The Lake Erie Bluff Coast of Pennsylvania:
A State of Knowledge Report on Coastal Change Patterns, Processes, and Management

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Unstable bluffs at a large translational slump in western Erie County where a bedrock toe is absent.

View to the northeast along the Pennsylvania coast of Lake Erie. The bluff coastline of the western coastal reach (in the foreground) is separated from the eastern coastal reach (in the background) by the Presque Isle peninsula and the urban bluff coast of Presque Isle Bay.

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The views expressed herein are those of the author and do not necessarily reflect the views of the Department of Environmental Protection

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Executive Summary

Pennsylvania has approximately 123 km (~76.6 mi) of Lake Erie shoreline, the majority of which is dominated by unconsolidated Quaternary-age bluffs ranging in height from 1.5-55 m (~5 - 180 ft) above lake level. Excluding the beach and wetland shoreline of Presque Isle peninsula, the 73 km of mainland coast is over 90% dominated by bluffs, with the remainder consisting of stream mouths and associated floodplain lowlands. Both coastal geomorphology and long-term records of coastal change show that erosion is a pervasive problem along the Pennsylvania bluff coast of Lake Erie. Based on an intermediate- to long-term (almost four decade) bluff monitoring program run by the Pennsylvania Department of Environmental Protection (PA DEP), the average rate of bluff-crest retreat for the entire Pennsylvania coast is ~0.16 m/yr (0.54 ft/yr). Average rates show significant variability with location and with the duration of the data sets. However, rates are on average higher in western Erie County (e.g., 0.29 m/yr; 0.96 ft/yr in Springfield Township) than elsewhere.

Approximately 34 million people live within the Great Lakes Basin, and about 12 million of those people live in the Lake Erie watershed. Populations in coastal counties nationally have been increasing at a rate of about 10% per decade, and population densities in coastal counties are now about six times greater than those of inland counties. In Pennsylvania, it can therefore be expected that problems associated with bluff retreat on the Lake Erie coast will continue to be an issue that will affect progressively more people over the next several decades. Fundamentally, the challenge in dealing with bluff erosion issues on the agricultural/urban Lake Erie coast is to continue to effectively manage the *natural coastal erosion - coastal population growth* nexus that is an underlying cause of problems in many global coastal regions. The challenge is greater on bluff coasts because bluff erosion is irreversible and the potential for sudden and catastrophic failure events is higher than for low-relief beach and wetland coasts. Because measures taken to reduce bluff erosion impact natural resources and human populations to varying degrees, the challenge is to maintain a flexible balance between conserving the natural environment and meeting the needs of growing coastal populations going forward.

This *State of Knowledge (SOK) Report* is an initial deliverable for a multi-component three-year (2015-2018) *Pennsylvania Great Lakes Services Integration Project (PGLSI)* funded by the Commonwealth of Pennsylvania, Department of Environmental Protection. Given the economic and environmental impacts associated with bluff retreat, and the potential for future acceleration in bluff-retreat rates on the Lake Erie coast, there is a need for high-resolution bluff monitoring data, better understanding of bluff dynamics, and updated bluff management guidance for municipalities and property owners. This *State of Knowledge Report* reviews the international literature pertaining to cohesive bluff coasts with a specific focus on the state of bluff science, engineering, and management. The report identifies gaps in scientific/engineering data and knowledge concerning: (i) bluff behavior and change mechanisms in the natural environment; (ii) forcing agents and mechanisms that induce bluff instability; and (iii) methods and practices in bluff monitoring, analysis, prediction, and hazard management. The *SOK Report* findings are then used to develop a suite of constructive recommendations relating to bluff erosion issues on the Lake Erie coast of Pennsylvania. The findings and recommendations are the outcome of an extensive literature review and may be incorporated into future coastal hazard management in Pennsylvania's Bluff Recession Hazard Areas. They may also help guide needed future geotechnical research on the NW Pennsylvania coast. Specifically, the *SOK Report*:

- Reviews the current understanding of, and identifies knowledge gaps in, coastal-change processes, causes, management, and forecasting on bluff coasts in the United States with a specific focus on Pennsylvania.
- Identifies and makes recommendations on information needed for the Pennsylvania Lake Erie coast in order to improve the quality and quantity of science information that may be used to help strengthen the scientific basis of future coastal management decision-making.
- Identifies a nationally-developing best-management practice (BMP) methodology for delineating bluff setback distances. Pennsylvania may consider adopting this more conservative approach (or a variation on it) in future delineation of setback buffers in the interests of reducing the economic risk associated with continued and possibly enhanced rates of bluff retreat on the Lake Erie coast.
- Incorporates an extended bibliography covering peer-reviewed, white-paper, agency, and other literature on coastal-bluff change, management, and policy with a focus on North American bluff coasts.
- Is being published online so that it is accessible to interested stakeholders and coastal planners via the Pennsylvania Great Lakes Water and Land Technical Resources Center (WALTER), a later web-interface deliverable for the PGLSI Project.

The general outline for the *State of Knowledge Report* is as follows:

Chapter 1: Study Description - reviews the scope and rationale for the *SOK Report* and the *PGLSI Project*; bluff retreat processes and how Bluff Recession Hazard Areas (BRHAs) are identified in Pennsylvania; the significance of the bluff crest as the mapping feature of choice; general bluff-change monitoring practices in Pennsylvania and the United States; and the general three-part geomorphic organization of the Pennsylvania coast.

Chapter 2: Management of Bluff-Related Issues by State Coastal Management and Affiliated Environmental Agencies: A Summary Snapshot from 2016 – compiles and summarizes coastal zone management issues related to bluffs for each of fourteen ocean and Great Lakes states through review of coastal hazards information from the most recent (2016-2020) NOAA Section 309 reports and agency web sites.

Chapter 3: State of Knowledge on the Coastal Setting, Geology and Stratigraphy of Pennsylvania's Lake Erie Bluffs and Nearshore Waters - summarizes what is known and not known about the geology and dynamics of the offshore lakebed-to-bluff hinterlands zone along the Pennsylvania coast.

Chapter 4: State of Knowledge on Bluff Stability in the Great Lakes Basin and Lake Erie - reviews bluff-retreat processes in the Great Lakes, rate-of-change and process studies in Pennsylvania, and the significance of groundwater dynamics in bluff retreat on the Pennsylvania coast.

Chapter 5: State of Knowledge on Lake Erie Climate Change and Water Levels - examines recent findings on expected climate-change impacts for the Pennsylvania coast of Lake Erie, the role of lake levels in bluff instability, and the almost three centuries (1722-2105) of lake-level records for Lake Erie.

Chapter 6: National and Regional Efforts to Mitigate Bluff Retreat - reviews current engineering, bioengineering, and biotechnical practices used nationally to mitigate the adverse effects of bluff erosion, and provides an aerial-photo tour of the Pennsylvania coast to illustrate methods commonly used to mitigate bluff instability problems.

Chapter 7: Current Trends in Monitoring and Modeling Coastal Bluff Retreat - examines three broad approaches used in monitoring and analyzing bluff retreat and in estimating future bluff-crest positions, specifically (i) classic deterministic methods, (ii) process-response models, and (iii) Bayesian probabilistic modeling.

Chapter 8: Current Practices and Trends in Bluff Setback Determination in North America - reviews three general approaches used to estimate appropriate construction-setback distances on bluff coasts to reduce the adverse impacts of bluff retreat.

Chapter 9: Data Gaps, Data Needs, and Research Questions for the Lake Erie Bluff Coast of Pennsylvania - provides a listing of over 40 data gaps, data needs, and research questions relating to bluff erosion on the Pennsylvania coast that are derived from the literature review.

Chapter 10: Conclusions and Technical/Management Recommendations for Bluff-Retreat Issues on the Lake Erie Bluff Coast of Pennsylvania - provides a set of eight recommendations intended to highlight areas where an increased level of knowledge on the management, science, and engineering of Pennsylvania's bluff coast may lead to improved coastal resiliency, help form a stronger basis for future coastal management and decision-making, and increase stakeholder awareness.

Chapter 11: Glossary of Bluff-Related Terms and Definitions for the Great Lakes and Pennsylvania Coasts - provides common definitions for coastal zone terms used throughout the report.

Chapter 12: Extended Bibliography - provides a listing of the literature used in this report or otherwise available through 2016, as a coastal information resource that focuses on bluff-retreat science, engineering, and management.

In the concluding chapter of this report, *Chapter 10: Conclusions and Technical/Management Recommendations for Bluff-Retreat Issues on the Lake Erie Bluff Coast of Pennsylvania*, eight bluff-management related recommendations are made that are pertinent to the Pennsylvania. The recommendations are based on data gaps and needs identified in *Chapter 9: Data Gaps, Data Needs, and Research Questions for the Lake Erie Bluff Coast of Pennsylvania* from a review of the literature on coastal bluff-retreat in the Great Lakes Basin and on US ocean coasts. While listed in no specific order, the emphasis is on science needs with the intent that addressing these needs over time can lead to better coastal management in areas such as: (i) defining better science- and engineering-based construction setbacks; (ii) identifying preferred engineering, bioengineering, and biotechnical solutions to slope instability and erosion; (iii) developing probabilistic models of future bluff-crest positions rather than relying on retrospective trend methods; and (iv) improving the quantity and quality of general and technical coastal-science information that is available to the public and coastal stakeholders. The *SOK Report* recommendations, discussed in more detail in *Chapter 10*, are summarized here as follows:

Recommendation 1: Continue to improve coastal-hazard information access for stakeholders and the general public. Existing and historical information on coastal stratigraphy, geotechnical properties, and the magnitude of bluff-failure hazards in Erie County, beyond a generally qualitative level, is scarce and insufficiently centralized and cross-referenced. This limits data accessibility needed for effective coastal planning, hazard mitigation, and increasing coastal resiliency. It also limits availability of information that may be important to buyers, sellers, and realtors involved in coastal (near-bluff) property transactions.

Recommendation 2: Provide more proactive technical information for planners and contractors. This will help meet planning, development, and conservation needs among city and municipal planning agencies, coastal contractors, and regulatory agencies. States such as Ohio and Wisconsin, for example, provide stakeholders and coastal contractors navigating the permit-design-build process with web-based information and calculators (Chapter 2).

Recommendation 3: Acquire a higher spatial density and broader coverage of bluff stratigraphic, hydrodynamic, and geotechnical data to facilitate future coastal modeling. For more effective long-term bluff-retreat mitigation planning and bluff-adjacent development planning, a significant quantity of new geotechnical, hydrodynamic, and stratigraphic data needs to be collected at an appropriate sampling scale.

Recommendation 4: Expand coordination efforts as a means to efficiently acquire and share data. Increasing coordination among research organizations; municipal, state, federal, and provincial agencies; and contractors working on Lake Erie is beneficial because it facilitates access to ongoing and future data collection and analysis that may be pertinent to bluff issues on the Pennsylvania coast.

Recommendation 5: Consider transitioning to better science-based methods for determining setback distances from the bluff crest. Current methods used to define construction setbacks along the bluff coast are functional and meet current needs, but are not state-of-the-art and should be improved as coastal population pressures increase (Chapters 7 and 8). The current methodology, which relies on a retrospective deterministic approach to estimate future bluff-crest locations, is being replaced by improved methodologies in other coastal states that add allowances for a stable slope angle and a building relocation buffer.

Recommendation 6: Acquire detailed bluff stratigraphic and geotechnical information at the individual- to multiple-property scale, if possible, through the construction permitting process. While this is challenging and likely impractical in the near term, an increasing number of municipalities elsewhere (e.g., in California) recommend or require a site geotechnical investigation by a licensed civil engineer or engineering geologist when determining setbacks on a bluff property as part of a construction permit application (Chapter 2). This information would then become part of the *Recommendation 2* resource.

Recommendation 7: Acquire detailed bluff stratigraphic and geotechnical information at representative sites in each of 10-15, geomorphically similar, coastal segments. If Recommendation 6 concerning bluff geotechnical characterization at the property-parcel scale is not feasible, obtaining that information at the multi-property to watershed (or coastal segment) scale may be more practical.

Recommendation 8: Consider modifying construction setbacks along the coast to reflect different bluff failure mechanisms, and associated magnitudes of bluff crest retreat, on different coastal segments. Based on a review of the PA DEP database of oblique coastal aerial photography, bluff failure mechanisms and magnitudes of bluff retreat vary significantly by coastal segment. For example, translational slumps appear to be more common along the western coastal reach while rotational slumps appear more common along the eastern coastal reach (Chapters 4 and 6).

While prevalent along the Pennsylvania coast, bluff retreat is a normal and natural process common to non-cohesive bluff coasts worldwide. However, this process often impacts coastal populations through landslide hazards and land and infrastructure losses, and is often enhanced by anthropogenic activities. Bluff-retreat processes remain difficult to quantify which makes it difficult to predict the future location of a bluff crest, bluff face, or bluff toe. This difficulty exists because:

- there are numerous variables that influence bluff retreat rates and magnitudes at a given site
- failure events, by often decreasing the bluff-face slope, may increase bluff stability until a bluff-toe accumulation of protective debris is removed by hydrodynamic forces and ice movement

- bluff behavior along a coast and over time can vary greatly due to changes in internal geotechnical properties governed by geology and climate
- the significant factors determining bluff retreat rate vary with location on a coast and with time

What is not yet known for the Lake Erie coast is the relative or absolute importance of the different factors driving bluff failure along different segments of coast. Determining whether a bluff retreats because of subaerial processes, because of hydrodynamic processes, or because of some combination of the two, remains difficult to establish with precision.

Climate-driven trends in bluff erosion for the Pennsylvania coast through the end of the century remain difficult to predict, largely because of climate data limitations, a lack of climate-model resolution, and feedbacks in climate and earth-surface systems that are not yet sufficiently well quantified. The general consensus among climate models for the Great Lakes Basin, however, is weighted towards an expected decline in the level of Lake Erie, potentially of as much as 0.5 m (~1.7 ft) by 2080 (Chapter 5). A decline in lake level is generally beneficial for bluff coasts because the shoreline and zone of breaking waves shift lakeward, away from the bluff toe (Chapter 2). With nearshore lakebed gradients of ~1:100 on the Pennsylvania coast, a 0.5 m drop in lake level would allow the shoreline to move lakeward by tens of meters, over a time period that may be two orders of magnitude greater than that seen seasonally. This will reduce the amount of toe erosion that can occur and can also allow accumulation, with sufficient sediment supply, of a larger protective beach.

Declining Great Lakes water levels through the end of the century are expected to occur primarily because of the likely continuation of an observed historical increase in atmospheric temperatures that affect the hydrologic cycle (Chapter 5). Increased evaporation because of higher temperatures alone will cause lake-level to fall. However, this process will likely be accompanied by erosion-enhancing feedbacks related to atmosphere-geosphere temperature differences (even if just for the initial decades). These feedbacks are expected to cause increased storminess in the Great Lakes Basin, which will permit larger waves to occur more of the time. This will in turn permit more wave energy to reach the shoreline, increasing erosion. Evaporation will also increase due to less open-lake and coastal ice (extent; duration) in winter (Chapter 5). This will permit larger fetches, coupled with stronger winds, to also favor larger waves that can cause increased erosion during a time of year when the shore is frequently frozen fast. Precipitation patterns are also expected to change in Pennsylvania and the Lake Erie basin (Chapter 5). Increased precipitation, larger and more frequent precipitation events, an increase of precipitation in the form of rain (in winter), and a decline in the number of frozen-ground days, may cause increased recharge of surficial coastal aquifers. Depending on the degree of sediment saturation, this can increase rates of bluff retreat (Chapter 4). Increased precipitation frequencies and magnitudes will also lead to increased surface runoff via streams and across the bluff face. This can increase erosion due to increased development of rills, gullies, soil creep, vegetation-mat slumps, and stream-bank instability.

Nationally, GIS is the dominant analytical tool used in coastal-change monitoring, analysis, and prediction. Analysis of historical and present bluff geometry and rates of change using state-of-the-art remotely sensed data (LiDAR; ortho-rectified aerial imagery) within a GIS framework is the state of the science at the national level. Continued use of this approach in Pennsylvania is allowing acquisition of the high-quality data that are needed to strengthen the scientific framework behind sustainable coastal development in municipalities along Lake Erie. The concomitant growth in digital coastal databases will provide input for any future predictive and probabilistic bluff-position modeling on the high-relief Pennsylvania coast.

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Chapter 1: Study Description

Introduction

Pennsylvania possesses approximately 123 km (~76.6 mi) of Lake Erie shoreline, and the geomorphology of its coastal zone is dominated by unconsolidated Quaternary-age bluffs that range in height from 1.5-55 m (~5 - 180 ft) above lake level. The coast along the short central sector, in the vicinity of Erie, also includes a large shore-attached offshore sand spit or strandplain (at Presque Isle State Park) separated from the mainland bluffs by Presque Isle Bay. Excluding the Presque Isle shoreline, the ~73 km mainland coast consists almost entirely of bluffs. Coastal geomorphology and long-term records of coastal change show that erosion is a pervasive problem along the majority of the Pennsylvania bluff coast of Lake Erie (Figure 1.1).

Figure 1.1: *The geographic setting of Lake Erie, the North American Great Lakes, and the Great Lakes watersheds (Image: modified from New York Sea Grant; http://seagrant.sunysb.edu).*

Project Scope and Rationale

Globally, about 45% of the world population lives within 160 km (100 mi) of a coast. In the United States, about 40% of the population lives in coastal counties, occupying almost 10% of the total US land area. Populations in these coastal counties have been increasing at a rate of about 10% per decade, while the population density is approximately six times greater than that of inland counties and continues to increase (www.noaa.gov). On the Lake Erie coast of northwest Pennsylvania, similar but more subtle trends in Erie County populations can be seen: within the county, populations of municipalities along the coast are generally increasing (2000-2010 period; ECDPS, 2012). It can therefore be expected that problems associated with coastal bluff retreat on the Pennsylvania coast of Lake Erie will become an issue that impacts progressively more people over the next several decades and beyond.

This State of Knowledge Report is an initial deliverable for a multi-component three-year (2015-2018) *Pennsylvania Great Lakes Services Integration* (PGLSI) Project funded by the Commonwealth of Pennsylvania, Department of Environmental Protection. Given the economic and environmental impacts associated with bluff retreat, and the potential for future changes in bluff-retreat rates on the Lake Erie coast, there is a need for updated bluff retreat-rate data; bluff retreat indices; and bluff management guidance for municipalities and property owners. The goal of this State of Knowledge component of the project is to conduct a literature review with a specific focus on the state of the science, and identify current gaps in scientific data and knowledge. The report focuses on: (i) bluff behavior and change mechanisms in the natural environment; (ii) forcing agents and mechanisms that induce bluff instability; and (iii) methods and practices in bluff monitoring, analysis, prediction, and hazard-management. The SOK Report then develops a suite of constructive recommendations relating to bluff erosion issues on the Lake Erie coast.

This State of Knowledge Report is the outcome of an extensive literature review and concludes by identifying scientific data needs and making recommendations that may help guide future research on the NW Pennsylvania coast and be incorporated into future hazard management in Bluff Recession Hazard Areas. Specifically, this report:

- Reviews the current understanding, and identifies knowledge gaps that exist in that understanding, of coastal-change processes, causes, management, and forecasting on bluff coasts in the United States with a specific focus on Pennsylvania.

- Identifies and makes recommendations on information needed for the Pennsylvania Lake Erie coast in order to improve the quality and quantity of science/engineering information that may be used to help form the basis of future coastal management decision-making.

- Identifies a nationally-developing best-management practice (BMP) methodology for delineating bluff setback distances that Pennsylvania may consider for future adoption in the interests of reducing the economic risk associated with continued and possibly enhanced rates of bluff retreat on the Lake Erie coast.

- Incorporates an extended bibliography covering peer-reviewed, white-paper, government/agency report, and other literature on coastal-bluff change, management, and policy with a focus on North American bluff coasts.

- Is being published online so that it is accessible to interested stakeholders via WALTER, a later web-interface deliverable for the PGLSI Project.

Additional significant follow-on components (deliverables) of the PGLSI Project include:

- Calculation of bluff retreat rates and identification of hazard areas along the Pennsylvania Lake Erie bluff coast based on GIS analysis of ground survey, ortho-rectified aerial photography, and LiDAR data from 2008, 2012, and 2015. Long-term bluff retreat rates (1938-2015) are also calculated by incorporating bluff-crest mapping data provided by the US Army Corps of Engineers (Cross et al., 2016).

- Generation of hydrology and watershed-boundary shape files to allow calculation of bluff retreat rates for each of the Pennsylvania Lake Erie sub-watersheds. The analysis methods, including use of the ArcGIS-based DSAS (Thieler et al., 2009), are consistent with methods being used nationally to quantify the occurrence and severity of coastal erosion and upland loss in regions as geographically and geologically diverse as California, Georgia, Hawaii, Oregon, Pennsylvania, Washington, and Wisconsin.

- Development of a Bluff Erosion Potential (BEP) Index to assist planners and property owners. The BEP Index will identify factors that are likely to be the most significant contributors to bluff erosion on the Pennsylvania Lake Erie coast. The tool will utilize a geometric-process approach that incorporates information on bluff retreat rates, existing and stable bluff slope angles, soils, geology, coastal structures, and inferences on groundwater flux to estimate the erosion potential along short coastal sectors (watershed to municipality scales).

- Development of a Pennsylvania Lake Erie Bluff Management Guide. The Guide will be designed to enhance existing services and information provided to municipalities and coastal property owners by PA DEP. The guide will include stormwater and wastewater guidance for municipalities, present the results of the bluff retreat analysis, describe the BEP Index, and provide recommendations and priorities for bluff management. The Guide will also compliment the Vegetative Best Management Practices Manual developed by Cross et al. (2007).

- The State of Knowledge Report, bluff retreat analysis data, the Bluff Management Guide, and the Bluff Erosion Potential Index will be web-hosted on a Pennsylvania Great Lakes Water and Land Technical Resources Center (WALTER) that will be constructed and come online towards the end of the project.

