but the project polygon clear occurs within an area with high-ranking Hubs. CREST allows users to upload proposed or actual project polygons to quickly calculate scores for all Assessment inputs and outputs.

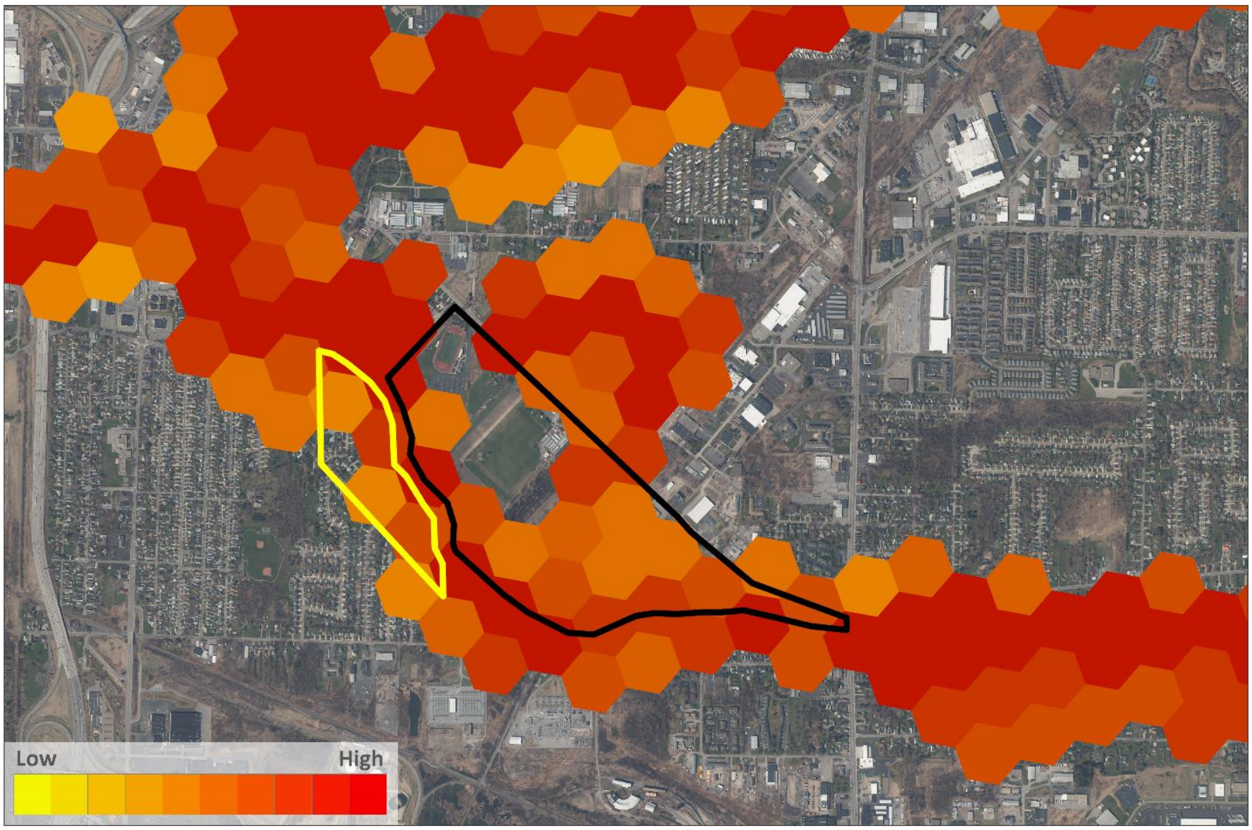

Figure 32. Resilience Hubs along Buffalo Creek highlight the suitability of this area for nature-based resilience projects with potential to benefit fish and wildlife and help build community resilience to flooding threats. The average Resilience Hub score within the project site is a 5.7 out of 10. The Resilience Hub Grid shows 4-hectare (10-acre) hexagons covering areas of open space. The black polygon outlines the proposed location of the floodplain reconnection project, which will help protect the Lexington Green neighborhood (yellow polygon).

CONCLUSION

5.1 Summary and Key Takeaways

As communities in the U.S. Great Lakes region face current and future flooding threats, tools such as this Coastal Resilience Assessment can help decision-makers and other stakeholders make informed decisions about how to identify areas that may be suitable for resilience-focused, nature-based projects. NFWF and NOAA remain committed to supporting programs and projects that improve community resilience by reducing communities' vulnerability to coastal storms, sea level and lake level change, and other types of coastal flooding by strengthening natural ecosystems and the fish and wildlife habitat they provide.

The U.S. Great Lakes Assessment identified many communities highly exposed to flood-related threats, particularly along the immediate coastlines, in urban areas, and in southern and eastern sections of the region. The Assessment also reveals an ecologically diverse landscape with an abundance of fish and wildlife assets, with slightly greater concentrations in the northern and eastern sections of the region. Combining the information in the Fish and Wildlife Index with the Community Exposure Index, numerous Resilience Hubs are found throughout the region, representing areas where resilience-building projects may benefit both human and wildlife communities.

As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans. The Regional Assessments are intended to be used as a screening-level tool designed to help identify areas that may be well-suited for nature-based solutions. The results are limited by those data available at the time of analysis and by the underlying accuracy and precision of the original data sources; therefore, the Assessment may not capture all flood-related threats, community assets, fish and wildlife resources, or areas of open space. Resilience Hubs are not intended to identify all potential opportunities for nature-based solutions, but rather are meant to help assess potential projects based on dual benefits for habitats and human communities.

5.2 Future Work

The Regional Coastal Resilience Assessments were developed through an iterative process supported by substantial guidance from technical and regional experts. The Regional Assessments and the associated Coastal Resilience Evaluation and Siting Tool (CREST) will continue to be updated, refined, and expanded by NFWF in the future as appropriate. The application and continued development of the Assessments will assist NFWF and others in the implementation of nature-based solutions that build community resilience to flooding threats while benefiting fish and wildlife populations nationwide.

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APPENDIX

The U.S. Great Lakes Coastal Resilience Assessment was completed at a 30-meter resolution, using the USA Contiguous Albers Equal Area Conic Projected Coordinate System Albers Projection (WKID 102003). The following sections describe data, methods, and other detailed information that were used for the U.S. Great Lakes Assessment.

A. Data Summary

A.1 Threat Index

The following is a comprehensive list of datasets used to create the Threat Index.

Layer Name	Dataset and Source
Flood-prone Areas	Federal Emergency Management Agency (FEMA) National Flood Hazard Layer; U.S. Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) Gridded Soil Survey Geographic (gSSURGO) Database & Gridded National Soil Survey Geographic (gNATSGO) Database
Soil Erodibility	USDA NRCS gSSURGO & gNATSGO Databases; National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management C-CAP Regional Land Cover and Change; NOAA Office for Coastal Management U.S. Great Lakes Hardened Shorelines Classification 2019
Areas of Low Slope	U.S. Geological Survey (USGS) National Elevation Dataset (30-m); NOAA Office for Coastal Management 2016 - 2017 FEMA Lidar DEM
Impermeability	USDA NRCS gSSURGO & gNATSGO Databases; NOAA Office for Coastal Management C-CAP Regional Land Cover and Change; U.S. Environmental Protection Agency (EPA) EnviroAtlas - 2002 Edge-of-Field Simulated Nitrogen, Phosphorus and Water Quantity Loss by 12-digit HUC for the Conterminous United States; USDA National Agricultural Statistics Service Cropland Data Layer
High Lake Levels	Joint Research Centre's Global Surface Water Dataset: Global Surface Water Explorer, Water Occurrence (1984-2020)

A.2 Community Asset Index

The following is a comprehensive list of datasets used to create the Community Asset Index.

Layer Name	Dataset and Source
Population Density	U.S. Census Bureau 2020 Decennial Census Total Population & Census Blocks State-Based TIGER/Line Geodatabases
Social Vulnerability	EPA Environmental Justice Screening and Mapping Tool
Critical Facilities (*Various Inputs, See Below*)	
Education	*USGS National Structures Dataset (Elementary/Middle/High Schools, Colleges/Universities, Technical/Trade Schools); Microsoft Building Footprints*
Emergency Response & Law Enforcement	*USGS National Structures Dataset (Ambulance Services, Fire Station/EMS Station, Law Enforcement, Prison/Correctional Facility); Microsoft Building Footprints*
Health and Medical	*USGS National Structures Dataset (Hospitals/Medical Centers); Microsoft Building Footprints*
Government	*USGS National Structures Dataset (Post Offices, State Capital buildings, Court Houses, City/Town Halls, Headquarters, Ranger Stations); Microsoft Building Footprints*
Critical Infrastructure (*Various Inputs, See Below*)	
Primary & Secondary Roads	*U.S. Census Bureau TIGER/Line data (Primary and Secondary Roads by state)*
Bridges	*U.S. Department of Transportation (DOT) Bureau of Transportation Statistics National Bridge Inventory; USGS National Hydrography Dataset Plus High Resolution (NHDPlus HR); U.S. Census Bureau TIGER/Line data (national roads geodatabase)*
Airport Runways	*Federal Aviation Administration Runways*
Ferry Terminals	*DOT National Census of Ferry Operators*
Railroads	*DOT Bureau of Transportation Statistics North American Rail Network Lines*
International Border Crossings	*Community Map of Canada Border Crossings in Canada*
Ports	*DOT Bureau of Transportation Statistics National Transportation Atlas Database (Docks)*
Locks	*DOT Bureau of Transportation Statistics National Transportation Atlas Database (Waterway Locks); International Joint Commission*
Levees	*U.S. Army Corps of Engineers (USACE) National Levee Database (Leveed Areas)*
Dams	*USACE National Inventory of Dams; Homeland Infrastructure Foundation-Level Data Dam Lines*
Wastewater Treatment Facilities	*EPA Facility Registry Service Integrated Compliance Information System Wastewater Treatment Plants*
Community Water Systems	*EPA Facility Registry Service (Community Water Systems)*
Cellular Towers	*Homeland Infrastructure Foundation-Level Data (Cellular Towers)*
FM Transmission Towers	*Homeland Infrastructure Foundation-Level Data (FM Transmission Towers)*
Power Plants	*U.S. Energy Information Administration (Power Plants)*
Electric Substations	*Homeland Infrastructure Foundation-Level Data (Electric Substations)*
Petroleum Product Terminals	*U.S. Energy Information Administration (Petroleum Product Terminals)*
Petroleum Refineries	*U.S. Energy Information Administration (Petroleum Refineries)*
Natural Gas Processing Plants	*U.S. Energy Information Administration (Natural Gas Processing Plants)*
Natural Gas Underground Storage	*U.S. Energy Information Administration (Natural Gas Underground Storage)*
Hazardous Sites	*EPA Facility Registry Service (Large Quantity Generators, Brownfield sites, Superfund National Priorities List Sites, hazardous waste landfills, Radioactively Contaminated Sites (National Priorities List Sites), and Radioactive Waste Isolation Pilot Plants)*

A.3 Terrestrial Index

The following table lists those datasets that were used to create the Terrestrial Index.

Layer Name	Dataset and Source
Critical Habitat Designations	U.S. Fish and Wildlife Service (FWS) Environmental Conservation Online System (ECOS) (federally-listed terrestrial species with designated critical habitat)
State Wildlife Action Plan Species of Greatest Conservation Need	USGS State Wildlife Action Plans (SWAP) Species Conservation Analysis Tool
Other Regionally Important Terrestrial Species	Great Lakes Indian Fish & Wildlife Commission (GLIFWC) Harvest Regulations
Predicted Habitat Models for Terrestrial Vertebrate Species	USGS - Gap Analysis Project (GAP) Species Habitat Maps
Important Bird Areas & Key Biodiversity Areas	BirdLife International Important Bird Areas; World Database of Key Biodiversity Areas
Coastal Bluffs and Dunes	NOAA Office for Coastal Management U.S. Great Lakes Hardened Shorelines Classification 2019; USDA NRCS gSSURGO & gNATSGO Databases

A.4 Aquatic Index

The following table lists those datasets used to create the Aquatic Index.

Layer Name	Dataset and Source
Critical Habitat Designations	FWS ECOS (federally-listed aquatic species with designated critical habitat)
State Wildlife Action Plan Species of Greatest Conservation Need	USGS State Wildlife Action Plans (SWAP) Species Conservation Analysis Tool
Other Regionally Important Aquatic Species	GLIFWC Harvest Regulations
Predicted Habitat Models for Aquatic Species	IUCN Red List of Threatened Species Digital Distribution Maps; NatureServe (2010) Digital Distribution Maps of the Freshwater Fishes in the Conterminous U.S. (Version 3.0); FWS Complete Current Range Vector Digital Data; Trout Unlimited Great Lakes Brook Trout Conservation Portfolio; GLIFWC WI Manoomin (Wild Rice) Inventory; Minnesota Dept. of Natural Resources Wild Rice Lakes and Rivers; USGS National Hydrography Dataset Plus High Resolution (NHDPlus HR); FWS National Wetlands Inventory; NatureServe Explorer
Fish Spawning Locations and Reef Locations	Great Lakes Aquatic Habitat Framework (GLAHF) Goodyear Spawning Atlas Plus Locations and Historic Sturgeon Spawning Locations; Great Lakes Aquatic Habitat Framework Known Reef Locations
Great Lakes Brook Trout Conservation Portfolio	Trout Unlimited Great Lakes Brook Trout Conservation Portfolio

A.5 Protected and Managed Areas for Wildlife

The following table lists those datasets used to create the Protected and Managed Areas for Biodiversity input.

Layer Name	Dataset and Source
Protected and Managed Areas for Biodiversity	USGS Gap Analysis Project (GAP), 2020, Protected Areas Database of the United States (PAD-US) 2.1: U.S. Geological Survey data release; NOAA National Marine Sanctuaries; ProtectedSeas Marine Area Map

A.6 Resilience Hubs

The following table lists those datasets used to create the Resilience Hubs.

Layer Name	Dataset and Source
National Hydrography Dataset Plus High Resolution	USGS National Hydrography Dataset Plus High Resolution (NHDPlus HR)
National Land Cover Dataset, 2019	Multi-Resolution Land Characteristics (MRLC) Consortium - USGS, EPA, NOAA, BLM, NASA, NPS, USDA-NASS, USFWS, USACE
National Elevation Dataset, NED 30-meter	USGS National Elevation Dataset (30-m)
12-Digit Watershed Boundary Dataset	USGS Watershed Boundary Dataset
Soils	U.S. Department of Agriculture, National Soil Survey Center, National Coordinated Major Land Resource Area (MLRA) Version 4.2
TIGER Primary and Secondary Roads	U.S. Census Bureau, Geography Division, 2021
TIGER Streets	U.S. Census Bureau, Geography Division, 2021
TIGER Rail Lines	U.S. Census Bureau, Geography Division, 2021
Wetlands	FWS National Wetlands Inventory
Great Lakes Bathymetry Collection	NOAA National Centers for Environmental Information
Potentially Restorable Wetlands	EPA EnviroAtlas - Percent Land Cover with Potentially Restorable Wetlands on Agricultural Land by 12-Digit HUC for the Conterminous United States
Coastal Beaches and Dunes	NOAA Office for Coastal Management U.S. Great Lakes Hardened Shorelines Classification 2019; USDA NRCS gSSURGO & gNATSGO Databases
Dams	USACE National Inventory of Dams; Homeland Infrastructure Foundation-Level Data Dam Lines
Fish Habitat	Great Lakes Aquatic Habitat Framework (GLAHF) Known Reef Locations; National Fish Habitat Partnership Inland Stream Assessment for the Conterminous United States

B. Geoprocessing Standards

The U.S. Great Lakes Coastal Resilience Assessment used consistent geoprocessing standards throughout the analysis. Standards are described below and apply to all methods outlined in Appendices D-J, except where otherwise noted.

- **Software**: The latest version of ArcGIS Pro at time of analysis was used for geoprocessing (ArcGIS Pro 3.1.1 at time of publication). QGIS, GRASS, and R were used to supplement ArcGIS Pro analyses as needed.
- **Data Storage**: Intermediate geoprocessing outputs were stored in file geodatabases. Final raster outputs were stored as TIFF files.
- **Languages:** Expressions within ArcGIS Pro Geoprocessing Tools were generally written in the default tool language and included SQL, Arcade, and Python3.
- **Vector Geoprocessing**
    - Pairwise Buffer *(referred to as "buffer" in Appendices D-J)*
        - Method: Planar
        - Dissolve Type: No Dissolve
    - Pairwise Clip *(referred to as "clip to regional boundary" for vector data in Appendices D-J)*
        - Clip features: Regional boundary *(see Section 2.2 for details)*
        - Environments:
            - Output Coordinate System: *USA Contiguous Albers Equal Area Conic Projected Coordinate System Albers Projection (WKID 102003)*
    - Pairwise Dissolve *(referred to as "dissolve" in Appendices D-J)*
        - Create Multipart Features: Checked
    - Export Features *(referred to as "export" for vector data in Appendices D-J)*
        - Environments:
            - Output Coordinate System: *USA Contiguous Albers Equal Area Conic Projected Coordinate System Albers Projection (WKID 102003)*
- **Raster Geoprocessing**
    - Polygon to Raster *(referred to as "rasterize" in Appendices D-J)*
        - Value Field: "Rank" *(field added to vector attribute table with appropriate input value)*
        - Cell Assignment Type: Maximum area
        - Priority Field: "Rank" *(field added to vector attribute table with appropriate input value; note exceptions occur when rank value = 0 and for other input-specific reasons)*
        - Cellsize: 30-m Resolution
    - Mosaic to New Raster *(referred to as "mosaic" in Appendices D-J)*
        - *Used "Copy Raster" geoprocessing tool as needed to ensure all rasters had the same pixel type and no data values before mosaicking.*
        - Input Rasters: *Input order and Mosaic Operator settings ensure that the input data were used where available followed by the rank 0 regional boundary area to ensure a complete raster output for the entire regional boundary.*
        - Spatial Reference for Raster: *USA Contiguous Albers Equal Area Conic Projected Coordinate System Albers Projection (WKID 102003)*
        - Pixel Type: 8-bit unsigned
            - Cellsize: 30-m Resolution
            - Number of Bands: 1
            - Mosaic Operator: First
            - Mosaic Colormap Mode: First
        - Clip Raster *(referred to as "clip to regional boundary" for raster data in Appendices D-J)*
            - Output Extent: Regional boundary *(see Section 2.2 for details)*
            - Use Input Features for Clipping Geometry: Checked
            - NoData Value: 255

- Environments (*raster geoprocessing tools such as Clip Raster, Reclassify, Polygon to Raster, Mosaic to New Raster, etc. always included consistent Environments settings)*
    - Output Coordinate System: *USA Contiguous Albers Equal Area Conic Projected Coordinate System Albers Projection (WKID 102003)*
    - Snap Raster: Regional Template *(a standardized raster template was used to snap all raster inputs; a template raster was created for the U.S. Great Lakes from an extended watershed boundary approximately one watershed larger than the regional boundary)*
    - Raster storage
        - Pyramid = Unchecked
        - Raster Statistics = Unchecked
        - Compression Type = LZW
        - Resample=Nearest

C. Detailed Methodology: Threat Index

Data processing for each of the indices used the geoprocessing standards described in Appendix B.

C.1 Create the Flood-Prone Areas Input

Prepare Floodplain Data

A. Import the *S_Fld_Haz_Ar* polygons for each county in the region. Using Export Data, rename and reproject the polygons individually. Use the same coordinate system as the data frame and create unique output location and name. Ensure each polygon has a unique name.
B. Merge all county-level FEMA data into one regional vector (or merge state vectors into a single regional vector)
C. Several different layers will be extracted from the FEMA data as separate layers. Export to create these vector layers where Expression is based on the following queries:
    a. To extract and export the floodway: *FLD_ZONE = 'AE' AND ZONE_SUBTY = 'FLOODWAY'*
    b. To extract and export the 100-year floodplain: *FLD_ZONE = 'A' Or FLD_ZONE = 'AE') AND (ZONE_SUBTY <> 'FLOODWAY' Or ZONE_SUBTY IS NULL*
    c. To extract and export the 500-year floodplain: *FLD_ZONE = 'X' AND ZONE_SUBTY = '0.2 PCT ANNUAL CHANCE FLOOD HAZARD'*
D. Add new Short (16-bit integer) field "Rank" value for each new layer using Calculate Field according to Table C1.
E. Merge ranked FEMA layers into a single layer.

Table C1. Flood-prone Area categories, rank type, and rank.

Flood-Prone Areas	Rank Type	Rank Value
Outside of floodplain and non-flood-prone soils	None	0
Occasionally flooded soils outside the flood zone	Very low	1
Frequently flooded soils outside the flood zone	Low	2
500-year floodplain	Moderate	3
100-year floodplain	High	4
Floodway	Very high	5

Soils Data Pre-processing

Soils data pre-processing methods apply to several Threat Index inputs including Flood-Prone Areas, Soil Erodibility, Impermeability as well as the Bluffs and Dunes input used in the Terrestrial Index (Appendix F).

F. gSSURGO (vector-based data for Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York)
    a. Create soil maps for attributes not already included in gSSURGO geodatabase Mapunit Aggregated Attribute table "muaggatt" for each state in the region using the Soil Data Development Tools for ArcGIS in ArcGIS Desktop. Export the results.
        i. Run *Create Soil Map* tool for variables of interest for each state and export to file geodatabase. Note that drainage class and flooding frequency class are available directly from the gSSURGO geodatabase Mapunit Aggregated Attribute table "muaggatt".
            1. arcpy.CreateSoilMap (Map_Unit_Layer="MUPOLYGON", SDV_Folder="Soil Erosion Factors", SDV_Attribute="K Factor, Whole Soil", Aggregation_Method="Dominant Condition", Primary_Constraint="", Secondary_Constraint="", Top_Depth__cm_="0", Bottom_Depth="1", Beginning_Month=" ", Ending_Month=" ", Tie_Break_Rule="Higher", Interpret_Nulls_as_Zero="false", Component_Percent_Cutoff="", Map_Interp_Fuzzy_Values="false", Include_Null_Values="false", Use_Property_Values="Representative", Exclude_State_Interps="true", Message="")

ii. Run Identify Dominant Components tool for each state.
   1. arcpy.GetDominantComponent(Input_Soils_Database="/gSSURGO_STATE.gdb", Output_Table=".gdb/DominantComponent_STATE")

b. Join Map unit and Components tables to MUPOLYGON for each state using ArcGIS Pro Jupyter Notebook script or similar geoprocessing tools
   i. Join state-specific dominant component feature class (exported results from "Run Identify Dominant Components tool" above) with the Component table using the "cokey" field
      1. DominantComponent = r".gdb/DominantComponent_STATE"
      2. Component =r"/gSSURGO_STATE.gdb/Component"
      3. DominantComponent_joined = arcpy.AddJoin_management(in_layer_or_view=DominantComponent, in_field="cokey", join_table=Component, join_field="cokey", join_type="KEEP_COMMON")
   ii. Join the Mapunit table with the joined dominant compenent-component join using the "mukey" field.
      1. Mapunit = r"/gSSURGO_STATE.gdb/Mapunit"
      2. Mapunit_joined = arcpy.AddJoin_management(in_layer_or_view=Mapunit, in_field="mukey", join_table=DominantComponent_joined, join_field="DominantComponent_IL.mukey", join_type="KEEP_COMMON")
   iii. Join the Mapunit Aggregated Attribute table to the joined Mapunit-dominant compenent-component table using the "mukey" field table.
      1. Muaggatt = r"/gSSURGO_STATE.gdb/muaggatt"
      2. Mapunit_joined_muaggatt = arcpy.AddJoin_management(in_layer_or_view=Mapunit_joined, in_field="mapunit.mukey", join_table=Muaggatt, join_field="mukey", join_type="KEEP_COMMON")
   iv. Join the MUPOLYGON feature class with the joined Mapunit Aggregated Attribute-Mapunit-dominant compenent-component table using the "mukey" field table.
      1. MUPOLYGON = r"/gSSURGO_STATE.gdb/MUPOLYGON"
      2. MUPOLYGON_joined = arcpy.AddJoin_management(in_layer_or_view=MUPOLYGON, in_field="MUKEY", join_table=Mapunit_joined_muaggatt, join_field="Mapunit.mukey", join_type="KEEP_COMMON")
   v. Exportjoined MUPOLYGON feature class to a new feature class to preserve the join for analysis.
      1. arcpy.FeatureClassToFeatureClass_conversion(MUPOLYGON_joined, "/.gdb", "MUPOLYGON_Join_STATE")

