CHAPTER 7

COASTAL PROCESSES

Lake Erie is a constantly changing and dynamic body of water. Many natural factors have shaped and continue the shape the physical settings of the lake and its coast, including glaciers, climate, weather, wind, waves, currents, ice and geology. Over the last 200 years, the construction of coastal structures—for port and harbor development, commercial and recreational access, erosion control and flood protection—has drastically influenced the shape, conditions and processes along Ohio's coast.

Ohio is situated in the "humid continental" climate zone. This zone exists exclusively over large mid-latitude land masses in the Northern Hemisphere where polar air from the north and tropical air from the south converge. The humid continental climate zone is categorized by noticeably changing patterns in seasonal weather. Summer and winter weather conditions are extremely opposite. Summer provides warmer temperatures, moderate cloud cover and occasional weather events, such as drought, thunderstorms and tornadoes. Winter is typified by colder temperatures, significant cloud cover, snowfall and occasional blizzards. Temperature differences increase farther inland. Lake Erie plays a significant role in regional microclimates and temperature control. Since water temperatures change slower than temperatures on land, areas near the lake tend to remain cooler in the spring and warmer in the fall. This is ideal for extending agricultural growing seasons, particularly for grapes, peaches and other produce.

In late fall and early winter, before the lake freezes, **lake-effect snow** events occur when polar air masses from the north and west move across the warmer water of Lake Erie. The cold, dry air collects rising water vapor from the lake and distributes it landward in the form of snow. Lake-effect snow produces substantial accumulations of precipitation (up to six inches of snow in one hour) and blizzard-like conditions in downwind locations, especially where elevations are higher. Regions most affected are called "**snowbelts**." Lake Erie's primary snowbelt stretches from eastern Cuyahoga County to Buffalo, and includes Lake, Geauga and Ashtabula counties (and areas farther to the southwest in extreme events). In Ohio, annual snowfall may range from 70 to 100 inches in the snowbelt. Lake-effect conditions end when Lake Erie freezes over. All five Great Lakes produce lake-effect snow.

LAKE LEVELS

As with all the Great Lakes, water level fluctuations on Lake Erie are common and range from several inches to several feet. Short-term fluctuations, on the scale of hourly to daily, are often caused by strong winds or rapid changes in barometric pressure. The most dramatic short-term lake level fluctuation is called a "**seiche**," which is a periodic motion that occurs when water is pushed from one end of the lake to the other. Most seiches on Lake Erie occur as water accumulates in the Eastern Basin due to predominant west winds. Consequently, lake levels in the Western Basin decrease. As the wind weakens, gravity causes the water to rebound toward the Western Basin, and then back to the east. This back-and-forth oscillation will continue with decreasing amplitude until the lake reaches a stable equilibrium. Lake levels may not return to normal until after a few oscillation cycles, which may take several hours, or longer. The shallowness and elongated southwest-to-northeast orientation of Lake Erie make it extremely prone to seiche events. Seiches can occur in any direction and can influence lake currents. Smaller fluctuations can occur in Sandusky Bay, river mouths and harbor areas.

Seasonal changes also affect Lake Erie's water levels. In general, lake levels are lower in the winter and higher in the summer. During the cooler and drier months of fall and early winter, lake levels decrease as warmer water is evaporated. Evaporation rates slow as air and lake temperatures decrease in mid-winter. When the lake freezes, water levels remain relatively constant—with minimal evaporation or precipitation. In early spring, runoff from melting snow adds water to the lake. From mid-spring to early summer, water temperatures in Lake Erie remain cooler than air temperatures. Cooler atmospheric conditions cause water vapors to rise (from Lake Erie and other surface water bodies, vegetation and soils), condense, and form clouds. Precipitation occurs—as water vapor particles collide within the clouds—and adds water to the lake. During summer months, air and lake temperatures are closer, resulting in minimal condensation and evaporation. Lake levels during the summer season are relatively constant. The difference between lower winter lake levels and higher summer lake levels can exceed one foot.

Long-term lake level fluctuations are caused by changes to seasonal/annual precipitation rates and temperatures. For instance, several consecutive years of relatively warm weather and less-than-average precipitation will cause lake levels to drop. Warmer atmospheric conditions will result in greater evaporation rates and the lack of precipitation will not allow the lake to adequately replenish itself. Conversely, consecutive years of cooler weather and greater-than-average precipitation will cause Lake Erie's lake levels will rise. This is due to more water entering the lake and less water evaporating into the atmosphere.

Erosion at Al Cummings Sunset Park, North Kingsville, Ashtabula County

The National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service owns and maintains four Lake Erie coastal stations as part of its Water Level Observation Network. These stations are located at Toledo, Marblehead, Cleveland and Fairport Harbor. Additionally, NOAA's National Data Buoy Center operates a Directional Wave Station in Lake Erie, located on the international border north of Vermilion, and a Coastal-Marine Fixed Station on South Bass Island, which is part of the Coastal-Marine Automated Network (C-MAN). See map on page 174.

EROSION

Erosion is the wearing away of land or the lakebed by the action of natural forces, such as wind, waves, currents and surface runoff. Rates of erosion vary by location and over time. Geomorphic and physical factors that contribute to erosion include: soil composition, conditions and slope; beach composition, width and slope; nearshore/lakebed shoals and slopes; erodibility of consolidated and unconsolidated materials; shoreline orientation, and; groundwater. Weather and lake conditions, such as precipitation, storm events, wave energy, wave duration, ice cover and lake levels also contribute to coastal erosion. The presence of shore structures can either reduce or accelerate erosion rates.

Erosion can reshape and alter the bluff, shore (beaches and dunes) and nearshore. The impacts to these areas occur as a result of different erosion processes and rates. The composition of the bluff, shore and nearshore can directly influence erosion rates at a given location. Non-cohesive sediments, such as sand and gravel, are easily erodible, whereas cohesive materials, such as clays and bedrock can be more resistant to erosion. However, clays that are typically more resistant can become fluid with excess amounts of water. This can lead to movement in the layers of sediment. Shale tends to fracture and wear in thin layers on the surface; however, shale bluff collapses are not uncommon. Limestone and dolomite are highly-resistant carbonate bedrock; erosion rates are not measurable over short periods of time.

A **bluff** is the natural upland landform directly adjacent to the lake. The bluffs along Lake Erie are composed of bedrock, glacial till or a combination of both, and usually contain complex soil sequences. In Ohio, coastal bluffs generally increase in height from west to east and can be extremely erodible. In eastern Ashtabula County, bluff heights reach more than 60 feet. Stability of the bluff is site specific and dependent on many factors, including the steepness of the slope, composition of the bluff, beach width/sand budget, lake bottom substrates in the nearshore, vegetation on the bluff and groundwater. The shores of the Western Basin are mostly low-lying post-glacial lake deposits.

Bluff slopes along Lake Erie range from gradual to steep. Slopes that are more gradual are generally more stable, while steeper slopes may exhibit greater rates of erosion. Lake Erie normally does not interact with bluff areas, except during storm events or extended periods of higher lake levels. Constant wave action can eat into and wash away the base, or "toe," of the bluff. Steeper bluffs composed of non-resistant bedrock or unconsolidated glacial materials are more susceptible to coastal erosion. The top of the bluff is also susceptible to erosion threats. Excess groundwater buildup, the removal of vegetation, storm water runoff and construction can all undermine the stability of the bluff. All bluffs erode over time. For more information about the composition of Ohio's Lake Erie bluffs, see pages 180 through 183.

"**Slumping**" occurs when a mass of loosely consolidated materials drops a short distance along a concave slip in the bluff, then continues to move downslope as an intact block of material. Bluffs composed of glacial till are more susceptible to slumping at the top of the bluff. Wave-based erosion at the toe of a till bluff, which causes a steeper slope, often precedes slumping at the top of the bluff, largely under the force of gravity and aided by the freeze/thaw process, runoff, heavy rains and fill, among other causes. Groundwater seepage and water buildup within the bluff also leads to slumping. An excess of groundwater reduces the stability of the bluff and acts as a lubricant between sediment layers. Groundwater movement can cause the upper layers of soil to slide downward. Artificial fill placed along the slope is very likely to slump because it is not consolidated, or compressed, like the natural material (which was compressed by the weight of the glaciers). Slumping is also caused by poor upland drainage.


Revetment at Geneva State Park, Ashtabula County

Surface water runoff can cut channels, called "rills" or "gullies" (see definitions on page 193), in the bluff face and lead to significant erosion. The severity of surface water-based erosion is dependent on the velocity and volume of water moving on or through the bluff. Sources of groundwater and surface water include precipitation, snow melt, a high water table and human activity. Human-induced causes include sprinkler systems, poorly-drained septic systems, broken water/drainage pipes and leaky pools.

Vegetation (e.g. shrubs, small trees and herbaceous plants) provides bluff stability. Plants absorb moisture from the soil, and through the process of transpiration, release water vapor into the atmosphere. The removal of water from within the bluff lessens the possibility of instability and erosion. For more information about the hydrologic cycle, see page 223. Root systems also provide bluff stability. Additionally, vegetated bluffs can weather storms better than an exposed bluff; vegetation protects the bluff from wind-induced and surface water erosion.

Freezing and thawing water can also trigger upland erosion. As groundwater within the bluff freezes, it expands and enlarges cracks, or fissures, in the bluff. Slumps can occur if a fissure becomes large enough and subsequently filled with additional water. Freeze events begin in late fall and are common throughout winter months. In spring, ice thaw and runoff from within and/or on the bluff can cause erosion as well.

The **shore** is the area between the toe of the bluff and the lake; it is essentially where the land meets the water. A shore zone composed of loose, unconsolidated materials, such as sand or gravel, is called a **beach**. **Dunes** are wave- and wind-driven mounds of sand (or other types of sandy sediment) that form landward of a beach (e.g. Headlands Dunes in Lake County). Over time, grasses and other vegetation types will establish a foothold in dune formations. Beaches and dunes provide a natural protective barrier between the water and upland. Due to a combination of natural processes and human activities, the Lake Erie shore is a dynamic area. Beaches are transient and continually changing.

Shore erosion occurs when the energy from breaking waves disturbs, removes and redistributes loose materials. It is a continuous process and one of the more visible forms of erosion. Shore erosion can lead to the wearing away of the bluff and further shore loss. The severity of wave action and subsequent shore erosion depends on lake levels, storm activity, bluff and shore composition and the nearshore profile. For instance, higher lake levels will lead to greater rates of shore and bluff erosion. Consolidated bedrock or cohesive sediments (clay or till), are generally more resistant to erosion, whereas those composed of non-cohesive, unconsolidated materials (sand and gravel) erode at a much higher rate. Additionally, the depth of the nearshore can have a significant impact on the size of the waves and energy reaching the shore. Shallower nearshore depths will reduce wave energy, while deeper nearshore depths will allow greater wave energy to reach the shore.