Bluff Recession Hazard Areas

Coastal zone areas where the rate of bluff retreat creates a substantial threat to the safety or stability of nearby existing or future structures or utility facilities are classified by the Pennsylvania Department of Environmental Protection (PA DEP) as lying within the Bluff Recession Hazard Area (BRHA) under the Bluff Recession and Setback Act (1980) (PA DEP, 2013). Within BRHAs, first established in 1980, any planned new construction and significant modifications to existing structures are subject to meeting a minimum bluff setback distance (MBSD) requirement under BRSA (1980). In the state regulations, the minimum height (relief) criterion for a coastal landform in order that it qualify as a bluff is set at 1.5 m (5 ft; Figure 1.2). Other coastal states with bluff erosion issues use a similar height-based definition. The BRHA excludes bluff areas where the bluff toe is greater than 76 m (250 ft) from the shoreline's Ordinary High Water Mark (OHWM is 174.7 m or 573.4 ft, IGLD 1985) or from a more lakeward bluff crest (in a tiered bluff case).

The Lake Erie coast (Figure 1.3) includes 56 stream mouths and associated floodplain lowlands that may locally lie outside of the BRHA; recreational, commercial and industrial waterfront; public-access points; and private and community properties within the City of Erie and eight municipalities along the lakefront. Land loss and a long-term record of bluff retreat along most of the coast threaten Pennsylvania's coastal economy due to losses of property, tax base, coastal agricultural land, recreational opportunity, and ecosystem services. The Erie County Department of Public Safety (ECDPS) recently conducted an analysis of at-risk buildings and property lying within Erie County's BRHAs (ECDPS, 2012). The analysis used decades of bluff-retreat data from the PA DEP bluff monitoring program, and building footprint and tax assessment data provided by Erie County. A conservative planning horizon of 100 years was chosen, to coincide with the largest of three structure lifespans used by the state to calculate the MBSD referenced in the BRSA (1980) regulations.

Figure 1.2: *Typical appearance of a low coastal bank (left) and a high coastal bluff (right) in eastern Erie County, west of Twentymile Creek and east of Twelvemile Creek, respectively. Groundwater is exiting a spring developed in late Pleistocene beach-ridge strata in the top-right corner of the bluff in the right image, causing sapping and headwall steepening (Images: from April 2015; available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

The ECDPS (2012) analysis showed that 265 structures were at risk of significant damage or complete destruction from coastal erosion over the next century. The buildings were distributed among all eight municipalities and the City of Erie, with about two-thirds of the projected economic losses occurring in western Erie County where bluff-retreat rates are in general higher. The 265 buildings had a total value of ~$27 million which, when added to the at-risk land areas associated with those buildings, resulted in a total at-risk real estate value of ~$66 million. In a separate study, the Pennsylvania Winery Association (2009) documented that Pennsylvania ranks within the top five US states in grape production. Much of this production occurs within 5 km of the Lake Erie coastline and would be susceptible to potential economic losses associated with bluff retreat. In 2007, viticulture contributed ~$2.4 billion (directly and indirectly) to the state economy.

The Pennsylvania Coastal Resources Management Program (CRMP) identifies beach erosion and bluff retreat as two of the most significant environmental problems on the Pennsylvania coast of Lake Erie. To paraphrase Chapter 85 of the Pennsylvania Code, bluff retreat is defined as the loss of material along a bluff face caused by the direct or indirect action of one or a combination of forcing agents, including groundwater seepage, littoral currents, wind-generated waves, and high water levels. These subaerial and hydrodynamic forcing agents have the potential to significantly modify the beach, bluff toe, bluff face, and adjacent uplands (tablelands) over various time scales (Figure 1.4).

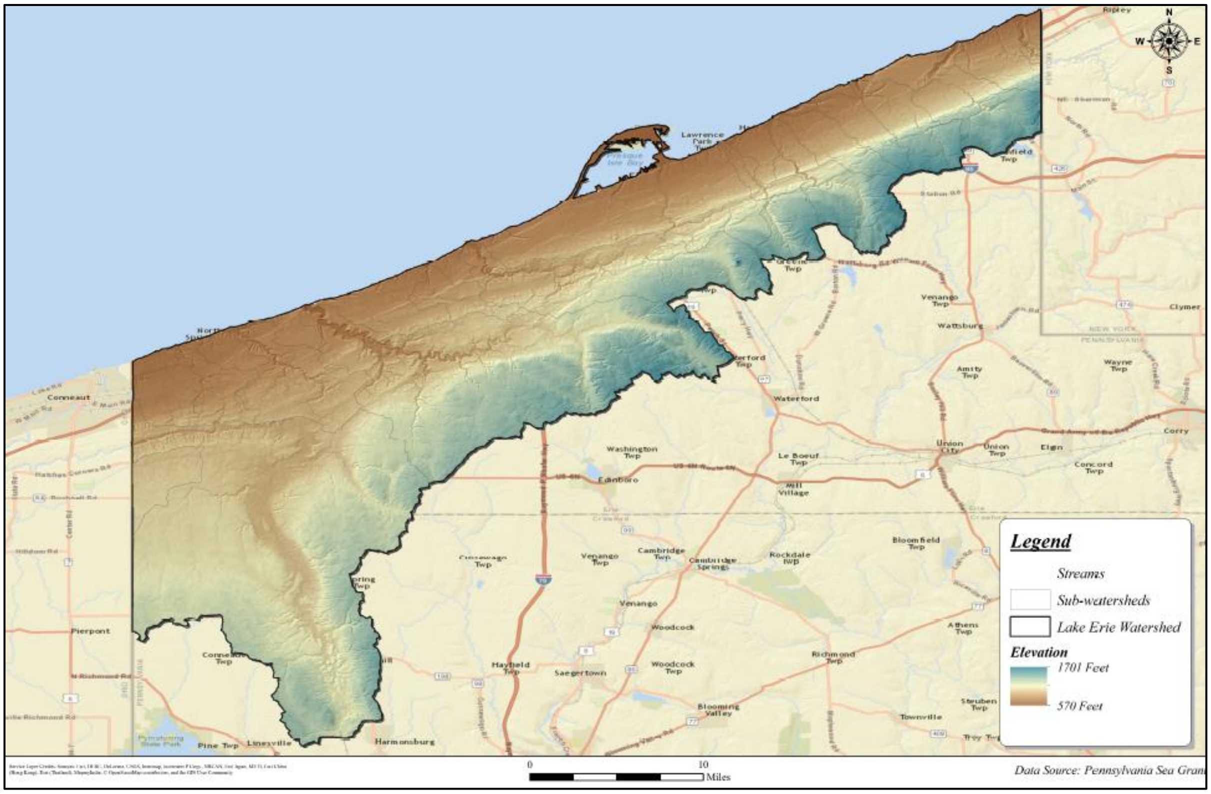

***Figure 1.3**: Topography of the Lake Erie watershed in NW Pennsylvania, showing larger streams, floodplains, and general landscape trends (Image: modified from Rafferty et al., 2015).*

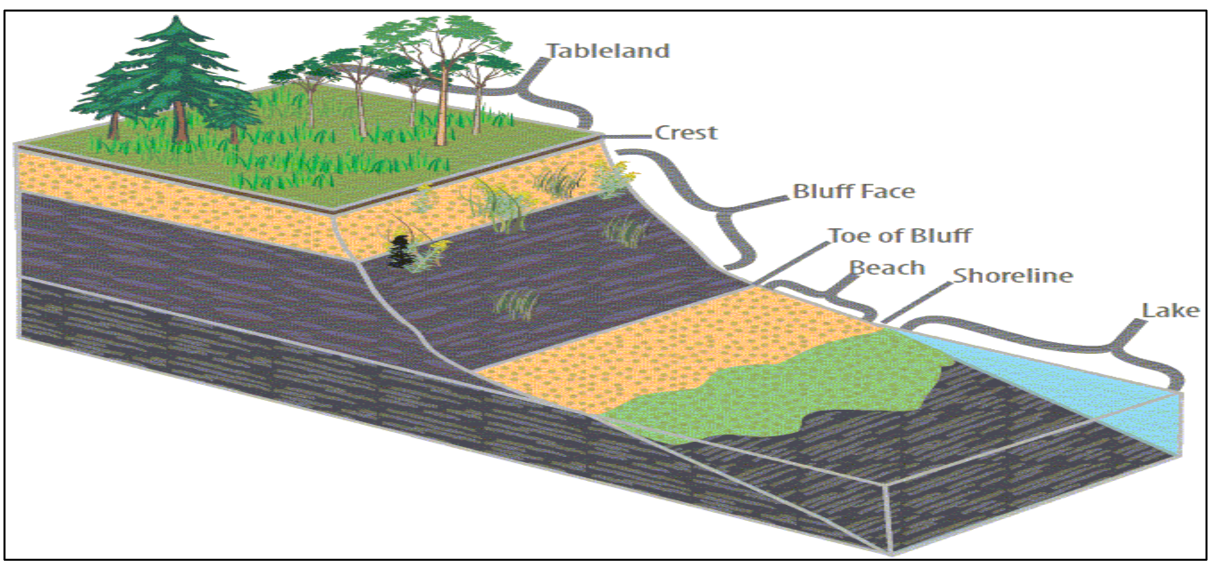

***Figure 1.4:** Bluff terminology and typical stratigraphy (geologic layering) along the Pennsylvania Lake Erie Coast. The bedrock is shown at or just below lake level, which is typical for western Erie County, but it may extend up the bluff face as much as 7 meters in eastern Erie County (Image: modified from Cross et al. (2007), Vegetative Best Management Practices: A Manual for Pennsylvania/ Lake Erie Bluff Landowners). The manual (2017 revised edition) is available from Pennsylvania Sea Grant at http://seagrant.psu.edu/sites/default/files/BluffBook2017_0.pdf.*

Bluff Retreat

Bluff retreat is a normal and natural process common to non-cohesive bluff coasts worldwide. Coastal populations spend significant time and effort trying to combat the problem (Cross et al., 2007). However, while a normal process that is often enhanced by anthropogenic influences, it remains difficult to predict the future location of a bluff crest or bluff toe because:

- numerous variables influence bluff retreat rates and magnitudes at a given site
- bluff failure events, by often decreasing the bluff-face slope, will increase bluff stability at least until the bluff-toe accumulation of protective colluvial material is removed by hydrodynamic forces such as waves, littoral currents, and ice movement
- bluff behavior along a coast and over time can vary greatly due to changes in internal geotechnical properties governed by geology, climate and hydrology
- significant factors determining bluff retreat rate vary with location on a coast and with time

Table 1.1 illustrates the principal physical factors that govern bluff behavior along the Pennsylvania coast and along bluff coasts generally. What is not yet known with certainty for the Lake Erie coast, nor for most bluff settings globally, is the relative or absolute importance of each of these factors at a specific site. Determining whether a specific bluff retreats because of subaerial processes exclusively, because of hydrodynamic processes exclusively, or because of some combination of these two process groups, remains difficult to ascertain with precision. Typically, an assumption or estimate is made on the relative importance of these two process groups based on local or site data.

Hydrodynamic factors	Base-of-bluff factors	Bluff face and internal factors	Hinterland factors
Wave energy flux	Bluff engineering	Slope, height, strength	*Winter snow and ice cover*
Seiche, tide, storm and seasonal lake level change	*Beach volume, morphology, and composition*	Composition, dip and strike of internal layering	Land slope, orientation and topography
Storm surge height, duration and frequency	*Presence of logs/large debris/ coastal structures*	*Bedrock toe strength, height, relative dip*	*Bluff crest road/foot traffic*
Width of winter nearshore ice complex	*Wave energy shielding by deltas and bathymetry*	Groundwater sapping, piping	*Anthropogenic water additions near bluff*
Nearshore bathymetry	*Littoral sediment supply*	*Seasonal runoff and freezing*	Hydraulic conductivity (*k*)
Lake ice stress on bluff toe	*Presence/absence of beach sand and gravel*	*Bluff orientation (wind, waves, sun)*	*Land use: low-density urban, forest, agricultural*
Nearshore substrate composition	*Presence/absence of folds, joints, and faults*	Internal aquifer heterogeneity	Runoff:infiltration ratio
Regional long-term change in lake level	*Bedrock freeze–thaw weathering*	*Vegetation; wildlife nesting and burrowing*	Water table slope, orientation and topography
		Groundwater discharge through the bluff face	Volume of rainfall intercepted/m of coast

Factors most responsible for along-coast (spatial) variability in recession rates are shown in normal font, and those less responsible in italic font.

Table 1.1: *Principal hydrodynamic and subaerial factors contributing to bluff change on the Pennsylvania coast of Lake Erie (Image: modified from Foyle, 2014).*

The process of bluff retreat is notably distinct from beach erosion, which receives more public attention, because the loss of sediment from a bluff is permanent. Beaches may gain and lose sandy sediments over various time scales (hours to centuries), but any sand lost from a beach to the littoral zone is likely to eventually return to the same beach or to downdrift beaches at a later time.

This occurs because the grain size of sandy material (0.0625-2.00 mm) is such that its settling velocity through water is relatively large and it therefore gets redeposited relatively quickly. Sand therefore has a propensity to remain in water depths where wave action can again return it to the beach. Conversely, material eroded from bluffs on Great Lakes coastlines typically consists of ~80% silt and clay, and ~20% sand and gravel (Morang et al., 2011; Jones and Hanover, 2014). The bulk of the material is thus very fine-grained "mud" with a grain size of less than 0.0625 mm. Erosion of a coastal bluff therefore can result in a permanent loss of 80% of its constituent material to deepwater areas of the lake, and temporarily to small stream-mouth estuaries. The offshore loss occurs because the settling velocity in water for silt and clay material is very low: it would take ~1 year for mud to settle through a 20 m (65 ft) deep column of still freshwater, about the average depth of Lake Erie. Mud can therefore easily escape the littoral system and contribute to deep-water sediment accumulation below wave base far offshore. Other factors being equal, it can be argued that the long-term prognosis for a bluff-bounded lake such as Lake Erie is that it will become larger but shallower over geologic time scales as coastal bluffs retreat.

While bluff retreat is a natural process globally that provides valuable ecosystem services (e.g., nourishment of nearshore environments with sediment, nutrients, groundwater and organic matter; provision of avian and insect habitat; etc.), anthropogenic factors near the bluff can ameliorate or exacerbate the natural background retreat rate which varies over time and location. These factors include common coastal-development activities (Figure 1.5) such as increasing stormwater runoff, non-ideal landscaping or farming practices, ineffective wastewater management, and unsustainable land development practices (Cross et al., 2007). Foyle and Naber (2011), suggest that because of their high clay and silt content, pulses of bluff-supplied sediments along the Pennsylvania coast can degrade nearshore water quality over time scales of hours to weeks.

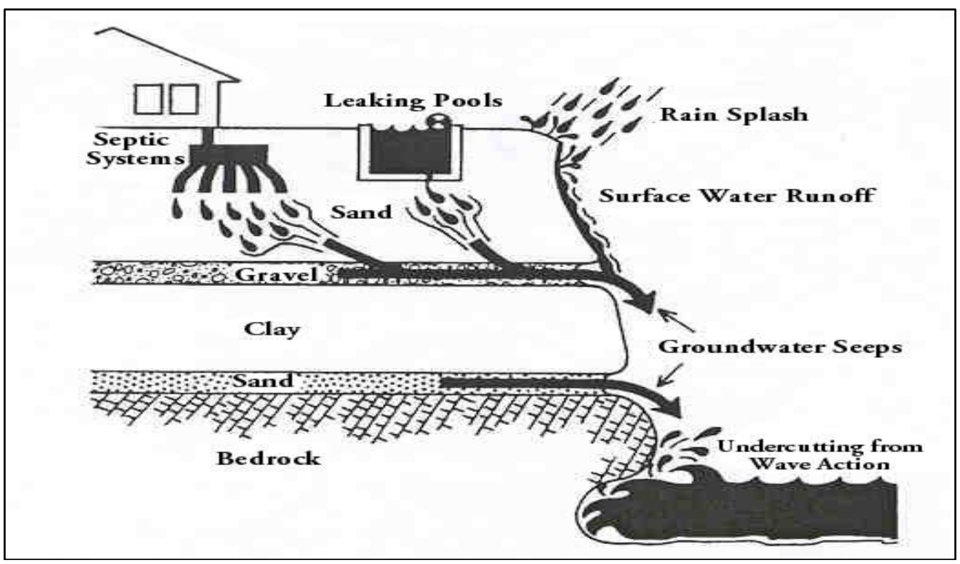

Figure 1.5: *Schematic illustration of several natural processes and anthropogenic factors that contribute to bluff instability on the Pennsylvania coast (Image: modified from PA DEP, 2002).*

Based on almost four decades of bluff-change monitoring by PA DEP, the average rate of bluff retreat for the entire Pennsylvania coast is ~0.16 m/yr (0.54 ft/yr; D. Benczkowski, pers. comm.) when measured at the bluff crest. Rates show significant variability with location and with the duration and timing of data coverage. Consequently, actual bluff-retreat rates at a specific location are often obscured by the averaging process. For example, recent large rotational slumps along the tallest bluffs in eastern Erie County near North East can result in over 20 meters of localized land loss occurring over a short several-week time period. For historical context, Figure 1.6 shows average annual bluff-retreat rates for the 1982 – 2007 era from PA DEP data (ECDPS, 2012).

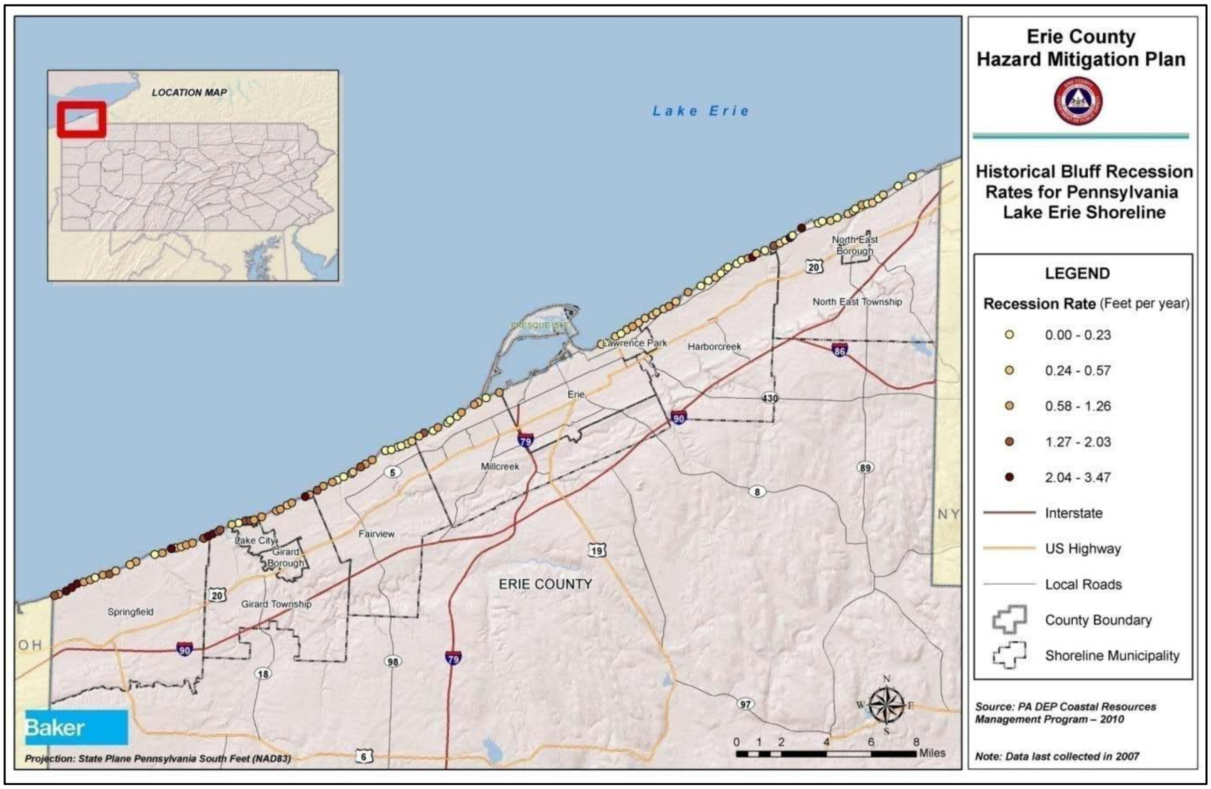

Figure 1.6: *Historical bluff-retreat rates along the Pennsylvania coast: 1982-2007. Rates are 25-yr averages derived from bluff-monitoring data collected by PA DEP approximately every 4 yrs at known field control points. Rates vary from less than ~0.05 m/yr to almost 1.1 m/yr, with higher rates being more prevalent in the western part of the county (Image: modified from ECDPS, 2012).*

Current Bluff-Change Monitoring Practices in Pennsylvania

From the perspective of PA DEP, the Bluff Recession and Setback Act (1980) allows regulation in the vicinity of the coastal bluff top through the establishment of Bluff Recession Hazard Areas. The aim is to balance the ecological benefits of natural bluff retreat with the risks posed to development. The intent is also to prevent development from encroaching upon the bluff in a manner that may accelerate bluff retreat and increase the risk of property loss (PA DEP, 2013). In general terms, the purpose of the regulations is to ensure that the bluffs are provided with adequate undeveloped hinterlands to allow for natural landward migration of the bluff crest, over timescales appropriate to buildings and infrastructure (multiple decades), while also limiting the risks to existing and proposed structures.

PA DEP notes that certain human activities at or near the bluffs have the potential to accelerate bluff retreat rates. Vegetation on the bluff face and crest typically stabilizes bluff sediments and soils with reinforcing root networks. Groundwater content in unconsolidated materials has an optimal value that enhances cohesion among sediment grains that in turn fosters increased bluff stability when compared to bluffs that are either too dry or over-saturated. Because a large tree may extract as much as 200 gals/day of groundwater through evapo-transpiration, removal of forest vegetation by landowners for farming and development can accelerate bluff retreat (PA DEP, 2013). Urban development often fosters an increase in impervious cover that leads to increased surface runoff that may enhance soil erosion through rill and gully development.

To manage the retreating bluffs along Pennsylvania's Lake Erie coast, the PA DEP Coastal Resources Management Program (CRMP), the City of Erie, and eight coastal municipalities along the Lake Erie shore currently rely on periodic physical-survey monitoring of bluff change at specific control-point sites along the coast. A local control point (e.g., rebar rod, telephone pole, building corner, etc.) exists at each of these sites and was installed beginning in 1982 and 1986. From each of these control points, distances to the bluff edge are measured every ~4 years along a specified compass bearing unique to each site. The control points are now spaced at ~500 m intervals along the coast. The regular monitoring allows continued determination of average annual bluff retreat rates, and can also be a means of ground-truthing LiDAR data. Figure 1.7 shows historical bluff-change rates for the 1982 – 1998 era derived from the CRMP monitoring. When compared with Figure 1.6, it can be seen that the duration and timing of data coverage affects calculated bluff-retreat rates, but that rates continue to show variability along the coast.