G. gNATSGO (raster-based data for Minnesota and Wisconsin)
   a. Create soil maps for attributes not already included in gNATSGO geodatabase Mapunit Aggregated Attribute table “muaggatt” for each state in the region using the [Soil Data Development Tools for ArcGIS]() in ArcGIS Desktop.
      i. Run *Create Soil Map* tool for variables of interest for each state and export to file geodatabase. *Note that drainage class and flooding frequency class are available directly from the gNATSGO geodatabase Mapunit Aggregated Attribute table “muaggatt”.*
         1. arcpy.CreateSoilMap(Map_Unit_Layer="MapunitRaster_10m", SDV_Folder="Soil Erosion Factors", SDV_Attribute="K Factor, Whole Soil", Aggregation_Method="Dominant Condition", Primary_Constraint="", Secondary_Constraint="", Top_Depth__cm_="0", Bottom_Depth="1", Beginning_Month=" ", Ending_Month=" ", Tie_Break_Rule="Higher", Interpret_Nulls_as_Zero="false", Component_Percent_Cutoff="", Map_Interp_Fuzzy_Values="false", Include_Null_Values="false", Use_Property_Values="Representative", Exclude_State_Interps="true", Message="")
         2. Right click layer in the Table of Contents > Data > Export Data
      ii. Run *Identify Dominant Components* tool for each state.
         1. arcpy.GetDominantComponent(Input_Soils_Database="/gNATSGO_STATE.gdb", Output_Table=".gdb/DominantComponent_STATE")
   b. Join Mapunit and Components tables to MapunitRaster_10m using ArcGIS Pro Jupyter Notebook script or similar geoprocessing tools.

i. Join state-specific dominant component feature class (exported results from "Run Identify Dominant Components tool" above) with the Component table using the "cokey" field.
    1. DominantComponent = r".gdb/DominantComponent_STATE"
    2. Component = r"/gNATSGO_STATE.gdb/Component"
    3. DominantComponent_joined = arcpy.AddJoin_management(in_layer_or_view=DominantComponent, in_field="cokey", join_table=Component, join_field="cokey", join_type="KEEP_COMMON")
ii. Join the Mapunit table with the joined dominant compenent-component join using the "mukey" field.
    1. Mapunit = r"/gNATSGO_STATE.gdb/mapunit"
    2. Mapunit_joined = arcpy.AddJoin_management(in_layer_or_view=Mapunit, in_field="mukey", join_table=DominantComponent_joined, join_field="DominantComponent_MN.mukey", join_type="KEEP_COMMON")
iii. Join the Mapunit Aggregated Attribute table to the joined Mapunit-dominant compenent-component table using the "mukey" field table.
    1. Muaggatt = r"/gNATSGO_STATE.gdb/muaggatt"
    2. Mapunit_joined_muaggatt = arcpy.AddJoin_management(in_layer_or_view=Mapunit_joined, in_field="mapunit.mukey", join_table=Muaggatt, join_field="mukey", join_type="KEEP_COMMON")
iv. Join the MapunitRaster_10m raster with the joined Mapunit Aggregated Attribute-Mapunit-dominant compenent-component table using the "mukey" field table.
    1. MURASTER = r"/gNATSGO_STATE.gdb/MapunitRaster_10m"
    2. MURASTER_joined = arcpy.AddJoin_management(in_layer_or_view=MURASTER, in_field="MUKEY", join_table=Mapunit_joined_muaggatt, join_field="Mapunit.mukey", join_type="KEEP_COMMON")
v. Exportjoined MapunitRaster_10m raster to a new raster to preserve the join for analysis.
    1. arcpy.CopyRaster_management(MURASTER_joined, ".gdb/MURASTER_Join_STATE")

Prepare Flood-prone Soils Data

H. Create flood-prone soils layer by extracting multiple inputs from the ".gdb/MUPOLYGON_Join_STATE" gSSURGO data and ".gdb/MURASTER_Join_STATE" gNATSGO data prepared above. Use the following queries to select and export the data for each state in the region.
    a. gSSURGO (vector-based data for Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York)
        i. Export the frequent/very frequent flood-prone soils data where flodfreqmax = 'Frequent' or flodfreqmax = 'Very frequent' and the occasional flood-prone soils data where flodfreqmax = 'Occasional'
        ii. Merge exported state-level feature classes into region-level feature classes (frequent/very frequent and occasional flood-prone soils), project to regional projection, and clip to regional boundary.
        iii. Erase from the clipped regional soils data those areas already covered by FEMA data extracted in above steps for both frequent/very frequent and one for occasional flood-prone soils.
        iv. Add new Short (16-bit integer) field "Rank" value to attribute table for soil layers frequent/very frequent and occasional using *Calculate Field* according to Table D1.
    b. gNATSGO (raster-based data for Minnesota and Wisconsin)
        i. Export the frequent/very frequent flood-prone soils data where flodfreqmax = 'Frequent' or flodfreqmax = 'Very frequent' and the occasional flood-prone soils data where flodfreqmax = 'Occasional'
        ii. Mosaic exported state-level rasters into region-level rasters, reclassify according Table D1, and clip to regional boundary (one for frequent/very frequent and one for occasional flood-prone soils). *Note that this may result in resampling from the raw data resolution to match the regional resolution.*

Combine Floodplain and Flood-prone Soils Data

I. Merge ranked gSSURGO and FEMA inputs.
J. Create a feature class using *Export Features* and add new Short (16-bit integer) field "Rank" value with a value of 0 for the regional boundary using *Calculate Field* to ensure there are values of 0 within the regional boundary where there are

not frequent/very frequent or occasional flood-prone soils data. This output will be used frequently across other inputs and indices to ensure that rasters fill the entire regional boundary.

K. Rasterize each of the vector data inputs (merged FEMA/gSSURGO and ranked regional boundary).
L. Mosaic all flood rasters (FEMA + gSSURGO merged and rasterized data (the erase tool was used in previous steps to ensure the FEMA data superseded the soils data where available), gNATSGO frequent/very frequent flood-prone soils data, gNATSGO occasional flood-prone soils data, and regional boundary raster with rank 0) into a single flood-prone areas input. Clip to regional boundary to ensure no data values outside of the regional boundary.

C.2 Create Soil Erodibility Input

Prepare the Beaches and Dunes Data

Beaches and dunes data were derived from land cover and soils data.

A. Land cover-derived beaches and dunes.
    a. Clip the land cover data to the regional boundary.
    b. Extract the land cover class(es) that represent beach and dune systems using *Extract by Attributes* where VALUE = 20 *(Barren Land – contains areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits, and other accumulations of earth material. Generally, vegetation accounts for less than 10 percent of total cover).* This may vary depending on the land cover dataset, use imagery to determine the most suitable class or classes. Reclassify the output so class(es) representing Beach and Dune systems a value of 5.
B. Soils-derived beaches and dunes.
    a. gSSURGO (vector-based data for Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York)
        i. Export soils data by state where Mapunit Name indicates sand beaches or dunes (rocky, gravel, cobble, stony, boulder qualifiers not included) where muname NOT LIKE '%gravel%' And muname NOT LIKE '%rocky%' And muname NOT LIKE '%cobbl%' And muname NOT LIKE '%boulder%' And muname NOT LIKE '%stony%' And muname NOT LIKE '%Stony%' And (muname LIKE '%Beach%' Or muname LIKE '%Dune%' Or muname LIKE '%beach%' Or muname LIKE '%dune%' Or muname LIKE '%coastal%' Or muname LIKE '%Coastal%'). Merge the exported state-level feature classes into a region-level feature class. Clip to the regional boundary. If necessary, remove any features that are not beaches or dunes (e.g., Lewbeach channery silt loam) using Export Features where muname NOT LIKE '%Lewbeach%'. Add new Short (16-bit integer) field “Rank” value (Rank = 5) to attribute table using Calculate Field and rasterize.
        ii. Export soils data by state where Geomorphic Description indicates sand beaches or dunes where (geomdesc LIKE '%beach%' Or geomdesc LIKE '%dune%') And geomdesc NOT LIKE '%outwash%' And geomdesc NOT LIKE '%plain%'). Merge the exported state-level feature classes into a region-level feature class and clip the projected soils feature classes to the regional boundary. Add new Short (16-bit integer) field “Rank” value (Rank = 5) to attribute table using Calculate Field and rasterize.
    b. gNATSGO (raster-based data for Minnesota and Wisconsin)
        i. Extract the soils data where Mapunit Name indicates sand beaches or dunes for each state using Extract by Attributes where muname NOT LIKE '%gravel%' And muname NOT LIKE '%rocky%' And muname NOT LIKE '%cobbl%' And muname NOT LIKE '%boulder%' And muname NOT LIKE '%stony%' And muname NOT LIKE '%Stony%' And (muname LIKE '%Beach%' Or muname LIKE '%Dune%' Or muname LIKE '%beach%' Or muname LIKE '%dune%' Or muname LIKE '%coastal%' Or muname LIKE '%Coastal%'). Mosaic into a region-level raster *(note that this may result in resampling from the raw data resolution to match the regional resolution)*, reclassify (Value = 5), and clip to project boundary.
        ii. Extract the soils data where Geomorphic Description indicates sand beaches or dunes for each state using Extract by Attributes where (geomdesc LIKE '%beach%' Or geomdesc LIKE '%dune%') And geomdesc NOT LIKE '%outwash%' And geomdesc NOT LIKE '%plain%'. Mosaic into a region-level raster *(note that this may result in resampling from the raw data resolution to match the regional resolution)*, reclassify (Value = 5), and clip to project boundary.

Prepare Coastal Bluffs and Dunes Data

C. Create a subset of the hardened shorelines line data or filter with a definition query to retain only bluff and dune classifications where Shoreline_Type_Description LIKE '%Bluff%' Or Shoreline_Type_Description LIKE '%bluff%' Or Shoreline_Type_Description LIKE '%Dune%' Or Shoreline_Type_Description LIKE '%dune%'.
D. Buffer the bluffs and dunes subset by 50 m and clip to regional boundary.
E. Process soils data.
    a. gSSURGO (vector-based data for Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York)
        i. Export state-level MUPOLYGON data to include only bluff and dune features where muname LIKE '%bluff%' Or muname LIKE '%Bluff%' Or muname LIKE '%Dune%' Or muname LIKE '%dune%' Or geomdesc LIKE '%dune%' Or geomdesc LIKE '%bluff%' Or geomdesc LIKE '%Dune%' Or geomdesc LIKE '%Bluff%'. *These state-level feature classes were created for the Threat Index > Flood-Prone Areas input where soil Mapunit and Components tables were joined to MUPOLYGON for each state using ArcGIS Pro Jupyter Notebook script or similar geoprocessing tools.*
        ii. Merge the state-level bluffs and dunes MUPOLYGON data.
    b. gNATSGO (raster-based data for Minnesota and Wisconsin)
        i. Clip the state-level MURASTER data to the regional boundary and extract bluff and dune features using Extract by Attributes where muname LIKE '%bluff%' Or muname LIKE '%Bluff%' Or muname LIKE '%Dune%' Or muname LIKE '%dune%' Or geomdesc LIKE '%dune%' Or geomdesc LIKE '%bluff%' Or geomdesc LIKE '%Dune%' Or geomdesc LIKE '%Bluff%'. Convert results to polygon feature class.
    c. Merge bluff and dune MUPOLYGON results with converted bluff and dune MURASTER results. If needed clip results to regional boundary.
    d. Select data that intersect the merged regional bluffs and dunes hardened shoreline line data (unbuffered) using *Select Layer by Location* (Relationship: Intersect, Selecting Features: bluffs and dunes subset (line feature class with definition query applied), Search Distance: 100 m, Selection Type: New Selection) and export results.
F. Merge intersected soils feature class with clipped and buffered dunes and bluffs subset feature class and dissolve results.
G. Add new Short (16-bit integer) field "Rank" value (Rank=5) to attribute table and rasterize.
H. Mosaic bluffs and dunes raster with the regional boundary and clip to regional boundary.

Prepare Soil Erodibility Factor Data

I. Use the soil maps created above (Threat Index > Flood-prone Areas) based on the **K Factor, Whole Soil** attribute from the gSSURGO and gNATSGO data for each state in the region.
    a. gSSURGO (vector-based data for Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York)
        i. Clip each state-level K Factor, Whole Soil feature class to the regional boundary.
        ii. Merge the clipped state-level feature classes into a region-level feature class.
        iii. Add new Short (16-bit integer) field "Rank" value to the merged data using Calculate Field according to Table C2.
            1. Expression (Arcade): Rank = When(IsEmpty($feature.KFACTWS_DCD_Numeric), 0,
               $feature.KFACTWS_DCD_Numeric<=0.10, 1, $feature.KFACTWS_DCD_Numeric < 0.20, 2,
               $feature.KFACTWS_DCD_Numeric < 0.30, 3,
               $feature.KFACTWS_DCD_Numeric < 0.40, 4,
               $feature.KFACTWS_DCD_Numeric >=0.40, 5, "")
        iv. Project the merged soils feature classes to match the regional projection.
        v. Rasterize each of the regional vector datasets.
    b. gNATSGO (raster-based data for Minnesota and Wisconsin)
        i. Reclassify the state-level rasters using the rank values according to the soil erodibility factor table below, except that NODATA should remain as NODATA until a later step in the process to ensure the data can be mosaicked together (otherwise 0 values and no data will be confounded in the raster envelope outside of the state boundary that overlaps with other states in the region). Mosaic into a region-level raster *(note that this may result in resampling from the raw data resolution to match the regional resolution)*, and clip to regional boundary.
J. Combine the regional-level polygon and raster soil erodibility data.
    a. Mosaic all soil erodibility rasters (gSSURGO merged and rasterized data, gNATSGO mosaicked soils data) into a single input.

Table C2. Soil Erodibility categories, rank type, and rank.

Soil Erodibility Factor	Rank Type	Rank Value
Null	None	0
< = 0.10 Kffact	Very low	1
0.15 and 0.17 Kffact	Low	2
0.20 – 0.28 Kffact	Moderate	3
0.32 and 0.37 Kffact	High	4
> = 0.43 Kffact	Very high	5

Combine the Beaches and Dunes, Coastal Bluffs and Dunes, and Soil Erodibility Factor Data

K. Mosaic the Soil map unit beaches and dunes soils raster, soil geomorphic description beaches and dunes soil raster, coastal bluffs and dunes raster, land cover beaches and dunes raster, soil erodibility factor raster, regional boundary raster with rank 0. Clip to regional boundary.

C.3 Create Areas of Low Slope Input

A. Import all the NED tiles to cover the region and create a mosaic.
B. Create a Raster Mosaic. Enter all the tiles as inputs. If tiles are overlapping, order the inputs so that the preferred tile supersedes the next and set the Mosaic Operator to 'First'.
C. If necessary, resample the DEM to the regional modeling resolution using *Resample*.
D. Clip the raster mosaic to the regional boundary.
E. Fill in "sinks" of the elevation raster to remove artifacts and unnatural depressions in the data using *Fill*.
F. Create a slope raster from the clipped and filled raster using *Slope* (Output measurement: Percent rise).
G. Reclassify the Slope raster to corresponding rank values according to Table C3.

Table C3. Areas of Low Slope categories, rank type, and rank.

Slope (%)	Rank Type	Rank Value
> 2.00	None	0
1.00 – 2.00	Very low	1
0.75 – 1.00	Low	2
0.50 – 0.75	Moderate	3
0.25 – 0.50	High	4
< 0.25	Very high	5

C.4 Create Impermeability Input

Prepare the Soil Drainage Data

A. Create the soil drainage layer by extracting multiple inputs from the ".gdb/MUPOLYGON_Join_STATE" gSSURGO data and ".gdb/MURASTER_Join_STATE" gNATSGO data prepared above (Threat Index > Flood-prone Areas). Use the following queries to select and export the data for each state in the region.
   a. gSSURGO (vector-based data for Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York)
      i. Clip each state-level feature class to the regional boundary.
      ii. Merge the clipped state-level feature classes into a region-level feature class.
      iii. Add new Short (16-bit integer) field "Rank" value to merged data using *Calculate Field* according to Table D4.

1. Expression (Arcade): Rank =
When(IsEmpty($feature.drclassdcd), 0,
$feature.drclassdcd == "Well drained", 1,
$feature.drclassdcd == "Moderately well drained", 2,
$feature.drclassdcd == "Somewhat poorly drained", 3,
$feature.drclassdcd == "Poorly drained", 4,
$feature.drclassdcd == "Very poorly drained", 5, 0)

iv. Project the merged soils feature classes to match the regional projection.

b. gNATSGO (raster-based data for Minnesota and Wisconsin)
   i. Reclassify the state-level rasters using the rank values according to Table C4, except that NODATA should remain as NODATA until a later step in the process to ensure the data can be mosaicked together (otherwise 0 values and no data will be confounded in the raster envelope outside of the state boundary that overlaps with other states in the region).
   ii. Mosaic the exported state-level rasters into a region-level raster *(this may result in resampling from the raw data resolution to match the regional resolution)* and clip to the regional boundary.

B. Combine the regional-level polygon and raster soil drainage data.
   a. Rasterize each of the vector data inputs (merged gSSURGO and ranked regional boundary).
   b. Mosaic all soil drainage rasters (gSSURGO merged and rasterized data, gNATSGO mosaicked soils data, regional boundary raster with rank 0) into a single input.

Table C4. Soil Drainage categories, rank type, and rank.

Soil Drainage	Rank Type	Rank Value
Null	None	0
Well-drained	Very low	1
Moderately well-drained	Low	2
Somewhat poorly drained	Moderate	3
Poorly drained	High	4
Very poorly drained	Very high	5

Note: "Excessively drained" and "Somewhat excessively drained" are not vulnerable to extended inundation and not considered in this analysis and should carry a value of 0. "Subaqueous" soils should carry a value of 5 where applicable. A detailed list on the Soil Drainage Class descriptions from the NRCS Survey Manual (USDA Natural Resources Conservation Services) are as follows:

- ***Well drained:*** *Water is removed from the soil readily but not rapidly. Internal free water occurrence commonly is deep or very deep; annual duration is not specified.*
- ***Moderately well drained:*** *Water is removed from the soil somewhat slowly during some periods of the year. Internal free water occurrence commonly is moderately deep and transitory through permanent.*
- ***Somewhat poorly drained:*** *Water is removed slowly so that the soil is wet at a shallow depth for significant periods during the growing season. The occurrence of internal free water commonly is shallow to moderately deep and transitory to permanent. The soils commonly have one or more of the following characteristics: low or very low saturated hydraulic conductivity, a high water table, additional water from seepage, or nearly continuous rainfall.*
- ***Poorly drained:*** *Water is removed so slowly that the soil is wet at shallow depths periodically during the growing season or remains wet for long periods. The occurrence of internal free water is shallow or very shallow and common or persistent. Free water is commonly at or near the surface long enough during the growing season so that most mesophytic crops cannot be grown, unless the soil is artificially drained.*
- ***Very poorly drained:*** *Water is removed from the soil so slowly that free water remains at or very near the ground surface during much of the growing season. The occurrence of internal free water is very shallow and persistent or permanent. Unless the soil is artificially drained, most mesophytic crops cannot be grown. The soils are commonly level or depressed and frequently ponded.*

Prepare Developed Land Cover Data

C. Create the developed land cover input by extracting developed land cover types from the regional land cover dataset.
   a. Extract the developed land cover classes using *Extract by Attribute* to select separate subsets of the data where VALUE = 2 (*Developed, High Intensity – contains significant land area and is covered by concrete, asphalt, and*

other constructed materials. Vegetation, if present, occupies < 20 percent of the landscape. Constructed materials account for 80 - 100 percent of the total cover. Class includes heavily built-up urban centers and large constructed surfaces in suburban and rural areas with a variety of land uses) Or Value = 3 (*Developed, Medium Intensity – contains areas with a mixture of constructed materials and vegetation or other cover. Constructed materials account for 50 - 79 percent of total area. This class commonly includes multi- and single-family housing areas, especially in suburban neighborhoods, but may include all types of land use*) Or Value = 4 (*Developed, Low Intensity – contains areas with a mixture of constructed materials and substantial amounts of vegetation or other cover. Constructed materials account for 21 - 49 percent of total area. This subclass commonly includes single-family housing areas, especially in rural neighborhoods, but may include all types of land use*).

b. Reclassify the developed land cover raster using the rank values for developed land cover according to Table C5, clip results to regional boundary, and mosaic with regional boundary.

Table C5. Developed Land Cover categories, rank type, and rank.

Land Cover Class	Rank Type	Rank Value
4 Low Intensity Developed	Moderate	3
3 Medium Intensity Developed	High	4
2 High Intensity Developed	Very high	5

Combine Soil Drainage and Developed Land Cover Data

D. Add and reclassify the developed land cover and soil drainage rasters.

a. Add the mosaicked developed land cover raster to the mosaicked soil drainage raster using the *Raster Calculator* geoprocessing tool's addition operator.

b. Reclassify the summed developed land cover and soil drainage according to Table C6.

Table C6. Impermeability categories, rank type, and rank.

Summed Value	Rank Type	Reclassified Rank Value
0	None	0
1	Well-drained soils	1
2	Moderately well-drained soils	2
3	Somewhat poorly drained soils; Low intensity development	3
4	Poorly drained soils; Medium intensity development; Low intensity development AND well-drained soils	4
5 - 10	Very poorly drained soils; High intensity development; Medium intensity development AND well-drained soils; Low intensity development AND moderately well-drained soils; Low intensity development AND somewhat poorly drained soils; Medium intensity development AND moderately well-drained soils; High intensity development AND well-drained soils; High intensity development AND moderately well-drained soils; Medium intensity development AND somewhat poorly drained soils; Low intensity development AND poorly drained soils; High intensity development AND somewhat poorly drained soils; Medium intensity development AND poorly drained soils; Low intensity development AND very poorly drained soils; High intensity development AND poorly drained soils; Medium intensity development AND very poorly drained soils; High intensity development AND very poorly drained soils	5

Prepare Subsurface Tile Drainage and Row Crops Data

Tile drainage agriculture was accounted for in the Impermeability input by subtracting high, medium, and low tile drainage, restricted to areas with row crops, from the soil drainage/land cover-derived impermeability input calculated above.

E. Subsurface tile drainage
    a. Clip the downloaded tile drainage feature class to the regional boundary.
    b. Add new Short (16-bit integer) field "Rank" value to rank tile drainage using *Calculate Field* where the existing classification scheme to combine the two lowest, two medium, and two highest classes into three valued classes plus a zero class.
        i. Expression (Arcade): Rank =
           When($feature.Ag_Tile_SSF<=0.01, 0,
           $feature.Ag_Tile_SSF<=0.70, 1,
           $feature.Ag_Tile_SSF<=32.63, 2,
           $feature.Ag_Tile_SSF>32.63, 3, "")
    c. Dissolve tile drainage polygon features by Rank and rasterize (Value Field: Rank, Priority Field: Shape_Area).
F. Row crops
    a. Reclassify each state-level cropland raster so crops typical in tile drainage areas (i.e., row crops and not orchards or vineyards; values 1-60, 196-254) are given a new value of 1 and all other values are given a new value of 0.
    b. Extract row crop values from each reclassified state-level row crop raster using *Extract by Attributes* where Value = 1.
    c. Mosaic the extracted state-level row crop rasters to a single regional raster. Use the *Copy Raster* tool to ensure the raster environment settings such as projection and snapping match the Assessment regional template.
    d. Reclassify the regional cropland mosaic raster so the new value = 0 where row crops are present. This will ensure data can be combined with the tile drainage raster but not change the value of the results so the output will be only the value of the tile drainage raster where it overlaps with the row crop raster.

Combine Soil Drainage and Developed Land Cover Data with Subsurface Tile Drainage and Row Crops Data

G. Use the *Raster Calculator's* addition operator to add the reclassified cropland mosaic raster and the subsurface tile drainage raster. Mosaic the output with the regional boundary to create a complete raster and clip to the regional boundary.
H. Use the Raster Calculator's subtraction operator to subtract the clipped subsurface tile drainage/row crop mosaicked raster from the reclassified soil drainage/developed land cover impermeability raster.
I. Extract the positive and negative values from the *Raster Calculator's* output using *Extract by Attributes* to create two separate rasters where Value >= 0 (extracted positive values raster) and Value < 0 (extracted negative values raster).
J. Use the *Raster Calculator's* addition operator to add the extracted negative values raster and clipped subsurface tile drainage/row crop mosaicked raster to create a corrected negative values raster. This will ensure the values are the three lowest classes of impermeability threat (0,1,2).
K. Mosaic extracted positive values and corrected negative values rasters into a single impermeability raster.
L. Mosaic impermeability raster with regional boundary and clip to regional boundary.

C.5 Create High Lake Levels Input

A. Obtain the Water Occurrence (1984-2020) dataset from the Joint Research Centre's Global Surface Water Dataset.
B. Clip the Water Occurrence raster to the regional boundary.
    a. Geoprocessing > Clip
        i. Input = Water Occurrence raster
        ii. Clip mask = 20-m depth regional boundary
C. Reclassify the clipped raster to contain only the values of 1 to 90. This will display only those areas where there is water less than 90% of the duration from 1984 to 2020.
    a. Geoprocessing > Reclassify
    b. Keep all values the same from 1 to 90
    c. Reclassify values from 91 to 100 as NULL or NODATA
D. Symbolize the reclassified raster with a 5-class quantile distribution.

E. Reclassify the symbolized raster with a 1 to 5 range of values according to the 5-class symbolized distribution of values, where areas that are more likely to have higher lake levels receive a 5 and the areas that are less likely to have higher lake levels a 1.
    a. Areas that are more likely to have higher lake levels have higher percentage values where areas that have water 74% to 90% of the 1984-2020 duration received the highest value.