The **nearshore** area extends offshore (lakeward) from the shore until the point at which the lakebed flattens and sediments are no longer able to move with the currents to deeper water depths. Depending on the slope of the lake bottom, the nearshore can extend offshore hundreds of feet to a depth of six to eight feet. Erosion within this zone is often unnoticed since it occurs below the surface of the water.

Nearshore erosion, also referred to as "lakebed downcutting," is the scouring of cohesive lake bottom substrates, such as till or bedrock, and is an irreversible process. Lakebed downcutting slowly increases the depth of the nearshore, which allows larger and more powerful waves to break closer to the shore. This process can increase erosion at the shore and result in bluff instability. Lakebed downcutting changes the nearshore profile and is permanent. Nearshore erosion occurs at a much slower rate here the nearshore is the bedrock.

Lake level fluctuations can significantly alter the rate of nearshore erosion. During periods of higher lake levels, waves break closer to the toe of the bluff. This will potentially result in greater shore and bluff erosion, while lessening erosion in the nearshore. In contrast, waves will break farther away from shore during periods of lower lake levels, increasing the potential for lakebed downcutting. If lower lake levels persist and nearshore depths increase significantly, larger waves reaching the shore zone will occur when lake levels rise. This will potentially increase erosion of the shore and lead to bluff instability. The impact that lakebed downcutting has on the bluff is noticeable where steep bluffs close to the water occur and higher-than-average erosion rates exist.

The build-up of ice along the shore can protect the shore from waves and erosion. Ice acts as a barrier and reduces the force that waves can exert on the shore. Ice can also blanket the sediment in the nearshore, further reducing overall erosion rates. However, lakebed downcutting can occur—where gradual nearshore slopes exist—as a result of waves hitting the ice. Additionally, once ice begins to break up, it can take with it significant amounts of sediment along the shore and materials at the toe of the bluff. Strong winds can move ice, and scour the lakebed and shore. Shore erosion and the undermining of the bluff due to ice can lead to slump.

Slumping at Nokomis Park, Vermilion, Erie County

SHORE STRUCTURES

Upon statehood in 1803, very few coastal structures along Ohio's Lake Erie shore existed. In the 1870s, 68 percent of the mainland shore had beaches. As waterborne commerce on Lake Erie gained momentum in the 1820s (see Chapter 4: Transportation and Shipping, page 84), many coastal structures, such as jetties and breakwaters, were constructed to protect newly-developed ports and harbors. Within the harbor areas, bulkheads and wharfs were built to provide commercial and recreational vessels better access to the lake.


Headlands Dunes State Nature Preserve, Lake County

Shore structures were also installed to reduce erosion and protect private and commercial property. The number of structures along the coast has increased as the number of lakefront properties and population have increased. In the late 1870s, there were approximately 60 shore structures along Ohio's Lake Erie shore. The number of structures significantly increased to around 1,400 in the late 1930s, and jumped to about 3,600 in the mid-1970s. Shore structure construction peaked during the early 1970s in response to higher water levels and significant storm events. Since then, the number of structures has continued to increase, but they are constructed at a slower pace despite fluctuating lake levels. Shore structures are rarely removed and can be effective for many decades if properly designed, built and maintained. Improperly designed or poorly constructed structures may fail during storms, result in sediment shortages, accelerate erosion or create adverse wave conditions. These effects can lead to the loss of habitat and protective beaches, as well as damage to property and infrastructure.

Today, the majority of Ohio's Lake Erie shore is hardened. Armoring has physically altered the characteristics and dynamics of the shore. In the 1800s, the natural sand-rich shore was relatively linear and tended to recede at a uniform rate. The current shoreline can be characterized as irregularly shaped, mostly protected and interspersed with small areas of recession-prone natural bluffs and beaches.

Shoreline recession rates have decreased in areas protected by shore structures; however, beaches are now much smaller. Beach size reduction is a direct impact of the interrupted sediment supply. Natural erosion of bluffs is an important source of beach-forming materials. Sediment also enters the lake from tributary discharges. While shore-parallel structures, such as revetments and seawalls, effectively minimize erosion, they also prevent naturally-occurring erosion from contributing sediments into the shore zone and nearshore. Sediments that enter the littoral system are often transported by alongshore currents (see page 172) and become trapped by shore-perpendicular structures, such as breakwaters, groins and jetties. This process results in sand accumulation on one side of a structure while leaving the other side lacking sediment. Large harbor structures, like the breakwaters at Fairport Harbor, Ashtabula and Conneaut, often cause the most noticeable alterations to the coast. Placement of these structures has created large depositional beaches on the updrift (west) side of the harbors (e.g. Headlands Beach and Headlands Dunes, west of Fairport Harbor), while diminished sediment volumes and severe bluff erosion have occurred downdrift (east) of the structures. Sediment shortages caused by the harbor structures at Conneaut are evident as far east as Presque Isle in Erie, Pennsylvania.

While coastal structures have created harbors and safe navigation channels, provided commercial and recreational access, and prevented coastal erosion, they have also led to the loss of beaches. The need to evaluate such impacts is key to restoring various aspects of Lake Erie's shore and natural functions. Today, coastal projects are designed to take into consideration not only the primary and secondary functions and structural integrity of the shore structure, but also the potential impacts they will have on sand resources and adjacent areas along the shore.

DREDGING

Dredging is the removal of rock, sand, gravel, silt, mud and clay from the bottom of navigable waterways, shipping channels, recreational channels, marinas and harbors. It is required to create or maintain sufficient depths to ensure safe navigation for waterborne commerce and recreation. Dredging is a critical activity, but it has contributed to the loss of sediment along the shore and in the nearshore. Sediment removal is done by mechanical scraping/scooping or by hydraulic pumping. Historically, materials dredged from federally-authorized harbors and channels have either been placed in confined disposal facilities (CDFs) or placed in the open waters of Lake Erie. Dredged material from recreational channels and marinas is commonly placed along the shore if it is mostly sand, in federally-designated off-shore areas if it is finer material, or on the upland. Enacted in 2015, Senate Bill 1 prohibits most open-lake placement of dredge material from major ports and harbors after July 1, 2020. For more information about dredging, see page 98.

BEACH NOURISHMENT AND DUNE CONSTRUCTION

Shoreline hardening alters the natural characteristics and dynamics of the lake, shore and nearshore, can disturb or destroy habitat, and interrupts the connection between the water and land. **Beach nourishment** is a 'soft' erosion control solution that involves the placement of sand in the shore and nearshore zones to build up and reinforce beach thickness (height) and width, and reduce the effects of waves. Wider beaches protect against the effects of waves better than narrow beaches.

The grain size and composition of the native beach material is an important factor to consider when conducting beach nourishment projects. If the newly-placed nourishment material is smaller than the natural beach material, it may erode faster. Conversely, if the nourishment material is the same size or larger than the natural material, it may provide better protection from incoming waves. Beach nourishment material should be obtained from an upland source and not from the nearshore.

Periodic re-nourishment may be required to maintain a beach. In some cases, projects are designed so that nourishment materials erode during storm events to protect landward areas. Vegetation and the creation of dunes can extend the life of a beach nourishment project.

Sand dune construction protects areas landward of the dune while enhancing a fronting beach. Dunes protect the upland by limiting the number and force of waves that reach inland, while also providing protection from storms and strong winds. The larger the dune, the greater the protection provided. Dunes also function to enhance beaches by periodically providing sand to the beach and nearshore area. Natural dunes are the result of wind-blown sand and tend to be made up of finer materials (than what is distributed along the shore and at beaches).

Artificial dune construction involves the build-up of sand directly behind a beach so that the dune has a slight-to-moderate increase in elevation. A snow fence or netting is often placed early in the process to capture wind-blown sand, while native vegetation is planted to keep the dune in place. In some cases, biodegradable material or wooden ramp-like structures are placed at the core of the dune to provide a base for sand to accumulate. Like beach nourishment, sand placed for dune construction should be of the same size or larger than the materials that occur naturally at that location. Sand that is smaller than the native material may erode faster.

Additional information about Lake Erie's coastal processes are presented throughout this chapter, including: (1) Lake Circulation; (2) Littoral Transport; (3) Recorded Wind Speed; (4) Lakebed Substrates, and; (5) Bluff Classification.

Confined disposal facility, Cleveland, Cuyahoga County

Learn more about the information presented in this chapter:

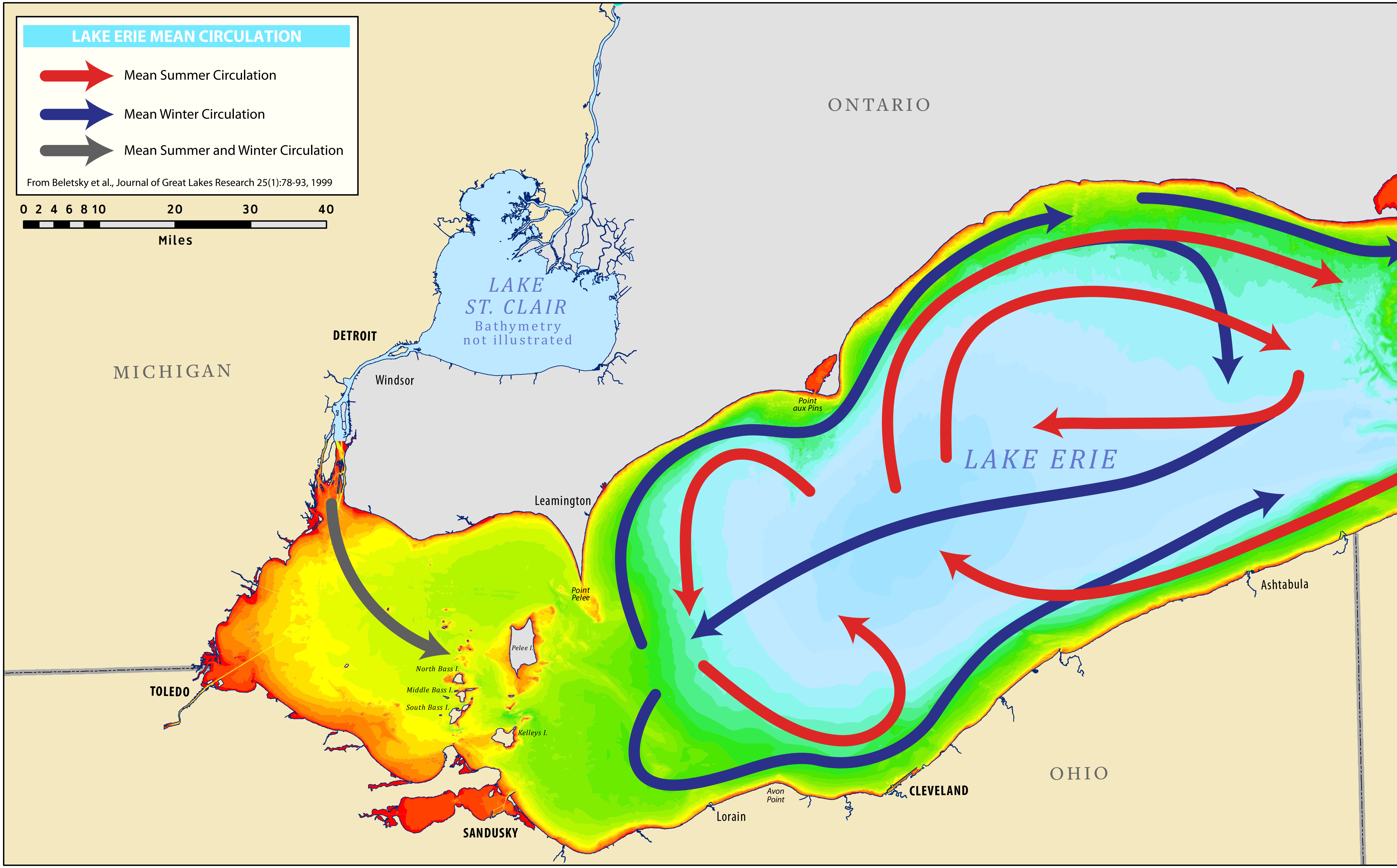
Ohio Coastal Design Manual
Ohio Department of Natural Resources, Office of Coastal Management
coastal.ohiodnr.gov/design