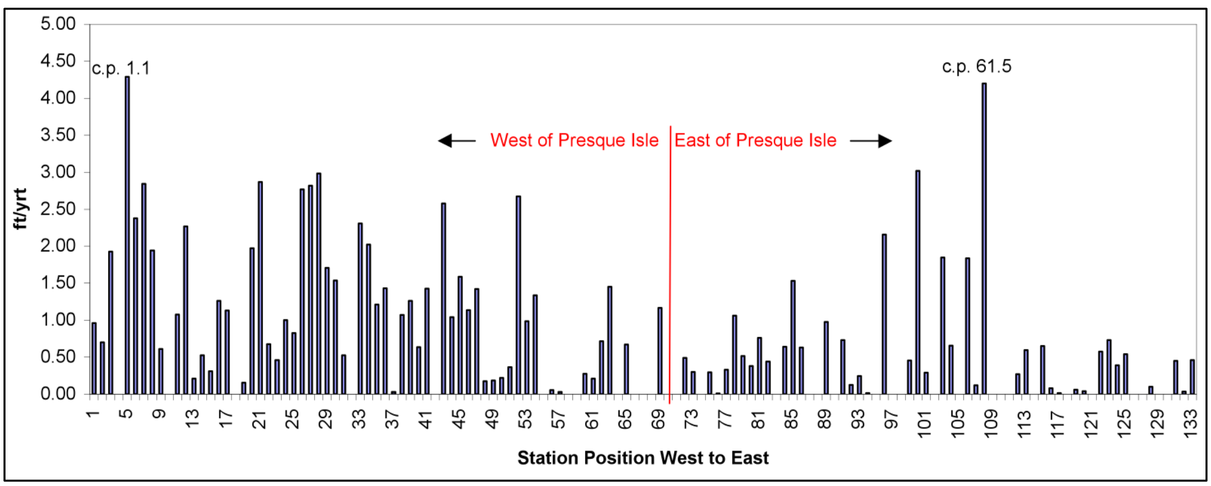

Figure 1.7: *Historical bluff-retreat rates along the Pennsylvania coast: 1982-1998. Rates are 16-yr averages derived from bluff-monitoring data collected by PA DEP approximately every 4 yrs at known field control points at ~0.5 km intervals. Bluff retreat rates are noticeably different between western and eastern Erie County (Image: modified from Knuth, 2001).*

While a valuable resource that extends the bluff-mapping record back to 1982, control-point monitoring can also be an excellent quality-control check on more recent (including this project) and future digital methods of mapping coastal change. However, the methodology does not provide sufficient spatial resolution on bluff retreat due to the relatively large control-point spacing, which is 25 to 50 times larger than that typically used in digital analysis of LiDAR and aerial photographic data using DSAS. The typical ~500 m spacing is also not closely scaled to the sizes of urban property parcels (25-100 m) on the Pennsylvania coast. Nor is it scaled to the dimensions of stable-bluff zones, common types of active slumps (5-100 m wide), and inactive historical slumps (pre-1880 era; 250-3000 m wide). These issues somewhat limit the utility of ground-survey methods in Pennsylvania and nationally as a means of providing the quality and sampling density of coastal-change data that is necessary for future high-resolution, science-supported, bluff hazard management. However, continuation of the method in Pennsylvania is advantageous because it permits regular interactions between CRMP personnel and lakefront communities and stakeholders, and it is an invaluable quality-control checking mechanism for digital mapping products generated through the increasing use of remotely sensed data (i.e., LiDAR).

Geospatial analysis is becoming the dominant analytical tool used in coastal-change monitoring, analysis, and prediction. Analysis of historical and present bluff geometry and rates of change using state-of-the-art remotely sensed data (LiDAR and ortho-rectified aerial imagery) and ground-checking within a GIS framework is becoming the state of the science at the national level. Such high-quality data is needed to provide the scientific basis for better recommendations related to sustainable coastal development for Pennsylvania's municipalities and individual properties along Lake Erie. It is also needed to form the basis of predictive and/or probability models of future bluff positions. Probability models, rather than commonly used deterministic methods based on past bluff behavior, appear to be the direction in which the science of bluff prediction is moving. Probability-based models have already been developed for flood hazard and earthquake hazard prediction at the federal level by the Federal Emergency Management Agency (FEMA) and by the US Geological Survey (USGS), respectively.

Additional deliverables as part of this PGLSI Project involve (i) GIS-based compilation, analysis, and visualization of ground survey, aerial photography, and LiDAR data for the years 1938, 2008, 2012, and 2015; (ii) identification of the locations of the present, recent, and historical bluff crest; and (iii) analysis of bluff-change over a 7-year to 77-year time period (between 1938 and 2015) using the Digital Shoreline Analysis System (DSAS; Thieler et al., 2005). The 1938 bluff-crest line feature was compiled and provided by the US Army Corps of Engineers from a recent sediment budget analysis of the US coast of Lake Erie (Cross et al., 2016). DSAS is an ArcGIS extension available from the USGS as freeware. It is used extensively for shoreline-change analysis on beach and bluff coasts nationally, and it is the principal change-analysis method used by the USGS National Assessment of Coastal Change Hazards (NACCH) program described below.

Bluff-Change Monitoring and Analysis at the National Level

In the broader national context, the USGS National Assessment of Coastal Change Hazards (NACCH) program (http://marine.usgs.gov/coastalchangehazards/) documents changes in shoreline position as a measure of broader coastal change (Morton et al., 2004; Morton and Miller, 2005; Hapke et al., 2006; Hapke and Reid, 2007; Hapke et al., 2009). The NACCH program quantifies coastal change hazards along open-ocean coasts in the United States and its territories. However, it does not currently provide data for the Great Lakes coast on its Coastal Change Hazards Portal (http://marine.usgs.gov/coastalchangehazardsportal/). Along most parts of the US ocean coast, coastal communities, emergency managers, and other stakeholders can now access science-based data (e.g., historical shoreline change, sea level rise, etc.), tools, models, and other products to enhance coastal resilience via the Coastal Change Hazards Portal (Figure 1.8).

In a recent Pennsylvania bluff-change study as part of the NACCH program (Hapke et al., 2009), and in another similar but much larger study on the California bluff coast (Hapke and Reid, 2007), the favored reference feature for tracking change on high-relief coasts is the bluff crest. This is also becoming the case nationally. The USGS, state coastal mapping agencies, and coastal-survey contractors are thus moving towards using the bluff crest (bluff edge, bluff top) as the mapping reference feature of choice instead of the bluff toe or shoreline which have been used in the past.

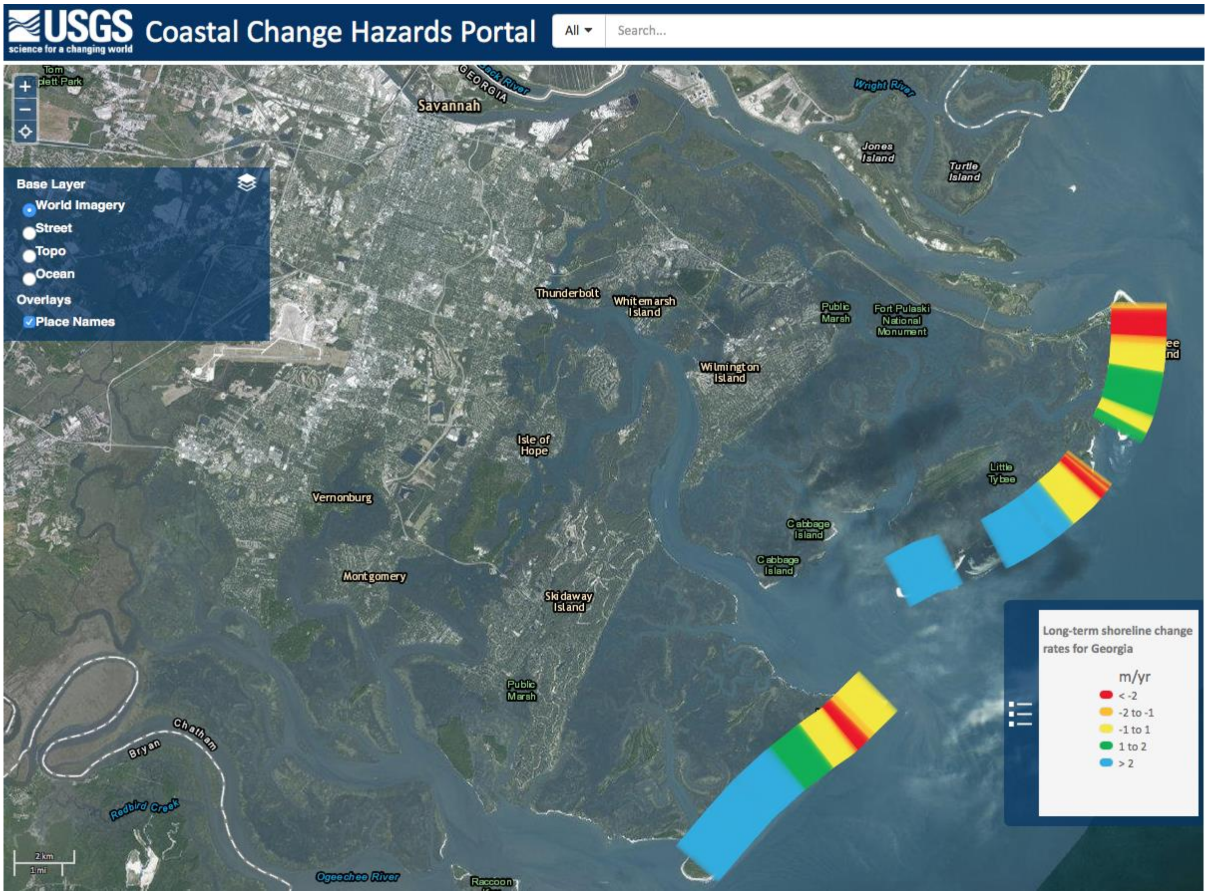

Figure 1.8: *Screenshot of the USGS NACCH Coastal Change Hazards Portal page (available at http://marine.usgs.gov/coastalchangehazardsportal/) showing long-term shoreline change rates on the Georgia barrier-island coast at Tybee Island near Savannah. Rates are based on a linear regression of mapped shoreline positions (1857 - 1999) and were generated using DSAS with a 50 m transect spacing. Bluff-change on the Pennsylvania coast is amenable to this style of presentation.*

The bluff crest is the preferred reference feature for a number of scientific and logistical reasons:

- The bluff toe is occasionally obscured by shadowing due to sun angle on both historical and modern aerial photography on high-relief steep coasts (not an issue for low-relief beach coasts).
- The bluff base (toe) position is prone to interpretation errors on historical imagery because the transition from bluff toe to backshore is often significantly more ambiguous that the transition from a bluff toe to a planar open-water surface in areas where beaches are absent.
- Construction of seawalls, artificial beaches, and revetments, some of which may not be identifiable on LiDAR data, can result in apparent accretion of a bluff toe and an apparent decrease in the bluff slope angle.
- Bluff failures in the form of rotational slumps, translational slides, liquefaction, and simple soil creep can result in apparent progradation of the lower section of the bluff face and bluff toe. This occurs due to the change (decrease) in grade caused by the mass movement and the associated deposition of a colluvial fan (Figure 1.9).

- In climates where coastal ice is common, such as Pennsylvania, springtime aerial photography and LiDAR surveys during leaf-off conditions are more likely, in most cases, to more accurately reveal the bluff crest location than the bluff toe location due to masking of the latter by shore ice and ice dunes.

- Geometrically, the often-sharp transition from a bluff face to a relatively flat paleo-lake bed (tableland, in PA) or paleo-marine terrace (in CA and OR) landward of the bluff crest make picking the break in slope at the bluff crest an easier proposition than picking the bluff toe which often transitions gradually to beach and dune environments.

- The bluff crest is the most obvious and least-abstract topographic feature for the general public and coastal landowners to visualize (Figure 1.9).

A principal goal of the USGS NACCH program is to develop similar and repeatable methodologies for measuring coastal change (Hapke et al., 2009). This will allow the coastal-change database for the entire coast of the United States to be periodically, systematically, and rapidly updated in a consistent manner. It will also allow interstate comparisons to be easily made because the methodologies used would be comparable (Hapke et al., 2009). Achieving the latter goal will allow meaningful comparisons of change rates and processes to be made independent of location and agency or contractor, whether the bluffs or beaches are on the Great Lakes or ocean coasts.

Hapke and Plant (2010) note that while coastal cliff and bluff retreat in general are difficult to model due to the variability of retreat events in time and space, there is a growing demand for predictive models that can be used to forecast the location and magnitude of coastal hazards. Probabilistic models are being employed that use data sets to define joint-probability density functions that can relate important forcing variables (e.g. wave conditions) and initial conditions (e.g. cliff geometry; long-term erosion rate; geotechnical properties such as material strength) to erosion events. In a model developed for two case-study sites on the southern California coast, Hapke and Plant (2010) found that a Bayesian modeling approach can be well-suited for forward modeling of coastal cliff retreat, with correct outcomes forecast in 70–90% of modeled transects.

Geomorphic Organization of the Lake Erie Coast: Littoral Cells, Coastal Reaches, and Coastal Segments

For the purposes of this report, the geomorphology of the Pennsylvania coast allows it to be subdivided into three distinct geomorphic reaches. The three onshore geomorphic reaches correspond spatially with three large nearshore littoral cells within which waves and longshore currents erode, transport, and deposit sand and gravel to build beaches and stream-mouth spits along the shoreline. This report thus adopts an approach used by Knuth (2001) who subdivided the coast into three major reaches based on general morphologic and stratigraphic characteristics (Figure 1.10). More recently, the nearshore has been similarly compartmentalized in sediment-budget studies by Morang et al. (2011) and Cross et al. (2016). Figure 1.11 shows the surficial Quaternary geology of Erie County (Tomikel and Shepps, 1967) from which it is clear that Knuth's western and eastern coastal reaches display geomorphic similarities and are distinct from the central coastal reach. The latter urban/industrial coastal reach is sheltered from Lake Erie by Presque Isle Bay. On the western and eastern coastal reaches, high-elevation beach-ridge deposits of the Warren paleo-shoreline (Schooler, 1974) curve towards the bluff edge near Lake City and North East, respectively. Both high-bluff coastal sectors are flanked, to the SW and NE, by lower-elevation lacustrine plain deposits. In general, the three-part organization of the Lake Erie coast means that bluff-change processes, and bluff responses to these processes, may be expected to be similar within each of the three reaches. It also means, for example, that the Warren high-bluff sectors should exhibit similar processes and responses despite their large geographic separation.

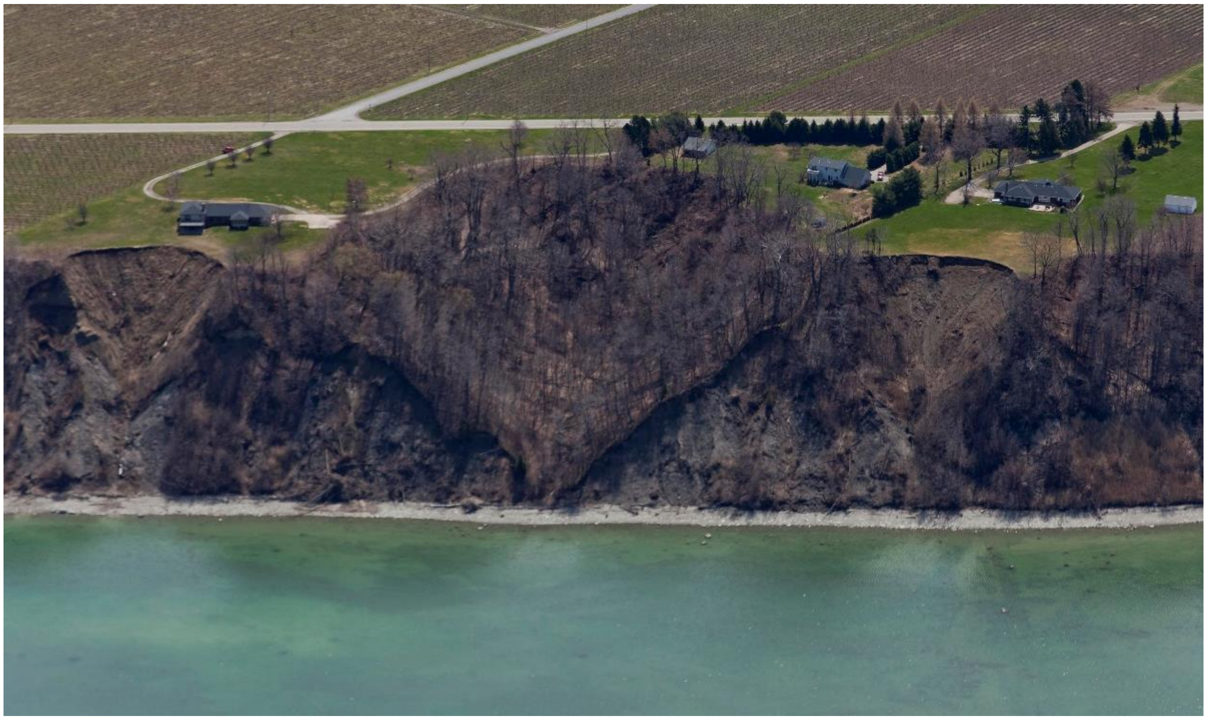

Figure 1.9: *A common failure pattern for high coastal bluffs, seen here in eastern Erie County, east of Twelvemile Creek in 2015. Two active rotational slumps are developed in sandy beach-ridge and lacustrine sediments of Quaternary age. The slumps bottom-out at the underlying glacial tills. Between the two modern slumps, an older stabilized (now vegetated) rotational slump or "Holocene bowl" records historical (pre-1880) slump activity (Foyle, 2014). At the active slumps, debris slides and soil creep keep the bluff face relatively free of vegetation (Image: available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

The western coastal reach extends 35.5 km from the Ohio state line (Figure 1.10) just east of Conneaut, Ohio, to the western edge of Presque Isle peninsula. The Conneaut Harbor walls define the updrift end of a corresponding littoral cell around which natural sediment transport towards Pennsylvania is now considered to be minimal. Sediment transport was significant prior to jetty construction in 1829 (Cross et al., 2016). The bluffs along the western coastal reach are characterized in most areas by a shale bedrock toe lying just above or below lake level. Unconsolidated bluff sediments are prone to wave attack along most of the reach (Amin, 2001), particularly where shore structures are absent.

The Presque Isle strandplain (peninsula), its Lake Erie beaches, and the bluffs along the south side of Presque Isle Bay define the ~9 km long central coastal reach (Figure 1.10). Although data are scarce, bluffs along this reach are more stable than bluffs in both the western and eastern reaches, largely due to the reduced wave fetch in Presque Isle Bay. A second factor contributing to bluff stability is that a large percentage of runoff from urban impervious surfaces is intercepted by storm drains and does not have the opportunity to percolate to the water table. Additionally, much of the south shore of the bay is armored, both in low-density residential areas west of Cascade Creek, and particularly in the more commercial areas east of Cascade Creek. The harbor jetties at the east end of the central reach define the downdrift (or terminal) end of the Presque Isle littoral cell. The jetties and navigation channel are a significant barrier to littoral sediment transport to the eastern coastal reach. Nummedal et al. (1984) calculated that potentially 110,000 m^3 of littoral sand arrive at this area and adjacent Gull Point annually. Because nearshore sediment supply entering the west end of the Presque Isle littoral cell has been estimated to range from 30,000 - 61,000 m^3/yr historically (Nummedal et al., 1984; Knuth, 2001; Morang et al., 2011), a significant quantity of the sand arriving at the terminal end of this cell is derived from erosion and beach nourishment along Presque Isle (Foyle and Norton, 2006).

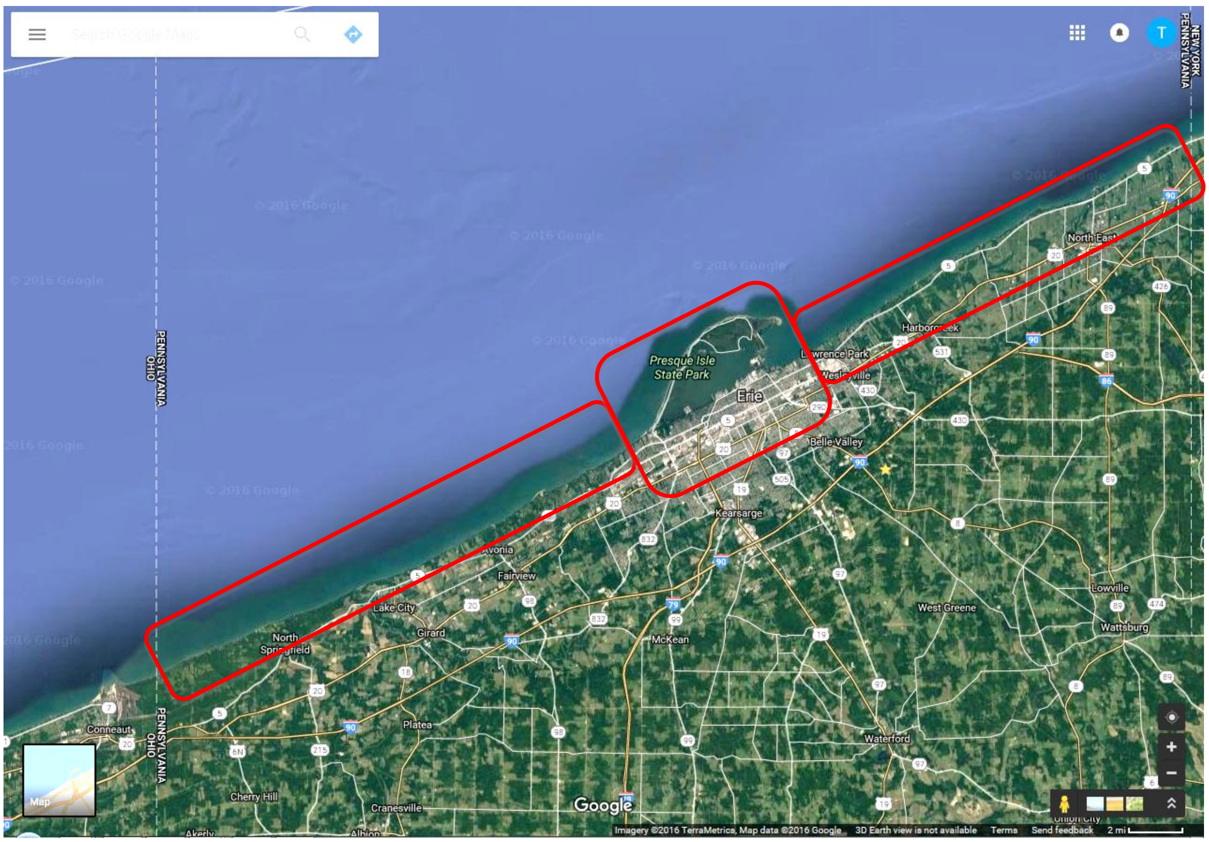

Figure 1.10: *Map showing the three principal geomorphic reaches on the Pennsylvania coast as proposed by Knuth (2001) and adopted in this report: the western coastal reach, the central Presque Isle reach, and the eastern coastal reach (Image: screenshot modified from maps.google.com).*

The coast east of the Presque Isle Bay entrance defines the eastern coastal reach that extends 28.6 km to the New York state line. At North East Marina, Knuth (2001) inferred that natural sand bypassing does occur but that much littoral material is trapped updrift or deflected offshore. Because oceanic long-period, long-wavelength, swells do not occur in Lake Erie, the sand deflected offshore is lost from the littoral sand system, and the beneficial role it would have had in beach nourishment is lost. Along the bluffs of the eastern coastal reach, shale bedrock may extend as much as 7 meters above average lake level. Consequently, the overlying unconsolidated cohesive bluff sediments are better shielded from wave attack than their western-reach counterparts. In general, lower retreat rates for the resistant bedrock toe tend to foster overall bluff retreat at lower average rates than those seen for unprotected bluffs common in the western coastal reach.