C.6 Calculating the Threat Index

The individual inputs (Flood-prone Areas, Soil Erodibility, Impermeability, Areas of Low Slope, and High Lake Levels) were combined into a single raster using the *Raster Calculator* geoprocessing tool's addition operator. The Threat Index was clipped to the Community Exposure Index masking layer and reclassified into 10 classes using a quantile breaks distribution. The distribution for the Threat Index is displayed in Table C7. The Threat Index was then combined with the Community Asset Index to create the Community Exposure Index.

Prepare Community Exposure Index Masking Layer

A. Process buffered shoreline mask. The output of each step becomes the input for the next.
    a. Buffer the continuous shoreline feature class by 500 m.
    b. Clip the regional boundary using the 500-m buffered shoreline feature class to create a 500-m shoreline buffer *(this output will be the polygon area outside of the 500-m buffered shoreline within the regional boundary that will be erased).*
    c. Erase the 500-m shoreline buffer from the regional boundary *(this output will be the polygon area remaining inside of the 500-m buffered shoreline within the regional boundary).*
    d. Use *Union* on the erased buffered shoreline to enclose any "doughnut holes" created by the buffered shoreline that are completely contained within the buffered distance.
    e. Convert features using *Multipart to Singlepart (this output will allow for manual feature editing).*
    f. Manually edit features as needed (e.g., removing fragments or small islands created by the buffered shoreline dataset that were not considered islands in the regional boundary and removing Canadian islands where the 500-m buffer extends into the regional boundary).
    g. Dissolve.
B. Process HLL High Lake Levels input mask.
    a. From the High Lake Levels input created above, use *Extract by Attributes* where Value <> 0.
    b. Rasterize (Simplify Polygons: checked, Create Multipart Features: checked), dissolve, and buffer by 500 m.
C. Merge buffered shoreline and High Lake Levels mask and dissolve to create Community Exposure Index masking layer.

Threat Index Calculation

D. Use the *Raster Calculator's* addition operator to add the individual threat inputs into a single raster output.
E. Clip the *Raster Calculator* results to the Community Exposure Index masking layer (500-m buffered shoreline intersected with the High Lake Levels created above).
F. Reclassify the clipped output into 10 classes based on a quantile distribution.

Table C7. Threat Index Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Threat Index Break Value	0 - 2	3 - 4	5	6	7	8	9	10	11 - 12	13 - 25
Final Rank Value	1	2	3	4	5	6	7	8	9	10

D. Detailed Methodology: Community Asset Index

Data processing for each of the indices used the geoprocessing standards described in Appendix B.

D.1 Create Population Density Input

The Population Density input was calculated using a combination of data processing and geoprocessing using R, QGIS, and ArcGIS Pro due to the large size of the regional census block dataset.

A. Merge individually downloaded state-level population data tables into a regional data table using R or similar data processing software.
  a. Merge state-level population data.
    i. Install and load libraries (dplyr, tidyr, foreign).
    ii. Read state-level data (if needed, tidy data so there is only one header).
      1. state_header <- read.csv("./DECENNIALPL2020.P1_data_with_overlays.csv", stringsAsFactor=F, nrows = 1, header=F, as.is=T)
      2. state <- read.csv("./DECENNIALPL2020.P1_data_with_overlays_.csv", stringsAsFactor=F, skip=2, header=F)
      3. colnames(state) <- mn_header
      4. state <- state[,c("GEO_ID", "NAME", "P1_001N")]
    iii. Merge state-level tables into a single region-level data table.
      1. Region <- bind_rows(state1, state2…)
    iv. If necessary, reformat GEO_ID to match census block polygon geography GEO_ID.
      1. region$GEO_ID_TIDY <- region$GEO_ID
      2. regionTidy <- region %>% separate(GEO_ID_TIDY, c("Pre","Post"), sep = "US")
      3. write.dbf(glTidy, "./Region_DECENNIALPL2020.P1_data_with_overlays_TIDY_R.dbf", factor2char = FALSE)

B. Join regional population data table to the regional census block polygons using QGIS or similar geoprocessing software.
  a. Join table to vector layer using census block GEOID field.
  b. Copy the joined population data (in memory) to a new field in the regional census block polygon layer using *Field Calculator* and export results as a new geopackage.
    i. Input Layer: regional population density feature class
    ii. Field Name: P1_001N_Join (Type: Integer, Length: 10, Precision: 0)
    iii. Formula Expression: "GL_DECENNIALPL2020.P1_data_with_overlays_TIDY_R_P1_001N"

C. Calculate the area of each census block using *Field Calculator* and export results as a new geopackage. *It is important that data not be clipped to the regional boundary as area needs to be calculated for the entire census block otherwise the population density calculation will not be correct.*
  a. Input Layer: joined regional population density feature class
  b. Field Name: Area_km_unclippec (Type: Float, Length: 12, Precision: 6)
  c. Formula Expression: ("Block20_ALAND" + "Block20_AWATER") / 1000000

D. Calculate the population density of each census block using *Field Calculator* and export results as a new geopackage.
  a. Input Layer: joined regional population density feature class
  b. Field Name: Pop_density (Type: Float, Length: 12, Precision: 6)
  c. Formula Expression: "P1_001N_Join" / "Area_km_unclipped"

E. Clip joined regional population density feature class to regional boundary.

F. Export the clipped joined regional population density feature class data as a .csv file. Limit the fields to only those necessary (ID, Pop_density) for more efficient processing.

G. Determine rank values and assign to each census block feature in the clipped joined regional population density feature class.
  a. Determine quantile breaks using R or similar data processing software.
    i. Install and load libraries (GGally, dplyr).
    ii. Read clipped joined regional population density data table export (.csv).
      1. pd <- read.csv("./Clipped-and-joined-census-block-population-density.csv", stringsAsFactor=F)
    iii. Filter 0 value and missing population density out of data.
      1. pd_exclude <- pd[pd$Pop_density!=0,]

2. pd_exclude <- pd_exclude[!is.na(pd_exclude$Pop_density),]

iv. Determine quantile distribution breaks for 5 classes of data.

1. pd_quantile <- pd_exclude %>%

```
        mutate(
        pdq   = cut_number(Pop_density, n = 5))
unique(pd_quantile$pdq)
```

b. Assign rank using *Field Calculator* in QGIS.

i. Field Name: Rank (Type: Integer, Length: 1, Precision: 0)

ii. Formula Expression: (based on regional quantile distribution breaks determined above)

```
CASE
 WHEN ““Pop_density””   =  0 THEN 0
 WHEN ““Pop_density””  <=  37.7224 THEN 1
 WHEN ““Pop_density””  <=  540.9796 THEN 2
 WHEN ““Pop_density””  <=  1619.3770 THEN 3
 WHEN ““Pop_density””  <=  2923.7249 THEN 4
 WHEN ““Pop_density””  <=  1028007 THEN 5
 ELSE 9
END
```

H. Rasterize the ranked population density feature class using *Rasterize*.

a. Field to Use for a Burn-in Value: Rank

I. Mosaic the ranked population density raster and the regional boundary and clip to regional boundary (performed in ArcGIS Pro where most geoprocessing and final input and index calculation occurred).

D.2 Create Social Vulnerability Input

A. Clip the national-level percentile feature class (from EJ Indexes Geodatabase of national data at the block group level) to the regional boundary and reproject.

B. Add new Short (16-bit integer) field “Rank” value to the attribute table using *Calculate Field*. For the U.S. Great Lakes region, ranking was assigned using the national percentile distribution at 10-percentile intervals starting with the 50th - 60th percentile = 1. Rasterize the results.

a. Expression (Arcade): Rank =
When($feature.P_VULEOPCT < 50, 0,
$feature.P_VULEOPCT < 60, 1,
$feature.P_VULEOPCT < 70, 2,
$feature.P_VULEOPCT < 80, 3,
$feature.P_VULEOPCT < 90, 4,
$feature.P_VULEOPCT <= 100, 5, 9)

C. Mosaic the social vulnerability raster with the regional boundary and clip to the regional boundary.

D.3 Create Critical Facilities Input

Critical Facilities include schools, emergency response and law enforcement facilities, health and medical facilities, and government and military buildings. These feature types were extracted from the USGS National Structures Dataset and intersected with Microsoft Building Footprints to create the Critical Facilities input to the Community Asset Index.

A. Prepare building footprints data by importing state-level data (Geoprocessing > JSON To Features, Geometry Type: Polygon), clipping to the regional boundary, and merging state-level clipped building footprints into a single regional building footprints feature class.

B. Clip National Structures data to the regional boundary.

C. Select all critical facilities of interest (Geoprocessing > Export Features where Structures: FTYPE <> 820). For the U.S. Great Lakes region, this included Education (FTYPE 730), Emergency Response and Law Enforcement (FTYPE 740), Post Office (FTYPE 780), Health and Medical (FTYPE 800) and Government and Military facilities (FTYPE 830). Public Attractions and Landmark Buildings (FTYPE 820) were not included.

D. Select building footprints that represent the facilities and export results (Geoprocessing > Select Layer By Location, Input Features: merged regional building footprints, Relationship: Intersect, Selecting Features: clipped selection of National Structures data, Search Distance: 10m).
E. Add new Short (16-bit integer) field "Rank" value (Rank = 5) to selected regional building footprints using *Calculate Field* and rasterize.
F. Mosaic into a single input.

D.4 Create Critical Infrastructure Input

Critical Infrastructure includes transportation, waterways, water treatment, communications, energy, and hazardous site infrastructure. For managing large numbers of individual datasets, data were merged by infrastructure category. Individual components were mosaicked to create the Critical Infrastructure input to the Community Asset Index.

Prepare the Transportation Infrastructure Data

Roads

A. Merge the state-level primary and secondary roads data, clip to the regional boundary, and reproject.
B. Buffer region-level roads by 20 m.

Railroads

C. Clip the national rail network lines dataset to the regional boundary and reproject.
D. Buffer region-level railroads by 10 m.

Airport Runways

E. Clip the national airport runways dataset to the regional boundary and reproject. *Note, this dataset contains airport runway and helicopter landing areas on land or water intended to be used either wholly or in part for the arrival, departure, and surface movement of aircraft/helicopters.*
F. Buffer region-level airport runways by 30 m.

Ferry Terminals

G. Clip the national ferry terminals dataset to the regional boundary and reproject. *Note, this dataset includes recreational ferries and water taxis.*
H. Buffer region-level ferry terminals by 100 m.

International Border Crossings

I. Clip the US-Canada border crossings dataset to the regional boundary and reproject. *Note, this dataset includes a centroid location along a controlled border crossing that serves as a proxy for these critical transportation infrastructure types. It includes areas where no other inputs overlapped including the Detroit-Windsor tunnel and Detroit-Ambassador Bridge.*
J. Buffer region-level border crossings by 100 m.

Bridges

K. Clip the National Bridge Inventory dataset to the regional boundary and reproject.
L. Export bridge points relevant to this analysis: bridges that go over bodies of water. *Note that this includes relief for waterway.* Do not include bridges that go over railways, roadways, or other obstacles and not water.
    a. Where ITEM 42b *(Type of Service Under Bridge)* >= '5' *(Waterway codes 5 - 9)* AND ITEM 71 *(Waterway Adequacy)* <> 'N' *(Bridge not over a waterway)*
M. Use the bridge length attribute, ITEM49 (Structure Length), calculate buffer distance for each feature *using Calculate Field*. Buffer selected bridge point locations using BLength calculation (output referred to as "buffered bridges" below).
    a. Field Name: BLength (Type: Float (single precision))
    b. Expression: (!structure_len_mt_049! / 2) + 40 *(the bridge length divided by two is used because a buffer extending outward from the bridge's midpoint will reach the surveyed bridge length. The additional 40 meters is to compensate for the area of a bridge that connects with the roadway. This section of a bridge is also highly susceptible to flooding.)*
N. Import all USGS National Hydrography Dataset Plus High Resolution (NHDPlus HR) features for the region and merge into a single regional waterbodies polygon feature class.

a. Import NHDFlowline, NHDArea, and NHDWaterbody hydrography features for each VPUID (NHDPlus_H__GDB.gdb file geodatabase, where VPUID is the identifier of each vector-processing unit) in the region.
b. For each feature type (NHDFlowline, NHDArea, and NHDWaterbody), merge VPUID-level feature classes into a single region-level feature class.
c. Buffer NHDFlowline feature class by 1 m to convert it from a polyline to a polygon.
d. If necessary, remove features from the buffered NHDFlowline feature class using *Export Features* where FTYPE <> 428 (pipeline) AND FTYPE <> 420 (underground conduit).
e. Merge the three region-level NHDPlus HR polygon feature classes (NHD Flowline, NHD Area, and NHD Waterbody) into a single feature class.

O. Download national-level roads dataset that includes all road categories *(note, this is different from the roads sub-input described above)*. Select roads that intersect waterways and the buffered bridge output. Output referred to as "selected roads" below. If necessary, remove ferry routes from the roads dataset.
  a. Roads-Waterbodies Selection (Select Layer by Location, Relationship: Intersect)
    i. Input Features: national roads feature class (includes all primary, secondary, and local roads)
    ii. Selecting Features: Merged NHDPlus HR polygons
  b. Roads-Waterbodies-Bridges Selection (Select Layer by Location, Relationship: Intersect)
    i. Input Features: Roads selection
    ii. Selecting Features: Buffered bridge output
  c. Export roads-waterbodies-bridges selection as a new feature.

P. Intersect the bridges buffered by length (buffered bridges) output with the selected roads-waterbodies-bridges output (Geoprocessing > Intersect, Input Features: Buffered bridges and selected roads) to isolate roadways that are bridges and remove slivers of roadway that are not actual bridge decks and bridge approaches. Output referred to below as "intersected bridge-road polylines".

Q. Use the bridge deck width field, "ITEM52" to calculate buffer distance for each feature using *Calculate Field*, changing any NULL or values of 0 in field "ITEM52" to 12 (12 meters is the average bridge width used in this analysis) to get approximate surveyed bridge deck width in meters. Buffer intersected bridge-road polylines using *BufferWidthCorrected* calculation and dissolve features by National Bridge Inventory FID ().
  a. Field Name: BufferWidthCorrected (Type: Float (single precision))
  b. Expression (Arcade):
```
When(IsEmpty($feature.deck_width_mt_052), 12,
$feature.deck_width_mt_052==0, 12,
$feature.deck_width_mt_052)
```

Combine the Transportation Infrastructure Outputs

R. Merge the processed roads, railroads, airport runways, ferry terminals, international border crossings, and bridges transportation outputs into a single layer.

Prepare the Waterways Infrastructure Data

Dams

S. Clip both national dam line and dam point datasets to the regional boundary and reproject (dam lines provide better representation of dam infrastructure but does not include all dams relevant to this Assessment).

T. Export dams to only include significant or high hazard potential dams where HAZARD = 'H' Or HAZARD = 'S' *(Downstream Hazard Potential Code to indicate the potential hazard to the downstream area resulting from failure or misoperation of the dam or facilities: S for Significant; H for High; note that dam lines are already limited to hazardous infrastructure Downstream Hazard Potential Code to indicate the potential hazard to the downstream area resulting from failure or misoperation of the dam or facilities: H for High).*

U. Buffer both dam lines and dam points by 100 m.

V. Inverse select by location to ensure that dam lines are used where available, supplemented by dam points (Geoprocessing > Select Layer ByLocation, Input Features: buffered dam points, Relationship: Intersect, Selecting Features: buffered dam lines, Search Distance: 1,000 m (to prevent selection of facility points attributed to a waterbody with a dam not specific to its infrastructure location), Selection Type: New selection, Invert Spatial Relationship: checked). Export results.

W. Merge point-based and line-based buffered dam polygons.

Ports

X. Clip the national ports dataset to the regional boundary and reproject.
Y. Buffer region-level ports by 100 m.

Locks

Z. Clip each of the locks datasets to the regional boundary and reproject.
AA. Export locks that are not recreation-only or recreation and power-generating combination-only where MULTI <> 'R' And MULTI <> 'RP' *(Multi use of structure: R=Recreation, P=Power).*
BB. Merge the locks datasets.
CC. Buffer region-level locks by 350 m.

Levees

DD. Clip the national leveed areas dataset to the regional boundary and reproject. *Note, this is a polygon footprint of the levee infrastructure and area protected by levees.*

Combine the Waterways Infrastructure Outputs

EE. Merge the processed dams, ports, locks, and levees waterways outputs into a single layer.

Prepare the Water Treatment Infrastructure Data

Wastewater Treatment Plants

FF. Filter the national wastewater input data by state using a *Definition Query* and export the results to a new feature class (filtering is necessary for exporting data from large feature services that would otherwise have more features than the server allows). Merge the state-level results into a single regional layer to continue processing.
GG. Clip the merged dataset to the regional boundary and reproject.
HH. Buffer the clipped dataset (point features) by 130 m.
II. Export to remove any inactive facilities from the dataset where CWP_PERMIT_STATUS_DESC <> 'Terminated' And CWP_PERMIT_STATUS_DESC <> 'Expired' And CWP_PERMIT_STATUS_DESC <> 'INACTIVE'.

Community Water Systems

JJ. Export the national EPA Facility Registry Service geodatabase dataset to include only active community water systems where (INTEREST_TYPE = 'COMMUNITY WATER SYSTEM') And ACTIVE_STATUS <> 'TERMINATED' And ACTIVE_STATUS <> 'EXPIRED' And ACTIVE_STATUS <> 'INACTIVE'.
KK. Clip the dataset to the regional boundary and reproject.
LL. Buffer the clipped dataset (point features) by 130 m.

Combine the Water Treatment Infrastructure Outputs

MM. Merge the processed wastewater and community water systems water treatment outputs into a single layer.

Prepare the Communications Infrastructure Data

Cellular Towers and FM Transmission Towers

NN. For each of the communications infrastructure datasets (cellular towers and FM transmission towers), clip the national datasets to the regional boundary and reproject.
OO. Buffer each of the clipped regional datasets (point features) by 10 m.

Combine the Communications Infrastructure Outputs

PP. Merge the processed cellular towers and FM transmission towers communications outputs into a single layer.

Prepare the Energy Infrastructure Data

Power Plants, Electric Substations, Petroleum Terminals, Petroleum Refineries, Natural Gas Processing Plants, and Underground Natural Gas Storage

QQ. For each energy input dataset (power plants, electric substations, petroleum terminals, petroleum refineries, natural gas processing plants, and underground natural gas storage), clip national datasets to the regional boundary and reproject.

RR. Buffer the clipped energy datasets using the following values:

   a. Power Plants
      i. Solar (capacity > 15 MW): 250 m
      ii. Capacity >= 10 MW and <= 100 MW (excluding solar above): 100 m
      iii. Capacity > 100 MW and <= 500 MW: 200 m
      iv. Capacity > 500: 500 m

   b. Electric Substations: 20 m

   c. Petroleum Refineries, Petroleum Terminals, Natural Gas Processing Plants, Underground Natural Gas Storage: 100 m

Combine the Energy Infrastructure Outputs

SS. Merge the processed power plants, electric substations, petroleum terminals, petroleum refineries, natural gas processing plants, and underground natural gas storage energy outputs into a single layer.

Prepare the Hazardous Sites Infrastructure Data

TT. Clip the National Facility Interests dataset to the regional boundary and reproject.

UU. Export the relevant interest types from the dataset where INTEREST_TYPE = 'SUPERFUND NPL' Or INTEREST_TYPE = 'LQG' Or INTEREST_TYPE = 'BROWNFIELDS PROPERTY' Or INTEREST_TYPE = 'HAZARDOUS WASTE LANDFILL' Or INTEREST_TYPE = 'HAZARDOUS, SOLID & C&D WASTE LANDFILL' Or INTEREST_TYPE = 'RAD NPL' Or INTEREST_TYPE = 'RAD WIPP'.

VV. Buffer clipped selection by 150 m to convert to polygon feature class.

Merge the Critical Infrastructure Data

Merge the transportation, waterways, water treatment, communications, energy, and hazardous sites merged feature class outputs into a single critical infrastructure layer.

WW. Add new Short (16-bit integer) field “Rank” value (Rank = 5) to critical infrastructure attribute table using *Calculate Field* and rasterize.

XX. Mosaic critical infrastructure raster with regional boundary.

D.5 Calculating the Community Asset Index

The individual inputs (Population Density, Social Vulnerability, Critical Facilities, and Critical Infrastructure) were combined into a single raster using the *Raster Calculator* geoprocessing tool's addition operator. The Community Asset Index was clipped to the Community Exposure Index masking layer and reclassified into 10 classes using a quantile breaks distribution. The distribution for the Community Asset Index is displayed in Table D2. The Community Asset Index was then combined with the Threat Index to create the Community Exposure Index.

A. Use the *Raster Calculator's* addition operator to add the individual community asset inputs into a single raster output.
B. Clip the *Raster Calculator* results to the Community Exposure Index masking layer (500-m buffered shoreline intersected with the high lake levels created in the Threat Index > Calculating the Threat Index > Prepare the Community Exposure Index Masking Layer above).
C. Reclassify the clipped output into 10 classes based on quantile distribution.

Table D2. Community Asset Index Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Asset Index Break Value	0	1	2	3	4	5	6	7	8 - 9	10 - 20
Final Rank Value	1	2	3	4	5	6	7	8	9	10

E. Detailed Methodology: Community Exposure Index

Data processing for each of the indices used the geoprocessing standards described in Appendix B. After classifying the Threat Index and Community Asset Index into 10 classes, they were multiplied to create the Community Exposure Index. Exposure is the overlap of community assets and flood threats. As this multiplication results in a final index with values from 1-100, the Community Exposure Index was further classified into 10 classes to make the results consistent and easier to understand. The distribution used for the Community Exposure Index in the U.S. Great Lakes region is shown in Table F1.

Table E1. Community Exposure Index Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Exposure Index Break Value	1 - 2	3	4	5 - 6	7 - 9	10 - 12	13 - 16	17 - 20	21 -30	31 - 100
Final Rank Value	1	2	3	4	5	6	7	8	9	10

F. Detailed Methodology: Terrestrial Index

Data processing for each of the indices used the geoprocessing standards described in Appendix B.

F.1 Species of Conservation Concern Included in the Terrestrial Index

For the purposes of the U.S. Great Lakes Assessment, species of conservation concern include species with federal-level protection status, species of greatest conservation concern as identified through State Wildlife Action Plans, and species with off-reservation harvest regulations in the 1837 and 1842 Ceded Territories in Wisconsin and Minnesota[20]. Refer to Table F1 for a complete list of terrestrial species included in the Assessment.

Table F1. List of species of conservation concern included in the Terrestrial Index organized by taxonomic group. Species included are species of greatest conservation concern in at least one State Wildlife Action Plan, species listed under the U.S. Endangered Species Act (denoted with asterisk), and/or other regionally important species with off-reservation harvest regulations in the 1837 and 1842 Ceded Territories in Wisconsin and Minnesota.