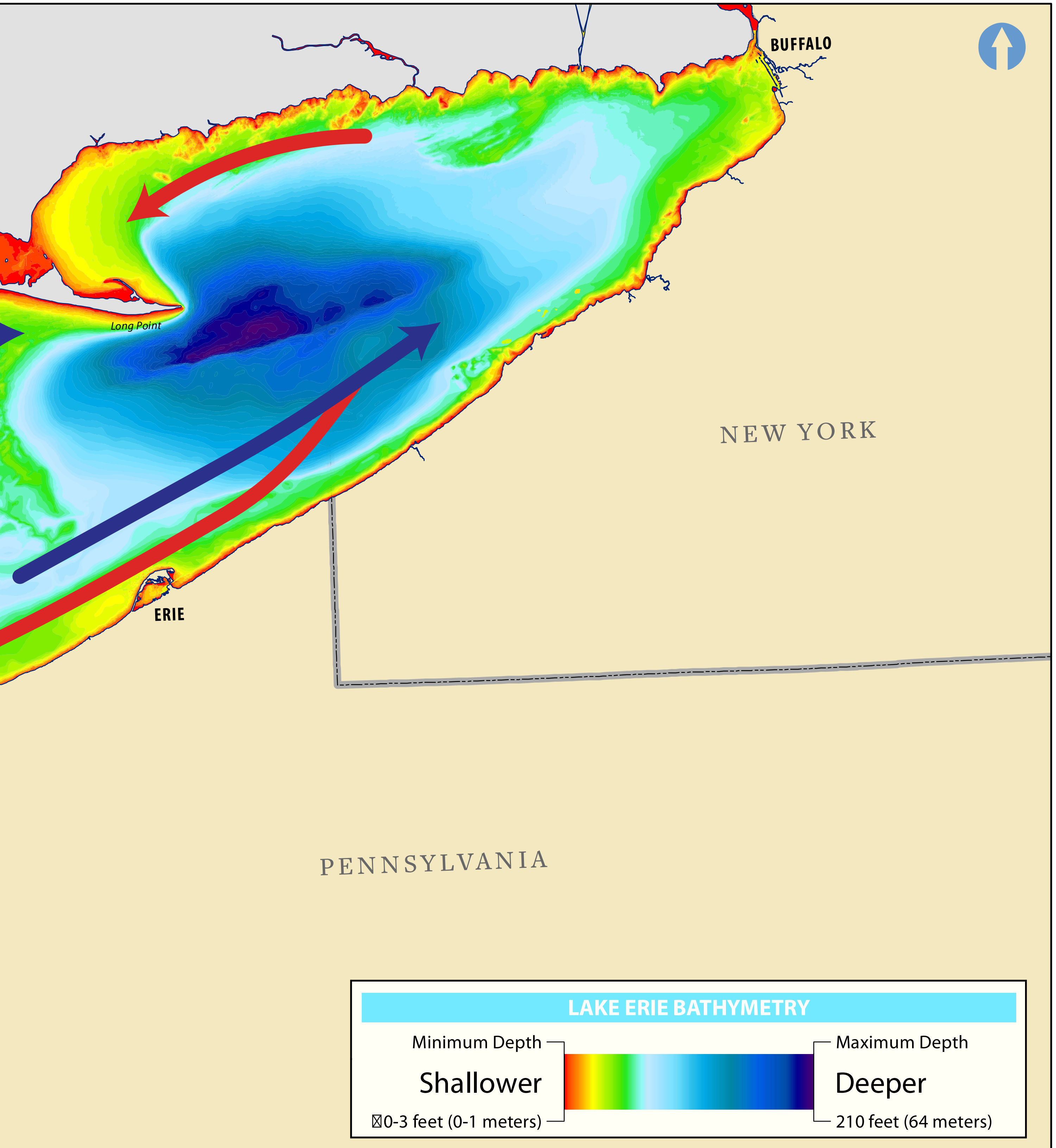
Lake Erie Shore Erosion Management Plan
Ohio Department of Natural Resources, Office of Coastal Management
coastal.ohiodnr.gov/erosion

Ohio Department of Natural Resources, Division of Geological Survey
geosurvey.ohiodnr.gov

A complete list of chapter sources is found in the Appendix.