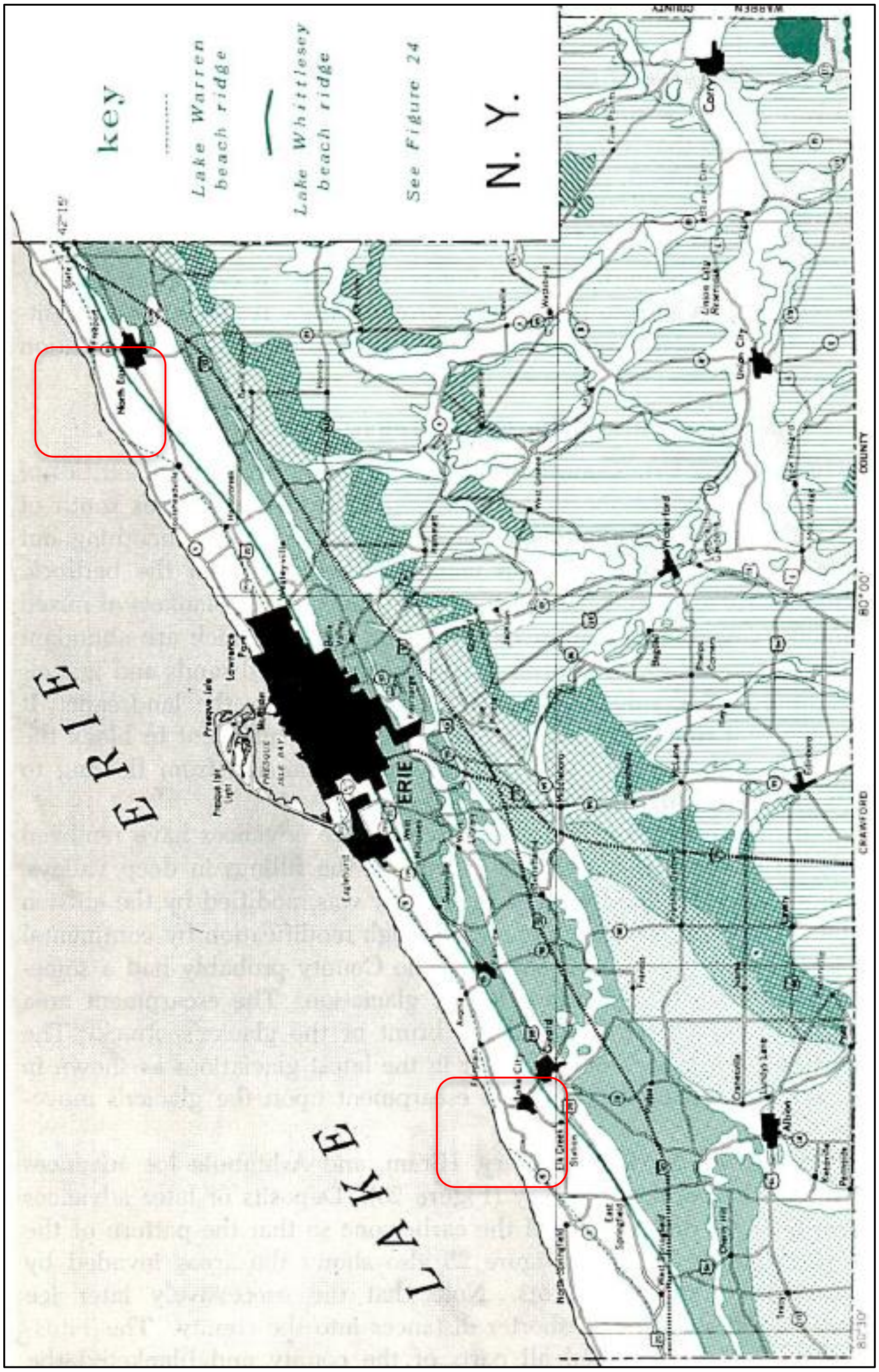

Figure 1.11: *Surficial geology map of NW Pennsylvania showing the distribution of late Pleistocene paleo-beach ridge (strandplain) deposits of the Warren (thin dashed line) and Whittlesey (solid dashed line) paleoshorelines along the coast. High-elevation, well drained, beach-ridge deposits of the Warren paleo-shoreline curve northward towards the bluff edge near both Lake City and North East (dashed line within red boxes). Bluff behavior at one of these locations can be useful in predicting behavior at the other. Both high-bluff coastal sectors are similarly flanked to the SW and NE by lower-elevation lacustrine plain deposits (Image: modified from Tomikel and Shepps, 1967).*

The three-part categorization of the Pennsylvania coast described above is reflected in the general trends that can be seen in bluff retreat rates shown in Figures 1.6 and 1.7. The benefit of this macro-scale three-part categorization, and a further potential sub-categorization of the coast into smaller distinct segments (suggested by Knuth, 2001; see Chapter 4) is that it can allow more accurate generalizations about bluff behavior to be made for shorter coastal reaches (approaching the multi-property parcel scale). For example, an estimate of the location of the bluff crest one hundred years in the future for a specific set of adjacent property parcels will have a smaller degree of uncertainty if that prediction is based on the characteristics of the short coastal sector that those properties are best described by. Given that bluff characterization at the single to multiple property-parcel scale should be an ultimate goal in coastal management, but also a costly and long-term goal, identifying coastal segments is important, for example, in future bluff-change modeling. Defining coastal segments within which bluff geotechnical properties and processes are similar will allow better coastal management until the time when the level of available geotechnical detail approaches the multi-property parcel scale.

Chapter 2: Management of Bluff-Related Issues by State Coastal Management and Affiliated Environmental Agencies: A Summary Snapshot from 2016

Individual State Summaries

This chapter presents a summary of issues relating to bluff retreat on a state-by-state basis for a selection of Atlantic, Pacific, and Great Lakes states. Information is simply extracted, verbatim and with minimal editing, from information that is publicly available on the websites of each state's coastal management and related environmental agencies. Each state summary also contains information extracted directly (verbatim; or with minimal editing) from the most recent NOAA-required Section 309 Report for states participating in the National Coastal Zone Management (CZM) Program. All the reviewed reports, with the exception of Minnesota, have 2015 publication dates and cover the 2016-2020 planning period. This information is included in the *Section 309 Report: Coastal Hazards* section of each state summary in this chapter. Section 309 Report information provides useful insight into the coastal erosion issues, challenges, monitoring methods, mitigation planning, and related coastal management efforts being undertaken by those states that have coastal bluffs. For reference, Section 309 of the Coastal Zone Management Act (1972) established a grant program to encourage states to improve their coastal management programs in nine enhancement areas. These enhancement areas are as follows: i) public access, ii) coastal hazards, iii) ocean resources, iv) wetlands, v) cumulative and secondary impacts, vi) marine debris, vii) special area management planning, viii) energy and governmental facility siting, and ix) aquaculture.

States were chosen to be included in this chapter review if they had significant issues related to coastal bluffs. As such, approaches being used by these states, and their existing and planned mitigation and management practices, may be suitable for consideration in other states including Pennsylvania. Each summary highlights the commonalities and differences in problems and methods between states that exhibit a wide variation in coastal geology, climate, and bluff-change processes. The state programs summarized in this chapter include:

1. California, Pacific coast
2. Illinois, Lake Michigan coast
3. Indiana, Lake Michigan coast
4. Maine, North Atlantic Bight coast
5. Maryland, Chesapeake Bay and Mid Atlantic Bight coast
6. Massachusetts, North Atlantic Bight coast
7. Michigan, Lake Superior, Lake Michigan, and Lake Erie coasts
8. Minnesota, Lake Superior coast
9. New York, Lake Ontario and Lake Erie coasts
10. Ohio, Lake Erie coast
11. Oregon, Pacific coast
12. Pennsylvania, Lake Erie coast
13. Washington, Pacific coast
14. Wisconsin, Lake Michigan and Lake Superior coasts

Every five years, states and territories are encouraged to conduct self-assessments of their coastal management programs (Section 309 Assessment) to determine problems and opportunities within each of the nine enhancement areas. Assessment and strategy development follows a process outlined in NOAA's recent guidance document, *Coastal Zone Management Act, Section 309 Program*

Guidance, 2016 to 2020 Enhancement Cycle. Submittal of a comprehensive Section 309 plan and approval of the plan by NOAA allows states to become eligible to receive Section 309 funds to implement strategies, in the case of this review, for the 2016-2020 fiscal years.

The current NOAA template used for Section 309 reports contains specific sections which are reproduced for each state summary in this chapter. The specific section on *Coastal Hazards* includes a broad overview of coastal resources at risk (Resource Characterization - Phase I Assessment); a general overview of ongoing management practices (Management Characterization - Phase I Assessment); an in-depth summary of management practices (In-Depth Management Characterization - Phase II In-Depth Assessment); and a detailed review of each state's coastal management priorities (Priority Needs and Information Gaps - Phase II In-Depth Assessment).

Within the *In-Depth Management Characterization (Phase II In-Depth Assessment)* section of each Section 309 Report, a lengthy tabulated summary of coastal management approaches being used to help identify, manage, and resolve various state-specific coastal-zone issues and challenges (including bluff erosion) is provided. Because this tabulated data is very similar for all states reviewed here that participate in the federal Coastal Zone Management Program, and is somewhat repetitive between states, a typical example is included below for reference rather than providing one for each state. State-specific versions of the table can be obtained from each state's Coastal Zone Management website to evaluate how each state is working to resolve coastal issues.

The following example is from the *California 2016–2020 Updated Draft Assessment and Strategy for the California Coastal Management Program (Public Review Draft, June 2015)* which is available online at http://documents.coastal.ca.gov/reports/2015/7/w6c-7-2015.pdf.

In-Depth Management Characterization (Phase II In-Depth Assessment)

Approaches employed by coastal hazard management category.

Management Category	**Employed by State/ Territory** (Y/N)	**CMP Provides Assistance to Locals that Employ (**Y/N)
Statutes, Regulations, and Policies:		
Shorefront setbacks/no build areas	Y	Y
Rolling easements	N	N
Repair/rebuilding restrictions	Y	Y
Hard shoreline protection structure restrictions	Y	Y
Promotion of alternative shoreline stabilization methodologies	Y	Y
Repair/replacement of shore protection structure restrictions	Y	Y
Inlet management	Y	Y
Protection of important natural resources for hazard mitigation benefits (e.g., dunes, wetlands, etc.)	Y	Y
Repetitive flood loss policies (e.g., relocation, buyouts)	Y	N
Freeboard requirements	Y	Y

Real estate sales disclosure requirements	Y	Y
Restrictions on publicly funded infrastructure	N	N
Infrastructure protection (e.g., considering hazards in siting)	Y	Y

Management Planning Programs or Initiatives:

Hazard mitigation plans	Y	N
Sea level rise/Great Lake level change or climate change adaptation plans	Y	Y
Statewide requirement for local post-disaster recovery planning	N	N
Sediment management plans	Y	Y
Beach nourishment plans	Y	Y
Special Area Management Plans (that address hazards issues)	Y	Y
Managed retreat plans	Y	Y
Other (resilience planning)		

Research, Mapping, and Education Programs or Initiatives:

General hazards mapping/modeling	Y	Y
Sea level rise mapping or modeling	Y	Y
Hazards monitoring (e.g., erosion rate, shoreline change)	Y	Y
Hazards education and outreach	Y	Y

California https://coast.noaa.gov/czm/mystate/
http://www.coastal.ca.gov/; http://www.bcdc.ca.gov/; http://scc.ca.gov/

The California Coastal Management Program (CCMP), approved by NOAA in 1978, is administered by three state agencies: (i) The California Coastal Commission (CCC) manages development along the California coast except San Francisco Bay; (ii) the San Francisco Bay Conservation and Development Commission oversees development on San Francisco Bay; and (iii) The California Coastal Conservancy purchases, protects, restores, and enhances coastal resources, and provides access to the shore statewide.

The California coastal zone generally extends 1,000 yards inland from the mean high tide line. The coastal zone for the San Francisco Bay Conservation and Development Commission includes the open water, marshes, and mudflats of greater San Francisco Bay, and areas 100 feet inland from the line of highest tidal action.

California Coastal Management Program

The California Coastal Commission is charged with implementing the California Coastal Act of 1976 (http://www.coastal.ca.gov/coastact.pdf). The Coastal Act establishes resource protection and coastal development policies for California's coastal zone, which extends three miles seaward to the outer extent of state jurisdiction, and which on land can be as narrow as several blocks in certain urban areas and up to five miles inland in rural areas.

In the CCC's most recent strategic plan, *California Coastal Commission Strategic Plan 2013-2018: Protecting California's Coast for Present and Future Generations (2013)* (http://www.coastal.ca.gov/strategicplan/CCC_Final_StrategicPlan_2013-2018.pdf), the three principal planning goals identified by the agency align closely with, and are incorporated in, the most recent (2016-2020) Section 309 report summarized below. Specific objectives within the "*Protect Coastal Resources*" goal that are relevant to beach and bluff erosion on the California coast, and the impacts of future sea-level rise, include:

Goal 2.2.12
Protect coastal resources by developing new or updated policy guidance to address beach nourishment, beach grooming, shoreline armoring, and dredging.

Goal 3.1.1
Adopt general sea level rise (SLR) policy guidance for use in coastal permitting and local coastal program (LCP) planning and amendment based on best available science, including the final report from the Natural Research Council of the National Academy of Science (Sea-Level Rise for the Coasts of California, Oregon, and Washington (June 2012)).

Goal 3.1.2
Based on the general SLR policy guidance, identify and develop specific regulatory guidance for addressing coastal hazards, including recommendations for analytic methods for accounting for SLR and increased storm events in project analysis, standards for redevelopment and development in hazard zones (e.g. bluff top and flood zones), buffers for coastal wetlands, and policies for shoreline structure design and impact mitigation.

California Coastal Records Project

The California Coastal Management Program has access to a very large historical database of oblique coastal photography compiled by the California Coastal Records Project, an aerial photographic survey of the California Coastline. Over 88,000 photographs (totaling over 509GB) of the California coast are now online, covering the coast from the Oregon Border (42N latitude) to the Mexican Border (32.5N latitude), except for the Vandenberg AFB restricted area. An additional 5,833 images from 1972, 8,000 images from 1979, 2,890 images from 1986, 4,173 images from 1987, 1,074 images from 1989, and 2,407 images from 1993 (http://www.californiacoastline.org/).

Coastal Bluff Erosion

The CCC is active in determining the risks from bluff retreat and in developing solutions to mitigate those risks. In *Establishing Development Setbacks from Coastal Bluffs* (Johnsson, 2003), the Commission recognizes that bluff retreat on the Pacific coast predominantly occurs via two mechanisms, namely (i) through sudden and catastrophic failure (e.g., landslides) involving much of the bluff face, and (ii) through "grain-by-grain" erosion by subaerial, marine, and groundwater-driven processes. These dynamic processes, variable in time and space, make setback planning especially challenging for bluff coasts (in either their natural or anthropogenically modified states) when compared to low-relief beach/dune coasts. Prescribing setbacks for stable slopes is an easier challenge to address and has consequently been incorporated in the *International Building Code*.

The goal in mitigating the economic and safety impacts of bluff retreat is to attempt to ensure that by the time a particular bluff retreats to sufficiently threaten development or infrastructure, the structures at risk are approaching their design life limit and becoming obsolete. CCC follows a deterministic approach to developing setback distances (based on erosion rates, slope stability, storm-wave attack, etc.) but recognizes that probabilistic coastal-hazard assessment, currently in its infancy as a science, may in the future provide better solutions to predicting bluff retreat (Johnsson, 2003).

Siting Development to Avoid Hazards

A critical element of LCP planning promoted by CCC is the designation of appropriate review and setback criteria for bluff, cliff, and beach level development (https://documents.coastal.ca.gov/assets/lcp/LUPUpdate/REVISED_DRAFT_LUP%20Guide_Update_8_Hazards_%20Feb_14_2016.pdf). Locating new development in hazardous areas should be avoided where feasible. Where not feasible, policies are favored that provide siting standards to minimize the exposure of development to hazards. These policies should account for any additional exposure to flooding and erosion as part of sea level rise. Coastal Act policy requires, in part, that new development neither create nor contribute significantly to erosion or in any way require the construction of protective devices that would substantially alter natural landforms along bluffs and cliffs.

Although there may be existing, legally authorized shoreline protection present on sites with existing development, any existing shoreline protective device has its own design life and, depending on conditions, it may not be appropriate for the geologic analysis to assume the permanence of such structure when assessing erosion rate and appropriate setback calculations for proposed development.

CCC states that LCPs should require a setback that assures that the structure will be stable for its economic life without the need for shoreline protective devices that alter the natural landform. The

Commission in recent actions has generally defined the economic life of a structure as 75 to 100 years. This lifespan may vary if the development included specific provisions for its removal from the hazard zone at the end of the specified economic life or when it became endangered.

For development along coastal bluffs or cliffs, both slope stability and erosion should be part of the analysis. The relative stability of a slope can be calculated quantitatively by a slope stability analysis, in which the forces tending to resist a potential landslide are divided by the forces tending to drive a potential landslide. The industry standard for a "stable" site is that this quotient, called a Factor of Safety, be at least 1.5 in the static condition, and 1.1 to 1.2 under seismic conditions. The Factor of Safety generally increases with distance from the bluff edge, so the point at which the factor of safety reaches 1.5 constitutes a minimum setback for existing conditions and without considering erosion. (https://documents.coastal.ca.gov/assets/lcp/LUPUpdate/ REVISED_DRAFT_LUP%20Guide_Update_8_Hazards_%20Feb_14_2016.pdf).

Most coastal bluffs in California are steadily retreating due to erosion, driven primarily by impacts from storm waves and the effects of sea level rise. In order to assure that the site will still have a 1.5 factor of safety at the end of its economic life, the amount of bluff retreat expected over its life must be added to the initial setback needed to minimize present-day hazards.

Sea level rise should also be incorporated into the erosion rate used in the Factor of Safety analysis. It is clear that future erosion rates are likely to be higher than historic rates; but, there is no fully accepted approach for estimating future bluff erosion with sea level rise. One approach used in the past has been to use the high range of historic erosion rates to represent future erosion rates. A more process-based method is to correlate future erosion rates with the expected increased frequency of wave impacts.

Section 309 Report: Coastal Hazards

The following information is extracted from*: 2016–2020 Updated Draft Assessment and Strategy for the California Coastal Management Program (Public Review Draft, June 2015)*. The document is available online at http://documents.coastal.ca.gov/reports/2015/7/w6c-7-2015.pdf.

Based on the Phase I Assessment and stakeholder input, California Coastal Commission (CCC) staff identified five enhancement areas considered high priority for future program improvements: Hazards, Public Access, Special Area Management Planning (SAMP/Local Coastal Programs - LCPs), Wetlands, and Cumulative and Secondary Impacts. The Phase II In-Depth Assessment focuses in more detail on these identified high-priority enhancement areas and details major gaps, needs and management priorities.

For FY 2016-2020, the federal Office for Coastal Management (OCM) designated "coastal hazards" as the enhancement area of national importance, to align with the "resilient coastal communities" emphasis in OCM's new strategic plan. Designating areas of national importance helps to further focus Section 309 funding and demonstrates a national impact for the National Coastal Zone Management Program by aligning resources to address critical coastal management issues across the country.