Terrestrial Species of Conservation Concern

Amphibians

Blanchard's cricket frog	*Acris blanchardi*	Marbled salamander	*Ambystoma opacum*
Blue-spotted salamander	*Ambystoma laterale*	Mink frog	*Lithobates septentrionalis*
Boreal chorus frog	*Pseudacris maculata*	Mudpuppy	*Necturus maculosus*
Cave salamander	*Eurycea lucifuga*	Northern dusky salamander	*Desmognathus fuscus*
Cope's gray treefrog	*Dryophytes chrysoscelis*	Northern leopard frog	*Lithobates pipiens*
Eastern hellbender	*Cryptobranchus alleganiensis alleganiensis*	Northern ravine salamander	*Plethodon electromorphus*
Eastern newt	*Notophthalmus viridescens*	Northern spring salamander	*Gyrinophilus porphyriticus porphyriticus*
Eastern red-backed Salamander	*Plethodon cinereus*	Pickerel frog	*Lithobates palustris*
Eastern tiger salamander	*Ambystoma tigrinum*	Plains leopard frog	*Lithobates blairi*
Four-toed salamander	*Hemidactylium scutatum*	Red salamander	*Pseudotriton ruber*
Fowler's toad	*Anaxyrus fowleri*	Small-mouthed salamander	*Ambystoma texanum*
Hellbender	*Cryptobranchus alleganiensis*	Southern two-lined salamander	*Eurycea cirrigera*
Jefferson salamander	*Ambystoma jeffersonianum*	Spotted salamander	*Ambystoma maculatum*
Lesser siren	*Siren intermedia*	Western chorus frog	*Pseudacris triseriata*
Long-tailed salamander	*Eurycea longicauda*	Wood frog	*Lithobates sylvaticus*

Reptiles

Blanding's turtle	*Emydoidea blandingii*	Gray rat snake	*Pantherophis spiloides*
Butler's garter snake	*Thamnophis butleri*	Kirtland's snake	*Clonophis kirtlandii*
Eastern box turtle	*Terrapene carolina*	Lake Erie or northern water Snake	*Nerodia sipedon insularum*
Eastern fox snake	*Pantherophis gloydi*	Midland smooth softshell turtle	*Apalone mutica mutica*
Eastern hog-nosed snake	*Heterodon platirhinos*	Musk turtle	*Sternotherus odoratus*
Eastern massasauga*	*Sistrurus catenatus*	North American racer	*Coluber constrictor constrictor*
Eastern mud turtle	*Kinosternon subrubrum*	Northern coal skink	*Plestiodon anthracinus anthracinus*
Eastern ribbon snake	*Thamnophis saurita*		
Five-lined skink	*Eumeces fasciatus*		
Gopher snake	*Pituophis catenifer*		
Graham's crayfish snake	*Regina grahamii*		

[20] For details see the Great Lakes Indian Fish and Wildlife Commission website: https://data.glifwc.org/regulations/

Table F1 Continued - Terrestrial Species of Conservation Concern

Reptiles *(continued)*

Northern copperhead	*Agkistrodon contortrix mokasen*	Prairie skink	*Eumeces septentrionalis*
Northern map turtle	*Graptemys geographica*	Queen snake	*Regina septemvittata*
Northern ringneck snake	*Diadophis punctatus edwardsii*	Short-headed garter snake	*Thamnophis brachystoma*
Northern spiny softshell turtle	*Apalone spinifera spinifera*	Six-lined Racerunner	*Cnemidophorus sexlineatus*
Ornate box turtle	*Terrapene ornata*	Slender glass lizard	*Ophisaurus attenuatus*
Ouachita map turtle	*Graptemys ouachitensis*	Smooth greensnake	*Opheodrys vernalis*
Plain-bellied water snake (includes copperbelly water snake subspecies)*	*Nerodia erythrogaster*	Smooth softshell	*Apalone mutica*
		Snapping turtle	*Chelydra serpentina*
		Spotted turtle	*Clemmys guttata*
		Timber rattlesnake	*Crotalus horridus*
		Western ribbon snake	*Thamnophis proximus*
Plains garter snake	*Thamnophis radix*	Wood turtle	*Glyptemys insculpta*

Mammals

American badger	*Taxidea taxus*	Northern myotis or northern long-eared bat*	*Myotis septentrionalis*
American black bear	*Ursus americanus*	Plains pocket gopher	*Geomys bursarius*
American marten	*Martes americana*	Prairie or North American deermouse	*Peromyscus maniculatus bairdii*
American water shrew	*Sorex palustris*	Prairie vole	*Microtus ochrogaster*
Bee or North American least shrew	*Cryptotis parva*	American pygmy shrew	*Sorex hoyi*
Big brown bat	*Eptesicus fuscus*	Eastern red bat	*Lasiurus borealis*
Bobcat	*Lynx rufus*	Red squirrel	*Tamiasciurus hudsonicus*
Brewer's or hairy-tailed mole	*Parascalops breweri*	Rock or long-tailed shrew	*Sorex dispar*
Canadian lynx*	*Lynx canadensis*	Rock vole	*Microtus chrotorrhinus*
Eastern chipmunk	*Tamias striatus*	Silver-haired bat	*Lasionycteris noctivagans*
Eastern fox squirrel	*Sciurus niger vulpinus*	Eastern small-footed myotis	*Myotis leibii*
Eastern pipistrelle	*Perimyotis subflavus*	Smokey shrew	*Sorex fumeus*
Eastern spotted skunk	*Spilogale putorius*	Snowshoe hare	*Lepus americanus*
Elk	*Cervus elaphus*	Southern flying squirrel	*Glaucomys volans*
Ermine	*Mustela erminea*	Southern red-backed vole	*Myodes gapperi*
Evening bat	*Nycticeius humeralis*	Star-nosed mole	*Condylura cristata*
Franklin's ground squirrel	*Poliocitellus franklinii*	Thirteen-lined ground squirrel	*Ictidomys tridecemlineatus*
Gray wolf*	*Canis lupus*	Ungava or eastern heather vole	*Phenacomys ungava*
Hoary bat	*Lasiurus cinereus*	Western harvest mouse	*Reithrodontomys megalotis*
Indiana myotis*	*Myotis sodalis*	White-tailed jack rabbit	*Lepus townsendii*
Least weasel	*Mustela nivalis*	Woodland jumping mouse	*Napaeozapus insignis*
Little brown bat	*Myotis lucifugus*	Woodland vole	*Microtus pinetorum*
Maryland or cinereus Shrew	*Sorex cinereus fontinalis*		
Meadow jumping mouse	*Zapus hudsonius*		
Moose	*Alces alces*		
Northern flying squirrel	*Glaucomys sabrinus*		

Birds

Acadian flycatcher	*Empidonax virescens*	American redstart	*Setophaga ruticilla*
American bittern	*Botaurus lentiginosus*	American or black scoter	*Melanitta nigra americana*
American black duck	*Anas rubripes*	American white pelican	*Pelecanus erythrorhynchos*
American coot	*Fulica americana*	American woodcock	*Scolopax minor*
American kestrel	*Falco sparverius*	Bald eagle	*Haliaeetus leucocephalus*

Table F1 Continued - Terrestrial Species of Conservation Concern

Birds *(continued)*

Bank swallow	*Riparia riparia*	Evening grosbeak	*Hesperiphona vespertina*
Bay-breasted warbler	*Setophaga castanea*	Field sparrow	*Spizella pusilla*
Bell's vireo	*Vireo bellii*	Forster's tern	*Sterna forsteri*
Belted kingfisher	*Megaceryle alcyon*	Golden eagle	*Aquila chrysaetos*
Bicknell's thrush	*Catharus bicknelli*	Golden-winged warbler	*Vermivora chrysoptera*
Black tern	*Chlidonias niger*	Grasshopper sparrow	*Ammodramus savannarum*
Black-and-white warbler	*Mniotilta varia*	Gray catbird	*Dumetella carolinensis*
Black-backed woodpecker	*Picoides arcticus*	Gray jay	*Perisoreus canadensis*
Black-billed cuckoo	*Coccyzus erythropthalmus*	Great blue heron	*Ardea herodias*
Blackburnian warbler	*Setophaga fusca*	Great crested flycatcher	*Myiarchus crinitus*
Black-crowned night heron	*Nycticorax nycticorax*	Great egret	*Ardea alba*
Blackpoll warbler	*Setophaga striata*	Henslow's sparrow	*Ammodramus henslowii*
Black-throated blue warbler	*Setophaga caerulescens*	Hooded warbler	*Setophaga citrina*
Black-throated green warbler	*Setophaga virens*	Horned grebe	*Podiceps auritus*
Blue-gray gnatcatcher	*Polioptila caerulea*	Horned lark	*Eremophila alpestris*
Blue-winged teal	*Anas discors*	Kentucky warbler	*Geothlypis formosa*
Blue-winged warbler	*Vermivora cyanoptera*	King rail	*Rallus elegans*
Bobolink	*Dolichonyx oryzivorus*	Kirtland's warbler	*Setophaga kirtlandii*
Bonaparte's gull	*Chroicocephalus philadelphia*	Lark sparrow	*Chondestes grammacus*
		Laughing gull	*Leucophaeus atricilla*
Boreal chickadee	*Poecile hudsonicus*	Le conte's sparrow	*Ammodramus leconteii*
Boreal owl	*Aegolius funereus*	Least bittern	*Ixobrychus exilis*
Brewer's blackbird	*Euphagus cyanocephalus*	Least flycatcher	*Empidonax minimus*
Broad-winged hawk	*Buteo platypterus*	Little gull	*Hydrocoloeus minutus*
Brown creeper	*Certhia americana*	Loggerhead shrike	*Lanius ludovicianus*
Brown thrasher	*Toxostoma rufum*	Long-eared owl	*Asio otus*
Canada warbler	*Cardellina canadensis*	Long-tailed duck	*Clangula hyemalis*
Canvasback	*Aythya valisineria*	Louisiana waterthrush	*Parkesia motacilla*
Cape may warbler	*Setophaga tigrina*	Marsh wren	*Cistothorus palustris*
Caspian tern	*Hydroprogne caspia*	Merlin	*Falco columbarius*
Cattle egret	*Bubulcus ibis*	Nashville warbler	*Leiothlypis ruficapilla*
Cerulean warbler	*Setophaga cerulea*	Northern bobwhite	*Colinus virginianus*
Chimney swift	*Chaetura pelagica*	Northern flicker	*Colaptes auratus*
Common barn-owl	*Tyto alba*	Northern goshawk	*Accipiter gentilis*
Common gallinule	*Gallinula galeata*	Northern harrier	*Circus cyaneus*
Common goldeneye	*Bucephala clangula*	Northern pintail	*Anas acuta*
Common loon	*Gavia immer*	Northern rough-winged swallow	*Stelgidopteryx serripennis*
Common merganser	*Mergus merganser*		
Common nighthawk	*Chordeiles minor*	Northern saw-whet owl	*Aegolius acadicus*
Common or ring-necked pheasant	*Phasianus colchicus*	Northern waterthrush	*Parkesia noveboracensis*
		Olive-sided flycatcher	*Contopus cooperi*
Common tern	*Sterna hirundo*	Osprey	*Pandion haliaetus*
Connecticut warbler	*Oporornis agilis*	Ovenbird	*Seiurus aurocapilla*
Dickcissel	*Spiza americana*	Peregrine falcon	*Falco peregrinus*
Eastern meadowlark	*Sturnella magna*	Philadelphia vireo	*Vireo philadelphicus*
Eastern whip-poor-will	*Antrostomus vociferus*	Pied-billed grebe	*Podilymbus podiceps*
Eurasian or green-winged teal	*Anas crecca*		

Table F1 Continued - Terrestrial Species of Conservation Concern

Birds *(continued)*

Pine siskin	*Spinus pinus*	Swainson's thrush	*Catharus ustulatus*
Piping plover*	*Charadrius melodus*	Three-toed woodpecker	*Picoides tridactylus*
Prairie warbler	*Setophaga discolor*	Trumpeter swan	*Cygnus buccinator*
Prothonotary warbler	*Protonotaria citrea*	Tundra swan	*Cygnus columbianus*
Purple finch	*Haemorhous purpureus*	Upland sandpiper	*Bartramia longicauda*
Purple martin	*Progne subis*	Veery	*Catharus fuscescens*
Red crossbill	*Loxia curvirostra*	Vesper sparrow	*Pooecetes gramineus*
Red-headed woodpecker	*Melanerpes erythrocephalus*	Virginia rail	*Rallus limicola*
Red-necked grebe	*Podiceps grisegena*	Western grebe	*Aechmophorus occidentalis*
Red-shouldered hawk	*Buteo lineatus*	Western meadowlark	*Sturnella neglecta*
Ruby-crowned kinglet	*Regulus calendula*	White-throated sparrow	*Zonotrichia albicollis*
Ruffed grouse	*Bonasa umbellus*	Willow flycatcher	*Empidonax traillii*
Rufous-sided or eastern towhee	*Pipilo erythrophthalmus*	Wilson's phalarope	*Phalaropus tricolor*
		Wilson's snipe	*Gallinago delicata*
Rusty blackbird	*Euphagus carolinus*	Winter wren	*Troglodytes hiemalis*
Sandhill crane	*Grus canadensis*	Wood duck	*Aix sponsa*
Savannah sparrow	*Passerculus sandwichensis*	Wood thrush	*Hylocichla mustelina*
Scarlet tanager	*Piranga olivacea*	Worm-eating warbler	*Helmitheros vermivorum*
Sedge wren	*Cistothorus platensis*	Yellow rail	*Coturnicops noveboracensis*
Sharp-shinned hawk	*Accipiter striatus*	Yellow-bellied flycatcher	*Empidonax flaviventris*
Sharp-tailed grouse	*Tympanuchus phasianellus*	Yellow-billed cuckoo	*Coccyzus americanus*
Short-eared owl	*Asio flammeus*	Yellow-breasted chat	*Icteria virens*
Snowy egret	*Egretta thula*	Yellow-crowned night heron	*Nyctanassa violacea*
Solitary sandpiper	*Tringa solitaria*	Yellow-headed blackbird	*Xanthocephalus xanthocephalus*
Sora	*Porzana carolina*		
Spotted sandpiper	*Actitis macularius*	Yellow-throated vireo	*Vireo flavifrons*
Spruce grouse	*Falcipennis canadensis*	Yellow-throated warbler	*Setophaga dominica*
Summer tanager	*Piranga rubra*		

Terrestrial Invertebrates

Hine's emerald dragonfly*	*Somatochlora hineana*	Poweshiek skipperling*	*Oarisma poweshiek*

Other Regionally Important Terrestrial Species
(additional species not included in State Wildlife Action Plans)

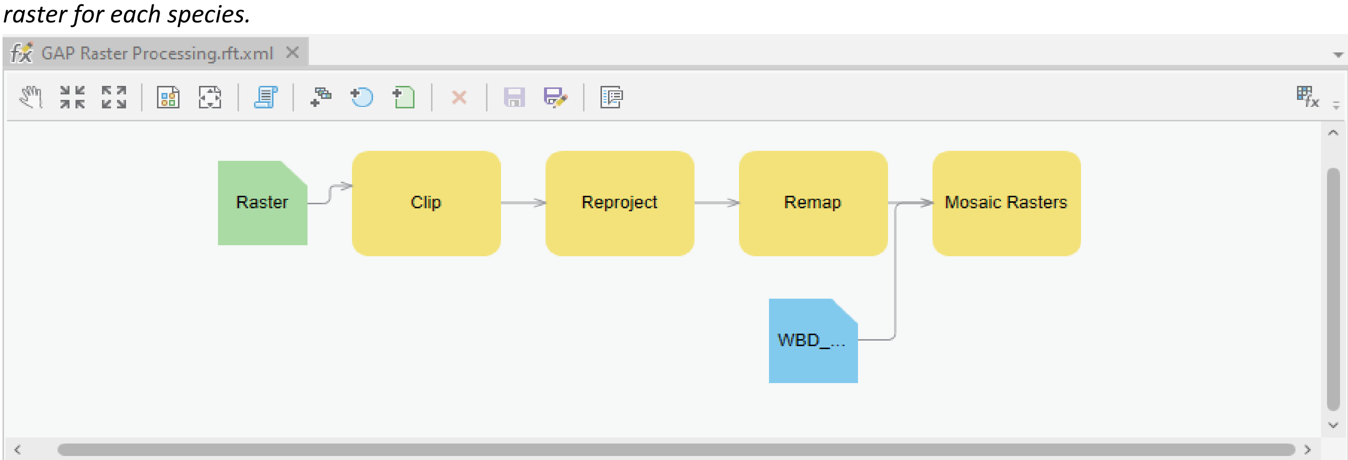
Mammals		***Birds***	
American beaver	*Castor canadensis*	Canada goose	*Branta canadensis*
American mink	*Neovison vison*	Gray partridge	*Perdix perdix*
Common muskrat	*Ondatra zibethicus*	Hooded merganser	*Lophodytes cucullatus*
Coyote	*Canis latrans*	Mourning dove	*Zenaida macroura*
Eastern cottontail	*Sylvilagus floridanus*	Mute swan	*Cygnus olor*
Eastern gray squirrel	*Sciurus carolinensis*	Red-breasted merganser	*Mergus serrator*
Fisher	*Martes pennanti*	Ring-necked duck	*Aythya collaris*
Gray fox	*Urocyon cinereoargenteus*	Wild turkey	*Meleagris gallopavo*
North American river otter	*Lontra canadensis*		
Raccoon	*Procyon lotor*		
Red fox	*Vulpes vulpes*		
White-tailed deer	*Odocoileus virginianus*		

F.2 Create Terrestrial Taxonomic Group Inputs

Process Predicted Habitat Model for Terrestrial Vertebrate Species

A. Process the predicted habitat model (U.S. Geological Survey (USGS) - Gap Analysis Project (GAP) Species Habitat Maps downloaded raster data) for *each* species using a series of geoprocessing tools to create a complete raster of the regional boundary where a value of 1 indicates presence and a value of 0 indicates absence of predicted habitat): Clip Raster (to regional boundary) > Project Raster (to regional projection) > Reclassify (1 if present) > Mosaic to New Raster (combine with regional boundary to ensure 0 value cells throughout the boundary wherever the species' habitat distribution is not present) or create a custom raster function combining the steps (Figure F1):
    a. Clip (Sets the extent of a raster using coordinates or another dataset.)
        i. Parameters
            1. Raster: <RasterFunctionVariable.Raster>
            2. Clipping Type: Outside
            3. Clipping Geometry/Raster: <Has-Geometry>
                a. Use input features for clipping geometry: checked
        ii. Variables: Raster (IsDataset = checked)
    b. Reproject (Modifies the projection of a raster dataset, mosaic dataset, or raster item in a mosaic dataset. It can also resample the data to a new cell size and define an origin.)
        i. Parameters:
            1. Raster = <Clip.OutputRaster>
            2. Spatial Reference: regional projection
    c. Remap (Changes pixel values by assigning new values to ranges of pixel values or using an external table.)
        i. Parameters:
            1. Raster: <Reproject.OutputRaster>
            2. Remap Definition Type:List
            3. Minimum=1, Maximum=9, Output=1
            4. Change missing values to NoData=checked
    d. Mosaic Rasters (Stitches a set of raster datasets together to create one dataset.)
        i. Rasters: (in order) <Remap.OutputRaster>, rank 0 regional boundary raster
        ii. Operation: First

Figure F1. Custom raster function combining a series of raster geoprocessing steps to process the USGS GAP Species Habitat raster for each species.



B. Copy temporary raster output (stored in memory) to an intermediate geodatabase.
C. Reclassify any federally listed species (Rank = 2).

Combine Predicted Habitat Model Data by Taxonomic Group

D. Add the individual processed intermediate species distribution rasters for all species within each taxonomic group (amphibians, reptiles, birds, mammals) using the Raster Calculator geoprocessing tool's addition operator. Note that it is important that each individual species input is a complete binary raster input (Value = 0 where absent or Value=1 or 2 where present) for the entire project area with NO DATA values within the species boundary. Running a *Raster Calculator* operation where there is NO DATA for even a single input will result in NO DATA for that pixel in the final output.

Reclassify Taxonomic Group Input

E. Use the *Reclassify* geoprocessing tool to classify the data within each taxonomic group using a quantile distribution. If necessary, use the *Clip Raster* geoprocessing tool before reclassifying to limit data to within the regional boundary before reclassifying as the values are based on the quantile distribution of data within the region. Classify into 6 classes (0-5) using a quantile distribution, ensuring that zero value cells are in their own class (0). If necessary, use the *Extract by Attributes* geoprocessing tool to extract all non-zero values, classify into 5 classes (1-5), then combine with extracted class zero using the *Mosaic to New Raster* geoprocessing tool.

F.3 Create the Terrestrial Critical Habitat Input

A. Select (or export to a new feature class) the terrestrial species where "status = final" from both the polygon and line feature classes downloaded from the U.S. Fish and Wildlife Service Threatened & Endangered Species Active Critical Habitat Report (note that for the U.S. Great Lakes Region there were only polygon features for terrestrial species). All terrestrial species with critical habitat, including terrestrial invertebrates, were included.
B. Clip and project the critical habitat line and polygon feature classes to the regional boundary.
C. Add new Short (16-bit integer) field "Rank" value (Rank = 1) to attribute table using *Calculate Field*.
D. If necessary, buffer clipped critical habitat lines by 1 m to convert to polygon feature class.
E. Rasterize each of the vector data inputs (i.e., one for each species). If there are both polygon and line critical habitat features, merge into a single polygon feature class before rasterizing.
F. Use the *Raster Calculator* tool to add each of the individual species-level critical habitat rasters.
    a. Map Algebra Expression *(Note that for each species a conditional statement is used to replace any null values with 0's to add rasters together. If this statement was not included there would only be values where every raster overlapped. Alternatively, each raster could be mosaicked individually with the rank 0 regional template prior to raster calculator processing to ensure a complete presence/absence dataset for the entire regional boundary. The template raster is a rank=0 dataset for the regional boundary and ensures 0 values where there are no inputs as opposed to no data.)*:
    "WBD_202204_GL_ExtendedArea_Project_TEMPATE_FW.tif" +
    Con(IsNull("CRITHAB_PipingPlover"),0,"CRITHAB_PipingPlover") +
    Con(IsNull("CRITHAB_HinesEmeraldDragonfly"),0,"CRITHAB_HinesEmeraldDragonfly") +
    Con(IsNull("CRITHAB_PoweshiekSkipperling"),0,"CRITHAB_PoweshiekSkipperling") +
    Con(IsNull("CRITHAB_GrayWolf"),0,"CRITHAB_GrayWolf") +
    Con(IsNull("CRITHAB_CanadaLynx"),0,"CRITHAB_CanadaLynx")
G. Mosaic the resulting critical habitat raster with the regional boundary. This step is necessary to ensure that the critical habitat raster extends beyond the sum of the species-level rasters to cover the entire regional boundary. Clip the mosaicked raster to the regional boundary and reclassify the results so where critical habitat for multiple species overlaps Value=5, where there is critical habitat for a single species Value=3, and where there is no critical habitat Value=0.

F.4 Create the Important Bird Areas and Key Biodiversity Areas Input

Note that in the U.S. Great Lakes region, all Key Biodiversity Areas are also designated as Important Bird Areas. Both datasets were included to account for any boundary differences and for consistency with other Regional Assessments.

A. Clip and project the feature class to the regional boundary and projection for each of the following datasets: Important Bird Areas and Key Biodiversity Areas.
B. Add new Short (16-bit integer) field "Rank" value (Rank=3) to attribute table using *Calculate Field* and rasterize.

C. Mosaic the Important Bird Areas raster, Key Biodiversity Areas raster, and the regional boundary and clip results to regional boundary.

F.5 Create the Coastal Bluffs and Dunes Input

See Appendix D.2 for a description of initial processing steps for the Coastal Bluffs and Dunes data. The rankings used for these data in the Threat Index and Terrestrial Index are different; therefore, use Geoprocessing > Reclassify may be needed to account for this difference.

A. Create a subset of the hardened shorelines line data or filter with a definition query to retain only bluff and dune classifications where Shoreline_Type_Description LIKE '%Bluff%' Or Shoreline_Type_Description LIKE '%bluff%' Or Shoreline_Type_Description LIKE '%Dune%' Or Shoreline_Type_Description LIKE '%dune%'.
B. Buffer the bluffs and dunes subset by 50 m and clip to regional boundary.
C. Process soils data.
    a. gSSURGO (vector-based data for Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York)
        i. Export state-level MUPOLYGON data to include only bluff and dune features where muname LIKE '%bluff%' Or muname LIKE '%Bluff%' Or muname LIKE '%Dune%' Or muname LIKE '%dune%' Or geomdesc LIKE '%dune%' Or geomdesc LIKE '%bluff%' Or geomdesc LIKE '%Dune%' Or geomdesc LIKE '%Bluff%'. These state-level feature classes were created for the Threat Index > Flood-Prone Areas input where soil Map unit and Components tables were joined to MUPOLYGON for each state using ArcGIS Pro Jupyter Notebook script or similar geoprocessing tools.
        ii. Merge the state-level bluffs and dunes MUPOLYGON data.
    b. gNATSGO (raster-based data for Minnesota and Wisconsin)
        i. Clip the state-level MURASTER data to the regional boundary and extract bluff and dune features from the clipped state-level MURASTER data where muname LIKE '%bluff%' Or muname LIKE '%Bluff%' Or muname LIKE '%Dune%' Or muname LIKE '%dune%' Or geomdesc LIKE '%dune%' Or geomdesc LIKE '%bluff%' Or geomdesc LIKE '%Dune%' Or geomdesc LIKE '%Bluff%'.
        ii. Convert bluffs and dunes state-level MURASTER data to polygon feature class.
    c. Merge bluffs and dunes MUPOLYGON results with bluffs and dunes MURASTER results. If needed clip results to regional boundary.
    d. Select data that intersect the bluffs and dunes hardened shoreline line data (unbuffered) using Select Layer by Location (Relationship: Intersect, Selecting Features: bluffs and dunes subset (line feature class with definition query applied), Search Distance: 100 m, Selection Type: New Selection). Export results.
D. Merge intersected soils feature class with clipped and buffered dunes and bluffs subset feature class. Dissolve.
E. Add new Short (16-bit integer) field “Rank” value (Rank=3) to attribute table using *Calculate Field* and rasterize.
F. Mosaic bluffs and dunes raster with the regional boundary and clip to regional boundary.

F.6 Calculate the Terrestrial Index

The individual inputs (Amphibians, Reptiles, Birds, and Mammals, Critical Habitat, Important Bird Areas/Key Biodiversity Areas, and Coastal Bluffs and Dunes) were combined into a single raster using the *Raster Calculator* geoprocessing tool’s addition operator. The output was reclassified into 10 classes using a quantile breaks distribution, displayed in Table F2. The Terrestrial Index was then combined with the Aquatic Index and Protected and Managed Areas for Biodiversity to create the Fish and Wildlife Index.

A. Use the *Raster Calculator’s* addition operator to add the individual terrestrial inputs into a single raster output.
B. Reclassify the clipped output into 10 classes based on quantile distribution.

Table F2. Terrestrial Index Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Terrestrial Index Break Value	0 - 5	6 - 7	8 - 9	10 - 11	12 - 13	14	15 - 16	17 - 18	19	20 - 28
Final Rank Value	1	2	3	4	5	6	7	8	9	10

G. Detailed Methodology: Aquatic Index

Data processing for each of the indices used the geoprocessing standards described in Appendix B.