LAKE CIRCULATION



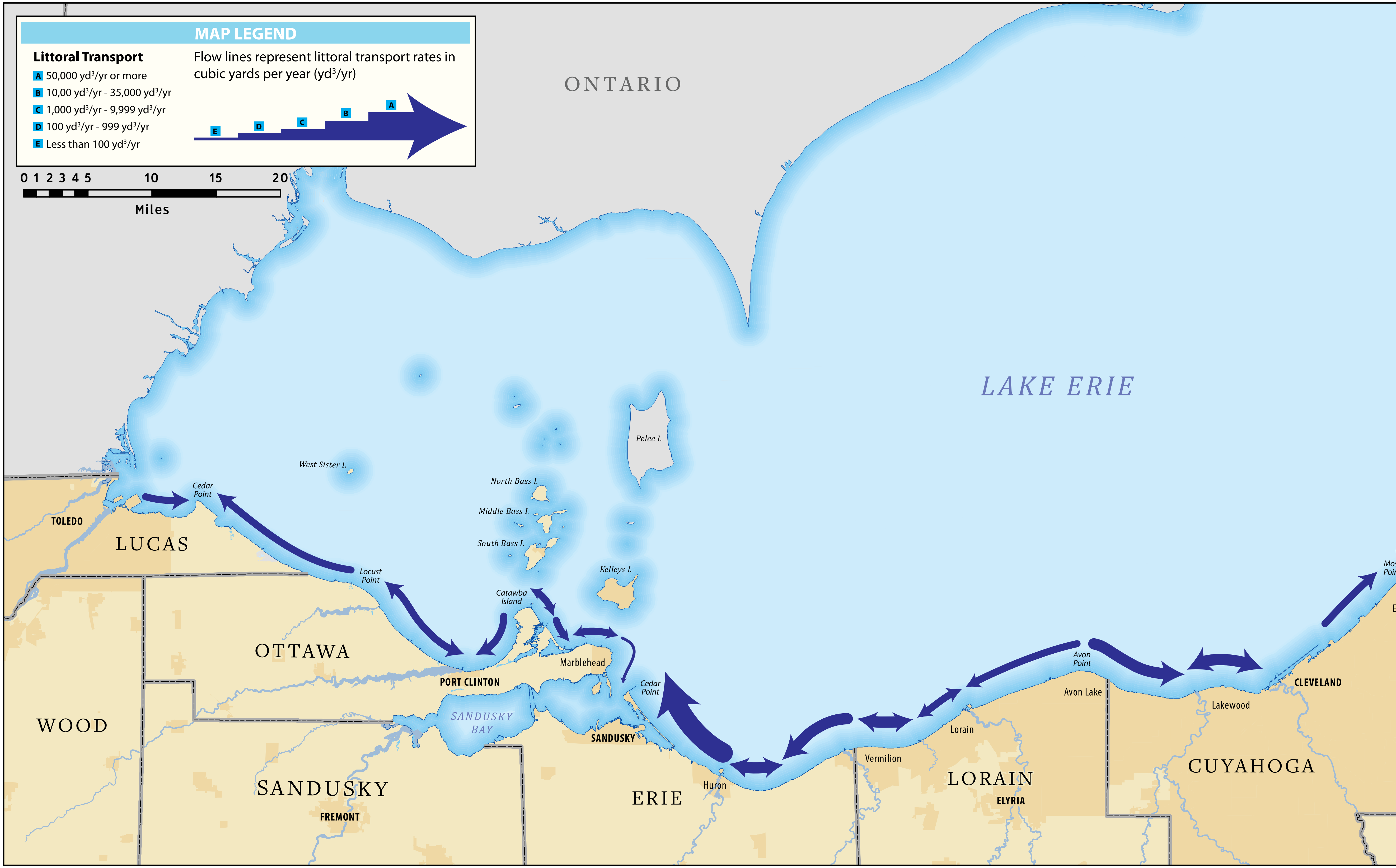


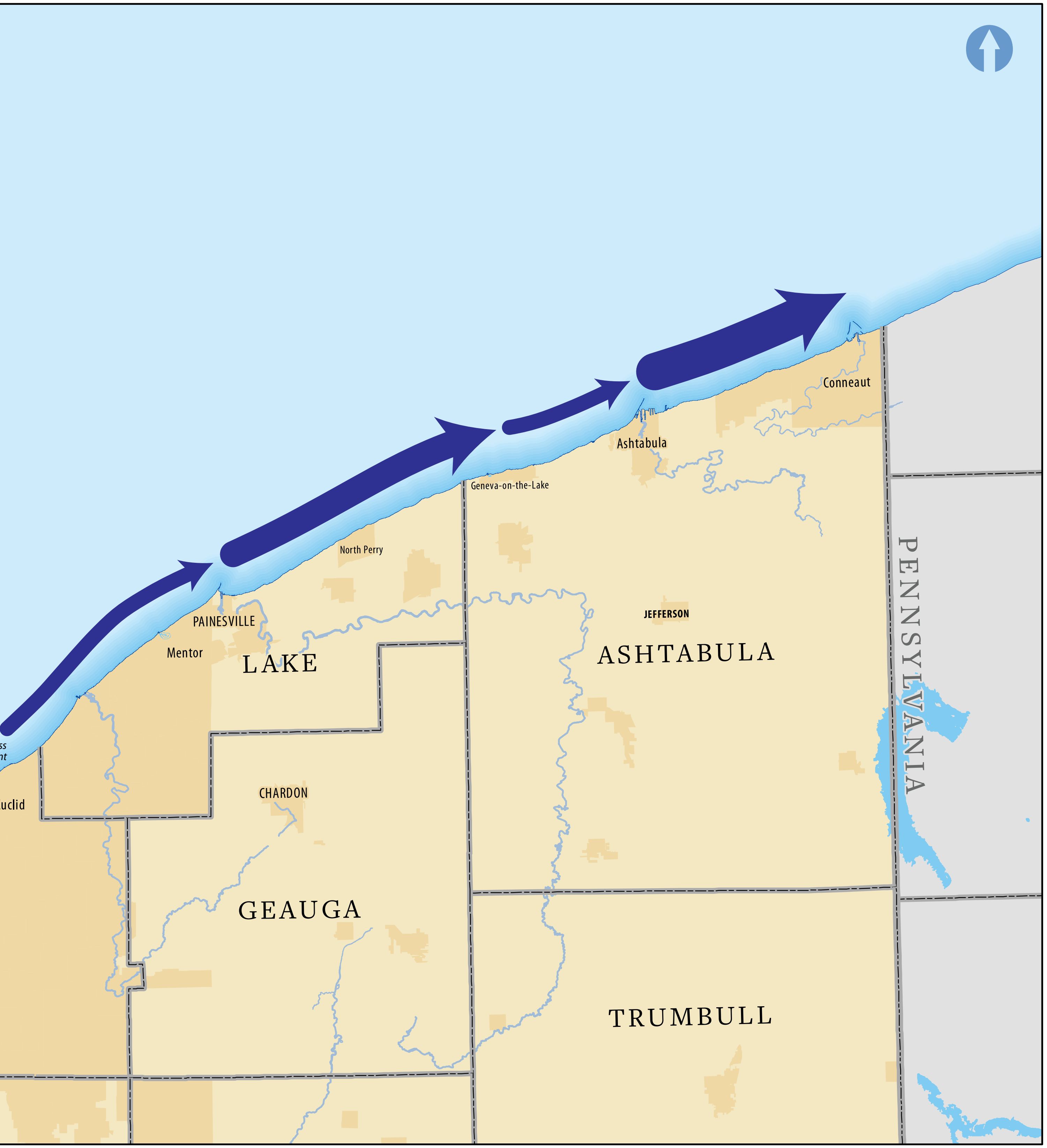
This map shows average surface currents in Lake Erie. Red flow lines represent mean summer circulation and blue flow lines represent mean winter circulation. The grey flow line represents both mean summer and mean winter circulation. Water entering Lake Erie from the Detroit River influences circulation in the Western Basin.

Surface currents tend to follow the direction of prevailing winds and may be amplified by shoreline features, such as harbor structures and peninsulas. Storm events and changing pressure systems can quickly impact and significantly increase or redirect currents. The lake's mean summer circulation is more intricate than its mean winter circulation. Winter currents are almost exclusively determined by wind and are typically stronger than summer currents, especially along the coast. Annual circulation patterns (not mapped) generally resemble the winter average due to greater wind speeds. As compared to ocean currents, average surface currents of all five Great Lakes are relatively weak. Bottom currents typically flow in an opposite direction and generally follow the shoreline and bathymetry (see pages 38 through 41). Reverse flow occurs to offset the displacement of surface water.

Thermal stratification also contributes to Lake Erie currents. Stratification occurs as summer temperatures warm the upper part of the water column. Warm water is less dense than cold water. As a result, denser, cooler water becomes trapped below the warm surface water. Stratification also prevents water from intermixing and can lead to the depletion of oxygen in the bottom layer, called the "hypolimnion." Denser water in the hypolimnion tends to flow as a separate mass and is influenced by reverse displacement currents. For example, south winds causing a north-flowing surface current may result in a south-flowing current in the hypolimnion, effectively moving cooler water closer to the southern shore. The transition layer between the surface water and the hypolimnion is called the "thermocline."

The circulation of water in Lake Erie is also influenced by the earth's rotation. Specifically, the Coriolis Effect causes currents to swirl and curve away from the primary flow. This triggers large-scale rotational circulation patterns, called "gyres." These circular patterns are guided by wind, the thermocline and physical features, such as the shore and bathymetry. Most gyres in the Great Lakes are counter-clockwise, or "cyclonic," however due to the occurrence of an atypical thermocline (deeper toward the center of the lake and shallower near the edge), Lake Erie exhibits a clockwise, or "anticyclonic," gyre in the Central Basin. While a cyclonic gyre is also present in the Central Basin, the lake's mean summer circulation is mostly anticyclonic. The mean winter circulation features a cyclonic gyre along the southern shore and an anticyclonic gyre along the northern shore. Circulation patterns are dynamic and can change—locally or lake-wide—over the course of a few days. Currents and gyres transport fine or suspended sediments, nutrients, algae, pollutants and floating or suspended debris.


MAP LEGEND
Littoral Transport
A 50,000 yd³/yr or more
B 10,00 yd³/yr - 35,000 yd³/yr
C 1,000 yd³/yr - 9,999 yd³/yr
D 100 yd³/yr - 999 yd³/yr
E Less than 100 yd³/yr
Flow lines represent littoral transport rates in cubic yards per year (yd³/yr)
E
D
C
B
A
0 1 2 3 4 5 10 15 20
Miles
ONTARIO
LAKE ERIE
Pelee I.
West Sister I.
North Bass I.
Middle Bass I.
South Bass I.
Kelleys I.
Catawba Island
Cedar Point
Locust Point
TOLEDO
LUCAS
WOOD
OTTAWA
PORT CLINTON
Marblehead
Cedar Point
SANDUSKY BAY
SANDUSKY
SANDUSKY
FREMONT
ERIE
Huron
Vermilion
Lorain
LORAIN
ELYRIA
Avon Point
Avon Lake
Lakewood
CLEVELAND
CUYAHOGA



Littoral transport is the natural movement and redistribution of unconsolidated sediments (mainly sand and sand-sized sediments) along the shore. The two primary ways new sediment enters the littoral system are bluff/shore erosion and discharges from tributaries. Erosion contributes the most material to the littoral system. Lake level changes and ice cover can affect nearshore sediment transport rates.

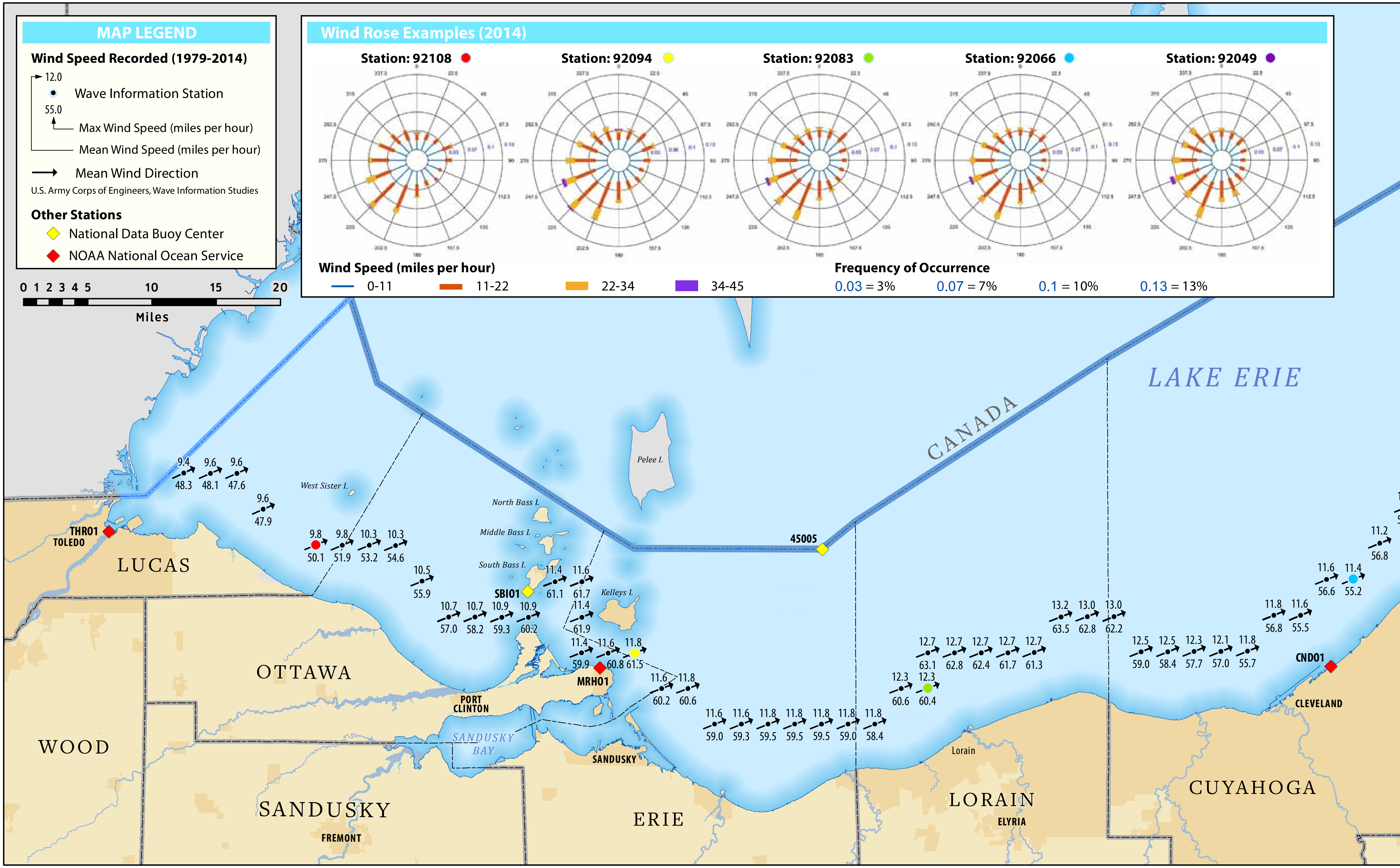
The physical characteristics of a wave, including wave height and wavelength (the spacing between wave crests), are determined by wind speed, duration and fetch (the unobstructed distance wind blows over water). In general, strong, prolonged winds produce larger waves. Longer fetch distances generate greater spacing between wave crests. When incoming waves reach the shore at an indirect angle, a shore-parallel current is formed within the littoral zone. These currents are often referred to as “longshore” or “alongshore” currents. Energy from breaking waves picks up sediment, or “littoral drift,” from nearshore areas and beaches and moves it along the shoreline via the alongshore currents that are generated. Larger waves intensify the littoral current and can transport larger materials, such as pebbles and cobble. Waves that approach the shore at a greater oblique angle transport littoral drift more rapidly.