During the preceding 2011-2015 cycle, CCC staff compiled background information on the latest science regarding Sea Level Rise (SLR), including information and projections contained in the National Academy of Sciences study "Sea Level Rise for Coastal Areas of California, Oregon and

Washington." CCC staff completed the California Coastal Commission Draft Sea Level Rise Policy Guidance document. This document provides an overview of the best available science on sea-level rise for California and recommends steps for addressing sea-level rise in Coastal Commission planning and regulatory actions. It will also provide guidance to local governments for update of LCPs.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	1,033,499	1,104,963	6.91 %
No. of people in coastal counties	24,260,090	25,345,252	4.47 %
Percentage of people in coastal counties in coastal floodplain	4.26 %	4.36 %	0.1 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

Vulnerability to Shoreline Erosion

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very low (>2.0m/yr) accretion	54	3 %
Low (1.0 to 2.0 m/yr) accretion	128	8 %
Moderate (-1.0 to 1.0 m/yr) stable	1375	88 %
High (-1.1 to -2.0 m/yr) erosion	-	- %
Very high (<-2.0 m/yr) erosion	-	- %

Sea Level Rise: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

Coastal Vulnerability to Historic Sea Level Rise

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very Low	-	-
Low	398	25 %
Moderate	1007	64 %
High	152	9 %
Very High	-	- %

Several recent reports have resulted in significant changes to the emphasis placed on climate change and sea level rise policy in California. The key reports are the California Department of Natural Resources' *Safeguarding California Plan (2014)*, the Ocean Protection Council's *Sea Level Rise Guidance* and the California Coastal Commission's *Draft Sea Level Rise Policy Guidance (2013)*. These three reports help bring attention to the potential consequences of climate change and sea level rise and to identify general and specific strategies and actions that the state can take to address these concerns. For example, the latter report provides guidance on how to incorporate sea level rise into projects in the coastal zone that require a Coastal Development Permit as well as into Local Coastal Programs, the plans adopted by all cities and counties lying wholly or partially in the coastal zone. It includes strategies to minimize current and future impacts to wetlands from development considering the influence of sea level rise.

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise/Great Lake level change	N	Y
Other hazards	N	Y

In-Depth Management Characterization (Phase II In-Depth Assessment)

The Section 309 Assessment and Strategy (2016-2020) identified the three most significant coastal hazards on the California coast. These are (i) erosion, which occurs statewide with differences in impacts due to different shoreline types (beaches, cliffs/bluffs, wetlands etc.); (ii) flooding, also statewide and with impacts that vary with shoreline characteristics (beaches, wetlands, areas protected by dikes/other infrastructure, urban areas, etc.); and (iii) storms/waves whose impacts on beaches and adjacent development (residential, docks/piers, infrastructure, etc.) also vary statewide with coastal characteristics. Each of these hazards will be exacerbated by sea level rise and the resulting changes may not be well understood. Surveyed stakeholders consider sea level rise in general, and/or these three hazards in particular, as issues of concern.

CCC also identified two emerging issues of concern which currently lack sufficient information to evaluate the level of the potential threat. These were (i) sea-level rise driven changes in coastal hazards; and (ii) sea-level rise responses. For the former, information and modelling methodologies related to sea level rise impacts in general are needed, including a better understanding of changes in (a) erosion rates due to differences in shoreline types; and (b) cumulative flooding impacts in areas where river floods combine with coastal flooding. For sea-level rise responses, better understanding of implementation techniques (plus related legal information) for a variety of common and innovative adaptation responses (including living shorelines, regional sediment management, and shoreline protective device removal) is needed. Additional information about where and under what conditions different techniques are most useful is also necessary, as is better understanding of the methodologies for monitoring sea level rise, local vertical land motion, and the effectiveness of adaptation strategies.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

CCC has identified four management priorities where there is opportunity for the CMP to improve its ability to effectively address the most significant hazard risks. All four are related directly or indirectly to bluff retreat problems and to access to scientific data and policy information on the California coast. The four priorities are:

Address implications of continued and accelerating sea-level rise

Continue current efforts to incorporate sea-level rise policies into LCPs through amendments and under newly-administered grants. Support efforts to better characterize vertical land movements, particularly near established tide gages. Support efforts to predict effects of the Pacific Decadal Oscillation on sea level off the California coast and possible future changes that might occur at the complex boundaries between coastal and riverine/estuarine systems.

Develop management options to ensure protection of Public Trust Lands

A major consequence of continued sea-level rise is the loss of public trust lands seaward of the mean-high tide line. This can occur through "passive erosion" resulting from fixing (anchoring) the back of the beach, and through permanent submergence of formerly intertidal areas. Develop strategies that protect such intertidal areas and ensure continued access and recreation opportunities while at the same time allowing for protection of private and public upland properties as allowable under the Coastal Act or certified LCPs.

Strengthen policies related to hazard avoidance

Support efforts to incorporate common and innovative approaches for avoiding coastal hazards into LCPs. For example, better incorporate coastal setback requirements developed by the Commission under the Coastal Act into existing LCPs and develop Transfer Development Rights programs to allow private property owners reasonable development opportunities while ceding hazardous properties to public use.

Improve coastal hazard information distribution

Improve local government and general public access to coastal hazard mapping through development of a web-based portal consolidating the many existing hazard mapping efforts. Coordinate efforts with the California Energy Commission and academia to develop probabilistic approaches to coastal hazard characterization. Develop mechanisms for incorporating such probabilistic approaches to coastal hazard assessment and hazard-avoidance strategies.

Hazards and hazard responses are an important CCMP program concern due to sea level rise and due to the potential impacts to public access, coastal resources, public trust lands and water quality from hazard responses such as shoreline armoring and bluff retaining structures. The CCC has identified priority needs and information gaps to address the coastal management priorities identified above:

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Research is needed to help better understand vertical land motion, dynamic changes to coastal/riverine systems from rising sea level, the effectiveness of

		adaptation strategies for various coastal types, and to support most policy changes. Management efforts directed toward coastal hazards will require research into many aspects of the coast to minimize risks from hazards, better understand where certain hazards may be of greater or lesser concern, and determining whether there are underlying causes for the hazardous condition that can be managed. For example, beach nourishment may not be effective in locations where beach erosion is due primarily to land subsidence. If research determines that ground water withdrawals are a major cause for land subsidence and sea level rise in certain areas, policies directed at changes in water withdrawals may be important in a beach management effort.
Mapping/GIS/modeling	Y	Mapping, GIS and modeling are planning tools and they have been used in LCPs for many years. In addition, mapping, GIS and modeling are major components of most local government's sea level rise vulnerability assessment and LCP updates. As the 76 coastal local governments undertake these efforts, one anticipated need will be an efficient way to collect, apply, compare and improve access to the spatial data. In the coming years the staff will need to explore options for best providing this data and information, through existing sites such as CalAdapt, or through new or modified sites.
Data and information mgmt.	Y	A large number of hazard maps, studies, tools and data sets have been developed over the years. They exist in various locations, in various formats and at various scales; they have been developed for a variety of uses. Some have outlived their usefulness, but are still being used, some have not received the exposure that is appropriate. Data and information management is important now to help planners and local communities best use existing data and information. Many new maps and tools are being developed in response to various sea level rise issues and planners and local government staff will need help in determining which if these will be useful, and under what conditions.
Training/Capacity building	Y	Staff and local planners need to be trained on the available hazard and sea level rise products so that they can make the best use of these new and emerging tools.
Decision-support tools	Y	Decision-support tools that bridge research and

		policy such as `applying the sea level rise guidance in LCPs, guidance for addressing sea level rise for specific topics such as infrastructure asset classes, or model policies or ordinances.
Communication and outreach	Y	Outreach is important to sea level rise vulnerability assessments and LCP updates and is fundamental to the Coastal Act.

Illinois https://coast.noaa.gov/czm/mystate/

The Illinois Coastal Management Program is the newest state partner in the National Coastal Zone Management (CZM) Program, gaining approval in 2012. Illinois' program, under the direction of the Illinois Department of Natural Resources, Office of Coastal Management, focuses on several priority issues in the Illinois coastal zone, a 63-mile stretch along Lake Michigan. The program manages impacts to its Lake Michigan shoreline through the Rivers, Lakes, and Streams Act, Lake Michigan Shore Line Act, and a network of other authorities.

Coastal Management Program

On January 31, 2012, the Illinois Coastal Management Program (ICMP) received Federal approval from the National Oceanic Atmospheric Administration, Office of Ocean and Coastal Resources Management. Illinois joins 29 coastal states and five island territories that have CZM programs and represent more than 99.9 % of the nation's 95,331 miles of oceanic and Great Lakes coastline (http://www.dnr.illinois.gov/cmp/Pages/default.aspx).

Illinois is dedicated to protecting and managing the natural and cultural resources along its 63-mile stretch of Lake Michigan shoreline. During the last two centuries, the Illinois coast has undergone nearly a complete metamorphosis with its monumental hydrologic modifications, enormous industrial impacts, building of an excellent transportation infrastructure, and creation of skyscrapers that grace the shoreline. With all these changes, it is remarkable that the state's coastal resources still contain some of the richest, rarest and most diverse set of plant and animal species and natural habitat areas in the state.

The Illinois shoreline is highly urbanized and has been subject to considerable stress from intense land use and competition to serve the economic and workforce needs and demands of this densely populated area. Lake and Cook counties are currently home to 6 million people and are projected to be home to nearly 6.8 million people by 2030. It is estimated that more than 20 million visitors visit the Lake Michigan shoreline each year. Illinois Beach State Park alone has over 2 million visitors annually. Lake Michigan provides water supply to nearly 7 million Illinois residents (over half of the state's entire population).

The environmental legacy of industrial sites and the needs and demands of a growing and vibrant urban community create a complex set of issues to balance as the state invests in programs that seek to restore ecosystems and meet demands for open space, recreation, and public access.

Perspectives on the Management of Coastal Erosion

Extracted from: *Illinois Coastal Management Program Issue Paper: Coastal Erosion along the Illinois Coastal Zone (2011)*. http://www.dnr.illinois.gov/cmp/Pages/issue.aspx

The high value of real estate will continue to be a prime reason why the Illinois shore will be defended. The ICMP provides an opportunity to do the needed evaluation, monitoring and planning related to the diverse erosion issues along the Illinois coast. The following series of focus items provide perspectives on how the management of Illinois coastal erosion can be perceived and addressed.

Erosion and Its Relationship to Lake Level
Coastal erosion along the Illinois coast occurs at all lake levels. Although high lake levels are times when erosion is perceived as most problematic, the erosion processes also continue during times of low lake levels. The focus of erosion simply shifts lakeward and impacts the nearshore lake bottom. Coastal erosion monitoring and mitigation should be ongoing management issues regardless of lake level.

Appreciation of the Erosional Natural State
Erosion dominated along the Illinois coastline in the natural state. Although some human activity has contributed to shore erosion, coastal engineering has also eliminated erosional trends such as bluff recession along the North Shore and long-term shoreline recession along nearly the entire Illinois coast except at Illinois Beach State Park. Because of the natural erosional trends along the Illinois coast, this coast will be perpetually dependent on coastal structures and/or artificial beach nourishment. However, wherever possible, both hard (structural) and soft (nourishment) solutions should be done in such ways to maintain or enhance habitat.

The Need for Erosion Defense
Prevention and remediation of shore erosion is a necessary management practice along the Illinois coast if the present shoreline is to be maintained. Both hard remedies (structures such as revetments, breakwaters, bulkheads, etc.) and soft remedies (beach nourishment) have a role in this erosion management. Shore-protection structures are an integral component of the Illinois coast and these need to be maintained, repaired, updated and augmented as needed.

Planning and Design of Shore Protection
To the greatest degree possible, new shore-protection structures built along the public lakeshore should be designed and built with maximum consideration of durability, public access, recreational applications, and aesthetics. The Chicago lakeshore provides numerous examples of shore-protection structures that are functional, user friendly and a compliment to the lakeshore scenery. Shore-protection structures that are most desirable are ones that provide the needed shore protection while minimizing impacts to natural coastal processes, enhancing nearshore and coastal-margin habitat, and providing access to the water's edge. Shore-protection structures that are built along private property but extend onto the public-trust lake bottom need to clearly satisfy their purpose of erosion protection.

Priority Erosion Concern
Shore erosion at Illinois Beach State Park should be the long-term priority for coastal-erosion management along the Illinois coast. The need for this focus relates to the intrinsic value of this unique coastal setting and habitat, the potential for sustained shore erosion along this state park shore, and the need to protect this public landscape for the enjoyment of future generations. Beach nourishment is the preferred erosion defense; use of structural measures should be minimized in order to preserve as much as possible a shore that is open, free and clear of shore structures.

Management of Dredged Sand
Sand dredged from harbor entrances or other areas where undesirable sand accretion occurs should be sand that is maintained within the littoral system. This can involve either placing the sand along the beaches or nearshore downdrift of the dredge area or, if conditions and management needs warrant, returning the sand to the beach or nearshore in the updrift direction and thus recycling the sand along a specific reach of shore.

Limited Reliance on Littoral Transport

Only Illinois Beach State Park should be a coastal reach along which erosion protection is dependent on a sustained supply and transport of littoral sand. This is needed to preserve the setting of this state park shore. This sand supply can be from beach nourishment and a sand recycling program of returning beach sand to the north end of the park after being captured at the south end of the park. The diminishing resource of littoral sand along the North Shore and the northern Chicago lakeshore requires that any location along this reach not be dependent on a sustained supply of littoral sand from the north.

Recognition of Chicago's Unique Coastal Setting

The maintenance and improvements to beaches and shore-protection structures along the lakeshore parkland in Chicago has special significance. This shoreline infrastructure provides erosion protection of made land, which in some locations can be readily lost to wave erosion if not protected. This shoreline infrastructure is also an urban recreational and aesthetic asset that annually benefits millions of users.

Lakebed Erosion

Lakebed erosion is an important coastal management issue that presents unique challenges. It occurs below water and thus it cannot be visibly evaluated and monitored. In addition, the erosion process may not be apparent until after adverse impacts occur. Maintaining a lakebed mapping and monitoring program would provide needed data to determine the extent, rate and trends of lakebed erosion along the Illinois coast and may also be a basis for mitigation.

Bluff Erosion

In order to stabilize the bluff slopes, erosion across the bluff face should be prevented or mitigated by using vegetation, appropriate grading, and proper management of surface water runoff. The natural erosional state of the bluff face prevented any extensive vegetation cover. Thus, there is no "native" bluff-face vegetation that can be employed, but plants best suited for the slope and soil conditions should be selected. Opportunities should be pursued that provide a vegetation stabilization of the slopes as well as provide habitat. A well-vegetated bluff slope is effective erosion prevention. Also effective is a bluff toe having a well-designed and maintained revetment and/or a wide beach. Both high bluffs and low bluffs need protection along the bluff toe. Although erosion along the high bluffs can be visually impressive, the low bluffs can have a greater potential recession rate because less material needs to be removed per unit of bluffline recession (Jibson et al. 1994).

Shore Erosion along Inland Waters

Coastal erosion management will primarily be concerned with the open-water Lake Michigan coast of Illinois, but there are other areas within the Illinois coastal management zone that also have potential issues related to shore erosion. These are the land areas bordering the Inland Waterways, Chicago's small-boat harbors, the Calumet River, Lake Calumet, Wolf Lake and Powder Horn Lake.

Coastal Sand as a Limited Commodity

There are essentially no new sand supplies being provided to the Illinois coast. The once primary source of sand supply from bluff erosion has been eliminated; and the volume of littoral sand coming south across the Illinois-Wisconsin state line has been substantially reduced. The need exists for conserving, recycling and enhancing the existing coastal sand resource.

Additional Perspectives on Coastal Erosion

Extracted from: *Illinois Coastal Management Program (Draft) Document, 2011.*
http://www.dnr.illinois.gov/cmp/Pages/documentation.aspx

The Lake Michigan coast is a dynamic setting influenced by waves, ice, and changing lake levels. The potential for coastal erosion exists along nearly the entire Illinois coast. This chapter discusses coastal erosion, how it has been addressed in the past, and how coastal erosion assessment and planning will occur in the ICMP. Two aspects of coastal erosion along the Illinois coast are important for understanding past, present, and future erosional trends.

Coastal Erosion in the Natural Setting

Prior to human modifications, the natural setting along the Illinois coast was nearly all erosional. There was an abundant supply of littoral sand moving along the shore. However, this sand was in transport to a depositional zone along the central Indiana coast. The exception to the erosional trend was the southern part of the Zion beach-ridge plain from near the mouth of Dead River southward to the North Chicago shoreline. This was the state's only accretional shore. The accretion resulted from the southward translation of the beachridge plain.

Lake Level Influence on Coastal Erosion

Erosion along the Illinois coast gains considerable public and media attention during times of high lake levels. High water causes partial to total submergence of some beaches; storm waves can damage and overtop shore structures, and localized coastal flooding may occur. A common misconception is that coastal erosion is limited to times of high lake levels. Erosion can be an ongoing process regardless of lake level. Changing lake levels simply shift the erosion zone either landward or lakeward.

Categories of Illinois Coastal Erosion

Three categories of coastal erosion continue to be an issue along the Illinois Lake Michigan coast: shore, bluff, and lakebed erosion. These correspond to different locations on the coastal profile.

Shore Erosion

Shore erosion impacts the exposed beach or land area adjacent to the shoreline. It results in a landward translation of the shoreline, loss of beach area, and sand volume. A related process to shore erosion is the damage and deterioration of engineered structures that occur along the shore such as revetments, riprap, groins, bulkheads and breakwaters. Because of the important role of shore protection structures to stabilize the land/water interface, damage and deterioration of these structures can be equally important as any beach area or land area erosional loss.

Bluff Erosion

Historically, the Illinois bluff coast was near-continuously eroding. The bluff erosion commonly involved wave erosion cutting into the toe of the bluff and undermining the bluff slope. The bluffs could also erode due to either surface runoff or ground water moving over or through bluff materials. In the late 1970s to 1990s, substantial shore protection was installed to halt bluff erosion. By 2000, a survey of the bluff coast determined that wave-induced bluff erosion was active along no more than about 600 feet of the entire bluff coast.

Lakebed Erosion

Lakebed erosion refers to underwater erosion across the bed of the lake. This erosion does not refer to the sand or gravelly sand that may occur along the lake bottom. Lakebed erosion refers to the erosion across the cohesive layers of glacial till or clay that underlie the sand. This type of erosion is also referred to as lakebed downcutting, or simply downcutting. The cause is wave and current action, as well as ice.

Lakebed erosion is non-reversible because the loss of cohesive material cannot be replaced other than by a new glacial episode. The long-term impact of lakebed erosion is the lowering of the lake-bottom profile. As a result, deeper water occurs closer to shore, and the profile is steeper between the beach and nearshore. The deeper water, and steeper profile, allow larger waves to impact the shore. This can increase the potential for erosion along the beaches and the toe of the bluffs.

Historical Mitigation of Coastal Erosion

A variety of coastal erosion mitigation approaches along the Illinois coast have been used over time. Hardening the shore with engineered structures is the most common practice. In recent decades, there has been greater interest in using "soft" solutions to retain sand volume, such as beach nourishment alone or in combination with hard structures to retain sand volume.

Shore-Protection Structures

A variety of shore-protection structures occur along the Illinois coast such as groins, riprap, revetments, and breakwaters. Many of the early shore-protection structures relied on timber to form the walls for rock-filled cribs in breakwaters and groins. Steel sheetpile is now the primary material for facing groins, jetties, and the base of stepped revetments. Quarry stone and reinforced concrete are also common materials.

Headland beach systems are a type of shore protection that also provide recreational and aesthetic benefits. These engineered pocket beaches are held by groins or rubble-mound breakwater headlands. These beach systems have the advantage of: 1) creating a contained beach that is not dependent on any influx of sand from littoral transport, and 2) creating a beach that will minimize loss of sand to littoral transport. The headland beach systems have been used extensively on the bluff coast along private residential properties.

Lakefill

Filling in the shallow nearshore area to create new land and establish a more lakeward shoreline position has been used as a means of shore protection, particularly along the Chicago lakefront. The lakefill results in a durable new shoreline edge that can be built to withstand direct wave and ice impact, and be more erosion-resistant than the pre-lakefill shoreline.

Beach Nourishment

Beach nourishment is used along many of the municipal beaches and, to a limited degree, along private lakeshore properties. The most rigorous beach nourishment is done at Illinois Beach State Park. Maintaining the state park shore to be free of any additional shore protection, or offshore structures, is a long-term coastal management objective for the state park.

Permitting Projects for Coastal Erosion Control

Two agencies are responsible for reviewing and permitting construction along the Illinois coast. They also are responsible for controlling coastal erosion. On the state level, permitting is done by the Office of Water Resources (OWR), Lake Michigan Management Section, of the Illinois Department of Natural Resources (IDNR). On the federal level, permitting is done by the USACE, Chicago District Regulatory Branch. In general, for both agencies, no projects are permitted that are deemed potentially disruptive to the movement of littoral transport along the beaches and nearshore areas. An exception to this restriction might include structures that will trap sand, but will have a sand management plan, which provides for the bypass or backpass of any sand that is captured.

An IDNR permit is required for any shore protection that involves building a beach. This requirement includes the filling of the beach to the maximum capacity of computed sand retention, and, in addition to this capacity volume, including a 20 percent overfill. This overfill assures sand is available, if needed, for any unforeseen adjustment to the beach and nearshore profile. The IDNR distributes public notices for any permit applications, allowing public review for proposed project plans. There is a 30-day period for written comments, and no work can begin until the permit is issued.

The wide range of historical lake-level fluctuation (over 6 feet) results in a need for shore protection that has direct interaction with lake water only during times of extremely high lake levels. An example is the revetments built at the toe of the bluffs. Although these revetments may have some wave impact during extreme storms, commonly a beach may exist adjacent to the revetment. Only at times of higher lake levels might the still water be in contact with the structure.

Permits are required for shore-protection structures for both private and public lakeshore property to be built extending onto the lake bottom. This is despite the lake bottom being state land held in public trust. Filling of lakeshore land is conditionally permitted by Illinois state law as long as the filling serves a public benefit. An example is the creation of the parkland on the Chicago lakefront.

Both the IDNR and the USACE, Chicago District, permit lakeshore construction to the Ordinary High Water Mark (OHWM). This is the typical or “ordinary” high level to which the lake water will rise in longterm fluctuation. Most often, the lake level is below this elevation. In some coastal states, the OHWM defines the boundary between private property and public beach. In Illinois, private property and riparian rights along the Illinois coast extend to the calm water shoreline and migrate landward or lakeward with changing lake level (Illinois case law: Brundage v. Knox, 1917).

As defined by the USACE, the OHWM along the Illinois coast is 581.5 feet (177.2 m) relative to the International Great Lakes Datum (IGLD-85). Only shore construction that occurs below this elevation is subject to permitting by the IDNR and the USACE.

ICMP Coastal Erosion Assessment and Planning

Assessment

The vast majority of the Lake Michigan coastline in Illinois is protected from erosion by hardened structures. IDNR estimates that upwards of 85% is protected, and that much of this work was financed privately, in the areas outside of public areas. In assessing coastal erosion issues, the ICMP reviews aerial photography that is conducted at three year intervals combined with visual inspections of areas not currently protected by hardened structures. Illinois Beach State Park represents approximately 95% of the area that is not currently protected by hardened structures.