G.1 Species of Conservation Concern Included in the Aquatic Index

For the purposes of the U.S. Great Lakes Assessment, species of conservation concern include species with federal-level protection status, species of greatest conservation concern as identified through State Wildlife Action Plans, and species with off-reservation harvest regulations in the 1837 and 1842 Ceded Territories in Wisconsin and Minnesota[21]. Refer to Table G1 for a complete list of aquatic species included in the Assessment.

Table G1. List of species of conservation concern included in the Aquatic Index organized by taxonomic group. Species included are species of greatest conservation concern in at least one State Wildlife Action Plan, species listed under the U.S. Endangered Species Act (denoted with asterisk), and/or other regionally important species with off-reservation harvest regulations in the 1837 and 1842 Ceded Territories in Wisconsin and Minnesota.

Aquatic Species of Conservation Concern			
Fishes			
American Brook Lamprey	*Lethenteron appendix*	Comely Shiner	*Notropis amoenus*
American Eel	*Anguilla rostrata*	Crystal Darter	*Crystallaria asprella*
Atlantic Salmon	*Salmo salar*	Cutlips Minnow	*Exoglossum maxillingua*
Banded Killifish	*Fundulus diaphanus*	Deepwater Sculpin	*Myoxocephalus thompsonii*
Bigeye Chub	*Hybopsis amblops*	Dusky Darter	*Percina sciera*
Bigeye Shiner	*Notropis boops*	Eastern Sand Darter	*Ammocrypta pellucida*
Bigmouth Buffalo	*Ictiobus cyprinellus*	Ghost Shiner	*Notropis buchanani*
Bigmouth Shiner	*Hybopsis dorsalis*	Gilt Darter	*Percina evides*
Black Buffalo	*Ictiobus niger*	Goldeye	*Hiodon alosoides*
Black Bullhead	*Ameiurus melas*	Gravel Chub	*Erimystax x-punctatus*
Black Redhorse	*Moxostoma duquesnii*	Greater Redhorse	*Moxostoma valenciennesi*
Blackchin Shiner	*Notropis heterodon*	Hornyhead Chub	*Nocomis biguttatus*
Blacknose Shiner	*Notropis heterolepis*	Iowa Darter	*Etheostoma exile*
Blackside Darter	*Percina maculata*	Ironcolor Shiner	*Notropis chalybaeus*
Bloater	*Coregonus hoyi*	Ives Lake Cisco	*Coregonus hubbsi*
Blue Sucker	*Cycleptus elongatus*	Kiyi	*Coregonus kiyi*
Bluebreast Darter	*Etheostoma camurum*	Lake Chub	*Couesius plumbeus*
Bluntnose Darter	*Etheostoma chlorosomum*	Lake Chubsucker	*Erimyzon sucetta*
Bowfin	*Amia calva*	Lake Sturgeon	*Acipenser fulvescens*
Brassy Minnow	*Hybognathus hankinsoni*	Lake Trout	*Salvelinus namaycush*
Bridle Shiner	*Notropis bifrenatus*	Lake Whitefish	*Coregonus clupeaformis*
Brindled Madtom	*Noturus miurus*	Largescale Stoneroller	*Campostoma oligolepis*
Brook Stickleback	*Culaea inconstans*	Least Brook Lamprey	*Lampetra aepyptera*
Brook Trout	*Salvelinus fontinalis*	Least Darter	*Etheostoma microperca*
Brown Bullhead	*Ameiurus nebulosus*	Longear Sunfish	*Lepomis megalotis*
Burbot	*Lota lota*	Longhead Darter	*Percina macrocephala*
Central Mudminnow	*Umbra limi*	Longnose Dace	*Rhinichthys cataractae*
Channel Darter	*Percina copelandi*	Longnose Sucker	*Catostomus catostomus*
Chestnut Lamprey	*Ichthyomyzon castaneus*	Margined Madtom	*Noturus insignis*
Cisco	*Coregonus artedi*	Mississippi Silvery Minnow	*Hybognathus nuchalis*

[21] For details see the Great Lakes Indian Fish and Wildlife Commission website: https://data.glifwc.org/regulations/.

Table G1 Continued - Aquatic Species of Conservation Concern

Fishes *(continued)*

Mooneye	*Hiodon tergisus*	Shortnose Gar	*Lepisosteus platostomus*
Mottled Sculpin	*Cottus bairdii*	Shovelnose Sturgeon	*Scaphirhynchus platorynchus*
Mountain Brook Lamprey	*Ichthyomyzon greeleyi*	Silver Chub	*Macrhybopsis storeriana*
Mountain Madtom	*Noturus eleutherus*	Silver Lamprey	*Ichthyomyzon unicuspis*
Muskellunge	*Esox masquinongy*	Silver Redhorse	*Moxostoma anisurum*
Ninespine Stickleback	*Pungitius pungitius*	Silver Shiner	*Notropis photogenis*
Northern Brook Lamprey	*Ichthyomyzon fossor*	Silverband Shiner	*Notropis shumardi*
Northern Madtom	*Noturus stigmosus*	Slender Madtom	*Noturus exilis*
Northern Redbelly Dace	*Chrosomus eos*	Smallmouth Redhorse	*Moxostoma breviceps*
Northern Pike	*Esox lucius*	Southern Brook Lamprey	*Ichthyomyzon gagei*
Ohio Lamprey	*Ichthyomyzon bdellium*	Southern Redbelly Dace	*Chrosomus erythrogaster*
Orangethroat Darter	*Etheostoma spectabile*	Spoonhead Sculpin	*Cottus ricei*
Ozark Minnow	*Notropis nubilus*	Spotted Darter	*Etheostoma maculatum*
Paddlefish	*Polyodon spathula*	Spotted Gar	*Lepisosteus oculatus*
Pallid Shiner	*Hybopsis amnis*	Spotted Sucker	*Minytrema melanops*
Pearl Dace	*Margariscus margarita*	Starhead Topminnow	*Fundulus dispar*
Pirate Perch	*Aphredoderus sayanus*	Streamline Chub	*Erimystax dissimilis*
Popeye Shiner	*Notropis ariommus*	Striped Shiner	*Luxilus chrysocephalus*
Pugnose Minnow	*Opsopoeodus emiliae*	Suckermouth Minnow	*Phenacobius mirabilis*
Pugnose Shiner	*Notropis anogenus*	Summer Sucker	*Catostomus utawana*
Pygmy Whitefish	*Prosopium coulterii*	Swallowtail Shiner	*Notropis procne*
Redfin Shiner	*Lythrurus umbratilis*	Tadpole Madtom	*Noturus gyrinus*
Redside Dace	*Clinostomus elongatus*	Tessellated Darter	*Etheostoma olmstedi*
River Chub	*Nocomis micropogon*	Tippecanoe Darter	*Etheostoma tippecanoe*
River Darter	*Percina shumardi*	Tonguetied Minnow	*Exoglossum laurae*
River Redhorse	*Moxostoma carinatum*	Trout-Perch	*Percopsis omiscomaycus*
River Shiner	*Notropis blennius*	Variegate Darter	*Etheostoma variatum*
Round Whitefish	*Prosopium cylindraceum*	Warmouth	*Lepomis gulosus*
Sauger	*Sander canadensis*	Weed Shiner	*Notropis texanus*
Scioto Madtom*	*Noturus trautmani*	Western Sand Darter	*Ammocrypta clara*
Shield Darter	*Percina peltata*	Yellow Bass	*Morone mississippiensis*
Shoal Chub	*Macrhybopsis hyostoma*	Yellow Perch	*Perca flavescens*
Shortjaw Cisco (includes Siskiwit Lake Cisco range)	*Coregonus zenithicus*		

Mollusks

Alewife Floater	*Pyganodon implicata*	Creek Heelsplitter	*Lasmigona compressa*
Black Sandshell	*Ligumia recta*	Eastern Elliptio	*Elliptio complanata*
Boreal Fossaria	*Galba galbana*	Eastern Pondmussel	*Ligumia nasuta*
Boreal Marstonia	*Marstonia lustrica*	Ebonyshell	*Fusconaia ebena*
Broadshoulder Physa	*Physella parkeri*	Elephant-ear	*Elliptio crassidens*
Brook Floater	*Alasmidonta varicosa*	Elktoe	*Alasmidonta marginata*
Brown Walker	*Pomatiopsis cincinnatiensis*	Fat Pocketbook*	*Potamilus capax*
Canadian Duskysnail	*Lyogyrus walkeri*	Flanged Valvata	*Valvata winnebagoensis*
Chittenango ambersnail*	*Novisuccinea chittenangoensis*	Flexed Gyro	*Gyraulus deflectus*
		Fragile Papershell	*Leptodea fragilis*
Clubshell*	*Pleurobema clava*	Giant Northern Peaclam	*Pisidium idahoense*
Coldwater Pondsnail	*Stagnicola woodruffi*	Globe Siltsnail	*Birgella subglobosus*

Table G1 Continued - Aquatic Species of Conservation Concern

Mollusks *(continued)*

Gravel Pyrg	*Marstonia letsoni*	River Fingernailclam	*Sphaerium fabale*
Great Lakes Physa	*Physella magnalacustris*	Rock Pocketbook	*Arcidens confragosus*
Grooved Fingernail clam	*Sphaerium simile*	Round Hickorynut	*Obovaria subrotunda*
Hickorynut	*Obovaria olivaria*	Round Peaclam	*Pisidium equilaterale*
Kidneyshell	*Ptychobranchus fasciolaris*	Round Pigtoe	*Pleurobema sintoxia*
Lake Floater	*Pyganodon lacustris*	Salamander Mussel	*Simpsonaias ambigua*
Lilliput	*Toxolasma parvum*	Scaleshell*	*Leptodea leptodon*
Long Fingernail clam	*Musculium transversum*	Sharp Sprite	*Promenetus exacuous*
Long-solid	*Fusconaia subrotunda*	Sheepnose*	*Plethobasus cyphyus*
Mapleleaf	*Quadrula quadrula*	Slender Walker	*Pomatiopsis lapidaria*
Mucket	*Ortmanniana ligamentina*	Slippershell Mussel	*Alasmidonta viridis*
Mud Amnicola	*Amnicola limosus*	Snuffbox*	*Epioblasma triquetra*
Northern Riffleshell*	*Epioblasma rangiana*	Spectaclecase*	*Margaritifera monodonta*
Pimpleback	*Cyclonaias pustulosa*	Spike	*Elliptio dilatata*
Pink Heelsplitter	*Potamilus alatus*	Spindle Lymnaea	*Acella haldemani*
Pink Mucket*	*Lampsilis abrupta*	Striated Fingernailclam	*Sphaerium striatinum*
Pink Papershell	*Potamilus ohiensis*	Three-Horn Wartyback	*Obliquaria reflexa*
Plain Pocketbook	*Lampsilis cardium*	Threeridge Valvata	*Valvata tricarinata*
Pocketbook	*Lampsilis ovata*	Triangle Floater	*Alasmidonta undulata*
Pointed Campeloma	*Campeloma decisum*	Ubiquitous Peaclam	*Pisidium casertanum*
Pond Fingernailclam	*Musculium securis*	Vernal Physa	*Physa vernalis*
Pondhorn	*Uniomerus tetralasmus*	Wabash Pigtoe	*Fusconaia flava*
Purple Lilliput	*Toxolasma lividum*	Wartyback	*Cyclonaias nodulata*
Purple Wartyback	*Cyclonaias tuberculata*	Washboard	*Megalonaias nervosa*
Purplecap Valvata	*Valvata perdepressa*	White Cat's Paw or Pearly Mussel*	*Epioblasma obliquata*
Rabbitsfoot*	*Theliderma cylindrica*		
Rayed Bean*	*Villosa fabalis*	White Heelsplitter	*Lasmigona complanata*
Ridgebeak Peaclam	*Pisidium compressum*	Yellow Lampmussel	*Lampsilis cariosa*

Crayfishes

Calico Crayfish	*Faxonius immunis*	Painted Mudbug	*Lacunicambarus polychromatus*
Devil Crawfish	*Lacunicambarus diogenes*	Prairie Crayfish	*Procambarus gracilis*
Digger Crayfish	*Creaserinus fodiens*	Sanborn Crayfish	*Faxonius sanbornii*
Little Brown Mudbug	*Lacunicambarus thomai*	Spinycheek Crayfish	*Faxonius limosus*
Northern Clearwater Crayfish	*Faxonius propinquus*	Teays River Crayfish	*Cambarus sciotensis*
Ortmann Mudbug	*Cambarus ortmanni*	Virile Crayfish	*Faxonius virilis*

Other Regionally Important Aquatic Species
(additional species not included in State Wildlife Action Plans)

Aquatic Plants			
Wild Rice	*Zizania spp.*		
Fishes		Rock Bass	*Ambloplites rupestris*
Black Crappie	*Pomoxis nigromaculatus*	Smallmouth Bass	*Micropterus dolomieu*
Bluegill	*Lepomis macrochirus*	Walleye	*Sander vitreus*
Channel Catfish	*Ictalurus punctatus*	White Bass	*Morone chrysops*
Largemouth Bass	*Micropterus salmoides*	White Crappie	*Pomoxis annularis*
Pumpkinseed	*Lepomis gibbosus*	Yellow Bullhead	*Ameiurus natalis*

G.2 Waterbody and Wetland Data Processing

Prepare Waterbody Data

NHD Classification by Feature Type and Size

Waterbody data were identified from the USGS National Hydrography Dataset Plus High Resolution (NHDPlus HR) NHD Waterbody (polygon), NHD Area (polygon), and NHD Flowline (line) features. Lake size classifications were based on The Nature Conservancy's Northeast Aquatic Habitat Classification System[22] and river size classifications were based on The Nature Conservancy's Aquatic Habitat Guides[23]. Features were removed from each of the NHD feature classes where applicable. These included:

- Remove features classified as pipeline, underground conduit, or canal/ditch. After merging the VPUID-level feature classes into a single region-level feature class (where VPUID is the identifier of each vector-processing unit) in the region), apply a definition query in the layer properties before continuing or export features with a filter applied Where FTYPE <> 428 (pipeline) AND FTYPE <> 420 (underground conduit) AND FTYPE <> 336 (canal/ditch).
- Remove Unclassified Local Resolution NHD features. State-level local resolution data from Indiana embedded in the High Resolution NHD Flowline data created disparities in the regional resolution of the data and distorted the Fish and Wildlife Index results along state boundaries. To correct for this issue, Indiana Geographic Information Council (IGIC) Unclassified Drainage Flowlines (https://www.arcgis.com/home/item.html?id=24e32be43ac54377b02e40cfdf5846f0) were erased from the NHD Flowlines.

A. NHD Waterbody. Note, this dataset contains river impoundments/reservoirs with a predominantly natural shoreline as opposed to an artificial basin. NHD Flowlines coded as reservoirs were not included as they were predominantly artificial basins.
   a. Import all USGS National Hydrography Dataset Plus High Resolution features for the region and merge (this step was described in Appendix E.4 - Bridges).
      i. Import NHDWaterbody hydrography features for each for each VPUID in the region (NHDPlus_H__GDB.gdb file geodatabase, where VPUID is the identifier of each vector-processing unit).
      ii. Merge VPUID-level feature classes into a single region-level feature class (Output Dataset: *GL_NHDWaterbody_Merge*).
      iii. Apply a definition query in the layer properties before continuing or export features with a filter applied Where FTYPE <> 428 (pipeline) AND FTYPE <> 420 (underground conduit) AND FTYPE <> 336 (canal/ditch).
   b. Clip merged NHD Waterbody features to the regional boundary (Output Feature Class: *GL_NHDWaterbody_Merge_Clip*).
   c. Classify merged and clipped NHD Waterbody features by size using *Export Features* where: Pond: AreaSqKm < 0.0404686 And FType = 390, Small lake: AreaSqKm >= 0.0404686 And AreaSqKm < 0.400639 And FType = 390, Medium lake: AreaSqKm >= 0.400639 And AreaSqKm < 4.04281 And FType = 390, Large lake: AreaSqKm >= 4.04281 And AreaSqKm < 40.46452 And FType = 390, Very large lake: AreaSqKm >= 40.46452 And FType = 390 *(Note, for very large lakes, any Great Lakes features missing because of NULL area attribution were manually appended;* Output Feature Class: *NHD_VeryLargeLakes*).
   d. Process classified NHD Waterbody features in preparation for combining with NHD Area lake features *(note that geoprocessing will continue for this output, prior to rasterizing, after lacustrine NHD Area features are classified by size)*. For each size class, add new Short (16-bit integer) field "Rank" value (Rank = 0) using *Calculate Field*. Rank = 0 was selected for raster calculator processing later when waterbodies/watersheds combine with species distribution rasters. Rasterize results (Value Field: Rank, Priority Field: Shape_Area *(note that this field was used because rank values of 0 cannot be used to assign priority. If rank 0 is used, not all features will be converted to*

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[22] The Nature Conservancy Northeast Aquatic Habitat Classification System (2008): https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/reportsdata/freshwater/habitat/Pages/Northeast-Stream-Classification.aspx.

[23] The Nature Conservancy Aquatic Habitat Guides: http://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/reportsdata/hg/fw/Pages/default.aspx.

raster where there is overlap and the output will be incomplete; Output Raster Dataset: *NHD_VeryLargeLakes_Raster – Key geoprocessing output: This output used to calculate NHD Area zonal statistics used for feature classification below).*

B. NHD Flowline

a. Export all USGS National Hydrography Dataset Plus High Resolution Flowline feature geometries to a single file geodatabase for the region, merge into a single region-level feature class, and clip to regional boundary.

i. Export VPUID-level (NHDPlus_H__GDB.gdb file geodatabase, where VPUID is the identifier of each vector-processing unit) NHD Flowline features to single .gdb. This step is necessary to preserve field types, attribution, etc. consistent with geodatabase tables for later joins.

1. Geoprocessing > Export Features
   I. Input Features: VPUID-level NHDFlowline hydrography feature class
   II. Output Feature Class: *GL_NHDFlowline.gdb\T0104,* T0107, etc… (*for the Great Lakes project area there were 69 NHDPLUS_H_…._HU4_GDB.gdb regions downloaded)*

ii. Merge exported VPUID-level NHD Flowline features into a single region-level feature class and clip to regional boundary.

1. Geoprocessing > Merge
   I. Input Datasets: GL_NHDFlowline.gdb\T0104, T0107, etc… (*for U.S. Great Lakes Assessment there were 69 NHDPLUS_H_…._HU4_GDB.gdb regions downloaded)*
   II. Output Dataset: *NHDFlowline_Merge*
   III. Apply a definition query in the layer properties before continuing or export features with a filter applied Where FTYPE <> 428 (pipeline) AND FTYPE <> 420 (underground conduit) AND FTYPE <> 336 (canal/ditch).
2. Geoprocessing > Pairwise Clip
   I. Input Features: *GL_NHDFlowline_Merge*
   II. Output Feature Class: *GL_NHDFlowline_Merge_Clip*

b. Merge VPUID-level value-added attribute table (NHDPlusFlowlineVAA table in the NHDPlus_H__GDB.gdb file geodatabase) into a single region-level table and join to clipped region-level NHD Flowline feature class. Export to preserve join outside of memory. The attribute field of interest in this table is TotDASqKm (TotalDrainageAreaSqKm), which will be used to classify rivers by size.

i. NHDPlusFlowlineVAA

1. Geoprocessing > Table to Geodatabase *(note that this is favorable to a merge because the geodatabase properties such as field type are maintained for later merge and data joins)*
   I. Input Table: *NHDPLUS_H_0104_HU4_GDB.gdb\NHDPlusFlowlineVAA, NHDPLUS_H_0107_HU4_GDB.gdb\NHDPlusFlowlineVAA, etc… (For Great Lakes project area there were 69 NHDPLUS_H_…._HU4_GDB.gdb regions downloaded; note that the analysis used an extended regional boundary in its initial iteration that was later clipped to the regional boundary; Data were processed in subgroups of ~10 for more efficient processing and QAQC)*
   II. Output Geodatabase: *GL_NHDPlusFlowlineVAA.gdb*
2. Geoprocessing > Merge
   I. Input Datasets: *NHDPlusFlowlineVAA, NHDPlusFlowlineVAA_1, NHDPlusFlowlineVAA_2, …NHDPlusFlowlineVAA_68*
   II. Output Dataset: *NHDPlusFlowlineVAA_Merge*
3. *Geoprocessing > Add Join*
   I. Input Table: *NHDFlowline_Merge_Clip_JoinQAMA*
   II. Input Join Field: NHDPlusID
   III. Join Table: *NHDPlusFlowlineVAA_Merge*
   IV. Join Table Field: NHDPlusID
4. Geoprocessing > Export Features
   I. Input Features: *NHDFlowline_Merge_Clip*
   II. Output Name: *NHDFlowline_Merge_Clip_JoinVAA*

c. Classify river features by size. Repeat for each of the river size classes (headwater/creek, small river, medium river, large river).

i. Geoprocessing > Export Features
    1. Input Features: *NHDFlowline_Merge_Clip_JoinVAA*
    2. Output Feature Class: *NHD_LargeRivers*
    3. Filter Expression: Select the expression to match the output feature class.
        I. Headwater/Creek: TotDASqKm < 101
        II. Small river: TotDASqKm >= 101 And TotDASqKm < 518
        III. Medium river: TotDASqKm >= 518 And TotDASqKm < 2590
        IV. Large river: TotDASqKm >= 2590

d. Process classified NHD Flowline features in preparation for combining with NHD Area river features. For each size class, erase waterbody features and inverse select features where the boundary touches a waterbody feature. Dissolve results, calculate rank field (rank value = 0 was selected for raster calculator processing later when waterbodies/watersheds combine with species distribution rasters), buffer, and rasterize.
    i. Geoprocessing > Pairwise Erase *(This geoprocessing step removes any features that directly intersect with a waterbody. Most lake features are represented by NHD Waterbody features so these would be redundant and interfere with classifying NHD Area features by type and size.)*
        1. Input Features: *NHD_LargeRivers*
        2. Erase Features: *GL_NHDWaterbody_Merge_Clip (created in NHD Waterbody classification geoprocessing above)*
        3. Output Feature Class: *NHD_LargeRivers_Erase*
    ii. Geoprocessing > Select Layer By Location *(This geoprocessing step removes any features that directly touch a waterbody. Many of these represent shorelines or waterbodies themselves and interfere with classifying NHD Area features by type and size. Where true connecting features erased inadvertently will be corrected later in the workflow for NHD Flowline Remainder. Note that the selection methods differ based on input size class.)*
        1. Input Features: *NHD_LargeRivers_Erase*
        2. Relationship: Boundary touches
        3. Selecting Features:
            I. For large rivers: GL_NHDWaterbody_Merge_Clip (created in NHD Waterbody classification geoprocessing above)
            II. For small and medium rivers: select by location twice (the first time using a new selection where the selecting features are NHD_VeryLargeLakes and the next using Add to the current selection where the selecting features are NHD_LargeLakes to prevent deleting large segments of river that are not artifacts)
            III. For headwaters/creeks: selection not applied to headwaters and creeks to prevent deleting segments that are not artifacts.
        4. Selection Type: New selection
        5. Invert Spatial Relationship = checked
    iii. Geoprocessing > Export Features
        1. Input Features: NHD_LargeRivers_Erase (with selection applied)
        2. Output Feature Class: NHD_LargeRivers_Erase_Select
    iv. Geoprocessing > Pairwise Dissolve
        1. Input Features: NHD_LargeRivers_Erase_Select
        2. Output Feature Class: NHD_LargeRivers_Erase_Select_Dissolve
        3. Create multipart features = checked
    v. Geoprocessing > Calculate Field
        1. Input Table: NHD_LargeRivers_Erase_Select_Dissolve
        2. Field Name: Rank
        3. Field Type: Short (16-bit integer)
        4. Expression: Rank = 0
    vi. Geoprocessing > Pairwise Buffer
        1. Input Features: NHD_LargeRivers_Erase_Select_Dissolve
        2. Output Feature Class: NHD_LargeRivers_Erase_Select_Dissolve_Buffer *(Note,geoprocessing will continue for this output, prior to rasterizing, after NHD Area river classification by size.)*

3. Distance: 1 m

vii. Geoprocessing > Polygon to Raster

1. Input Features: NHD_LargeRivers_Erase_Select_Dissolve_Buffer
2. Value Field: Rank
3. Output Raster Dataset: NHD_LargeRivers_Erase_Select_Dissolve_Buffer_Raster ***(Key geoprocessing output: This output used to calculate NHD Area zonal statistics used for feature classification below.)***
4. Priority Field: BUFF_DIST (Note, this field was used because it is the same across all features (buffer = 1 m) and rank values of 0 cannot be used to assign priority. If rank 0 is used, not all features will be converted to raster where they overlap and the output will be incomplete.)

C. NHD Area

a. Import all USGS National Hydrography Dataset Plus High Resolution features for the region and merge (this step was performed in Asset Index > Critical Infrastructure > Bridges above).

i. Import NHDArea hydrography features for each VPUID in the region (NHDPlus_H__GDB.gdb file geodatabase, where VPUID is the identifier of each vector-processing unit).

ii. Merge VPUID-level feature classes into a single region-level feature class.