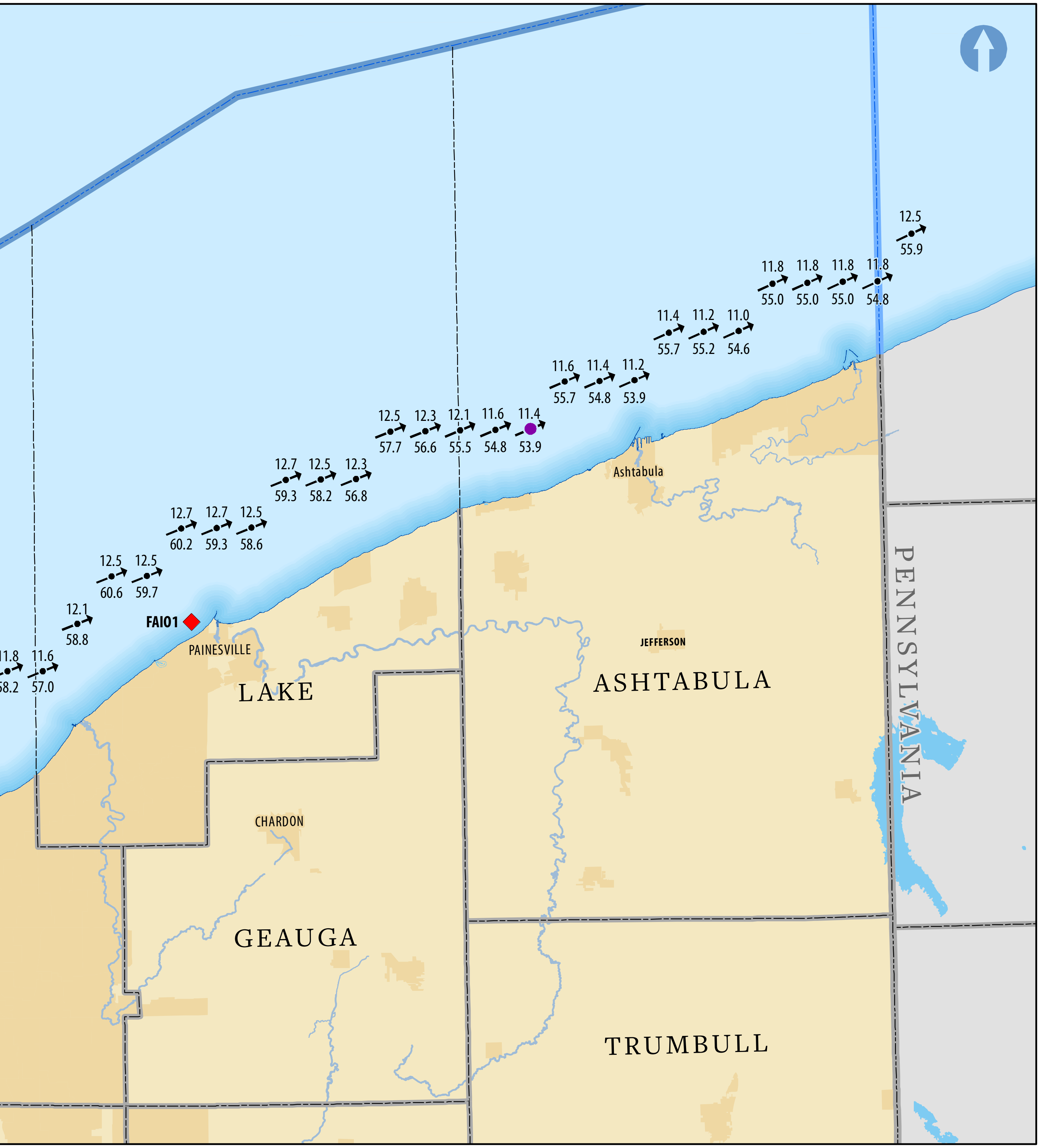
Sediments captured in the littoral current are transported along the coast in a “downdrift” direction. This map shows the general directions littoral currents in the nearshore and net sediment transport amounts. East of Cleveland, the littoral current flows east. Avon Point, Marblehead and Catawba Island are significant headland features where currents diverge or converge. Currents diverge at Avon Point. To the east, the general downdrift direction is east, whereas the downdrift direction to the west—with a few exceptions—is to the west. Divergence also occurs at smaller headlands (e.g. Lakewood and Lorain) and from the embayments at Huron and Vermilion. Zones of convergence are present at Cedar Point (Lucas County), Port Clinton and at the Sandusky Bay entrance.

Line widths represent littoral transport rates in cubic yards per year. The rates illustrated in this map are based mostly on the U.S. Army Corps of Engineers’ Historical Sediment Budget report (2016). Sand transport volumes vary along different stretches of shore. This is due to multiple factors, including bluff composition, erosion rates and shore structures. Shore-perpendicular structures—such as breakwaters, groins and jetties—trap sand and greatly impact sediment transport.

“Cross-shore currents” (not mapped) flow and carry sand in a back-and-forth motion perpendicular to the shore. Sediment that breaks free from these currents may enter the alongshore current. Most cross-shore currents are associated with storm events and are also responsible for sand bar formation in the nearshore. Strong cross-shore currents can push sediments well offshore and permanently out of the littoral system.

RECORDED WIND SPEED AND DIRECTION





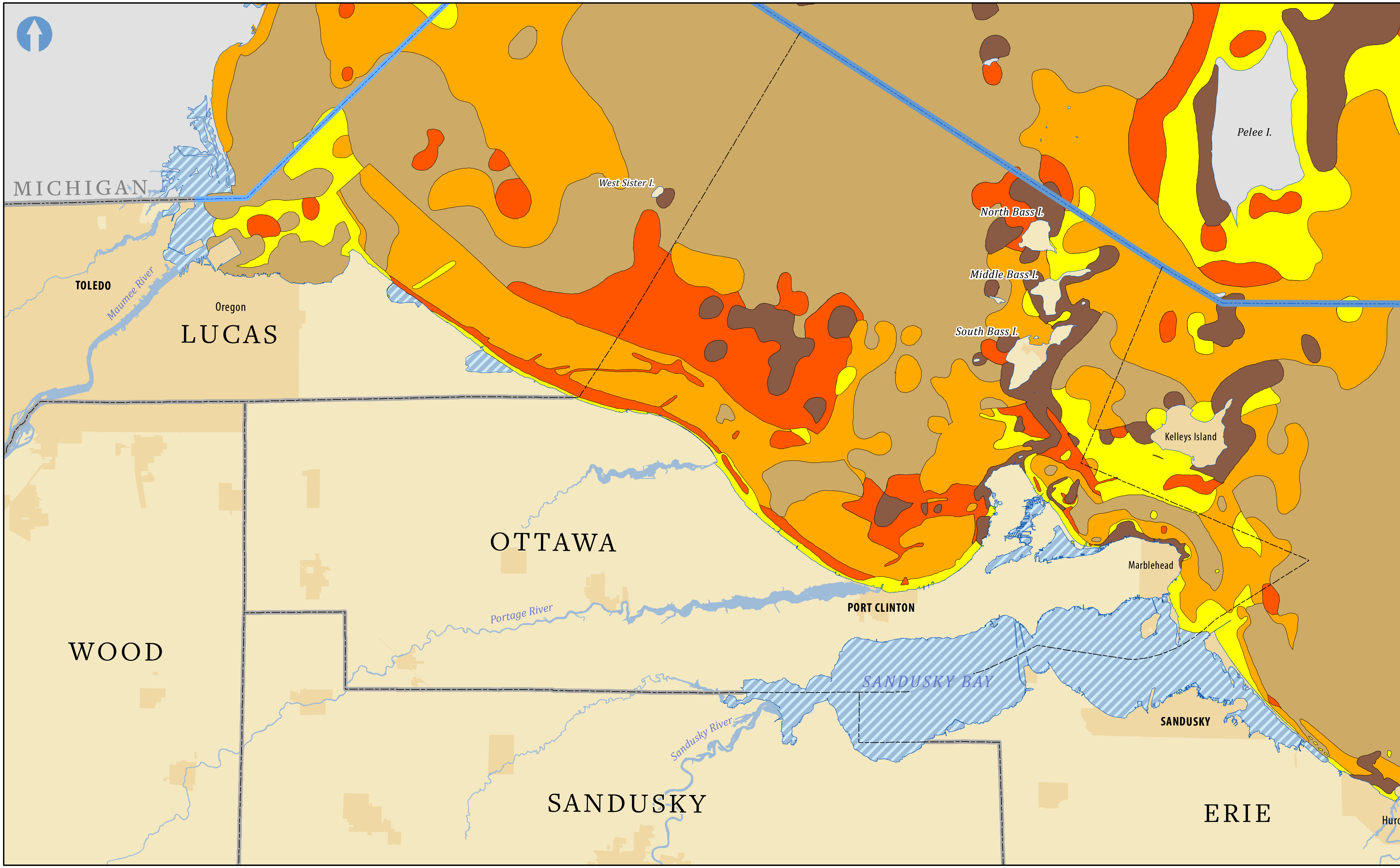
Sponsored by the U.S. Army Corps of Engineers in 1976, the Wave Information Studies (WIS) program was created to provide a nationwide database of comprehensive and consistent, long-term historical wave climate information. **Wave climate** refers to the hourly, daily, seasonal or annual changes in wave height, period and direction. In general, wave climate is the expected range of winds and storms and their ability to create elevated water levels and waves along the shore. Wave information is used to understand littoral currents and sand transport; analyze beach profile changes and bluff/shore erosion; properly design and construct shore structures; respond to hazardous material spills and coastal storm-induced flooding; and support the shipping industry—among other uses.