Planning

When the IDNR erosion assessment process identifies a coastal erosion problem, the next step is to engage stakeholders and develop a management plan that incorporates several key perspectives regarding coastal processes along the Illinois coast. These are:

The Illinois coast was nearly all erosional in its pre-development setting. The exception was the southern end of the Zion beach-ridge plain. Human activity has been responsible, in places and at times, for focusing and exacerbating erosion. However, the human erosional influence is additional to naturally occurring erosion.

Waves are the dominant agent of Illinois coastal change. Fluctuating lake levels, changing sediment budgets, and ice dynamics all contribute to change. However, waves provide the energy to move sediment and ice and cause the impact energy against shore structures.

Lake-level change is a continuous and natural process with various times scales (hourly, daily, monthly, seasonally, yearly, decadal and geologic). Erosion planning needs to include consideration of future lake-level change while also recognizing the uncertainty in long-term lake level prediction.

Waves are the agent for moving sediment along the Illinois coast. Sediment can be moved northward by waves from the southeast quadrant or southward by waves from the northeast quadrant. Because of the greater fetch for northerly waves, these produce the net and regional littoral transport from north to south.

The Illinois coast has experienced a reduction in littoral sand transport volumes during historical time. This is a result of both reduced sediment input from shore and bluff erosion, and structural blockage and entrapment of littoral sand. Conservation of existing sand resources is critical.

The Illinois coast is a “cohesive coast.” This means the upland to nearshore profile primarily consists of cohesive materials (glacial till). Any sand or gravel along the beaches and nearshore is a lens or veneer superimposed on the cohesive material. Erosion of the cohesives is non-reversible.

Areas of greatest concern for coastal erosion will change with time, and the ICMP efforts toward erosion management will adjust accordingly. For example, in the 1970s, most of the bluff coast was a critical erosion area, and during the record high lake levels of 1986-1987 erosion of beaches, parkland and deteriorated shore protection was a major concern along the Chicago lakefront.

Section 309 Report: Coastal Hazards

The following information is extracted from: *Illinois Coastal Management Program Section 309 Assessment and Strategy 2016-2020 (May, 2015).* The document is available online at http://www.dnr.illinois.gov/cmp/Documents/Section309/ICMPSection309PlanFINAL.pdf.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA’s State of the Coast* “Population in the Floodplain” viewer and summarized by coastal county through NOAA’s Coastal County Snapshots for Flood Exposure. People located within the state’s coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	232,238	248,709	+6.62 %
No. of people in coastal counties	6,021,097	5,898,137	-2.04 %
Percentage of people in coastal counties in coastal floodplain	3.86 %	4.22 %	+0.36 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

No data provided

Sea Level Rise: Data from NOAA's State of the Coast "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

No data provided

Other Coastal Hazards: *In the table below, indicate the general level of risk in the coastal zone for each of the coastal hazards. The state's multi-hazard mitigation plan is a good additional resource to support these responses.*

Type of Hazard	General Level of Risk (H, M, L)
Flooding (riverine, stormwater)	H (high)
Coastal storms (including storm surge)	H
Geological hazards (e.g., tsunamis, earthquakes)	L (low)
Shoreline erosion	H (in Lake county)
Great Lake level change	M (moderate)
Land subsidence	L

The Lake County Hazard Mitigation Plan indicates that the most prevalent natural hazards in Lake County are flooding, winter storms, and tornadoes. Seiche events and meteo-tsunamis impact Lake County and the Chicago area approximately once a year, with water levels rising 2 to 3 feet during such an event. The potential of bank erosion in Lake County is relatively high due to the number of steep slopes, streams, and channels in the Lake Michigan watersheds. There has been no recorded history, however, of landslides in Lake County.

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y

Hazards mapping or modeling programs or initiatives for:

Sea level rise/Great Lake level change	Y	Y
Other hazards	Y	Y

The ICMP's Program Document does not contain a definition or designation of "high-hazard areas" for the Coastal Zone. The document identifies Areas of Particular Concern (APC) which have important coastal-related values or characteristics, or may face pressures which require detailed attention beyond the general planning and regulatory system. Designation of APCs entails considerations of hazards under Section 923.21(7) as follows:

Areas where, if development were permitted, it might be subject to significant hazard due to storms, slides, floods, erosion, settlement, saltwater intrusion, and sea level rise;

Hazard areas are addressed as part of the APC Category for "Areas that protect, maintain or replenish coastal lands and significant resources subject to storms, floods, erosion, and settlement, including floodplains, wetlands, sand dunes, natural areas, offshore sand deposits, recreational areas, ports, lakefronts, marinas, public utilities, roads, infrastructure, and historic structures."

Hazards identified as part of this APC include erosion occurring on the coastal shoreline, in the ravine systems, and in the Waukegan River. APCs also include the Illinois Beach State Park and North Point Marina, including the Dead River and Kellogg Creek watersheds.

In-Depth Management Characterization (Phase II In-Depth Assessment)

In the 1970's and 1980's, Illinois had a very active shoreline processes research program. Unfortunately this program has not been active for many years, resulting in a significant need to update knowledge and understanding of coastal processes, including littoral transport, and coastal erosion and accretion. The Illinois shoreline has several distinct geologic features, and includes two counties, 14 municipalities and a 7 mile reach of a state park. Reestablishing a coastal research program will allow us to incorporate not only advances in coastal science but also will allow us to include potential climate change impacts which will assist in developing management strategies that are more resilient.

The following are specific areas of needs and gaps related to improving knowledge and understanding of coastal processes along the Illinois shoreline:

- Investigations for management of the State-Owned, Illinois Beach State Park, where areas of high quality dune and swale habitat are being lost; recreational beaches and infrastructure are being damaged; and accelerated erosion is releasing buried debris from abandoned housing and development.
- Compiling an inventory of shoreline structures. This inventory, when coupled with a long term monitoring of shoreline changes, can enable the beginning of an analysis of individual and cumulative effect of shoreline structures and protection measures on erosion, accretion and in-lake and on shore habitats.
- Analysis of traditional and novel shoreline protection measures and sediment bypass strategies for use along the Illinois Coast.
- Re-initiation of a long-term shoreline monitoring program.
- Development of tools and outreach material to promote cooperation, coordination, and use of regional strategies for shoreline management.

Priority Needs and Information Gaps

Two management priorities identified in the 2015 report are pertinent to coastal geology issues on the Illinois coast and provide opportunity for the ICMP to more effectively address significant hazards.

Management of shoreline erosion and accretion

Coordinate efforts and studies and develop strategies for management of shoreline erosion and accretion; and improve strategies and outreach for management of ravine erosion

Improving stormwater management

Stormwater management is an increasing challenge in the urban environment. A variety of solutions should be employed to effectively capture water and reduce flooding and the damage associated with it. Coordination of work among different entities, performing research and studies, and utilization of green infrastructure will allow development of solutions to increase infiltration, improve water quality, and minimize flooding.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Erosion mitigation strategies; wetland Characterization.
Mapping/GIS/modeling	Y	Shoreline changes; wetland locations; sediment movement.
Data and information mgmt.	Y	Manage and share data effectively.
Training/Capacity building	Y	Ravine management strategies; sand management strategies; wetland usage for stormwater.
Decision-support tools	Y	n/a.
Communication and outreach	Y	Shoreline and sediment management; ravine management; stormwater management.

Indiana https://coast.noaa.gov/czm/mystate/
http://www.in.gov/dnr/lakemich/6039.htm

The Indiana Coastal Management Program, approved by NOAA in 2002, is led by the Indiana Department of Natural Resources. The coastal management program is a networked program built upon a framework of state laws and authorities addressing key coastal priorities. The Coastal Advisory Board, which represents various stakeholder groups, determines the priorities for each grant funding cycle and provides a forum for public input on regional issues affecting Lake Michigan coastal resources. The Indiana coastal zone is based on watershed boundaries and varies from a little less than two miles to 17 miles from the shore.

Coastal Management Program

The Lake Michigan Coastal Program (LMCP) supports coordination and partnerships among local, state, and federal agencies and local organizations for the protection and sustainable use of natural and cultural resources in the Lake Michigan region. Through the LMCP, Indiana participates in the Coastal Zone Management Program with 33 other coastal states and territories to protect, restore, and responsibly develop Indiana's coastal area. Funding will be available annually to implement the LMCP and to provide grants to communities in northwest Indiana.

Indiana's Coastal Zone

The Coastal Program Area defines the lands and waters eligible for financial and technical assistance through the Lake Michigan Coastal Program. Based on public participation and comment, the proposed program boundary was established to approximate the region's watershed. The watershed encompasses the majority of the area that drains into Indiana's portion of Lake Michigan through its rivers, streams, ditches, wetlands, lakes, and groundwater. A watershed approach provides a comprehensive approach to planning for and managing natural resources that focuses on producing environmental results while incorporating the communities that depend on those natural resources. A watershed approach can also leverage financial and other resources, improve coordination among intergovernmental jurisdictions, and reduce duplication of efforts and conflicting actions. The boundary follows the 45-mile shoreline and the approximately 54 miles along an east-west trajectory across the Valparaiso Moraine.

The Coastal Program Area encompasses a total of approximately 604 square miles of land and approximately 241 square miles of Lake Michigan. It covers the northern portions of Lake, Porter, and LaPorte Counties. At its greatest extent, the inland boundary is approx. 17 miles from the Lake Michigan shoreline, and at its narrowest extent the inland boundary is less than 2 miles inland. It is located in the northern portions of Lake, Porter and LaPorte Counties along the southern shore of Lake Michigan. Included within the boundary are lands subject to lake flooding and erosion, estuaries and wetlands, ecologically significant areas formed by glacial Lake Michigan, coastal recreation areas, and areas of cultural and historic significance to the region.

Section 309 Report: Coastal Hazards

The following information is extracted from: *Indiana Lake Michigan Coastal Program: Coastal Zone Management Section 309 Enhancement Grant Program Assessment and Multi-Year Strategy 2016-2020.* The document is available online at http://www.in.gov/dnr/lakemich/files/lm-IN_Sect_309_Plan.pdf.

The Indiana Lake Michigan Coastal Program (LMCP) received Federal Approval in August 2002. The Section 309 process consists of three mandatory and one optional step. The LMCP conducts a Phase I (High Level) Assessment for each of the nine enhancement areas. If an enhancement area receives a ranking of "High" priority, the CMP is to conduct a Phase II (In-depth) Assessment for the enhancement area. The CMP may then develop a Strategy for an enhancement area, in order to address the issues identified in the Phase II Assessment. In addition, the CMP may opt to develop a strategy for Coastal Hazards that can be submitted to the NOAA Project of Special Merit (PSM) competition.

Participation in the Coastal Zone Management Program makes it possible for the Lake Michigan Coastal Program to support activities that achieve the following goals in the coastal region:

Protect and restore significant natural resources;
Prevent the loss of life and property in coastal hazard areas;
Improve public access for recreational purposes;
Protect and restore important historic and cultural resources;
Improve government coordination and policy and decision-making;
Prevent, reduce, or remediate nonpoint source pollution that affects coastal waters;
Revitalize urban waterfronts and ports; and
Provide for priority water dependent uses.

Indiana Lake Michigan Shoreline Coastal Hazards Model Ordinances were developed by the LMCP to provide guidance for coastal communities to understand the ecological value of the natural shoreline and associated coastal resources, and the coastal hazards that can negatively impact the shoreline, public safety, and shoreline properties and infrastructure. High Erosion Hazard Areas (HEHAs) are identified for the entire Indiana Lake Michigan shoreline. The Indiana LMCP identifies a HEHA as a portion of the shoreline with a long-term erosion rate greater than one foot per year. The Indiana shoreline includes several HEHAs; although, many of the areas are currently protected from erosion by man-made structures or are included in the National Park or State Park where the natural shoreline is preserved. The document further addresses the challenges faced by municipalities and decision makers when planning for shoreline development and permit issuing. Model ordinances are suggested to help assure that coastal redevelopment proceeds in a manner that will most likely assure the future social and financial health of the community. The likely result of these ordinances will be communities avoiding construction in hazard areas as well as the protection of coastal natural resources. Additional information on coastal ordinances is available at http://in.gov/dnr/lakemich/files/lm-HazardOrd_TechnicalAssistance.pdf

The LMCP and partners identified coastal data as a gap in addressing Indiana coastal hazards and recently performed GIS mapping of the Indiana Lake Michigan shoreline. The LMCP utilized Section 309 funding to contract with the Polis Center and 39 Degrees North to fill this gap. The professional services contract contained two deliverables completed in 2013:

Updated Indiana Lake Michigan shoreline GIS data layers, maps and attributes on shoreline structures and land use within 1000 ft of the shore, and Indiana Lake Michigan shoreline structures, land use, and processes, for an electronic inventories catalogue.

A variety of data layers collected and created during the GIS project can be used by local communities to reduce hazard risk. The inventory contained information on shoreline armoring, structures, and associated analysis. The packaged geodatabase was initially distributed in late 2014. The intended outcome was to use it as a tool to help direct future public and private development and redevelopment away from hazardous areas. The latter include High Erosion Hazard Areas (HEHAs), hazard areas delineated as FEMA V-zones, and areas vulnerable to inundation from Great Lakes level fluctuations. Use of the tool will help prevent or minimize threats to existing populations and property from both episodic and chronic coastal hazards. The Indiana Geological Survey is expected to place the GIS data on the Lake Rim GIS website for ease of access. See the http://igs.indiana.edu/LakeRim/index.cfm website for additional information.

Resource Characterization (Phase I Assessment):

The Section 309 Enhancement Objective is to: Prevent or significantly reduce threats to life and property by eliminating development and redevelopment in high-hazard areas, managing development in other hazard areas, and anticipating and managing the effects of potential sea level rise and Great Lakes level change. For purposes of the assessment, coastal hazards include the following traditional hazards and those identified in the CZMA: flooding; coastal storms (including associated storm surge); geological hazards (e.g., tsunamis, earthquakes); shoreline erosion (including bluff and dune erosion); sea level rise; Great Lake level change; land subsidence; and saltwater intrusion.

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer, summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure, was used in the assessment. The following table indicates how many people were located within the state's coastal floodplain as of 2010 and how that has changed since 2000.

Population in the Coastal Floodplain

	2000	2010	Percent Change
Population in coastal floodplain	70,885	71,903	1.4%
No. of people in coastal counties	741,468	771,815	4.1%
Percentage of people in coastal counties in coastal floodplain	9.6%	9.0%	- 0.6%

Other Coastal Hazards: The following table shows the general level of risk in the coastal zone for each of the coastal hazards.*

Type of Hazard	**General Level of Risk (H, M, L)**
Flooding (riverine, stormwater)	M (moderate)
Coastal storms (including storm surge)	H (high)
Geological hazards (e. g. , tsunamis, earthquakes)	L (low)
Shoreline erosion	H
Sea level rise	NA
Great Lake level change	H
Land subsidence	L

Saltwater intrusion	NA
Other – Ice Damage	M

*The Indiana Dunes National Lakeshore Shoreline Management Plan (2014) identified high erosion areas along the Indiana Lake Michigan Shoreline and addressed alternative measures for beach sand loss and replacement in areas impacted by breakwalls. Further information is available at http://parkplanning.nps.gov/document.cfm?parkID=139&projectID=33151&documentID=61458

Additionally, some Lake Michigan coastal counties recently developed Hazard Mitigation Plans with the help of contractual consultants and the Northwest Indiana Planning Commission (NIRPC):
Lake County http://www.nirpc.org/media/23587/lake_county_mhmp.pdf
Porter County http://www.nirpc.org/media/23584/porter_county_mhmp.pdf

In-Depth Management Characterization (Phase II In-Depth Assessment)

Information summarized in general tabulated format.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

Beach and Dune Resource and Shoreline Community Protection

Natural processes, storms, lake levels, and human influences have resulted in loss of native beach and dune resources. Not all Coastal Communities have the resources and capacity to develop protective measures and practices to protect, restore and manage dune and shoreline resources within their boundaries. It is important to provide tools, technical assistance, and resource guidance to these communities in order to protect both natural and community shoreline resources.

Shoreline and Coastal Region planning and Development

Coastal hazards challenge municipalities and decision makers when planning for new development, redevelopment, and permit issuing in the Coastal Region. Along with shoreline hazards, hazards associated with tributary flooding, loss of wetlands and green space, and effective storm water management, must be addressed. These needs call for an integrated approach to natural resource management within coastal communities that unifies the different levels of government agencies responsible for regulating natural resources and community development with a balance between development and conservation.

It is important that sustainable coastal planning and development address and integrate all coastal hazards relevant to that community. The current LMCP "toolkit" and model ordinances address many of the issues faced by coastal communities, but additional coastal community hazard protection tools need to be developed for wetland protection and green infrastructure practices. To support planning efforts, coastal community natural resource maps need to be updated in conjunction with the Coastal Hazards GIS Layer developed by the Coastal Program. Further outreach, training, and technical assistance is needed to provide communities with options to address their planning and development needs.

Wetlands, Greenspace and Flood Protection

The LMCP has identified the need to incorporate wetland protection and green infrastructure flooding prevention ordinances in the community technical assistance "toolbox". In many cases community decision-makers are not aware of the ecosystem services provided by wetlands and greenspace in their communities. New green infrastructure measures can contribute to flood reduction as well as providing community enhancements such as parks, trails, and gardens. Flood protection is overseen through community zoning ordinances regulating flood plain boundaries but the connectivity between wetlands, open space, and green infrastructure in flood management is not always incorporated into siting and development planning. Existing wetland maps for the coastal region are not complete or accurate in some areas and need to be updated for community wetland protection and planning as recommended in the Wetlands section of this report.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Review existing model ordinances for wetland and flooding protection for inclusion in Lake Michigan Coastal Hazards Toolbox
Mapping/GIS/modeling	Y	Coastal resource maps need to be created and updated with a focus on wetlands and a wetlands permitting database.
Data and information management	Y	Tracking model ordinance adoption and effectiveness
Training/Capacity building	Y	Training for staff and communities on community needs and adoption of model ordinances
Decision-support tools	Y	Coastal Atlas website with hazard maps and model Ordinance Toolbox
Communication and outreach	Y	Effective outreach and education program to Coastal Communities on Coastal Hazards and model ordinances

Maine https://coast.noaa.gov/czm/mystate/ http://www.maine.gov/dacf/mcp/index.htm

The Maine Coastal Management Program (MCP), approved in 1978, is led by the Maine Department of Agriculture, Conservation, and Forestry. The coastal management program consists of a network of 19 state laws with four state agencies working in cooperation with local governments, nonprofit organizations, private businesses, and the public to improve management of coastal resources. Maine's coastal zone extends to the inland boundary of all towns bordering tidal waters and includes all coastal islands.

Maine Coastal Program

The majority (58%) of the Maine coast is hard rock and is relatively stable over time (a century or more). Another 40%, or 1,400 miles, of the Maine shoreline has soft bluffs: tall (over three feet), with steep slopes of loose rock, gravel, clay, or sand that easily erode. A significant hazard associated with bluffs is the threat of landslides, especially in high coastal bluffs consisting of fine-grained sediment. Beaches and dunes do not form bluffs, except along the seaward dune edge as a result of erosion. Notably, Maine classifies all areas below the highest annual tide elevation as "Coastal Wetlands" that are grouped into three categories: Beaches & Dunes; Bluffs & Rocky Shores; and Coastal Wetlands. (Maine Sea Grant, 2016: http://www.seagrant.umaine.edu/coastal-hazards-guide).

The Maine Coastal Atlas is an online repository for coastal and marine spatial data. It contains hundreds of data layers on ocean species, human uses and ocean characteristics. It was developed to identify potential conflicts between existing and new uses in the ocean and to increase the efficiency, transparency, and effectiveness of siting and permitting decisions. The website is at http://www.maine.gov/dacf/mcp/coastalatlas/index.htm

The Maine Coastal Mapping Initiative (MCMI), which began in 2013, acquires critical data on seafloor terrain and composition that are used by regulatory and planning agencies to maintain vibrant marine ecosystems, expand offshore economic opportunities, improve maritime safety, and prepare for anticipated environmental changes. To date, topographic and habitat maps have been created for 150 square miles of the seafloor off of Maine's Mid-coast region, and priority areas for future mapping have been identified. The MCMI is a collaboration between several state, federal, and non-profit partners (http://www.maine.gov/dacf/mcp/planning/mcmi/index.htm).

Coastal Bluff and Landslide Hazards

The Maine Geological Survey (MGS) has mapped (by boat) shoreline types and relative stability of bluffs along the Atlantic coast. These maps help identify shorelines with increased risk of coastal erosion. Understanding local erosion rates can help determine erosion severity, and perhaps the longevity of coastal development along a bluff edge. Bluff maps were instrumental in a revision to Maine's model shoreland zoning ordinance to require setbacks for new principal structures to be measured from the top of unstable and highly unstable coastal bluffs. This requirement will afford protection from mass movement and prevent premature bluff movement or failure due to development near the bluff edge. Factors known to affect bluff stability on the Maine coast include: bluff height, sediment type, slope, slope aspect, topography, vegetation, microclimate, waves, tides, sea level, drainage, surface water, ground water, physical and chemical weathering processes, earthquakes, and land use characteristics.

Online datasets containing line-data describing shoreline features on the Maine coast are available from the Maine Office of GIS (MEGIS) at http://www.maine.gov/megis/catalog/. The Maine Geological Survey used this dataset to produce maps showing shoreline types, relative bluff stability, and landslide hazards. Mapped at a scale of 1:24,000, they are available for viewing at (http://www.maine.gov/dacf/mgs/pubs/mapuse/series/descrip-bluff.htm) and at (http://www.maine.gov/dacf/mgs/pubs/mapuse/series/descrip-slide.htm). By definition, a bluff is defined as a steep shoreline slope formed in sediment (loose material such as clay, sand, and gravel) that has three feet or more of vertical elevation above the high tide line. Shoreline segments are classified as either being bluff, non-bluff, or unmapped or undetermined. Bluffs are classified as either (1) ledge (exposed bedrock outcrops); (2) armored (seawall, riprap, gabion, bulkhead, etc.); (3) salt marsh; (4) beach, mud flat, or other loose sediment; or (5), unmapped or undetermined. The relative stability of a bluff face is classified as being either (1) not a bluff, (2) stable, (3) unstable, (4) highly unstable, or (5) unmapped or undetermined.