1. Geoprocessing > Merge
   - I. Input Datasets: NHDArea feature classes for each VPUID in region
   - II. Output Dataset: GL_NHDArea_Merge

iii. Apply a definition query in the layer properties before continuing or export features with a filter applied Where FTYPE <> 428 (pipeline) AND FTYPE <> 420 (underground conduit) AND FTYPE <> 336 (canal/ditch).

b. Clip merged NHD Area features to the regional boundary.

i. Geoprocessing > Pairwise Clip

1. Input Features: GL_NHDArea_Merge
2. Output Feature Class: GL_NHDArea_Merge_Clip

c. Classify clipped NHD Area features by waterbody type (river or lake) and size.

i. Calculate zonal statistics for NHD Area features for each of the river and lakes rasters by size class (headwaters/creeks raster, small rivers raster, etc.). Use COUNT summary statistic to calculate a new field attributed by waterbody and size class (e.g., large rivers).

1. Geoprocessing > Zonal Statistics as Table
   - I. Input Raster or Feature Zone Data: GL_NHDArea_Merge_Clip
   - II. Zone Field: Permanent_Identifier
   - III. Input Value Raster: NHD_LargeRivers_Erase_Select_Dissolve_Buffer_Raster *(output created in NHD Classification > NHD Waterbody and NHD Flowline geoprocessing above)*
   - IV. Output Table: NHDArea_Zonal_LargeRivers
   - V. Statistics Type: All
2. Geoprocessing > Calculate Field
   - I. Input Table: NHDArea_Zonal_LargeRivers
   - II. Field Name: LargeRivers
   - III. Expression: !COUNT!

ii. Using a series of joins, join the zonal statistics output tables to the clipped NHD Area feature class. Exportresults to a new feature class to preserve the joins outside of memory. Export the results as a .csv file to continue data processing in R or similar data processing software.

1. Geoprocessing > Add Join
   - I. Input Table: GL_NHDArea_Merge_Clip
   - II. Input Join Field: Permanent_Identifier
   - III. Join Table: NHDArea_Zonal_LargeRivers
   - IV. Join Table Field:Permanent_Identifier
   - V. Keep All Target Features = checked
2. Geoprocessing > Export Features
   - I. Input Features: GL_NHDArea_Merge_Clip *(with joins)*

II. Output Feature Class: GL_NHDArea_Merge_Clip_JoinZonal
III. Fields > Field Map > Output Fields > Remove all joined fields except calculated fields (e.g., LargeRivers)
3. Geoprocessing > Export Table
I. Input Table: GL_NHDArea_Merge_Clip_JoinZonal
II. Output Table: GL_NHDArea_Merge_Clip_JoinZonal.csv

iii. Classify NHD Area polygons using intersection of classified NHD Flowlines where a polygon is attributed based on the classification of the sum of merged NHD Area and NHD flowline maximum area.
1. Using R or similar data processing software:

```
library(dplyr)
library(tidyr)

nhdArea <- read.csv("...GL_NHDArea_Merge_Clip_JoinZonal.csv", stringsAsFactor=F)
df <- nhdArea

df <- nhdArea %>% mutate(
VeryLargeLakes = ifelse(is.na(VeryLargeLakes), 0, VeryLargeLakes),
LargeLakes = ifelse(is.na(LargeLakes), 0, LargeLakes),
MediumLakes = ifelse(is.na(MediumLakes), 0, MediumLakes),
SmallLakes = ifelse(is.na(SmallLakes), 0, SmallLakes),
Ponds = ifelse(is.na(Ponds), 0, Ponds),
LargeRivers = ifelse(is.na(LargeRivers), 0, LargeRivers),
MediumRivers = ifelse(is.na(MediumRivers), 0, MediumRivers ),
SmallRivers = ifelse(is.na(SmallRivers), 0, SmallRivers),
HW_Creeks = ifelse(is.na(HW_Creeks), 0, HW_Creeks))

f <- function(x){ifelse(rowSums(x)==0, NA, names(x)[max.col(x, "first")])}
MaxArea <- df %>% mutate(MaxArea = f(across(VeryLargeLakes:HW_Creeks)))

write.csv(MaxArea, "...GL_NHDArea_Merge_Clip_JoinZonal_MaxArea.csv",
row.names=FALSE)
```

iv. Join summarized data to NHD Area layer and export results.
1. Geoprocessing > Add Join
I. Input Table: GL_NHDArea_Merge_Clip_JoinZonal
II. Input Join Field: NHDPlusID
III. Join Table: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea.csv
IV. Join Table FIeld: NHDPlusID
2. Geoprocessing > Export Features
I. Input Features: GL_NHDArea_Merge_Clip_JoinZonal
II. Output Feature Class: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea

v. Erase merged NHD Waterbody from resulting NHD Area layer (this will eliminate features that overlap with lakes that have already been defined in the NHD Waterbody features).
1. Geoprocessing > Pairwise Erase
I. Input Features: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea
II. Erase Features: GL_NHDWaterbody_Merge_Clip
III. Output Feature Class: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase

vi. Calculate the difference between area classification to determine if there are categories that are close in value and require manual inspection. There are numerous large rivers (e.g., St Marys River) with many tributaries extending into the polygon’s center (the center line is used to demarcate an NHD Line feature). Where needed, manually edit the Classification field.
1. Geoprocessing > Calculate Field (repeat for each of the following):
I. LR-MR: !LargeRivers! - !MediumRivers!
II. LR-SR: !LargeRivers! - !SmallRivers!
III. LR-HW: !LargeRivers! - !HW_Creeks!
IV. LR-R: !LargeRivers! - (!MediumRivers! + !SmallRivers! + !HW_Creeks!)

V. Classification = !MaxArea! (This new field “Classification” will be edited as needed preserving the calculated MaxArea field where they are not identical.)
VI. Rank = 0

2. Manually edit feature classification as needed using the Classification field, including using “Remove” if features should not be added to the resulting waterbody layers.
    I. Features were omitted from the manual classification process using a definition query where FType <> 403 (inundation area) And FType <> 343 (dam/weir). Note that these feature types were included in NHD Flowlines and NHD Area where joins were automated. The results will be merged with NHD Flowline (rivers) and NHD Waterbody (lakes) feature classes by size classification.
    II. Great Lakes system rivers were manually attributed as needed (St. Marys River, St. Clair River, Detroit River, Niagara River, St. Lawrence River).
    III. Remove slivers of lakes where:
        i. Shape_Area < 900 And MaxArea LIKE '%Lakes'
        ii. Shape_Area < 900 And MaxArea NOT LIKE '%Lakes' And FType = 460
    IV. Manually attribute MaxArea <> 'LargeRivers' And (LR_MR <= 0 Or LR_SR <= 0 Or LR_HW <= 0). Rivers that have multiple features within their zonal polygon are generally largest river classification or adjacent to a known feature classification.
    V. Classification = 'NA' where Shape_Area <10,000m2 or GNIS_Name is not NULL.
    VI. Manually attribute any dams, lock chambers, bridges, etc. where there are discrepancies between adjacent features.

NHD Processing - Lakes

Lakes are represented as the merging of NHD Waterbody and NHD Area features classified as lacustrine. The following provides a demonstration for very large lakes. Repeat geoprocessing for each category of lake including pond, small lake, medium lake, large lake, very large lake. Note that for some categories there were no NHD Area features classified.

D. Combine NHD Waterbody and lacustrine NHD Area features and rasterize.
    a. Geoprocessing > Merge
        i. Input Datasets:
            1. NHD_VeryLargeLakes (feature class output from NHD Waterbody classification geoprocessing described above)
            2. GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase *(output created in NHD Classification > NHD Area geoprocessing above)*
                I. Where Geoprocessing > Select Layer by Attributes > Classification = 'VeryLargeLakes'
        ii. Output Dataset: NHD_VeryLargeLakes_MergeNHDArea
    b. Geoprocessing > Polygon to Raster
        i. Input Features: NHD_VeryLargeLakes_MergeNHDArea
        ii. Value Field: Rank
        iii. Output Raster Dataset: *NHD_VeryLargeLakes_MergeNHDArea_Raster* **(*Key geoprocessing output: This output will be combined with species distribution rasters.)***
        iv. Priority Field: Shape_Area (Note,this field was used because rank values of 0 cannot be used to assign priority. If rank 0 is used, not all features will be converted to raster where there is overlap and the output will be incomplete.)

NHD Processing - Rivers

Rivers are represented as the merging of NHD Flowline and NHD Area features classified as riverine. Below is a demonstration for large rivers, except where it was necessary to show methods based on size class. Repeat geoprocessing for each category of river including headwater/creek, small river, medium river, large river. Note that for some categories there were no NHD Area features classified.

E. NHD Area (riverine classifications)**:** For each river size classification, dissolve NHD Area features and perform a cascading series of erases that will ensure that if a feature has disparate classifications that the largest feature type is prioritized. This step ensures pixels are consistently attributed across feature types (artifacts may remain in dataset where NHDFlowline is outside of NHDArea for a river segment, but overall, this method will resolve most issues of NHDFlowline and NHDArea discrepancy). Rasterize the outputs so there is an NHD Area raster for each size class that will be mosaicked with NHD Flowline outputs later in the geoprocessing workflow.

a. Geoprocessing > Pairwise Dissolve
    i. Input Features: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase *(output created in NHD Classification > NHD Area geoprocessing above)*
        1. Where Geoprocessing > Select Layer by Attributes > Classification = 'LargeRivers'
    ii. Output Feature Class: GL_NHDArea_LargeRivers_Dissolve
    iii. Dissolve Fields: Classification
    iv. Statistics Fields:
        1. Field: Rank
        2. Statistic Type: Mean
    v. Create Multipart Features: selected
b. Geoprocessing > Pairwise Erase (This cascading series of erasing will ensure that if a feature has disparate classifications that the largest feature type is prioritized; repeat the geoprocessing starting with headwaters/creeks and ending with large rivers.)
    i. Headwaters/Creeks
        1. Erase NHD Area lakes and rivers larger than headwaters/creeks.
            I. Input Features: GL_NHDArea_HW_Creeks_Dissolve
            II. Erase Features: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase
                i. Where Geoprocessing > Select Layer by Attributes > Classification = 'VeryLargeLakes' Or Classification = 'LargeLakes' Or Classification = 'SmallLakes' Or Classification = 'LargeRivers' Or Classification = 'MediumRivers' Or Classification = 'SmallRivers' (note that no ponds or medium lakes were classified in the NHD Area for this this region)
            III. Output Feature Class: GL_NHDArea_HW_Creeks_Dissolve_Erase
    ii. Small Rivers
        1. Erase NHD Area lakes and rivers larger than small rivers.
            I. Input Features: GL_NHDArea_SmallRivers_Dissolve
            II. Erase Features: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase
                i. Where Geoprocessing > Select Layer by Attributes > Classification = 'VeryLargeLakes' Or Classification = 'LargeLakes' Or Classification = 'SmallLakes' Or Classification = 'LargeRivers' Or Classification = 'MediumRivers'
            III. Output Feature Class: GL_NHDArea_MediumRivers_Dissolve_Erase
        2. Erase NHD Area headwaters/creeks
            I. Input Features: GL_NHDArea_SmallRivers_Dissolve_Erase
            II. Erase Features: GL_NHDArea_HW_Creeks_Dissolve_Erase
            III. Output Feature Class: GL_NHDArea_SmallRivers_Dissolve_Erase
    iii. Medium Rivers
        1. Erase NHD Area lakes and rivers larger than medium rivers.
            I. Input Features: GL_NHDArea_MediumRivers_Dissolve
            II. Erase Features: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase
                i. Where Geoprocessing > Select Layer by Attributes > Classification = 'VeryLargeLakes' Or Classification = 'LargeLakes' Or Classification = 'SmallLakes' Or Classification = 'LargeRivers'
            III. Output Feature Class: GL_NHDArea_MediumRivers_Dissolve_Erase
        2. Erase NHD Area headwaters/creeks.
            I. Input Features: GL_NHDArea_MediumRivers_Dissolve_Erase
            II. Erase Features: GL_NHDArea_HW_Creeks_Dissolve_Erase
            III. Output Feature Class: GL_NHDArea_MediumRivers_Dissolve_Erase_Erase
        3. Erase NHD Area small rivers.
            I. Input Features: GL_NHDArea_MediumRivers_Dissolve_Erase_Erase
            II. Erase Features: GL_NHDArea_SmallRivers_Dissolve_Erase_Erase

III. Output Feature Class: GL_NHDArea_MediumRivers_Dissolve_Erase_Erase_Erase

iv. Large Rivers
1. Erase NHD Area lakes.
I. Input Features: GL_NHDArea_LargeRivers_Dissolve
II. Erase Features: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase
i. Where Geoprocessing > Select Layer by Attributes > Expression: Classification = 'VeryLargeLakes' Or Classification = 'LargeLakes' Or Classification = 'SmallLakes'
III. Output Feature Class: GL_NHDArea_LargeRivers_Dissolve_Erase
2. Erase NHD Area headwaters/creeks.
I. Input Features: GL_NHDArea_LargeRivers_Dissolve_Erase
II. Erase Features: GL_NHDArea_HW_Creeks_Dissolve_Erase
III. Output Feature Class: GL_NHDArea_LargeRivers_Dissolve_Erase_Erase
3. Erase NHD Area small rivers.
I. Input Features: GL_NHDArea_LargeRivers_Dissolve_Erase_Erase
II. Erase Features: GL_NHDArea_SmallRivers_Dissolve_Erase_Erase
III. Output Feature Class: GL_NHDArea_LargeRivers_Dissolve_Erase_Erase_Erase
4. Erase NHD Area medium rivers.
I. Input Features: GL_NHDArea_LargeRivers_Dissolve_Erase_Erase_Erase
II. Erase Features: GL_NHDArea_MediumRivers_Dissolve_Erase_Erase_Erase
III. Output Feature Class: GL_NHDArea_LargeRivers_Dissolve_Erase_Erase_Erase_Erase

c. Geoprocessing > Polygon to Raster
i. Input Features: GL_NHDArea_LargeRivers_Dissolve_Erase_Erase_Erase_Erase
ii. Value Field: MEAN_Rank (input with Rank had been dissolved for faster geoprocessing earlier; alternatively add new field Rank)
iii. Output Raster Dataset: GL_NHDArea_LargeRivers_Dissolve_Raster ***(Key geoprocessing output: This output will be mosaicked with NHD Flowline output below to create a mosaicked raster for each size class of river.)***
iv. Priority Field: NONE

F. NHD Flowline: For each river size classification, erase classified NHD Area features for all other size classes to ensure that NHD Area is prioritized where available over NHD Flowline features and to prevent disparate classified features from overlapping. Rasterize the outputs so there is an NHD Flowline raster for each size class that will be mosaicked with NHD Area outputs later in the geoprocessing workflow.

a. Geoprocessing > Pairwise Erase
i. Input Features: NHD_LargeRivers_Erase_Select_Dissolve_Buffer *(Output created in NHD Classification > NHD Flowline geoprocessing above.)*
ii. Erase Features: GL_NHDArea_Merge_Clip_JoinZonal_MaxArea_Erase
1. Where Geoprocessing > Select Layer by Attributes > Expression *(All lake and river classifications except Large Rivers. Note that for some categories there were no NHD Area features classified)*:
'VeryLargeLakes' Or Classification = 'LargeLakes' Or Classification = 'SmallLakes' Or Classification = 'MediumRivers' Or Classification = 'SmallRivers' Or Classification = 'HW_Creeks'
iii. Output Feature Class: NHD_LargeRivers_Erase_Select_Dissolve_Buffer_Erase

b. Geoprocessing > Calculate Field
i. Input Table: NHD_LargeRivers_Erase_Select_Dissolve_Buffer_Erase
ii. Field Name: Rank
iii. Field Type: Short (16-bit integer)
iv. Expression: Rank = 0

c. Geoprocessing > Polygon to Raster
i. Input Features: NHD_LargeRivers_Erase_Select_Dissolve_Buffer_Erase
ii. Value Field: Rank

iii. Output Raster Dataset: NHD_LargeRivers_Erase_Select_Dissolve_Buffer_Erase_Raster ***(Key geoprocessing output: This output will be mosaicked with NHD Area output below to create a mosaicked raster for each size class of river.)***

iv. Priority Field: BUFF_DIST (Note, this field was used because it is the same across all features (buffer = 1 m) and rank values of 0 cannot be used to assign priority. If rank 0 is used, not all features will be converted to raster where there is overlap and the output will be incomplete.)

G. Combine NHD Area and NHD Flowline for each size classification.

a. Geoprocessing > Mosaic to New Raster

i. Input Rasters:

1. *GL_NHDArea_LargeRivers_Dissolve_Raster (outputs created in NHD Processing - Rivers > NHD Area geoprocessing above)*
2. *NHD_LargeRivers_Erase_Select_Dissolve_Buffer_Erase_Raster (outputs created in NHD Processing - Rivers > NHD Flowline geoprocessing above)*

ii. Raster Dataset Name with Extension: *Mosiac_LargeRivers* ***(Key geoprocessing output: This output will be mosaicked with NHD Flowline Remainder output below to create a mosaicked raster for each size class of river)***

H. Correct for NHD Flowline Remainder: Correct for flowlines previously eliminated because they were classified as shorelines or directly touched waterbody features; these remainders are often connections between lakes and rivers, or between lakes. These features were eliminated to better classify NHD Area features by size. A series of erases were applied to the NHD Flowline features (first the NHD Flowlines already processed above, then by buffered NHD Area derived rivers and all lakes). This prevented shorelines and waterbodies identified from NHD Waterbody and NHD Area features from re-entering the data but keeps connectors greater than 1 pixel (30 m regional resolution). The output for each river size class is then rasterized to create an NHD Flowline Remainder raster that can be combined with the mosaicked NHD Area/NHD Flowline rasters. Note that NHD Flowline remainder methods were not applied to headwater/creek.

a. Geoprocessing > Pairwise Erase

i. Input Features: NHD_LargeRivers_Erase *(output created in NHD Classification > NHD Flowline geoprocessing above)*

ii. Erase Features: NHD_LargeRivers_Erase_Select_Dissolve *(output created in NHD Classification > NHD Flowline geoprocessing above)*

iii. Output Feature Class: NHD_LargeRivers_Erase_Remainder

b. Geoprocessing > Pairwise Buffer

i. Input Features: Repeat geoprocessing for both merged NHD Area for all river categories (GL_NHDArea_Rivers_Merge) and merged lake polygons (NHD_Lakes_Merge)

ii. Output Feature Class: 1) GL_NHDArea_Rivers_Merge_Buffer30m and 2) NHD_Lakes_Merge_Buffer30m

iii. Distance: 30 m

c. Geoprocessing > Pairwise Erase

i. Erase merged buffered lakes.

1. Input Features: NHD_LargeRivers_Erase_Remainder
2. Erase Features: NHD_Lakes_Merge_Buffer30m
3. Output Feature Class: NHD_LargeRivers_Erase_Remainder_EraseLakes

ii. Erase merged buffered river areas.

1. Input Features: NHD_LargeRivers_Erase_Remainder_EraseLakes
2. Erase Features: GL_NHDArea_Rivers_Merge_Buffer30m
3. Output Feature Class: *NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea*

d. Geoprocessing > Pairwise Dissolve

i. Input Features: NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea

ii. Output Feature Class: NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea_Dissolve

iii. Create Multipart Features: Selected

e. Geoprocessing > Pairwise Buffer

i. Input Features: NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea_Dissolve

ii. Output Feature Class: NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea_Dissolve_Buffer1m

            iii. Distance: 1 m
    f. Geoprocessing > Calculate Field ()
        i. Input Table: NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea_Dissolve_Buffer1m
        ii. Field Name: Rank
        iii. Field Type: Short (16-bit integer)
        iv. Expression: Rank = 0
    g. Geoprocessing > Polygon to Raster
        i. Input Features: NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea_Dissolve_Buffer1m
        ii. Value Field: Rank
        iii. Output Raster Dataset: NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea_Dissolve_Buffer1m_Raster ***(Key geoprocessing output: This output will be mosaicked with NHD Area/NHD Flowline mosaic below to create a mosaicked raster for each size class of river.)***
        iv. Priority Field: Shape_Area (Note, this field was used because rank values of 0 cannot be used to assign priority. If rank 0 is used, not all features will be converted to raster where there is overlap and the output will be incomplete.)

I. Combine Mosaiced NHD Area/NHD Flowline with processed NHD Flowline Remainder
    a. Geoprocessing > Mosaic to New Raster
        i. Input Rasters:
            1. Mosiac_LargeRivers *(output created in NHD Processing - Rivers >* Combine NHD Area and NHD Flowline *geoprocessing above)*
            2. NHD_LargeRivers_Erase_Remainder_EraseLakes_EraseNHDArea_Dissolve_Buffer1m_Ras*ter (output created in NHD Processing - Rivers > Correct for NHD Flowline Remainder geoprocessing above)*
        ii. Raster Dataset Name with Extension: Mosiac_LargeRivers_Remainder ***(Key geoprocessing output: This output will be combined with species distribution rasters.)***

Prepare Wetland Data

Wetland data were identified from the U.S. Fish and Wildlife Service (FWS) National Wetlands Inventory features and classified by type: emergent, scrub/shrub, and forested wetlands.

J. Clip state-level National Wetlands Inventory (NWI) feature class to the regional boundary for each state using *Batch Pairwise Clip*.
K. Export each clipped state-level NWI feature class to only include palustrine features where WETLAND_TYPE <> 'Lake' And WETLAND_TYPE <> 'Riverine' And WETLAND_TYPE <> 'Freshwater Pond'.
L. Merge filtered state-level feature classes into a single regional-level feature class.
M. Join NWI Code Definitions table to region-level NWI feature class to expand ATTRIBUTE field classifications. Export features to permanently keep joined fields in feature class rather than in memory.
N. For each classification, subset NWI features into emergent, scrub/shrub, and forested wetlands classifications using Select Layer by Attribute where Emergent: CLASS_NAME = 'Emergent' Or (WETLAND_TYPE = 'Freshwater Emergent Wetland' And CLASS_NAME IS NULL), Scrub/Shrub: CLASS_NAME = 'Scrub-Shrub' Or (WETLAND_TYPE = 'Freshwater Forested/Shrub Wetland' And CLASS_NAME IS NULL), Forested: CLASS_NAME = 'Forested' Or (WETLAND_TYPE = 'Freshwater Forested/Shrub Wetland' And CLASS_NAME IS NULL). Export selected features and dissolve (if needed to reduce feature size, Dissolve Fields: ATTRIBUTE). Add new Short (16-bit integer) field "Rank" value (Rank = 0) and rasterize (Value Field: Rank, Priority Field: Shape_Area (cannot be Rank because Rank = 0 and not all features will be processed). ***Key geoprocessing output: This output will be combined with species distribution rasters***.

G.3 Create the Aquatic Species Distribution Input

For each species, descriptive habitat data were assigned to waterbody/wetland classification categories and used to filter the NHD waterbody and NWI wetland features. These were combined with watershed-level species distributions to create a species-habitat distribution raster for each species of conservation concern (Table G1) showing where distribution overlapped with suitable waterbody/wetland features (Figure G1). Within each taxonomic group, all species-habitat distribution rasters were added and classified based on the quantile distribution of data within the region.

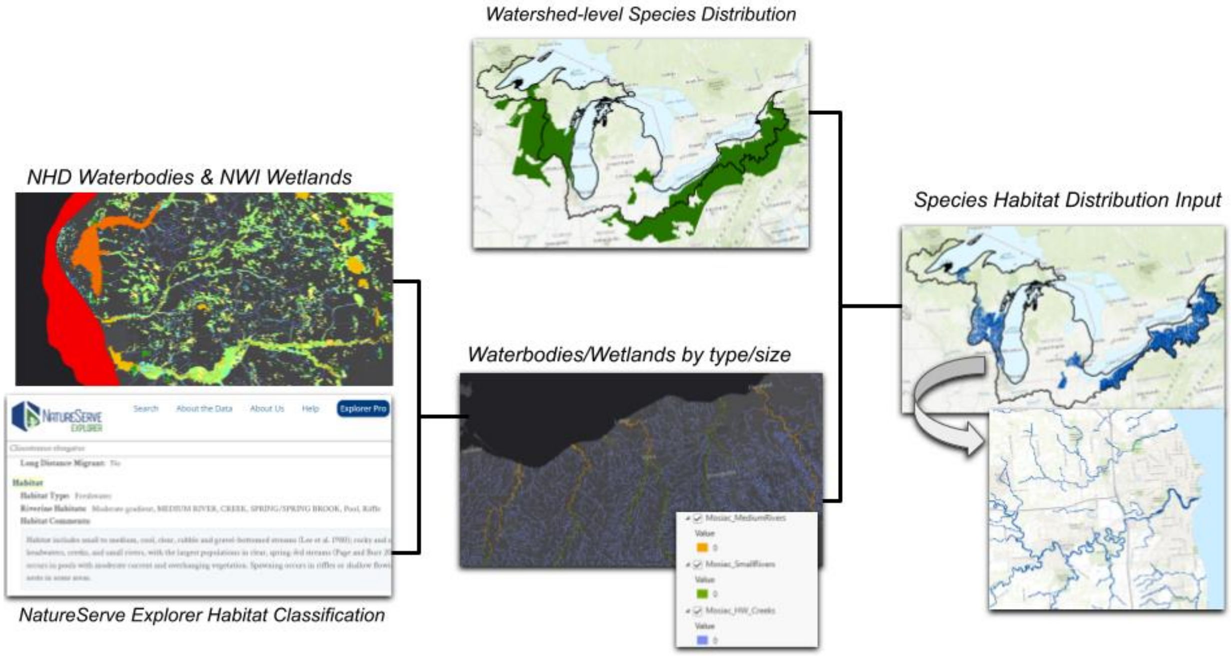

Figure G1. Diagram of data inputs used to create a species-habitat distribution raster for each species of conservation concern.