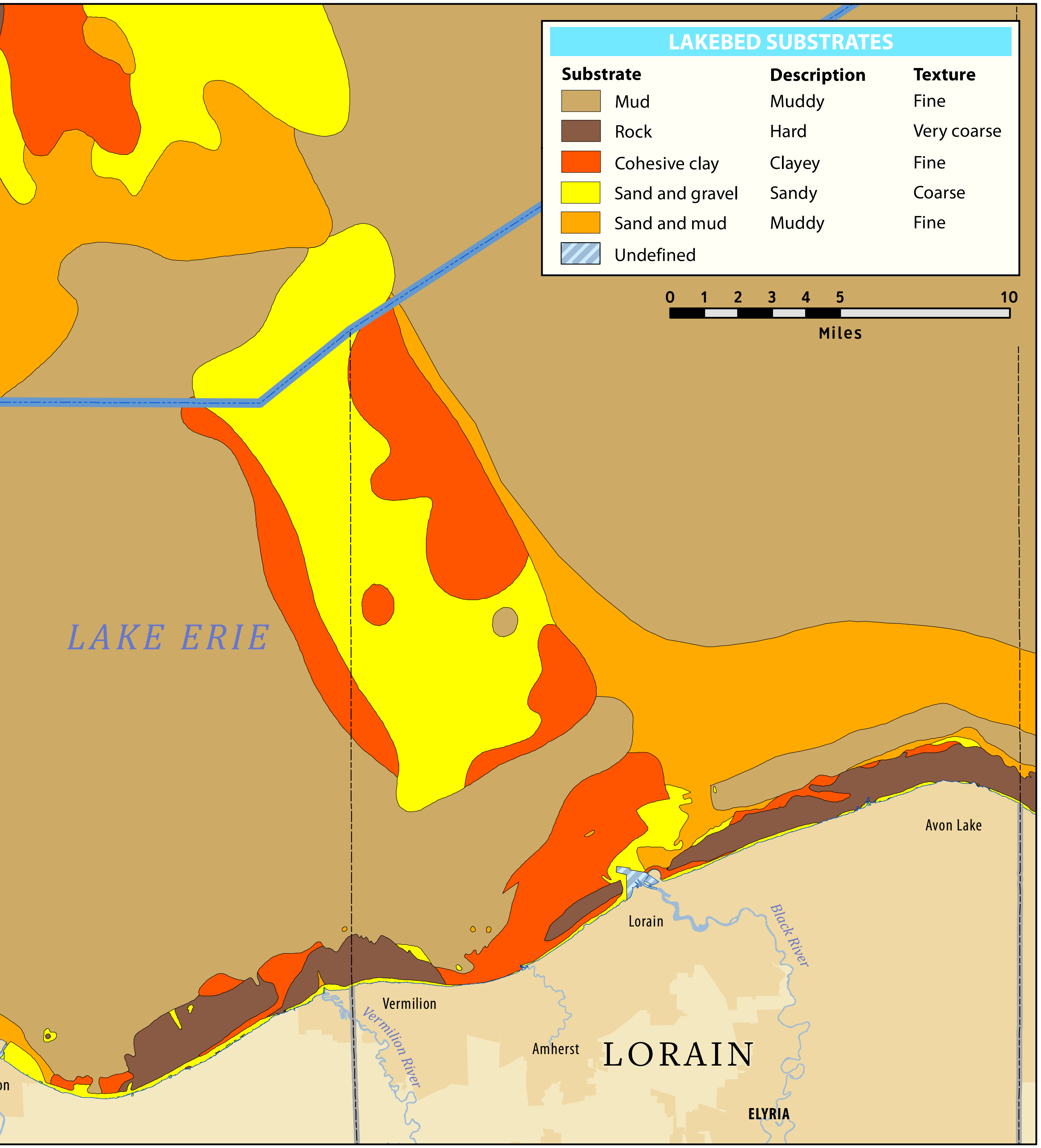
The WIS program originated in the Great Lakes and subsequently expanded to the Atlantic, Pacific and Gulf coasts. The compilation of data is based on multiple decades worth of hindcast modeling, present-day ground and satellite observations and storm event archives. Hindcasting estimates probable historic open-lake conditions at a given offshore location. Information includes hourly wind/wave information, such as wind speed, wind direction and various wave condition values (height, period and direction). While computer-modeled hindcast information cannot predict future conditions, it is generally more accurate than forecast models.

Each wave information station is a fixed computer-generated output point. There are 1,950 'virtual' wave information stations in the Great Lakes (in both the U.S. and Canada), including a network of 243 densely-spaced stations in Lake Erie. This map shows the locations of Ohio's 74 stations. The accompanying wind speed information at each output point is based on observations recorded between 1979 and 2014. The top number indicates the mean wind speed (miles per hour) at that location, while the bottom number identifies the maximum wind speed (miles per hour) recorded at that station. Arrows represent the mean wind direction.

Wind speed, direction and frequency for each output point is graphically illustrated using wind roses (see the five examples on map). A WIS wind rose is similar to a 16-point compass rose: includes cardinal directions (0 degrees to the north, 90 degrees to the east, and so on), ordinal directions (NE, SE, SW and NW) and the eight half-wind directions (NNE, ENE, ESE, SSE, SSW, WSW, WNW and NNW). Wind speed is represented by lines of varying colors and widths. Wind direction is captured on the wind rose spoke that corresponds with where the wind is blowing from. The concentric circles indicate frequency of occurrence; originating from zero at the innermost circle. The longer the wind speed line on a directional spoke, the more frequently wind blows from that specific direction. For instance, in all five examples, winds blowing from the southwest occur more frequently than winds from any other direction. This trend is consistent with the mean wind direction arrows. Wave roses (not pictured) are also produced for each virtual output point. Much the same as a wind rose, wave roses evaluate the probability of wave height and direction and assess wave conditions.

LAKEBED SUBSTRATES (WEST)





The following maps (see also the "East" section on the next page) show lake bottom substrate types in the coastal, nearshore and open-lake zones of Lake Erie. **Substrate** is the material that physically rests on or makes up the bottom of the lake. The data included in these maps is part of a larger Great Lakes substrate mapping effort and features a composite of many surveys and sources, including work from the Ohio Department of Natural Resources (ODNR) Division of Geological Survey, Ohio Sea Grant and the Lake Erie Habitat Task Group (Great Lakes Fishery Commission).

Side-scan sonar is frequently used to map substrate distributions in the lake and is helpful for evaluating fish habitat in the nearshore. It can also be used to locate shipwrecks. In the 1990s, ODNR mapped nearshore substrates using side-scan sonar, extending 0.3 to 2.5 miles offshore. The Lake Erie Habitat Task Group has also used side-scan sonar to identify and map substrate types at multiple nearshore and offshore sites. Sediment sampling and underwater videos help confirm findings.

'Sand and mud' (sandy mud and muddy sand), cohesive clay and mud are prominent bottom types in the nearshore between Cedar Point (Lucas County) and Marblehead. Sandy mud and muddy sand are unconsolidated sediments containing ten to 50 percent and 50 to 90 percent sand, respectively, with a remaining composition consisting of either a one-to-two or two-to-one silt-to-clay ratio. The shore composition in eastern Lucas and Ottawa counties consists primarily of glacial till and lacustrine sediments, which is also prevalent throughout Ohio's flat western landscapes. As wave-based erosion wears away at the shore, sand is sorted and deposited in the nearshore, while finer sediments are suspended and become subject to the littoral current. During periods of calm water, variable amounts of fine-grained silts and clays settle to the bottom and mix with the sand, creating sandy mud and muddy sand substrates.

Minimal sand deposits ('sand and gravel') are present along the Western Basin shore. This is due to the absence of high bluffs, which through erosion, would contribute greater quantities of sand to the littoral system and nearshore. Additionally, low-gradient tributaries that empty into the Western Basin (e.g. the Portage and Toussaint rivers) carry primarily fine-grained sediments and very little sand. Thin sand deposits are found near the Cedar Point headland in Lucas County and along the shore between Reno Beach (Lucas County) and Port Clinton. Extensive deposits of alluvial sand and gravel and the occurrence of sand bar ridges are found along the lower reaches of the Maumee River (not mapped). Sand and gravel is prevalent in Maumee Bay.

Bedrock substrates and higher rock relief are common near and around the Lake Erie Islands. Two distinct bands of erosion-resistant lake-bottom bedrock types occur in this area, including remnant dolomite stretching from Catawba Island to North Bass Island and remnant limestone stretching from Marblehead to Kelleys Island. Outcroppings of bedrock make up the Western Basin Reef Complex which is an important reproductive area for multiple fish species.