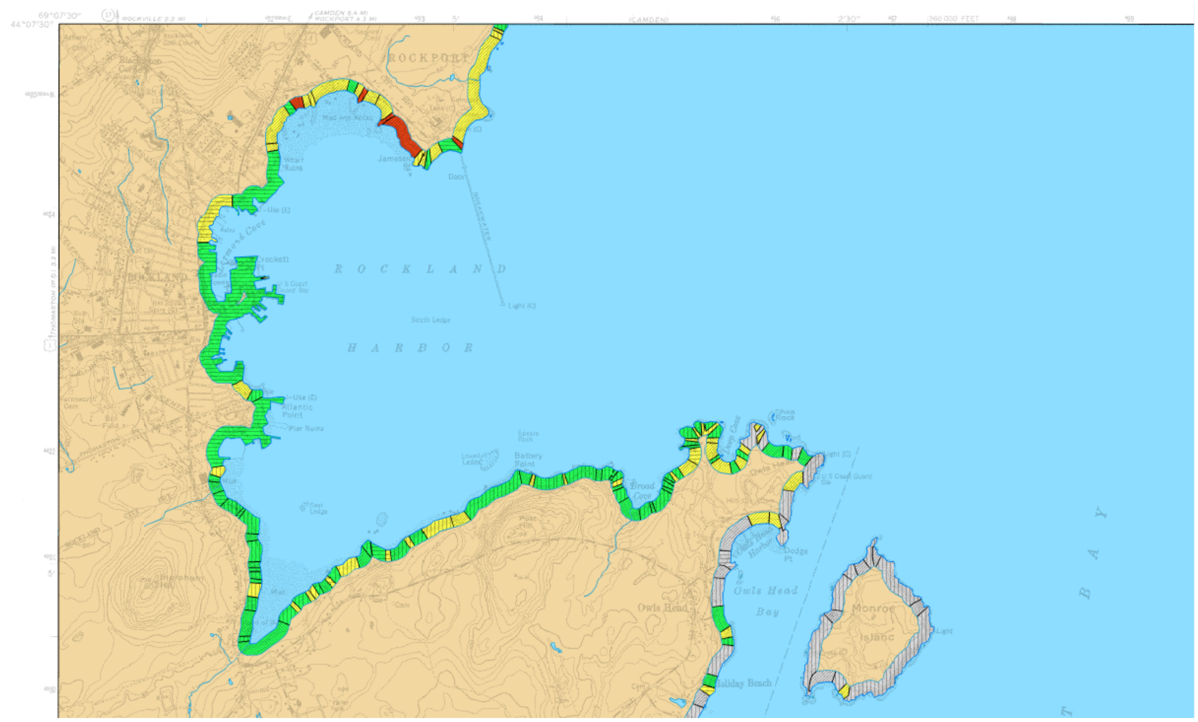

Figure ME 1*: Typical bluff characteristics map for the Maine coast (Rockland Quadrangle). Bluff and stability categories are indicated by color and line-pattern scales.*

The landslide hazard is given by line data describing the internal stability of sediment bluffs along Maine's shoreline. The landslide hazard is classified by one of the following: (i) the bluff is the site of a past historical or photo interpreted landslide; (ii) the bluff has an elevated risk of a landslide based on field observation; (iii) the bluff has an elevated risk of a landslide based on aerial photo interpretation, but needs field assessment; (iv) there is no landslide potential; or (v) the landslide potential is unmapped or undetermined. Because of the map scale, landslide hazard characteristics are generalized into segments of 150 feet or more in length that show the average hazard inferred.

Landslide risk may change over time. Natural changes, or changes due to land alteration or shoreline engineering, may cause a segment of the shoreline to have a different level of landslide risk than that shown on the most recent map. Continued erosion on the face of a bluff may make the bluff steeper and more likely to fail via a landslide. Conversely, an area that has experienced a landslide may have less risk of future landslides, but the land may still be unstable and subject to minor amounts of settlement. Where the height of a bluff has been reduced and graded to a lower slope, the risk of a landslide may also have decreased.

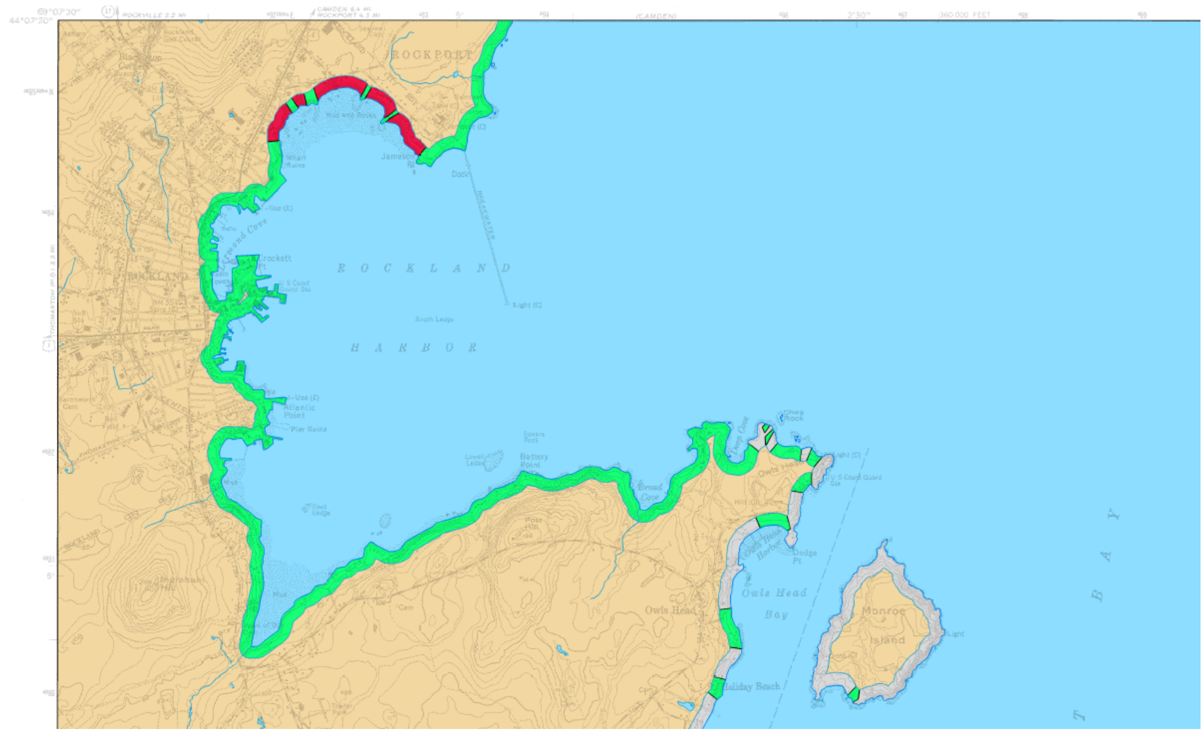

Figure ME 2*: Typical landslide hazard map for the Maine coast (Rockland Quadrangle). Landslide-hazard categories are indicated by color and line-pattern scales.*

Section 309 Report: Coastal Hazards

The following information is extracted from*: Maine Coastal Program, Strategic Outlook 2016-2020: Assessment and Strategy under Section 309 of the Coastal Zone Management Act (October, 2015)*. The document is available online at http://www.maine.gov/dacf/mcp/downloads/strategic_outlook_2016_2020.pdf.

Maine's coastal zone includes 5,408 miles of coastline; all municipalities with tidal waters in their jurisdiction; and state-owned submerged lands and islands out to three nautical miles offshore.

To foster innovation and continuous improvement in state coastal programs, the NOAA-administered the Coastal Zone Enhancement Program (Section 309 of the CZMA) provides incentives to states to enhance their coastal programs in nine key areas of national concern. Section 309 Enhancement Area funds are intended for states to achieve "program changes" such as new or revised state statutes and rules, new or revised municipal plans and ordinances, guidance, agreements, creation of new funding sources, procedures, policies, and agreements.

For the Section 309 Strategic Outlook (2016-2020), MCP conducted Phase I Assessments of all nine issue areas, compiling existing data and summarizing trends in demographics, resource use, conservation and economic development and assessing past work. Of the nine federal enhancement areas, four were chosen as priorities in the 2016-2020 Strategic Outlook -- Coastal Hazards, Cumulative and Secondary Impacts of Development, Ocean Resources, and Wetlands. For these priority enhancement areas, more detailed Phase II Assessments were developed that examined stressors/threats to resources, emerging issues, data and information needs, and management priorities. Coastal Hazards have been ranked High Priority in both the 2016-2020 and the prior 2011-2015 Strategic Outlooks.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	75,314	81,929	8.8 %
No. of people in coastal counties	1,183,750	1,238,956	4.7 %
Percentage of people in coastal counties in coastal floodplain	6.4 %	6.6 %	0.2 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

According to data downloaded from *NOAA's State of the Coast* "Coastal Vulnerability Index" for Maine, 17 miles of Maine's shoreline has a Low vulnerability, while 1452 miles has a Moderate vulnerability to shoreline erosion; this dataset is clearly incomplete, as it *provides data for just over one-quarter of Maine's overall shoreline*. Thus, the Maine Geological Survey (MGS) used Maine's Coastal Marine Geologic Environments* data combined with Coastal Bluff Stability mapping data to create a slightly different classification for vulnerability of the Maine shoreline to erosion. The table below does not use calculated shoreline change rates; instead, it uses geologic shoreline types and/or mapped bluff types as proxies for shoreline change vulnerability. According to this data, about 13% of the shoreline is a High or Very Highly susceptibility to erosion.

Vulnerability to Shoreline Erosion (CMGE* and Bluff Types)

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very low (rocky, armored)	1827	34 %
Low (flats, stable bluffs)	2549	47 %
Moderate (coarse beaches)	355	7 %
High (unstable bluffs)	406	8 %
Very high (sand beaches & dunes, highly unstable bluffs)	271	5 %
Total Shoreline	5408	100 %

Sea Level Rise: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

According to data downloaded from *NOAA's State of the Coast* "Coastal Vulnerability Index" for Maine, 658 miles of Maine's shoreline has a "Low" vulnerability, while 831 miles has a Very Low vulnerability to sea level rise; again, this dataset is clearly incomplete, as it *provides data for just over one-quarter of Maine's overall shoreline*. Again, MGS created a different table that uses data described in the Shoreline Erosion section above. These data show that a high percentage of the coastline, about 31%, is very highly vulnerable to sea level rise because it is comprised of either flats or highly unstable bluffs. If sandy beaches, dunes, and unstable bluffs are included, then about 42% of Maine's coastline is vulnerable to sea level rise.

Coastal Vulnerability to Sea Level Rise (CMGE* and Bluff Types)

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very Low (rocky, armored)	1827	34 %
Low (coarse beaches)	355	7 %
Moderate (stable bluffs)	942	17 %
High (sand beaches & dunes, unstable bluffs)	617	11 %
Very High (flats, highly unstable bluffs)	1667	31 %
Total Shoreline	5408	100 %

Shoreline Erosion

Many beaches, dunes, and bluffs in Maine are experiencing more acute erosion and flooding problems since the last assessment (Ezer and Atkinson, 2014; Sweet et al. 2014; Slovinsky, 2012, 2014; Slovinsky and Dickson, 2011; 2009; Slovinsky et al. 2013).

Maine does not have a specific state-wide definition of "high hazard area". For beach and dune systems, Maine regulates activities through the Coastal Sand Dune Rules (Chapter 355 of the NRPA), which use a geologic definition of frontal dune and back dunes. Higher hazard areas are typically considered to be areas of the frontal dune, and areas of back dunes that are defined as Erosion Hazard Areas, or EHAs (all frontal dunes are EHAs).

EHAs are defined as any portion of the coastal sand dune system that can reasonably be expected to become part of a coastal wetland in the next 100 years due to cumulative changes in the shoreline from (i) historical long-term erosion, (ii) short-term erosion resulting from a 100-year storm, or (iii) flooding in a 100-year storm after a two-foot rise in sea level. EHAs also include any portion of the coastal sand dune system that is mapped as an AO flood zone by the effective FEMA Flood Insurance Rate Map. The sand dune system is presumed to be located in an Erosion Hazard Area unless the applicant demonstrates, based upon site-specific information, as determined by the department, that a coastal wetland will not result from either (i), (ii), or (iii) occurring on an applicant's lot given the expectation that an AO-Zone, particularly if located immediately behind a frontal dune, is likely to become a V-Zone after 2 feet of sea level rise in 100 years.

Sea level rise

The rate of sea level rise in the Gulf of Maine has accelerated in the last decade (Yin and Goddard, 2013; Goddard et al. 2015) and has also increased along the Maine coastline. In the last 100 years of tide gauge data, 83% of the highest recorded average monthly sea levels occurred in the last decade (Slovinsky, 2012). In the next 5 years, updated digital Flood Insurance Rate Maps (DFIRMs) should be completed for all coastal counties and can form the basis for additional sea level rise scenarios.

Bluff Stability

Statewide mapping is completed except for Washington County. This has resulted in the mapping of around 1,400 miles of bluffs, categorized as stable, unstable, or highly unstable in the Coastal Bluff Map series by MGS. Landslide susceptibility has also been mapped and is available as part of the Coastal Landslide Hazards Map series. However, with the availability of new coastal LiDAR, many new landslides have been revealed through analysis. Geomorphic features in and around Casco Bay suggest that there are more than 10 times the number of landslides than previously known. The risk is medium at this time because the age, and hence frequency, of landslides is yet to be determined.

Maine has classified its bluff shorelines as Stable, Unstable, or Highly Unstable. Per Maine's Mandatory Shoreland Zoning Act, areas of the coastline defined as Unstable or Highly Unstable require that development be set back 75 feet from the top of a bluff, instead of 75 feet from the highest annual tide line (which is the standard for stable bluff areas).

Coastal Erosion: Maine Beach Mapping Program

MGS continues mapping shoreline features using RTK-GPS as part of the Maine Beach Mapping Program (MBMAP) at southern and mid-coast Maine's larger beach systems. The U.S. Geological Survey Digital Shoreline Analysis System program is used to calculate short-term shoreline change rates. Additionally, Maine continues to hold the biennial State of Maine's Beaches Conference on coastal erosion issues. The conference coincides with the release, biennially, of the State of Maine's Beaches report. Data from MBMAP is integrated into this report, as well as beach changes measured as part of the Maine Beach Profile Monitoring Program (MBPMP).

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lakes level change	Y	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise and marsh migration	Y	Y
Coastal sand dunes	Y	Y
Hurricane inundation	Y	Y
Maine Beach Mapping Program	Y	Y

In-Depth Management Characterization (Phase II In-Depth Assessment)

The Strategic Outlook's (2016-2020) three most significant coastal hazards on the Maine coast are identified as (i) Sea level rise, affecting coastal beaches, dunes, wetlands, bluffs, and low-lying uplands; (ii) Flooding, affecting coastal beaches, dunes, wetlands, bluffs, and low-lying uplands; and (iii) Shoreline erosion, affecting coastal sand dunes and erodible bluffs.

Sea Level Rise and Flooding

Maine's Phase I assessment showed that about 42% (2,284 miles) of Maine's coastline is highly or very highly vulnerable to long-term sea level rise, and in turn, short-term coastal inundation. These numbers do not include regions of the coastal zone that may be vulnerable to freshwater flooding during precipitation events, which remain unclassified. Areas vulnerable to both sea level rise and inundation include all of Maine's mapped coastal sand dunes, coastal wetlands, other low-lying areas (such as developed water-dependent areas or freshwater wetlands), and unstable, erodible bluffs.

Maine's vulnerability to both long-term sea level rise and short-term coastal flooding (Sweet et al. 2014) is further exacerbated by abrupt short-term sea level rise caused by ocean circulation and recurring weather patterns (Goddard et al., 2015; Yin and Goddard, 2013). In 2010, sea levels in the Gulf of Maine deviated more from normal levels (on average, about 5 inches) than anywhere on the U.S. East Coast. Analysis by MGS found that averaged annual sea levels in 2010 were the highest for five months (December through April) out of the year since data has been recorded starting in 1912 (Slovinsky, 2012). As a result of these higher-than-normal sea levels coupled with storm events, extensive beach erosion occurred at many of Maine's beaches in 2010 (Slovinsky and Dickson, 2011; Slovinsky et al. 2013). In fact, erosion was the worst experienced in a half century at some locations (Slovinsky and Dickson, 2011). This particular event has shown how just small changes in sea level – even on short time frames – can greatly exacerbate shoreline erosion.

The vulnerability of low-lying developed areas to both sea level rise and storm surge inundation has been clearly demonstrated in sea level rise/storm surge mapping undertaken using local to regional approaches under Maine's Coastal Hazard Resiliency Tools project. Maine has also completed statewide mapping of the Highest Annual Tide (HAT) in support of Shoreland Zoning and as the basis for sea level rise planning. Scenarios of 1, 2, 3.3, and 6 feet of sea level rise (or storm surge) on top of the HAT were mapped as well. An online mapping website is in the process of being developed in order to release these datasets.

Shoreline Erosion

About 13% (677 miles) of Maine's coastline is classified as highly or very highly vulnerable to shoreline erosion. These areas are generally limited to coastal sand dunes (including beaches) and erodible unstable or highly unstable bluffs. Through the Maine Beach Mapping Program (MBMAP), MGS monitors around 21.4 miles of sandy beaches and dunes in southern and mid-coast Maine. In addition, MGS has also either measured with GPS or digitized approximately 16 additional miles of seawall within and adjacent to these sandy beach areas. Based on these data, about 28% of Maine's sandy beach shoreline is measurably eroding, while 43% is "stable due to armoring."

Maine is also concerned about the potential impacts of long-term sea level rise and short-term storm events on the erodible bluff shoreline, which comprises about 33% (1874 miles) of mapped shorelines. A Project of Special Merit titled *Building Resiliency along Maine's Bluff Coast* is developing better predictive models relating to bluff response (and landslide hazard) to increased sea levels and storms. This project includes a pilot study area within Casco Bay, where approximately 250 landslide sites were identified using newly available LiDAR data. Previously only 118 identified landslide sites had been identified in this populated section of Maine coast.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

The Maine Coastal Program (MCP) has identified five emerging issues, and their associated data gaps, of which three are specifically related to coastal erosion processes along the Maine coast:

Issue	**Information Needed**
Coastal landslides	More complete documentation of historic slides and increased understanding of the process
Bluff recession	Historic information on bluff position
Changes to coastal wetlands from sea level rise	Sedimentation rates for coastal marshes

MCP has also identified two management priorities (of a total of three) closely related to coastal erosion-related hazards where there is opportunity to improve its ability to address the most significant hazard risks:

Advancing Coastal Community Hazard Identification and Mitigation

In the Gulf of Maine, the rate of sea level rise in the 21st century is double that of the 20th century, and tides have reached record levels in the last decade. Increased tide levels have resulted in a 300% increase in nuisance flooding this century. Communities preparing local coastal floodplain management programs and infrastructure improvement plans need technical guidance to develop adaptive management strategies that identify cost-effective pre-disaster actions. Effort in this priority will focus on coastal community vulnerability assessments to prioritize and systematically build a “roadmap” for hazard reduction efforts as well as to build local capacity and policy direction for mitigation efforts in preparation of storms of today and higher tides of tomorrow.

Shoreline Erosion Rate Mapping and Modeling

Mapping shoreline change and erosion trends are critical to identifying the severity of coastal hazards. Data are necessary to understand the magnitude of erosion and coastal hazards driven by small amounts of sea level rise or specific storms. Understanding geospatial trends in erosion leads to better regional sediment management, dune or beach restoration analysis, and assessment of vulnerability to increased flooding. These data are necessary for guiding local and state mitigation plans, implementing cost-effective strategies, and defining short-term pre- and post-storm actions.

The MCP has identified priority needs and information gaps to address the coastal management priorities identified above:

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Shoreline response to small amounts of sea level rise (beaches and bluffs). Updated mapping of intertidal geology and habitats to replace low-resolution 50-year old data.
Mapping/GIS/modeling	Y	Modeling of mixed fresh/salt water and the influence of increased precipitation on storm water flow;

		water-penetrating LiDAR along the coastal zone for seamless topo-bathymetry.
Data and information management	Y	Online access to coastal hazards data. Online access to development permits. Long-term measurements of the performance of coastal engineering methods and structures, wetlands restoration, and monitoring of cumulative impacts.
Training/Capacity building	Y	Local stakeholder training on using new data, resiliency tools, that are available from the State of Maine.
Decision-support tools	Y	Resiliency Toolkit (MPAP, DEP, MGS, etc.).
Communication and outreach	Y	Tools to help move discussion at the community level forward from vulnerability assessment to adaptation action including more focus on determination and assumption of risk.

Maryland https://coast.noaa.gov/czm/mystate/
http://dnr2.maryland.gov/ccs/Pages/default.aspx

The Maryland Coastal Management Program was approved by NOAA in 1978, with the Department of Natural Resources acting as the lead agency. The coastal management program is a networked program composed of several state planning and regulatory programs implementing a suite of enforceable policies to protect coastal resources and manage coastal uses, including the Chesapeake Bay Critical Area Protection Program. Maryland's coastal zone follows the inland boundary of the counties (and Baltimore City) bordering the Atlantic Ocean, Chesapeake Bay, and the Potomac River (as far as the municipal limits of Washington, D.C.).

Chesapeake Bay Bluff Retreat

Larsen, Clark, and Herzog (2010), in *So You'd Like to Stop Shore Erosion along the Calvert Cliffs: You'd Better Think Before You Act*, review bluff retreat along the Chesapeake Bay coast. The Powerpoint report, available at http://dnr.maryland.gov/ccs/Documents/training/secc_cl.pdf, concludes that there are two basic processes acting on eroding sea cliffs in Maryland, specifically (i) initial bluff retreat via a failure event and (ii) slope failure and bluff-top retreat until a stable angle of repose is attained. In a large Calvert Cliffs study area, the stable slope angle averages 35 degrees. Once the first active-erosion process ends, the bluff top may be expected to recede until the stable slope angle is reached. In Calvert County, this process takes about 30 years.