Habitat Classification for Each Species of Conservation Concern

A. For each species of conservation concern (Table H1), descriptive habitat data were collected from NatureServe Explorer[24] (Ecology and Life History > Habitat), State Wildlife Action Plans, and IUCN Red List[25] (Habitat and Ecology). Habitat data were assigned to waterbody/wetland classification categories, crosswalking where necessary between sources and between states. When habitat data were not as specific as the size/type categories, classification was broad and included all subcategories (ponds and very large lakes were not included with all lakes unless specifically mentioned in habitat comments or size classification). Categories included the following (waterbody/wetland processing methods described in detail above):
   a. Rivers: headwater/creek, small river, medium river, large river
   b. Lakes/Ponds: pond, small lake, medium lake, large lake, very large lake
   c. Wetlands: emergent, scrub/shrub, and forested

Combine Species Distribution Data with Habitat Classification to Create Predicted Habitat Models for Each Species of Conservation Concern

Watershed-level distribution data for fish, mollusks, and crayfish (Table G1) were downloaded from IUCN, NatureServe, and FWS as vector data inputs. These distribution data were combined with a species-specific subset of the waterbodies/wetlands data to create a species-habitat distribution raster input each species of conservation concern showing where distribution data overlapped with suitable waterbody/wetland features.

B. Clip the species distribution feature class to the regional boundary for each individual species.
C. Add new Short (16-bit integer) field "Rank" value (Rank = 1 (except for federally listed species whereby Rank = 2)) to attribute table using *Calculate Field* and rasterize.
D. Mosaic clipped species distribution raster with regional boundary.
E. For each species, use *Raster Calculator* to create a raster where watershed-level species distribution data (output of previous mosaic geoprocessing) overlap with waterbodies/wetlands suitable for that species (waterbodies were parsed

[24] NatureServe. 2023. NatureServe Network Biodiversity Location Data accessed through NatureServe Explorer [web application]. NatureServe, Arlington, Virginia. Available https://explorer.natureserve.org/.
[25] IUCN. 2021. The IUCN Red List of Threatened Species. Version 2021-3. https://www.iucnredlist.org.

into lakes and rivers by size and wetlands by type in processing described above; suitable waterbody/wetland classifications were identified for each species described above). Below is a demonstration for the silverband shiner (*Notropis shumardi*), which uses medium and large rivers.

   a. Geoprocessing > Mosaic to New Raster
      i. Input Rasters: large rivers raster, medium rivers raster (results from NHD processing described above). Note that inputs were ordered from lakes (largest to smallest) to rivers (largest to smallest) to wetlands.
      ii. Raster Dataset Name: Rivers_MediumLarge
   b. Geoprocessing > Raster Calculator
      i. Map Algebra Expression: *"SilverbandShiner.tif" + "Rivers_MediumLarge"*
      ii. Output Raster: SilverbandShiner_Habitat

Species-specific Data Processing

Eastern Brook Trout

Additional regional-scale data were available for eastern brook trout (*Salvelinus fontinalis*) and were combined with the watershed-level distribution data used for other aquatic species of conservation concern above. These data help serve as a proxy for cold-water aquatic habitat.

E. Join the Trout Unlimited Great Lakes Brook Trout Conservation Portfolio[26] habitat patch summary data to the habitat patch geometry feature class using the NewPatchID field.
F. Export the joined data to a new feature class and clip to regional boundary.
G. Add new Short (16-bit integer) field “Rank” value to the attribute table using *Calculate Field* based on Conservation Strategy (0 where there are “No trout” and 1 for all other classifications) and rasterize.
   a. Expression (Arcade): Rank = When($feature.Cons_strat=="No trout", 0, 1)
H. Mosaic habitat patch raster with the regional boundary.
I. Extract by Attributes where Value <> 0.
J. Use *Raster Calculator* to create a raster where extracted habitat patches overlap with waterbody types used by eastern brook trout (all size classes of ponds, lakes, and rivers).
K. Use *Raster Calculator* to create a raster where watershed-level eastern brook trout distribution data overlap with waterbody types that may be used by eastern brook trout (all size classes of ponds, lakes, and rivers) following the same methods used for all other species above.
L. Mosaic the habitat patch-waterbodies with the distribution-waterbodies rasters and reclassify so the output is a binary raster input (Value = 0 or Value = 1), with 1 indicating waterbodies are suitable for eastern brook trout based on either habitat patches and/or watershed distribution data.

Wild Rice

Wild rice (*Zizania spp.*) was identified as regionally important through stakeholder engagement and was the only plant species included for the U.S. Great Lakes region. The data include off-reservation delineated waters within the Ceded Territories (Treaty of 1837 and Treaty of 1842) (off reservation) in Wisconsin and Minnesota lakes and rivers with rice stands.

M. Merge all state-level species distribution data into one regional vector.
N. Clip the species distribution feature class to the regional boundary.
O. Add new Short (16-bit integer) field “Rank” value (Rank = 3) to attribute table using *Calculate Field* and rasterize.
P. Mosaic clipped species distribution raster with regional boundary. Note that for the U.S. Great Lakes region, the only aquatic plant included was wild rice and this step represents the input for the aquatic plants taxonomic group.

Combine Individual Species-Habitat Distribution Rasters by Taxonomic Group

Q. Add the mosaicked species-habitat distribution rasters within each taxonomic group (fish, mollusks, crayfish) using the *Raster Calculator* geoprocessing tool’s addition operator to add all individual species rasters. Within taxonomic groups, rasters were grouped alphabetically into subsets to make processing and QA/QC more efficient. Wild rice was the only aquatic plant included in the Assessment.

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[26] Trout Unlimited Great Lakes Brook Trout Conservation Portfolio: https://trout.maps.arcgis.com/apps/webappviewer/index.html?id=63870ecf17a14d1a9d11ba4328bcef3f.

a. Map Algebra Expression *(Note, for each species a conditional statement is used to replace any null values with 0 values to add rasters together. If this statement was not included there would only be values where every raster overlapped. Alternatively, each raster could be mosaicked individually with the rank 0 regional template prior to raster calculator processing to ensure a complete presence/absence dataset for the entire regional boundary. Note that the template raster is a rank=0 dataset for the regional boundary and ensures 0 values where there are no inputs as opposed to no data.)*
"WBD_202204_GL_ExtendedArea_Project_TEMPATE_FW.tif" +
Con(IsNull("AmericanBrookLamprey_Habitat"),0,"AmericanBrookLamprey_Habitat") +
Con(IsNull("AmericanEel_Habitat"),0,"AmericanEel_Habitat") +
Con(IsNull("AtlanticSalmon_Habitat"),0,"AtlanticSalmon_Habitat") + …

Reclassify Taxonomic Group Input

R. Use the *Reclassify* geoprocessing tool to classify data within each taxonomic group (fish, mollusks, crayfish) using a quantile distribution. If necessary, use the *Clip Raster* geoprocessing tool before reclassifying to limit data to within the regional boundary before reclassifying as the values are based on the quantile distribution of data within the region. Classify into 6 classes (0-5) using a quantile distribution, ensuring that zero value cells are in their own class (0). If necessary, use the *Extract by Attributes* geoprocessing tool to extract all non-zero values, classify into 5 classes (1-5), then combine with extracted class zero using the *Mosaic to New Raster* geoprocessing tool. Wild rice (*Zizania spp.*) was the only aquatic plant included in the Assessment; this taxonomic group input was not reclassified but remained a binary raster input (Value = 0 or Value = 3).

G.4 Create the Aquatic Critical Habitat Input

A. Select (or export to a new feature class) the aquatic species where “status = final” from both the polygon and line feature classes downloaded from the U.S. Fish and Wildlife Service Threatened & Endangered Species Active Critical Habitat Report (note that for the U.S. Great Lakes region there were only line features for aquatic species).
B. Clip and project the critical habitat line and polygon feature classes to the regional boundary.
C. Add new Short (16-bit integer) field “Rank” value (Rank = 3) to attribute table using *Calculate Field*.
D. Buffer clipped critical habitat lines by 1 m to convert to polygon feature class.
E. Rasterize each of the vector data inputs (i.e., one for each species). If there are both polygon and line critical habitat features, merge into a single polygon feature class before rasterizing.
F. Mosaic the resulting critical habitat raster with the regional boundary.

G.5 Create the Fish Spawning and Reef Locations Input

Multiple feature classes were included in the Great Lakes Aquatic Habitat Framework (GLAHF) fish spawning download, including the Goodyear Spawning Atlas and 2011 updates for some species along with river mouth locations with known historic lake sturgeon (*Acipenser fulvescens*) spawning.

Prepare the Fish Spawning Locations Data

A. From Goodyear Spawning Atlas dataset, export spawning locations data for all species except those that have more updated data available (2011 updated data) where FISH <> 'Alewife' And FISH <> 'Bloater' And FISH <> 'Burbot' And FISH <> 'Emerald shiner' And FISH <> 'Lake herring' And FISH <> 'Lake trout' And FISH <> 'Lake whitefish' And FISH <> 'Rainbow smelt' And FISH <> 'Slimy sculpin' And FISH <> 'Smallmouth bass' And FISH <> 'Walleye' And FISH <> 'Yellow perch'.
B. From Sturgeon locations dataset, export spawning locations that are not attributed as “Extirpated” where GAP_Sts = STATUS <> 'Extirpated'.
C. Merge the fish spawning datasets (2011 spawning sites for select species, Goodyear Spawning Atlas - remove 2011 species, and Great Lakes sturgeon locations - remove extirpated sites).
D. Clip the merged fish spawning locations feature class to the regional boundary.
E. Buffer merged fish spawning locations (point data) by 250 m.
F. Add new Short (16-bit integer) field “Rank” value (Rank = 3) to the attribute table using *Calculate Field* and rasterize.

Prepare the Reef Locations Data

G. Clip the reef locations feature class to the regional boundary.
H. Buffer reef locations (point data) by 250 m.
I. Add new Short (16-bit integer) field "Rank" value (Rank = 3) to the attribute table using *Calculate Field* and rasterize.

Combine Fish Spawning Locations and Reef Locations Data

J. Mosaic fish spawning locations and reef locations rasters with the regional boundary. If needed, clip the mosaicked raster to the regional boundary.

G.6 Create the Great Lakes Eastern Brook Trout Habitat Input

This input is processed from the same data as Appendix G.3 - Eastern Brook Trout described above and could be reclassified to a binary raster input (Value = 0 or Value = 3).

A. Join the Trout Unlimited Great Lakes Brook Trout Conservation Portfolio habitat patch summary data to the habitat patch geometry feature class using the field NewPatchID.
B. Export the joined data to a new feature class and clip to regional boundary.
C. Add new Short (16-bit integer) field "Rank" value to the attribute table using *Calculate Field* based on Conservation Strategy (0 where there are "No trout" and 3 for all other classifications), rasterize, and clip to regional boundary.
    a. Expression (Arcade): Rank = When($feature.Cons_strat=="No trout", 0, 3)
D. Mosaic habitat patch raster with the regional boundary.

G.7 Calculate the Aquatic Index

The individual inputs (Fish, Mollusks, Crayfish, Wild Rice, Critical Habitat, Fish Spawning and Reef Locations, and Great Lakes Brook Trout Habitat) were combined into a single raster using the *Raster Calculator* geoprocessing tool's addition operator. The output was reclassified into 10 classes using a quantile breaks distribution, displayed in Table G2. The Aquatic Index was then combined with the Terrestrial Index and Protected and Managed Areas for Biodiversity to create the Fish and Wildlife Index.

A. Use the *Raster Calculator's* addition operator to add the individual threat inputs into a single raster output.
B. Reclassify the clipped output into 10 classes based on quantile distribution.

Table G2. Aquatic Index Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Aquatic Index Break Value	0	1 - 2	3	4	5	6 - 7	8	9	10 - 12	13 - 21
Final Rank Value	1	2	3	4	5	6	7	8	9	10

H. Detailed Methodology: Fish and Wildlife Index

Data processing for each of the indices used the geoprocessing standards described in Appendix B.

H.1 Create the Protected and Managed Areas for Biodiversity Input

Protected and managed areas were added to the Fish and Wildlife Index directly because these areas are neither distinctly aquatic nor terrestrial. The Protected and Managed Areas input was combined with the Aquatic and Terrestrial Indices to create the Fish and Wildlife Index.

A. Prepare PAD-US dataset.
   a. Clip the Protected Areas Database of the United States (PAD-US) 2.1 feature class to the regional boundary.
   b. Export the features with a GAP status of 1 or 2 (GAP_Sts = '1' Or GAP_Sts = '2'). The GAP Status Code is a measure of management intent to conserve biodiversity:
      1. ***Status Code 1:*** *an area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events are permitted to proceed without interference or are mimicked through management.*
      2. ***Status Code 2:*** *an area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.*
   c. Add new Short (16-bit integer) field “Rank” value (Rank = 1) to attribute table using *Calculate Field* and rasterize.

B. Prepare National Marine Sanctuaries dataset: This dataset was used to supplement aquatic protected and managed areas that were missing from PAD-US (National Marine Sanctuaries were determined to be relevant to biodiversity). Project to the regional projection (if necessary, use pairwise clip if feature extends past regional boundary; if necessary, merge multiple boundary polygons into a single feature class). Add new Short (16-bit integer) field “Rank” value (Rank = 1) to attribute table using *Calculate Field* and rasterize.

C. Prepare ProtectedSeas dataset: This dataset was used to supplement aquatic protected and managed areas that are missing from PAD-US. ProtectedSeas areas were included where there were fishing restrictions and the purpose was not primarily cultural (e.g., to protect lighthouses or shipwrecks) or to provide recreational opportunities (e.g., hiking trails or boating access).
   a. Filter data using a *Definition Query* or exporting a subset of features to remove any features where the purpose of the restriction was primarily cultural or to provide recreational opportunities where *removal_of_marine_life <> 'Least restrictive: No known fishing restrictions' And purpose <> 'To properly manage the natural resources within the state of New York.' And purpose <> 'To protect the very first natural gas lighthouse in the country. Finished in 1829, the 40-foot tall Barcelona Lighthouse (Portland Harbor) was in Federal Lighthouse Service until 1859. At that time it became privately held through various owners until 2008, when New York State Office of Parks, Recreation and Historic Preservation acquired it. Though it no longer has the original lens, nor is used for navigational purposes, it is still lit and visible today through an agreement with the Town of Westfield. The lighthouse is listed on the U.S. National Register of Historical Places.' And protection_focus <> 'Cultural Heritage' And purpose NOT LIKE '%To provide recreational opportunities%' And purpose NOT LIKE '%To preserve this area including the historic Thirty Mile Lighthouse%' And purpose <> 'To provide access to the water for boating and fishing.' And purpose <> 'To provide access to the water for small and power boats, and fishing.' And purpose <> 'To protect this area where land and water clash, sculpting the most dramatic landscape on the Lake Ontario shore. Visitors can experience massive earthen spires from above or along the lakeshore on nature trails.'*
   b. Project to the regional projection (if necessary, use pairwise clip if feature extends past regional boundary). Add new Short (16-bit integer) field “Rank” value (Rank = 1) to attribute table using *Calculate Field* and rasterize.

D. Mosaic all protected and managed areas rasters (PAD-US protected and managed areas raster, National Marine Sanctuaries raster, ProtectedSeas raster, regional boundary raster with rank 0).

H.2 Combine Terrestrial Index, Aquatic Index, and Protected and Managed Areas for Biodiversity Input

The Terrestrial and Aquatic Indices were previously classified into 10 classes (1 to 10) before they were added together along with the Protected and Managed Areas for Biodiversity binary raster input (Value = 0 or Value = 1) using the *Raster Calculator* geoprocessing tool's addition operator to create the Fish and Wildlife Index. The output was reclassified into 10 classes using a quantile breaks distribution displayed in Table H1, to allow readers to distinguish values more easily.

A. Use the Raster Calculator's addition operator to add the individual threat inputs into a single raster output.
B. Reclassify the clipped output into 10 classes based on quantile distribution.

Table H1. Fish and Wildlife Index Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Fish & Wildlife Index Break Values	2 - 3	4 - 5	6	7	8	9	10	11 - 12	13 - 14	15 - 21
Final Rank Value	1	2	3	4	5	6	7	8	9	10

I. Detailed Methodology: Resilience Hubs

I.1 Create Terrestrial Habitat Cores

The generation of the Terrestrial Habitat Cores was conducted following the automated processes described in *Evaluating and Conserving Green Infrastructure Across the Landscape: A Practitioner's Guide*, by Karen Firehock (February 2015). The scripts used to automate the processes were modified from the original toolbox, titled "Green Infrastructure Center Model for ArcGIS Desktop." Due to this automation, detailed steps for the development of Habitat Cores are not provided here.

The National Land Cover Database (2019) was used to delineate Terrestrial Habitat Cores including all natural, undeveloped land cover classifications, while excluding cultivated crops and all developed lands. All Habitat Cores were developed with a minimum area of 4-hectares (10-acres). Fragmenting features included roads, railroads, and an extended shoreline boundary. This process will result in Habitat Cores that will be separated into Terrestrial and Lacustrine Habitat Cores. To delineate Terrestrial and Lacustrine Habitat Cores, the shoreline boundary was extended 100-meters inland, where Lacustrine Habitat Cores included nearshore areas that do not exceed 20-meters depth in water, and Terrestrial Habitat Cores are those inland.

The datasets required were prepared individually as inputs for the Green Infrastructure Center model used to determine habitat core geometry according the Green Infrastructure Center Model for ArcGIS Desktop.

After processing the Green Infrastructure model with the inputs detailed in Appendix A.6, separate the resulting Terrestrial Habitat Cores from nearshore habitat.

A. Using the NHD Waterbody data, select FTYPE=390 to select all large bodies of water and export.
B. Select all Terrestrial Habitat Cores that intersect the FTYPE=390 features.
C. Add text field "hub_type" to the Terrestrial Habitat Cores attribute table and calculate the field of selected cores as "lacustrine".
D. Select all cores that do not intersect NHD Waterbody features (by inverting selection).
E. In field "hub_type" of the Terrestrial Habitat Cores attribute table, calculate the field of selected cores as "terrestrial".
F. Export each "terrestrial" and "lacustrine" core type as separate layers.
G. For both "terrestrial" and "lacustrine" layers, add integer field "hub_id" and calculate the field to match that of the Feature ID of the attribute table.
H. Smooth both resulting layers by 100-meters.

I.2 Create Riparian Habitat Cores

The National Hydrography Dataset Plus High Resolution (NHDPlus HR) "flowlines" and "area" feature classes were used to identify Riparian Habitat Cores that would have otherwise been excluded from the analysis due to the 4-hectare (10-acre) size minimums and other topographical characteristics that are considered in the Green Infrastructure methodology. Riparian features such as headwaters/creek, pipelines, underground conduit, and canal/ditches were not included. Process as follows:

A. Select riverine features within a 5-kilometer (3.1-mile) buffer of any community asset and merge selections into a single feature class.
B. Buffer riverine features by 100 m (Side Type = Full).
C. Dissolve buffered riverine features.
D. Erase riverine features that are already covered by a Terrestrial Habitat Core and apply an inverse buffer.
    a. Use the *Erase* geoprocessing tool to erase smoothed Terrestrial Habitat Cores from the dissolved riverine buffers.
    b. Apply an inverse buffer (-10 m, Side Type = Full) to the resulting features to create separation between Terrestrial Habitat Cores and riverine buffers.
    c. Convert the resulting features to singlepart features using the *Multipart to Singlepart* geoprocessing tool.
  E. Many of the Riparian Corridors are long, contiguous features. Fragment these features with dams and areas of known fish habitat *(Source: National Fish Habitat Partnership Inland Stream Assessment for the Conterminous United States)*
      a. Select By Location areas where dams and fish habitat intersect, or intersect within 30 m.
      b. Split Riparian features.
F. Calculate the area of each of the resulting single part features and filter out fragments.
    a. Calculate Geometry Attributes for a new field (Area) where the Area Unit = Acres.

    b. Select Layer by Attribute where Area is greater than or equal to 10 acres.
    c. Export resulting selection to a new feature class.
G. Create a text field “hub_type” (11 characters) in the attribute table.
    a. Calculate field as “riparian”.
H. Merge resulting exported selection with smoothed Terrestrial Habitat Cores to create a combined layer with Terrestrial and Riparian Habitat Cores.

I.3 Creating a Regional Hexagonal Grid

Using the merged Terrestrial and Riparian Habitat Cores layer, prepare a hexagonal grid to cover the regional extent.

A. Use a “*Create Grid*” tool and select “hexagon” as the grid type.
B. Set the grid extent to the regional boundary.
C. Determine the parameters of the hexagon geometries.
    a. 10-acres in area, or, where applicable, set horizontal and vertical spacing to 216.17-meters.
    b. Results in hexagonal grid that encompasses the entire region.
D. Add text field “hub_type” (11 characters) to the hexagons attribute table.
    a. Select hexagonal features that have their centroids intersecting with the Lacustrine Habitat Cores
        i. Calculate the field of selected hexagons as “lacustrine”.
    b. Select hexagonal features that have their centroids intersecting with Terrestrial or Riparian Habitat Cores.
        i. Calculate the field of selected hexagons as “terrestrial_riparian”.
    c. Select hexagonal features that have their centroids intersecting with Riparian Habitat Cores
    d. Calculate the field of selected hexagons as “riparian”.
E. Export Terrestrial and Riparian hexagon types as an individual layer, and Lacustrine hexagon types as another.
F. For both Terrestrial and Riparian and Lacustrine hexagon layers, add integer field “hex_id” and calculate the field to match that of the Feature ID of each respective attribute table.

I.4 Creating Lacustrine Hexagon Grid and Habitat Cores

Unlike Terrestrial and Riparian Habitat Cores, Lacustrine Habitat Cores lack fragmenting features, which results in large, contiguous open water areas. The following steps describe how to fragment or subdivide these large open water areas. Bathymetric data are used to divide open water areas to generate a Lacustrine hexagon grid and to create Lacustrine Habitat Cores.

A. Prepare the bathymetric raster with the standard hydrographic processing method.
    a. Fill sinks in the bathymetric raster to remove small imperfections in the data.
        i. Geoprocessing > Fill
    b. Using GRASS, run the *r.watershed* function on the filled, bathymetric raster.
        i. Select the bathymetry raster as the elevation input.
        ii. Minimum size of basin = 25000
        iii. Maximum length of surface flow = 1000
        iv. Toggle on “Enable Single Flow Direction D8”.
        v. Toggle on “Allow only horizontal and vertical flow of water”.
        vi. Set the GRASS processing extent to the 20-meter depth boundary extent (vector).
        vii. Set the GRASS region cell size at 30 meters.
        viii. Only the Half-basins product is needed from this process; deselect all products if preferred (deselecting all other products will result in faster processing time).
        ix. An underwater surface raster representing general sub-basins will be generated. *(Note, if the resulting sub-basins are too fine in scale and too numerous, consider resampling the input bathymetric raster to have a coarser cell size. Alternatively, use a higher minimum size of basin.)*
B. Vectorize the resulting sub-basin surface raster.
    a. Geoprocessing > Raster to vector
    b. Remove artifacts from the vectorized sub-basin data. It is normal to have small artifacts or slivers resulting from generating sub-basins from bathymetric data. Additionally, many sub-basins may be too small in area to effectively group lacustrine hexagons into Lacustrine Habitat Cores. Many of these areas may require manual editing to merge the smaller features into larger, nearby neighbors.

i. The Esri geoprocessing tool "*Eliminate*" eliminates polygons by merging them with neighboring polygons that have the largest area or the longest shared border.
   1. Geoprocessing > Eliminate (The *Eliminate* tool may not eliminate all selected features, depending on your dataset. If this occurs, manually merge polygons of concern to a larger, sub-basin neighbor. The objective is to generate a result that can be used to group hexagons into a suitable Habitat Core size.)

C. After the sub-basin vector data have been sufficiently cleaned and processed, calculate the area in acres for each sub-basin.
   a. (QGIS) If data are in meters, calculate a new decimal field "acres" with the expression: $area * 0.00024711.