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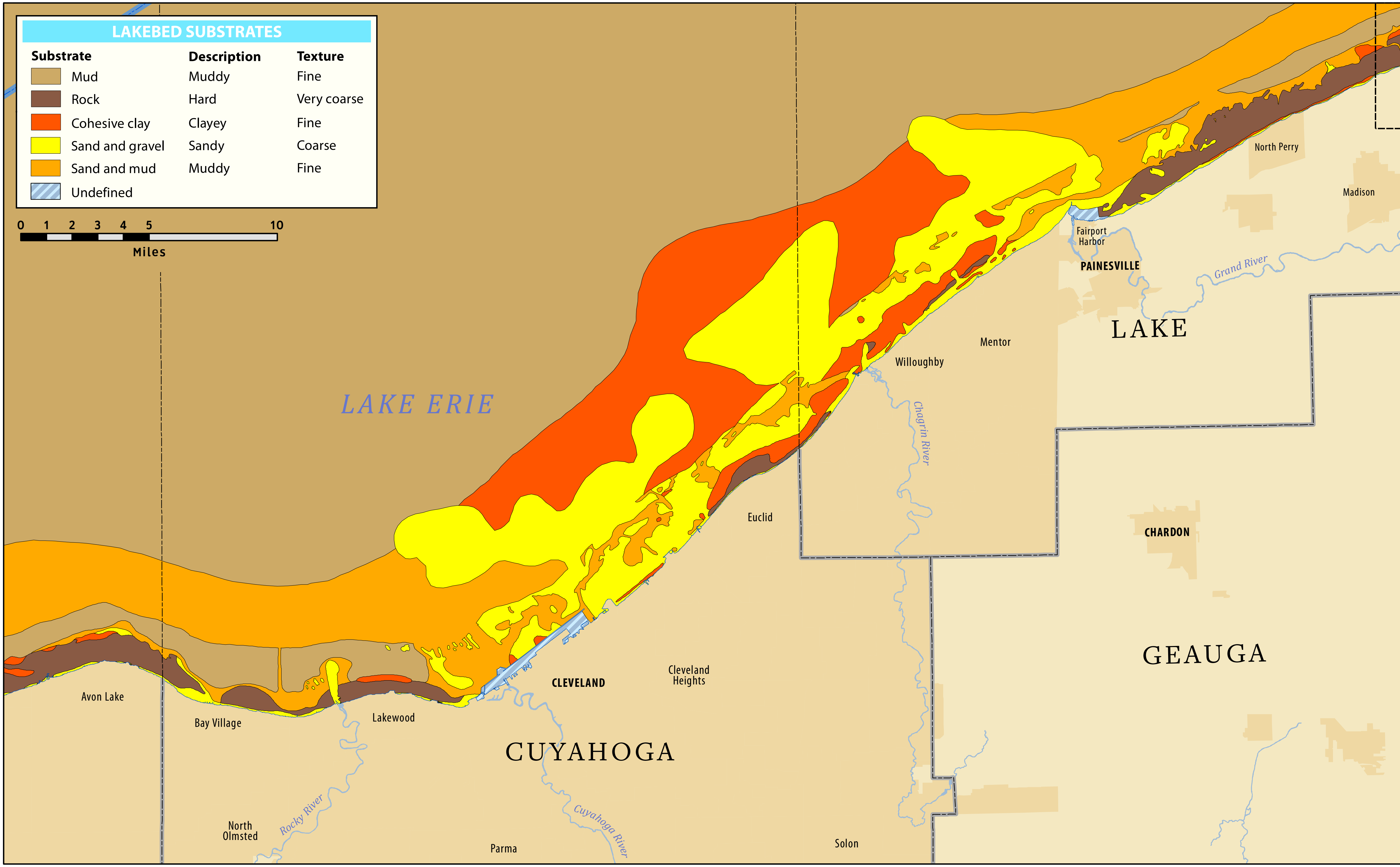
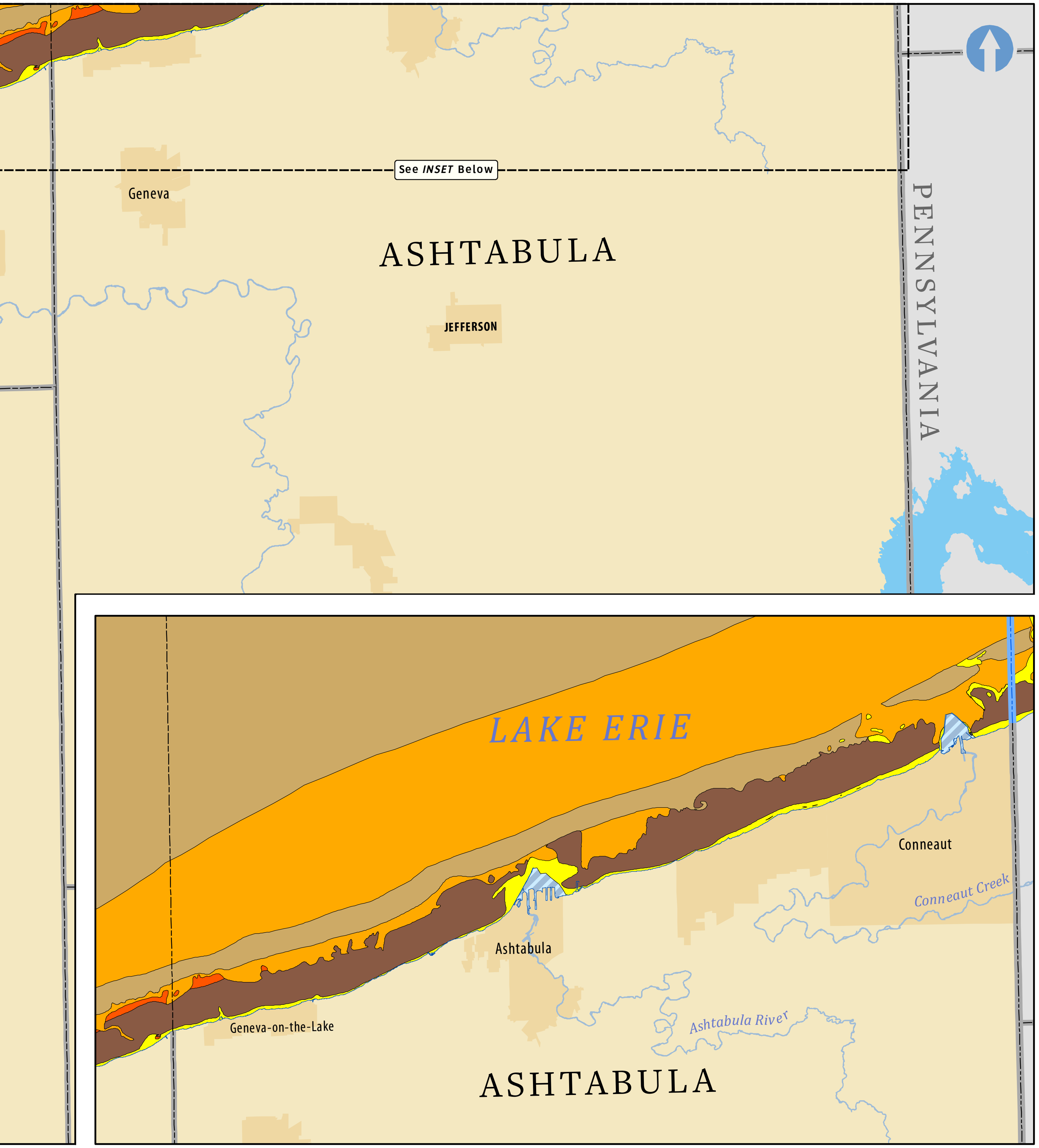
Map 7-4: Lakebed Substrates (West)

LAKEBED SUBSTRATES (EAST)





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Between Huron and Lakewood, exposures of shale in the nearshore occur where the bedrock surface is higher. Along this stretch, significant portions of the bluff are also composed of shale. Sediments from eroded bluffs (between Vermilion and Avon Lake) enter the littoral system and are transported in a downdrift (westward) direction via the alongshore current. Nearshore sand deposits and wide beaches are found along the Cedar Point Peninsula, at the mouth of the Sandusky Bay and east of the Huron River.

Mud is an unconsolidated sediment resulting from the mixture of water and various non-cohesive materials of varying sizes (such as silt and sand). Mud is present in many nearshore areas between Sandusky and Lakewood and between North Perry and Conneaut. This is because the nearshore terrain in these areas is steeper. Nearshore sediments settle in deeper areas and create the mud substrate. Mud is the dominant offshore substrate in the Central and Western basins.

Rock outcrops are prevalent near the shore in the Euclid area and between Fairport Harbor and Conneaut. Shale occurs in the nearshore where bedrock elevations are higher. In eastern Lake and Ashtabula counties, shale rises slightly above lake level in a few locations. Where rock occurs in the nearshore, the bathymetric slope tends to be more gradual and gentler. As a result, water depths near the shore are shallower and waves typically keep the bedrock scoured of any settling material, except for a very thin layer of mud during periods of calm wave conditions. Aquatic vegetation is not common along the Central Basin shore. Nearshore habitat consists of scattered cobble and boulders that favor species like smallmouth bass and the non-native round goby. The lack of sand along the eastern Ohio shore is due to the large harbor structures that trap materials and disrupt littoral transport.

Between Euclid and Mentor, a band of cohesive clay has been exposed due to the loss of sand. A deficiency of sand in the area is likely the result of the adverse impacts caused by man-made barriers, which impede the natural transport of sediments (e.g. Cleveland Harbor structures and shore protection structures east of Cleveland). Sediment deposits from the Cuyahoga River are quickly trapped by harbor structures and settle within harbor. The removal of these materials contributes to the lack of sand. Between Cleveland and Euclid, very little sand enters the nearshore.

The broad expanse of offshore sand (see 'sand and gravel' classification) between Cleveland and Fairport Harbor is derived in part from the deposits made by the Grand River, and likely the Cuyahoga and Chagrin rivers, too (before the installation of harbor structures). Sand deposits are also associated with a relict glacial moraine that extends across Lake Erie to Erieau, Ontario. Lake-bottom terrain and notable bathymetric features are responsible for many concentrations of substrate material within Lake Erie. Such features include the Point Pelee Ridge and Pelee-Lorain Ridge (see the Lake Erie Bathymetry and Landforms map on page 38).

BLUFF CLASSIFICATION (WEST)

The bluffs along Ohio's Lake Erie shore are generally comprised of limestone, dolomite or shale bedrock overlain by layers of glacial till or deposits of glaciolacustrine materials. Glacial till that overlays the bedrock is highly variable, and ranges from very dense and nearly impermeable materials, to lighter, more permeable clay-silt materials and pockets of gravel. Lake-deposited materials also vary greatly, ranging from nonpermeable clays and silts to very permeable sandy clays. Bluffs generally increase in elevation from west to east—mostly between Huron and Conneaut—and can reach heights of 60 feet above lake level. The following maps (see also the "East" section on the next page) show both the physical composition of Ohio's Lake Erie bluffs and bluff elevation. Bluff composition values are illustrated lakeward of the shoreline and bluff elevation values are illustrated landward of the shoreline. Elevations are represented using a six-class color ramp, where lighter reds represent lower relief ranges and darker reds represent higher relief ranges.

Wetlands, narrow barrier beaches, sand spits, low-lying lake plains and low bluffs characterize the shore area in Lucas, Ottawa and Sandusky counties. Most of the shore between Toledo and Port Clinton is composed of cohesive glacial lacustrine clay (lake-deposited sediment and sand). Severe erosion generally occurs where bluff material contains softer cohesive lacustrine clay. Many dikes and other shore-parallel structures have been constructed along the Western Basin shore to protect low-lying areas from erosion and coastal flooding. Cedar Point in Lucas County is a dynamically-fluctuating sand spit derived from the transport of sediments via alongshore currents (see page 172).

East of Port Clinton, bedrock exposed at the surface or buried beneath glacial deposits is mostly Devonian-age limestone or Silurian-age dolomite. Limestone is exposed along the shores of Kelleys Island, Johnson's Island and Marblehead. Dolomite underlies Sandusky Bay and crops out on the west side of Catawba Island and in the Bass Islands. These bedrock types are more resistant to wave-based erosion and slumping. Bluff relief on the west side of Catawba Island ranges from moderate to high (ten to 40 feet). The bluffs on the islands are mostly rocky and low-lying; however, moderately-high bluffs (21 to 30 feet) occur at a few locations. Rocky bluffs are also characteristic on Catawba Island's west side. The east side of Catawba Island is low-lying and consists of less-resistant cohesive glacial till and sand. Pebble, cobble and sand beaches are common between Scott Point (northeast tip of Catawba Island) and East Harbor. Cobble beaches found throughout the Lake Erie Islands/Marblehead area are derived mostly from the limestone and dolomite bluff outcroppings.

Bay Point (Ottawa County) and Cedar Point (Erie County) are both sand spits. These features nearly converge and separate Sandusky Bay from Lake Erie. Like the sand spit at Cedar Point in Lucas County, both have formed due to the transport of sediment via alongshore currents. The southern portion of Bay Point is undeveloped, unprotected and constantly changing. The Cedar Point Peninsula extends in a northwest direction from Erie County, just east of Sandusky.

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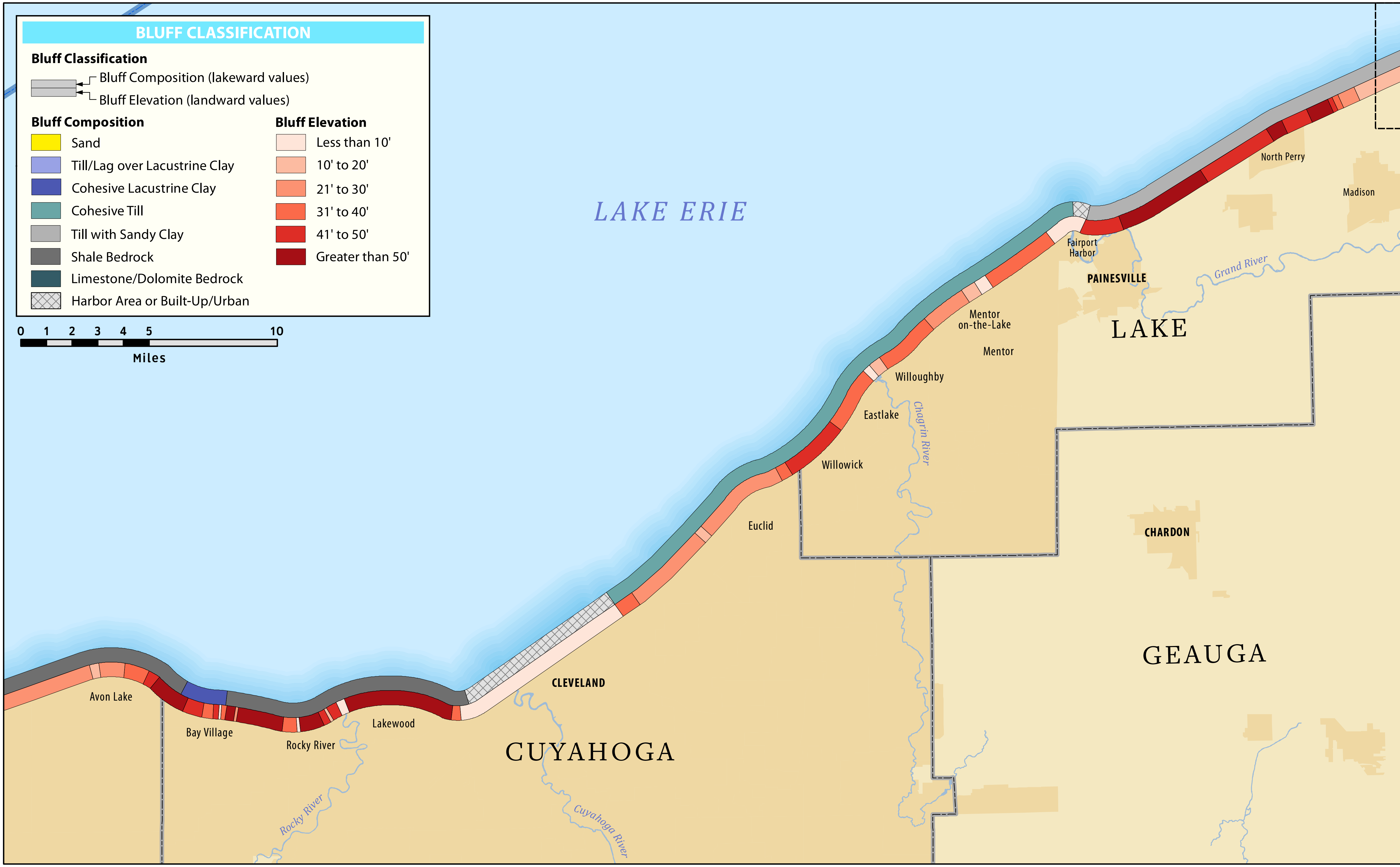
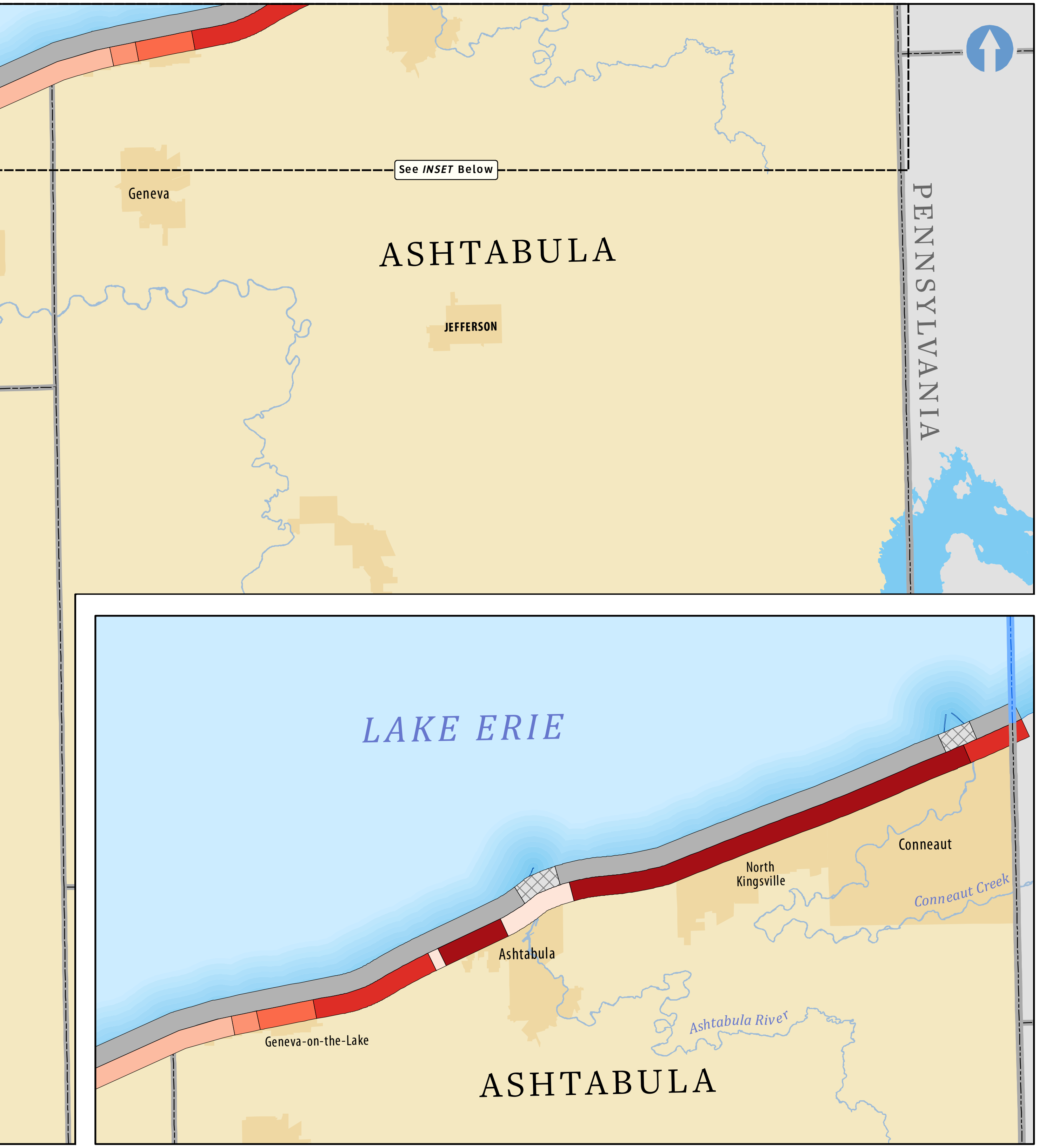
BLUFF CLASSIFICATION (EAST)





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Deposits of sand have historically accumulated along Cedar Point. Sand buildup increased significantly following the installation of the shore-perpendicular jetty at the northwest end of the peninsula in 1914. Southeast of the Cedar Point sand spit is a barrier beach at Sheldon Marsh State Nature Preserve.

The area surrounding Sandusky Bay and the area landward of Cedar Point is relatively low-lying and includes wetland areas. Bluff composition of Sandusky Bay's south shore, including Muddy Creek Bay, consists of till/lag over lacustrine clay. The north shore consists of till/lag over lacustrine clay and cohesive clay. "Lag" deposits are residual coarse-grained materials left behind after finer-grained particles were transported away, either by wind or waves. The western part of Sandusky Bay and Muddy Creek Bay are predominantly wetlands and protected with a network of dikes. In downtown Sandusky, harbor structures and the placement of fill have created a heavily-armored shore and artificial upland areas.

Between Cedar Point and Huron, low-lying areas transition to glaciolacustrine clay and till bluffs that range in height from ten feet to 20 feet. East of Huron, bluff relief begins to increase and ranges from ten feet to 50 feet in eastern Lorain County. Devonian-age shale bedrock is gradually exposed above lake level to the east and along much of the Central Basin shore. Near Vermilion, shale bluffs also include glaciolacustrine deposits and are capped with glacial till. Moderate-relief cohesive clay bluffs occur between Vermilion and Sheffield Lake. Bluff composition transitions to mostly shale at the Avon Point headland in eastern Lorain County. Near-vertical shale bluffs ranging in height from 20 feet to over 50 feet dominate between Avon Lake and Edgewater Park, west of downtown Cleveland.

Bluff relief in the Cleveland Harbor area decreases significantly due to the Cuyahoga River. Harbor structures and the placement of fill have created a heavily-armored shore and artificial upland areas. In some areas between downtown Cleveland and Bratenahl, the natural till bluffs rise hundreds of feet landward of the man-made shore.

Aside from river valleys and smaller swales, relief between eastern Cuyahoga County and Conneaut generally increases from west to east, and ranges from 20 feet to over 60 feet. The greatest relief occurs in eastern Ashtabula County. Bluffs are composed primarily of cohesive till between Bratenahl and the Grand River, while bluffs in eastern Lake County and Ashtabula County are composed of glacial till with sandy clay deposits over shale bedrock that have an elevation near, but typically below, the lake level. Lake-deposited materials along the shore vary greatly, and range from nonpermeable clays and silts to very permeable sandy clays, characteristic to the upper layers in much of Ashtabula County. Porous materials, such as sand and gravel, allow surface water to penetrate the ground and the water table to easily fluctuate. Bluffs with a higher sand content can slump more easily and erode at a faster rate as groundwater escapes.

Map 7-7: Bluff Classification (East)