D. Some resulting sub-basins may be too large to serve as meaningful hexagon core groups. To correct this, further subdivide very large sub-basins.
   a. Select sub-basins over 10,000 acres.
   b. (QGIS) Geoprocessing > Split Polygons
      i. Input = selected sub-basins
      ii. Number of parts = value (*Note, the number of parts is dependent on the number of selected sub-basins. Refer to tool documentation to determine the appropriate number of parts. For this assessment, each sub-basin over 10,000 acres was split individually to best determine a suitable number of divisions.)*
      iii. Voronoi Algorithm = Thiessen Polygons
      iv. Number of parts = 100
   c. Delete the sub-basin features over 10,000 acres and merge with the sub-basins that have been split.

E. Add integer field "basin_id" to the sub-basin attribute table and calculate a unique ID to each basin.
   a. (QGIS) expression: $ID

F. Spatially join the sub-basins layer to the lacustrine hexagon grid.
   a. Geoprocessing > Join Attributes by Location
      i. Base layer = lacustrine hexagon grid
      ii. Join layer = lacustrine sub-basins
      iii. Geometric predicate = intersects
      iv. Join type = "Take attributes of the feature with the largest overlap only (one-to-one)

G. Dissolve hexagons by field "basin_id".
   a. Geoprocessing > Dissolve
   b. Dissolve field = "basin_id"

H. Smooth the hexagons grouped by basin ID.
   a. Geoprocessing > Smooth Polygon
   b. Smoothing algorithm = PAEK
   c. Smoothing tolerance = 500-meters

I. Ensure there are no multipart features.
   a. Geoprocessing > Multipart to singlepart

J. The smoothing process may cause some features to overlap. Check grouped hexagons layer for any overlapping features.
   a. (SAGA) Geoprocessing > Polygon Self-Intersection
   b. Identifier = "basin_id"
   c. This resulting layer will contain a new "id" field, containing the "id"s of their original buildings split by a | sign. Open the *Field Calculator* of this new layer and calculate a new field with the expression = if(regexp_match("ID",'\\|') > 0, regexp_substr("ID",'[^|]*'), "ID"). *(Note, this expression looks in your "ID" field to determine whether it contains a | character. If so, it chooses the ID before or after the | character. If it does not contain this character, it will just copy over the ID to the "mergeID".)*
   d. Dissolve the features.
      i. Geoprocessing > Dissolve
      ii. Dissolve field = "mergeID"

K. The resulting layer is the grouped Lacustrine Habitat Cores.

I.5 Preparing the Habitat and Asset Distance Raster Datasets

Resilience Hubs are intended to identify areas where resilience-building efforts may simultaneously mitigate flooding *and* benefit fish and wildlife. Therefore, to generate Resilience Hubs scores, the analysis considered important habitat types that are most likely to provide flood protection benefits to nearby human community assets and the average distance from critical facilities and infrastructure.

Prepare the Habitat Datasets

The habitat types considered in the analysis varied for Terrestrial and Riparian and Lacustrine Habitat Cores. Terrestrial and Riparian Habitat Cores considered the presence and proximity of forested wetlands, emergent wetlands, FEMA floodplains (floodway, 100-yr, and 500-yr), and the stream habitat (using National Fish Habitat Partnership[27] data). Lacustrine Habitat Cores considered the presence and proximity of beaches and dunes, reef locations, and emergent wetlands. Habitat Cores with the presence of one or more habitat types and Habitat Cores near one or more habitat types receive a higher value.

A. Prepare the habitat datasets. Prepare both vector (to calculate Euclidean distance) and raster (to calculate proportional mean area) versions.
    a. Ensure the proper raster resolution and spatial coordinate system (in meters) are set.
    b. For the vector version of a habitat, create an integer field in the attribute table “value”.
        i. Calculate field = 1
    c. Geoprocessing > Vector to Raster
        i. Field to rasterize = “value”
    d. Geoprocessing > Resample raster
        i. Check that NODATA or NULL values are a 0 and not NULL
        ii. The prepared rasters should have values 0 — 1 *(Note, for conditional data that suggests value or quality of habitat, use the values assigned to each condition, e.g., Poor = 1, Fair = 2, Moderate = 3, etc.)*
    e. Repeat these steps for each habitat type.
    f. The resulting rasters will be used for the proportional mean area analyses described below.

B. Run *Euclidean Distance* on each vector version of the habitats to generate raster datasets that indicate the distance of a habitat in every direction.
    a. Run Euclidean distance on the merged layer.
        i. Geoprocessing > Euclidean Distance
            1. Input = vector features of a habitat
            2. Output cell size = 30m
            3. Maximum distance = 1500-meters
            4. Distance method = Planar
    b. Classify the symbology of the Euclidean raster result with a 5-class quantile distribution.
        i. Reclassify the Euclidean distance raster to where the lowest class of values of the quantile symbology receives a new value of 5, the second lowest receives a new value of 4, the third class receives a value of 3, the fourth class receives a new value of 2, and the highest class of values receives a new value of 1. Make sure all NULL or NODATA values are “0”. This reclassification allows areas closest to another habitat type to receive a higher value.
    c. Repeat to have Euclidean distance rasters for each habitat type.
    d. These resulting habitat rasters will be used to score Habitat Cores.

Prepare the Asset Distance Dataset

The analysis considered the proximity of all Habitat Cores to critical facilities and critical infrastructure (see Appendix E for details on how the critical facilities and critical infrastructure inputs were generated). Habitat Cores closer to community assets receive a higher value.

C. Prepare asset distance raster using the vector datasets for both critical infrastructure and critical facilities.
    a. Merge the infrastructure and facilities layers into one vector layer.
    b. Run Euclidean distance on the merged layer.
        i. Geoprocessing > Euclidean Distance

[27] National Fish Habitat Partnership Inland Stream Assessment for the Conterminous United States.

1. Input = merged vector features of facilities and infrastructure
2. Output cell size = 30m
3. Maximum distance = 1500-meters
4. Distance method = Planar

c. Classify the symbology of the Euclidean raster result with a 5-class quantile distribution.
d. Reclassify the Euclidean asset distance raster to where the lowest class of values of the quantile symbology receives a new value of 5, the second lowest receives a new value of 4, the third class receives a value of 3, the fourth class receives a new value of 2, and the highest class of values receives a new value of 1. Make sure all NULL or NODATA values are "0". This reclassification allows areas closest to a critical facility or infrastructure to receive a higher value.
e. The resulting asset distance raster will be used to score Habitat Cores.

I.6 Scoring Terrestrial and Riparian Habitat Cores and Hexagons

The same methods are used to score and rank Terrestrial and Riparian Habitat Cores and the Terrestrial and Riparian hexagonal grids. The final Terrestrial and Riparian Habitat Cores and hexagonal grids are each scored separately using the average values of the Community Exposure Index, Fish and Wildlife Index, the habitat rasters, and the asset distance raster.

A. Ensure that fields "hub_id" or "hex_id" have been calculated *(from previous steps).*
B. Buffer the Habitat Cores or hexagonal grid by 1-km.

Calculate Community Exposure Index Scores

C. To calculate Community Exposure Index scores, perform zonal statistics on the buffered Cores and hexagons. *(Note, check that there are no NULL or NODATA values in the Community Exposure Index. These values should be "0".)*
   a. Geoprocessing > Zonal Statistics
      i. Use buffered Cores or hexagons as the input layer.
      ii. Select "Mean" as the statistic to calculate.
      iii. Select the Community Exposure Index as the input raster.
      iv. Prepare a field "exp_" to contain mean scores *(Note, the statistic "mean" will auto-populate at the end of the field name after the zonal statistic has finished running.)*
      v. Run zonal statistics.
   b. "expbuf_mean" now contains the mean Community Exposure Index score for each buffered Core or hexagon.
D. Perform a spatial join to join the "expbuf_mean" scores from the buffered Cores or hexagons to the attribute table of the non-buffered Cores or hexagons.
   a. Spatial join or "join attributes by field value," set join parameter to "one-to-one"
   b. Input layer 1 = non-buffered Cores or hexagons, table field to join by = "hub_id"
   c. Input layer 2 = buffered Cores or hexagons, table field to join by = "hub_id"
   d. If applicable, select only the field "expbuf_mean" field to be joined to the non-buffered cores or hexagons. This will help keep a more manageable attribute table without duplicate fields.
   e. When complete, the non-buffered Cores or hexagons will contain the buffered Community Exposure Index scores in the field "expbuf_mean".

Calculate Fish and Wildlife Index Scores

E. To calculate Fish and Wildlife Index scores, perform zonal statistics on the Cores and hexagons.
   a. Geoprocessing > Zonal Statistics
      i. Use Cores or hexagons as the input layer.
      ii. Select "Mean" as the statistic to calculate.
      iii. Select the Fish & Wildlife Index as the input raster.
      iv. Prepare a field "fw_" to contain mean scores.
      v. Run zonal statistics.
   b. "Fw_mean" now contains the Fish and Wildlife score for each Core and hexagon.
F. For each "exp_mean" and "fw_mean" field, select any features that have NULL or NODATA values, and calculate those values as "0".

Combine Community Exposure and Fish and Wildlife Index Scores

G. Hub Score is the product of the Fish and Wildlife mean and the Community Exposure mean for each Habitat Core or hexagon. Calculate the score of each Habitat Core or hexagon.
   a. In the attribute table of the Cores or hexagons, add decimal (real) field = "score".
   b. Using the *Field Calculator*, populate the field "score" by multiplying the fields "fw_mean" and "exp_mean": "Score" = ("fw_mean" * "exp_mean").
   c. The result is the intermediate "Score" of each Habitat Core or hexagon.

Incorporate Habitat Scores

H. Run zonal statistics on each area habitat raster (non-conditional values of only 1 or 0), calculating the mean of cells contained within each Core or hexagon. Do not buffer the cores for this step. The results of these zonal statistics will be the proportional area of each habitat within each Core or hexagon. For each resulting zonal statistic calculated for each habitat, ensure there are no NULL values in the resulting attribute table field by converting any NULL values to "0".
   a. Geoprocessing > Zonal statistics
      i. Input layer = Cores or hexagons that have been scored with Fish & Wildlife and Community Exposure values
      ii. Raster layer = proportional habitat raster *(Ex: emergent wetlands).*
      iii. Select "mean" as the statistic to calculate.
      iv. Prepare a field "ew_prop_" to contain mean scores *(this naming aims to capture "ew" as "emergent wetlands" and "prop" as proportional. Floodplains would be "fp_prop", for example).*
      v. Repeat zonal statistics (mean) for each habitat proportional raster.

I. Run zonal statistics on each Euclidean distance habitat raster, calculating the mean of cells contained within each core. The results of these zonal statistics will be the average distance of each habitat from each core, representing each core or hexagon's distance value in relation to each habitat. Do not buffer the Cores or hexagons for this step. For each resulting zonal statistic calculated for each habitat, ensure there are no NULL values in the resulting attribute table field by converting any NULL values to "0".
   a. Geoprocessing > Zonal statistics
      i. Input layer = Cores or hexagons that have been scored with Fish & Wildlife and Community Exposure values and proportional areas habitat rasters.
      ii. Raster layer = Euclidean distance habitat raster *(Ex: emergent wetlands).*
      iii. Select "mean" as the statistic to calculate.
      iv. Prepare a field "ew_dv_" to contain mean scores *(This naming aims to capture "ew" as "emergent wetlands" and "dv" as the distance value. Floodplains would be "fp_dv", for example).*
      v. Repeat zonal statistics (mean) for each habitat proportional raster.

J. After all the zonal statistics have been calculated and all "prop" and "dv" mean values for each habitat have been obtained, add two fields (use real, or decimal values) in the attribute table "dv_score" and "prop_score".

K. Calculate each new field "dv_score" and "prop_score" as follows:
   a. *prop_score" = ("prop_mean1") + ("prop_mean2") + ("prop_mean3") + ("prop_mean4")*
      "dv_score" = ("dv_mean1") + ("dv_mean2") + ("dv_mean3") + ("dv_mean4")
   b. For this assessment, nf = fish locations; ew = emergent wetlands; fwl = forested wetlands; fp = floodplains. The expression reads:

      "prop_score" = ("nf_prop_mean") + ("ew_prop_mean") + ("fwl_prop_mean") + ("fp_prop_mean")
      "dv_score" = ("ew_dv_mean") + ("fw_dv_mean") + ("fp_dv_mean") + ("nf_dv_mean")

L. Add a field "hab_fac" with real (decimal) values. This field will contain the score, or habitat factor, of all habitat rasters. Calculate this field as follows:
   a. *"hab_fac" = ("prop_score") + ("dv_score")*

Incorporate Asset Distance Scores

M. Run zonal statistics on the asset distance raster capturing the mean distance in a field "ast_dv_mean", with real (decimal) values.
   a. Geoprocessing > Zonal Statistics

i. Input layer = Cores or hexagons that have been scored with Fish & Wildlife and Community Exposure values and habitat rasters.
ii. Raster layer = Euclidean asset distance raster
iii. Select "mean" as the statistic to calculate.
iv. Prepare a field "ast_dv_" to contain mean scores *(this naming aims to capture "ast" as "asset").*

N. Add a field "hub_rank" with real (decimal) values. Calculate this field as follows:
   *a. "hub_rank" = (("score") * ("ast_dv_mean")) + ("hab_fac")*

Calculate Final Rankings

O. Reclassify into 10 classes based on quantile distribution. Drop the lowest 50% in a 10-class quantile distribution to identify only the highest-ranking Resilience Hubs.

P. Determine the final Resilience Hub Rank from the resulting scored Cores and hexagons.
   a. Add a field in the attribute table called "rank_val" (integer field type).
   b. Using a 10-class quantile distribution, symbolize the values of field "hub_rank".
      i. Distribution of ranked Terrestrial and Riparian Cores is shown in Table I1.
      ii. Distribution of ranked Terrestrial and Riparian hexagons is shown in Table I2.
   c. The first classification of "hub_rank" values (lowest values) will be Rank 1 Hubs, whereas the last, or tenth classification of score values (highest), will be Rank 10 Hubs.
      i. Use selection expressions to select Cores or hexagons of the first, lowest distributed class of values.
      ii. With the *Field Calculator*, and with Rank 1 Hubs selected, calculate field "rank_val" to contain values of "1".
      iii. Select by attribute the Hubs that have a "hub_rank" of the second-lowest, class 2 distribution and calculate the field "rank_val" to contain values of "2".
      iv. Repeat this process until all ten classes have been assign rank values (1-10).
   d. The result is final ranked Resilience Hubs associated with the Terrestrial and Riparian Habitat Cores and hexagons.

Table I1. Terrestrial and Riparian Cores Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Score Break Value	53 - 63	63 - 75	75 - 87	87 - 102	102 - 117	117 - 133	133 - 153	153 - 177	177 - 213	213 - 735
Final Rank Value	1	2	3	4	5	6	7	8	9	10

Table I2. Terrestrial and Riparian Hexagon Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Score Break Value	1- 23	23 - 45	45 - 60	60 - 74	74 - 90	90 - 108	108 - 130	130 - 157	157 - 199	199 - 5485
Final Rank Value	1	2	3	4	5	6	7	8	9	10

I.7 Scoring Lacustrine Habitat Cores and Hexagons

The final Lacustrine Habitat Cores and hexagonal grid are scored separately using the average values of the Community Exposure Index, Fish and Wildlife Index, the habitat rasters, and the asset distance raster.

A. Ensure that fields "hub_id" or "hex_id" have been calculated *(from previous steps).*
B. Buffer the Cores or hexagonal grid by 1-km.

Calculate Community Exposure Index Scores

Follow the steps outlined in Appendix I.6 using the buffered Lacustrine Cores and hexagons as input layers.

Calculate Fish and Wildlife Index Scores

Follow the steps outlined in Appendix I.6 using the buffered Lacustrine Cores and hexagons as input layers.

Combine Community Exposure and Fish and Wildlife Index Scores

C. "Hub Score" is the product of the Fish and Wildlife mean and the Community Exposure mean for each Habitat Core or hexagon. Calculate the score of each Habitat Core or hexagon.
    a. In the attribute table of the Cores or hexagons, add decimal (real) field = "score".
    b. Using the field calculator, populate the field "score" by multiplying the fields "fw_mean" and "exp_mean": "Score" = ("fw_mean" * "exp_mean").
    c. The result is the Hub Score of each Habitat Core or hexagon.
D. Run zonal statistics on the bathymetry raster to obtain mean depth for each Lacustrine Core or hexagon. Do not apply a buffer for this step. For the resulting zonal statistic calculated for bathymetry, ensure there are no NULL values in the resulting attribute table field by converting any NULL values to "0".
    a. Geoprocessing > Zonal statistics
        i. Input layer = Cores or hexagons that have been scored with Fish & Wildlife and Community Exposure values.
        ii. Raster layer = mosaicked, regional bathymetric raster dataset.
        iii. Select "mean" as the statistic to calculate.
        iv. Prepare a field "d_" to contain mean scores where "d" is "depth".
E. Calculate the depth factor for each lacustrine habitat core/hexagon, where the depth factor considers depth of a Core or hexagon to the 20-m depth boundary used for the Assessment.
    a. Add (decimal) field "d_fac". This field will contain the depth factor of each lacustrine core or hexagon.
    b. Lacustrine Cores or hexagons that have a mean depth of 0 to 3-meters receive a depth factor of "3"; those with a mean depth of 3 to 5-meters receive a depth factor of "2"; those with a mean depth of 5 to 20-meters receive a depth factor of "1".
        i. Select by an expression those cores/hexagons that have a depth of 0 to 3-meters and use the field calculator to apply a value of "3" in the added field "d_fac".
        ii. Select by an expression those cores/hexagons that have a depth of 3 to 5-meters and use the field calculator to apply a value of "2" in the added field "d_fac".
        iii. Select by an expression those cores/hexagons that have a depth of 5 to 20-meters and use the field calculator to apply a value of "1" in the added field "d_fac".
        iv. Check that there are no NULL or NODATA values remaining in the field "d_fac". Where there is missing or insufficient bathymetric data, use local nautical assessments for those areas to determine a reasonable depth factor for the cores or hexagons in that area.

Incorporate Habitat Scores

Follow the steps outlined in Appendix I.6 using the input layer with the scored Community Exposure, Fish and Wildlife, and depth factor.

F. After all the zonal statistics have been calculated and all "prop" and "dv" mean values for each habitat have been obtained, add two fields (use real, or decimal values) in the attribute table "dv_score" and "prop_score"
G. Calculate each new field "dv_score" and "prop_score" as follows:
    a. *"prop_score" = ("prop_mean1") + ("prop_mean2") + ("prop_mean3")*
    "dv_score" = ("dv_mean1") + ("dv_mean2") + ("dv_mean3")

b. For this assessment, rf = reef locations; ew = emergent wetlands; b = beaches/dunes. The expression reads:
"prop_score" = ("rf_prop_mean") + ("ew_prop_mean") + ("b_prop_mean")
"dv_score" = ("rf_dv_mean") + ("ew_dv_mean") + ("b_dv_mean")

H. Add a field "hab_fac" with real (decimal) values. This field will contain the score, or habitat factor, of all habitat rasters. Calculate this field as follows:
   *a. "hab_fac" = (("prop_score") + ("dv_score")) * ("d_fac")*

Incorporate Asset Distance Scores

Follow the steps outlined in Appendix I.6 using the input layer with the scored Community Exposure, Fish and Wildlife, depth factor, and habitat scores.

I. Calculate this field as follows:
   *"hub_rank" = (("score") * ("ast_dv_mean")) + ("hab_fac")*

Calculate Final Rankings

Follow the steps outlined in Appendix I.6 to create the final ranked Resilience Hubs associated with the Lacustrine Habitat Cores and hexagons. The distributions of ranked Lacustrine Cores (Table I4) and hexagons (Table I4) are shown below.

Table I3. Lacustrine Resilience Hub Cores Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Score Break Value	20 - 27	27 - 35	35 - 43	43 - 53	53 - 67	67 - 84	84 - 113	113 - 157	157 - 285	285 - 1005
Final Rank Value	1	2	3	4	5	6	7	8	9	10

Table I4. Lacustrine Resilience Hub Hexagonal Grid Distribution for the U.S. Great Lakes Coastal Resilience Assessment.

Score Break Value	1 - 3	3 - 6	6 - 23	23 - 43	43 - 61	61 - 84	84 - 113	113 - 150	150 - 350	350 - 3089
Final Rank Value	1	2	3	4	5	6	7	8	9	10

I.8 Combining Lacustrine and Terrestrial and Riparian Habitat Cores and Hexagons

A. Merge the Terrestrial/Riparian and Lacustrine Habitat Cores into one layer and the Terrestrial/Riparian and Lacustrine hexagons into another layer.
   a. Geoprocessing > Merge
B. Check that there are no overlapping Habitat Cores. The Lacustrine and Terrestrial/Riparian hexagons should never overlap, as they have been derived from the same contiguous grid. There are two approaches that can be taken depending on the number of overlapping cores:
   a. First approach:
      i. (SAGA) Geoprocessing > Polygon Self-Intersection
      ii. Identifier = "hub_id"
      iii. Resulting layer will contain a new "id" field, containing the "id"s of their original buildings split by a | sign. Open the field calculator of this new layer and calculate a new field with the expression = if(regexp_match("ID",'\\|') > 0, regexp_substr("ID",'[^|]*'), "ID"). *(Note, this expression looks in your "ID" field to determine whether it contains a | character. If so, it chooses the ID before or after the | character. If it does not contain this character, it will just copy over the ID to the "mergeID".)*
      iv. Dissolve the features.

        1. Geoprocessing > Dissolve
        2. Dissolve field = "mergeID"
   b. Second approach:
      i. Geoprocessing > Erase
         1. Input layer = Lacustrine cores
         2. Erase layers from = Terrestrial cores
      ii. Geoprocessing > Multipart to Singlepart
      iii. Recalculate area in acres.
      iv. Remove any slivers or artifacts from the dataset.
      v. Use "*Eliminate Polygon*" tool if necessary.

C. For each resulting layer, fix geometries to ensure topological quality.
   a. Geoprocessing > Fix
      i. Input layer = Merged cores/hexagons

D. For each layer, symbolize field "rank_val", which shows the final Resilience Hub rank value (1-10) per Habitat Core or hexagon.

E. Results generate the final, ranked Resilience Hubs Core output and Resilience Hub Grid output.

J. Stakeholder Engagement

To encourage regional stakeholders to review and provide input on preliminary Assessment products, the Project Team hosted two stakeholder workshops. The virtual stakeholder workshop included two meetings: one focused on fish and wildlife on September 7, 2022 and the second on community exposure, held on September 8, 2022. A second, in-person workshop was held on September 21 as part of the 2022 Great Lakes Coastal Symposium in Sault Ste. Marie, MI. All invited stakeholders had access to written materials and an online GIS viewer to review draft models and provide comments during and after the workshop. The following list includes organizations invited to participate in the stakeholder review process.

1854 Treaty Authority
American Society of Adaptation Professionals
Applied Research Institute, University of Illinois Urbana-Champaign
Audubon Great Lakes
Biohabitats
Bureau of Indian Affairs
Central Michigan University
Chicago Metropolitan Agency for Planning
Chippewa Ottawa Resource Authority
City of Port Washington Department of Public Works
Cleveland Metroparks
Coastal States Organization
Cooperative Institute for Great Lakes Research, University of Michigan
Ducks Unlimited
Edgewater Resources, LLC
Federal Emergency Management Agency
Fond du Lac Band of Lake Superior Chippewa
GEI Consultants of Michigan
Grand Portage Band of Lake Superior Chippewa
Great Lakes and St. Lawrence Cities Initiative
Great Lakes Commission
Great Lakes Indian Fish & Wildlife Commission
Great Lakes Research Center, Michigan Technological University
Huron Pines
Illinois Department of Natural Resources
Indiana Department of Natural Resources
International Joint Commission
Keweenaw Bay Indian Community
Lac Vieux Desert Band of Lake Superior Chippewa Indians
Lake Superior National Estuarine Research Reserve
Laughing Whitefish Audubon Chapter
Little River Band of Ottawa Indians
Little Traverse Bay Bands of Odawa Indians
Mary Griggs Burke Center for Freshwater Innovation, Northland College
Mayor's Office of Waukegan, Illinois
Michigan Department of Environment, Great Lakes, and Energy
Michigan Department of Natural Resources
Michigan Natural Features Inventory, Michigan State University
Michigan Sea Grant Extension
Minnesota Department of Natural Resources
National Audubon Society
New York Department of Environmental Conservation
New York Department of State
NOAA National Marine Fisheries Service

NOAA Great Lakes Environmental Research Laboratory
NOAA Office for Coastal Management
Ohio Department of Natural Resources
Old Woman Creek National Estuarine Research Reserve
Pennsylvania Department of Environmental Protection
Pennsylvania Fish and Boat Commission
Pokagon Band of Potawatomi
Saint Regis Mohawk Tribe
Sault Ste. Marie Tribe of Chippewa Indians
Surfrider Foundation
The Nature Conservancy
Throwe Environmental
U.S. Army Corps of Engineers
U.S. Department of Agriculture
U.S. Fish and Wildlife Service
U.S. Geological Survey
University of Michigan
Village of Sodus Point, New York
Wisconsin Coastal Management Program
Wisconsin Department of Natural Resources