The stable angle of repose for the Calvert County area is estimated from recent studies of fossil bluffs at three different sites, the oldest of which has had bluffs isolated from the shoreline for approximately 1700 years. At a second site, a similar study in an area where fossil bluffs have been shielded from modern coastal processes for about 400 years showed that the 35 degree slopes were attained within a time period as short as 400 years. At a third site where bluffs became isolated from coastal processes due to construction of a jetty and beach accretion, the slope bluff angles changed from 70 degrees to 45 degrees over a 25 year period and remain active as they continue to adjust to an expected 35 degree slope.

Assuming a 35 degree stable angle of repose for any bluff means that taller bluffs can be expected to experience more bluff-top retreat than lower bluffs. For planning purposes, this presents a dilemma because the slope:height relationship will obviously affect decision-making on any construction setbacks that are proposed as a coastal hazard mitigation tool.

Maryland Coastal Zone Management Program

The Maryland coastal zone extends from three miles out in the Atlantic Ocean to the inland boundaries of the 16 counties and Baltimore City that border the Atlantic Ocean, Chesapeake Bay and the Potomac River up to the District of Columbia. This area encompasses two-thirds of the State's land area and is home to almost 70% of Maryland's residents.

Maryland's CZM program is now known as the Chesapeake and Coastal Service (CCS). By shifting from a decentralized, program-specific approach, to a more centralized objective-based approach, the CCS is better able to leverage core competencies from different programs, avoid duplicate efforts, and leverage and efficiently prioritize resources to advance the goals of the CZMA.

***Figure MD 1**: Typical appearance of upland bluffs on the Chesapeake Bay coast, near Calvert Cliffs State Park, Maryland, looking south (top) and north (bottom) (Images: modified from Larsen et al. 2010).*

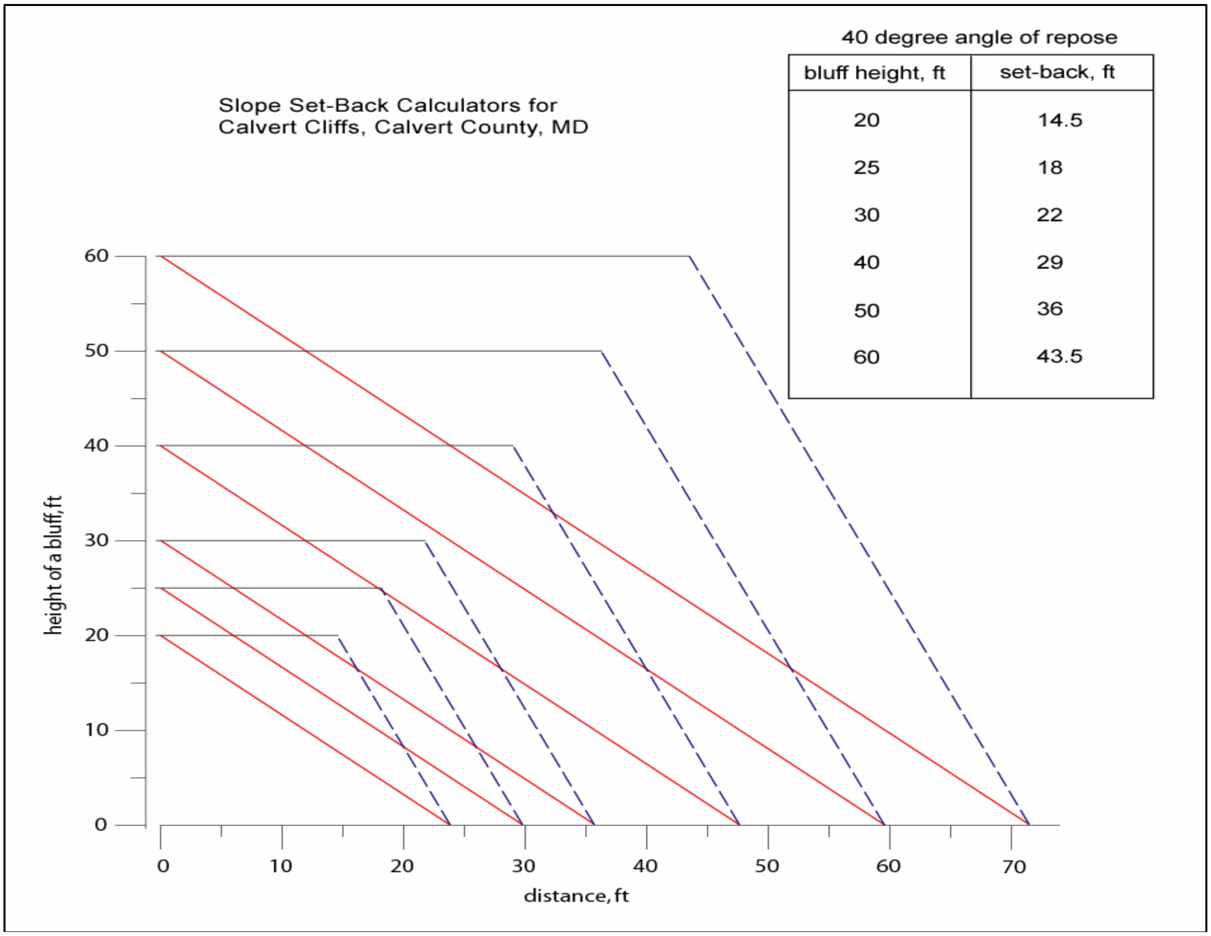

Figure MD 2*: Schematic relationship between a 40 degree angle of repose and safety setback distances that would be required for bluffs of different elevations on the Maryland Chesapeake Bay bluff coast. This model assumes there are no other complicating factors (Image: modified from Larsen et al. 2010).*

CCS, administered by the State Department of Natural Resources, is a partnership among local, regional and state agencies. It also collaborates with many private organizations such as local land trusts and economic development groups. Through this networked approach, no one agency or department is responsible for Maryland's entire coast. Rather, all partners help to ensure its proper management.

In 2010, Maryland developed a five-year Assessment and Strategy that addressed enhancement areas and established two strategies that addressed multiple Section 309 priorities: (i) a Coastal Hazards and Climate Change Adaptation Planning strategy (Coastal Hazards, Cumulative and Secondary Impacts, and Ocean/Great Lakes Resources); and (ii) a Comprehensive Ocean and Coastal Planning strategy (Aquaculture, Cumulative and Secondary Impacts, Energy & Government Facility Siting, Ocean/Great Lakes Resources, and Public Access).

The main goals of the Coastal Hazard and Climate Change Adaptation strategy are: (i) Coastal community hazard assessments and *CoastSmart* Communities Program; (ii) Training, data support, and outreach; and (iii) State-level climate change and sea level rise adaptation. Section 309 funding was instrumental in establishing the *CoastSmart* Communities Online Resource Center, launched in

June 2010. It was developed to assist businesses, communities and local governments by providing access to available products and services that address the current risks associated with coastal hazards and the potential increased impacts of those hazards in the future due to climate change (http://dnr2.maryland.gov/ccs/coastsmart/Pages/cs_Resources.aspx). A key feature of the Online Resource Center is the Shorelines mapping application of Maryland's Coastal Atlas, which was updated in 2015. The Shorelines mapper provides access to an interactive mapping tool to display historical rates of shoreline change, the Comprehensive Shoreline Inventory, storm surge inundation, and areas at risk from sea level rise.

Section 309 Report: Coastal Hazards

The following information is extracted from*: Maryland's Coastal Enhancement Plan, Coastal Zone Management Act §309 Assessment and Strategy 2016-2020 (Draft, May, 2015)*. The document is available online at http://dnr2.maryland.gov/ccs/Documents/20152016_czeplan.pdf.

Coastal hazards is a high priority enhancement area because of the high level of risk posed to Maryland's coastal communities. There is a serious threat that risk will only increase with changes in climate and sea level. The Assessment & Strategy 2016-2020 report assigned Priority Rankings to nine coastal management issues: Coastal Hazards received the highest ranking.

CCS has begun updating the Shoreline Rates of Change data for Maryland's coast. It has been nearly two decades since the last revision and the data and information were becoming less useful in shoreline management. Since the last recorded shoreline change rate was calculated (1990), Maryland has experienced several large storms that have likely changed the shorelines in a number of coastal counties.

CCS and the Maryland Geological Survey (MGS) recently updated shoreline change information for Anne Arundel and Baltimore counties by adding two post-2000 shorelines, determining shoreline rates-of-change, and assigning generalized erosion rate categories. MGS worked with CCS to upload the results to Maryland's Coastal Atlas (http://dnr2.maryland.gov/ccs/Pages/coastalatlas.aspx), disseminate and communicate the information to key stakeholders, and incorporate the work into shoreline management. The project served as the first step of a statewide shoreline change update for the remaining tidewater counties.

MGS, Towson University's GIScience Center, and the U.S. Geological Survey, ran the Digital Shoreline Analysis System (DSAS) on a series of digital shoreline vectors dating from 1841 through 1995. Shorelines were derived from three sources: (1) maps from a Historical Shorelines and Erosion Rates Atlas, (2) Coastal Survey maps (T-sheets) produced by the National Ocean Service, and (3) a digital wetlands delineation based on photo interpretation of digital orthophoto quarter-quads. DSAS used a "baseline" landward of and approximately parallel to the shorelines, inserted nodes every 20 m along the baseline, and cast straight-line transects from each node, perpendicular to the baseline, across the shorelines. Based on the time elapsed and the along-transect distance between shoreline pairs, DSAS calculated rates of change for each transect.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	233,261	284,477	22 %
No. of people in coastal counties	3,593,067	4,148,642	15.5 %
Percentage of people in coastal counties in coastal floodplain	6.5 %	6.9 %	0.4 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

Vulnerability to Shoreline Erosion

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline*
Very low (>2.0m/yr) accretion	757	39 %
Low (1.0 to 2.0 m/yr) accretion	20	1 %
Moderate (-1.0 to 1.0 m/yr) stable	81	4 %
High (-1.1 to -2.0 m/yr) erosion	87	4.5 %
Very high (<-2.0 m/yr) erosion	985	51 %

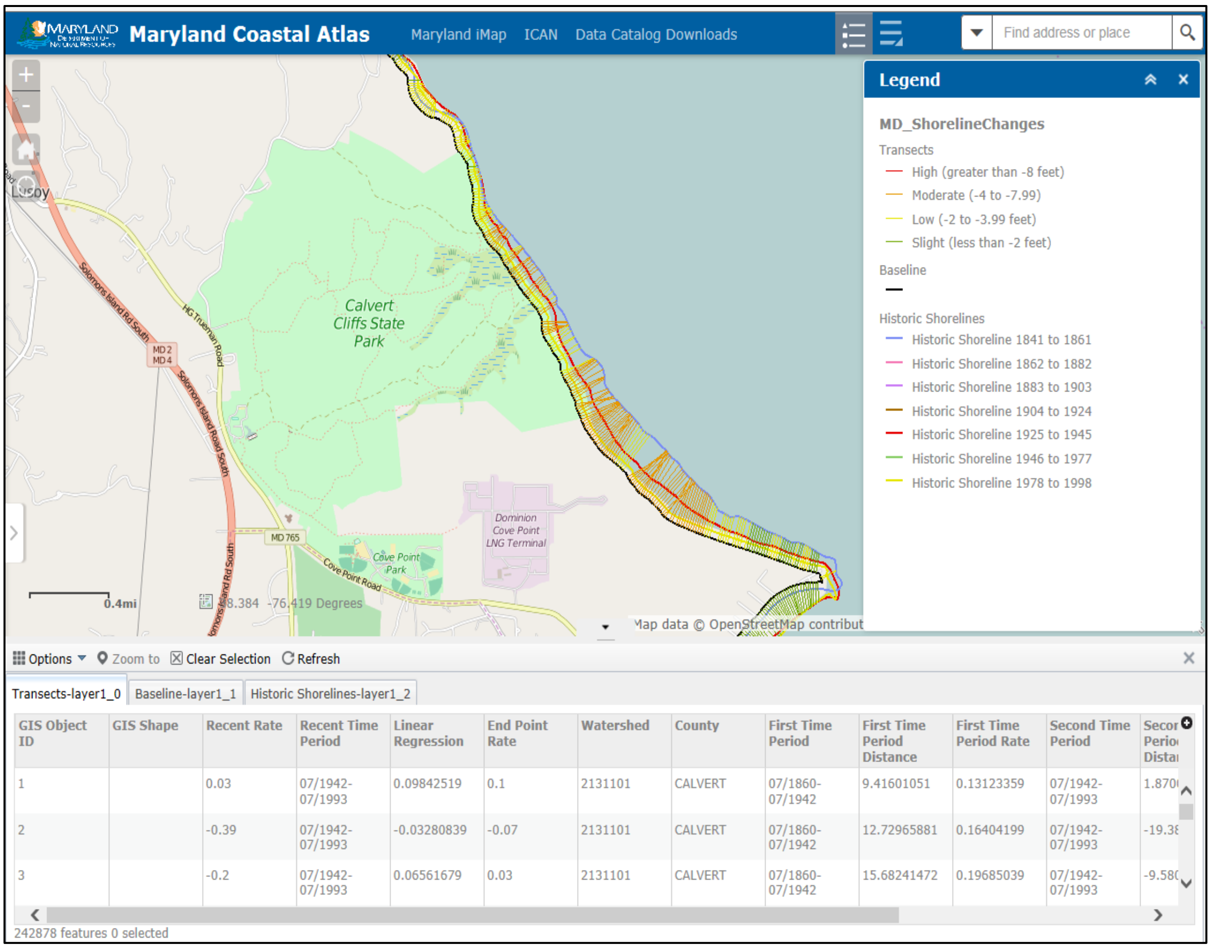

***Figure MD 3**: Screenshot from the Maryland Coastal Atlas showing long-term historical shoreline positions, half-century shoreline change rates, and associated attribute data for part of the Chesapeake Bay bluff coast.*

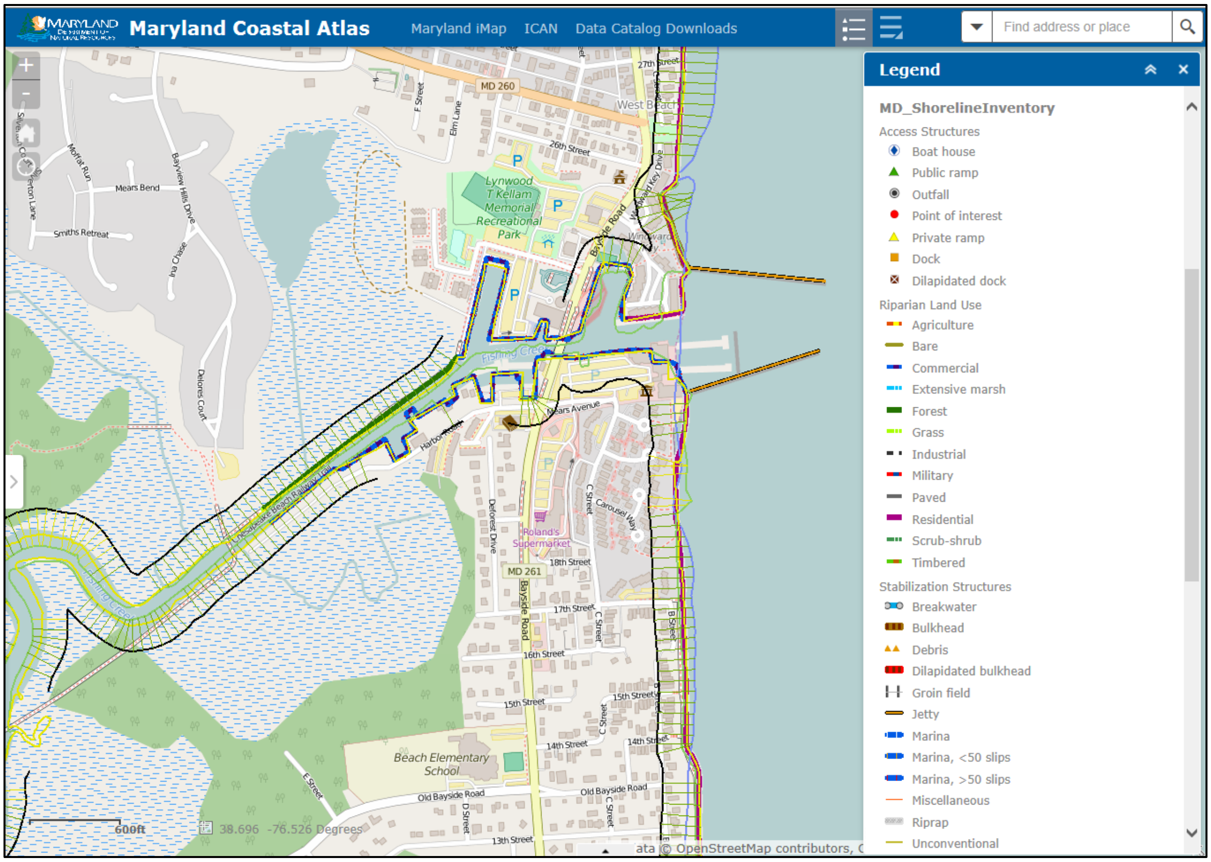

***Figure MD 4**: Screenshot from the Maryland Coastal Atlas showing long-term historical shoreline positions, half-century shoreline change rates, and shoreline inventory data for the urbanized Chesapeake Beach area.*

Sea Level Rise: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

Coastal Vulnerability to Historic Sea Level Rise

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very Low	0	0 %
Low	39	2 %
Moderate	1044	54 %
High	847	43 %
Very High	0	0 %

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	N	Y
Management of development/		

redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lakes level change	Y	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise or Great Lakes level change	Y	Y

In-Depth Management Characterization (Phase II In-Depth Assessment)

Information summarized in tabulated format.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

Maryland has long addressed coastal hazards and climate change at the state and local levels. With more than 7,000 miles of shoreline and intense coastal development, including large urban population centers such as Annapolis, Baltimore and Ocean City, coastal communities and natural resources still remain highly exposed to coastal hazards. Due to the State's broad coastal hazard and climate vulnerabilities, building resilience to coastal hazards remains a top priority for the state.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Need a better scientific understanding of coastal environments to inform/improve local risk assessments and inform risk reduction strategies.
Mapping/GIS/modeling	Y	Need for fine scale inundation data to sufficiently assist local floodplain, land use, and emergency planners.
Data and information management	Y	New and updated hazards data will continually become available. Data will have to be carefully managed and integrated into existing or new platforms, such as the MD Coastal Atlas.
Training/Capacity building	Y	Training can be used as a way to holistically increase the resiliency of the State by reaching local and state planners.
Decision-support tools	Y	Need to educate a wide range of stakeholders, including elected officials, on hazard risk and vulnerability.

Communication and outreach	Y	Need to effectively communicate the risks of hazards to coastal communities.
Other	Y	Address the challenge that low income and otherwise vulnerable communities will likely be impacted disproportionately by climate change.

Massachusetts https://coast.noaa.gov/czm/mystate/
http://www.mass.gov/eea/agencies/czm/

The Massachusetts Coastal Management Program, approved by NOAA in 1978, is administered by the Office of Coastal Zone Management within the Executive Office of Environmental Affairs and serves as the lead for coastal policy and technical assistance in the state. The Executive Office of Environmental Affairs enforces 20 program policies and nine management principles governing activities within the coastal zone. The Massachusetts coastal zone roughly includes all land within a half-mile of coastal waters and salt marshes, as well as all islands.

Massachusetts Coastal Zone Management Program

As described in the *Massachusetts Office of Coastal Zone Management Policy Guide*, the Massachusetts coastal zone includes the lands and waters within an area defined by the seaward limit of the state's territorial sea, extending from the Massachusetts-New Hampshire border south to the Massachusetts-Rhode Island border, and landward to 100 feet inland of specified major roads, rail lines, other visible rights-of-way, or in the absence these, at the coordinates specified below. The coastal zone includes all of Cape Cod, Nantucket, Martha's Vineyard, and the Elizabeth Islands. The coastal zone includes all islands, transitional and intertidal areas, coastal wetlands, and beaches. In isolated instances where the boundary line might exclude coastal resource area(s), these resources are included in the coastal zone although the written description follows the boundary line. Tidal rivers and adjacent uplands are included, at a minimum, to the extent of vegetation affected by measurably saline water. Anadromous fish runs are included, as well as their floodplains, to the freshwater breeding area, if such area is within a coastal town. Land owned or controlled by the federal government is excluded by law from the coastal zone.

Two particularly significant coastal-erosion related efforts within the Massachusetts Office of Coastal Zone Management (CZM) are (i) the StormSmart Coasts Shoreline Change Project and (ii) the StormSmart Coasts Inventories of Seawalls and Other Coastal Structures Project. The former project focuses on high-water shoreline mapping, rather than on bluff-crest mapping, given the dominance of beach morphologies on the MA coast. However, low-bank/cliff coastal sectors are common on the northern MA coast and the methodologies used by CZM state-wide in the Shoreline Change Project are very applicable to modern bluff-top mapping methods now being conducted on most Great Lakes coasts. Both projects are summarized below.

The two StormSmart projects described below are part of a larger program that also involved the development of a StormSmart Properties Fact Sheet Series to give coastal property owners important information on a range of measures that can effectively reduce coastal erosion and storm damage while minimizing impacts to shoreline systems. This information is intended to help property owners select the best option or combination of options for their circumstances. The first six fact sheets include: *Artificial Dunes and Dune Nourishment; Controlling Overland Runoff to Reduce Coastal Erosion; Planting Vegetation to Reduce Erosion and Storm Damage; Bioengineering – Coir Rolls on Coastal Banks; Bioengineering – Natural Fiber Blankets on Coastal Banks; and Sand Fencing.*

StormSmart Coasts - Massachusetts Shoreline Change Project

Excerpted from: http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/shoreline-change/

To help make informed decisions, coastal managers, shorefront landowners, and potential property buyers need information on shoreline trends, including erosion and accretion rates. The goal of the Massachusetts CZM Shoreline Change Project is to develop and distribute scientific data that will support local land-use decisions.

CZM's Shoreline Change Project illustrates how the shoreline of Massachusetts has shifted between the mid-1800s and 2009. Using data from historical and modern sources, up to eight shorelines depicting the local high water line (i.e., the landward limit of wave run-up at the time of local high tide) have been generated with transects at 50-meter intervals along the ocean-facing shore. For each of more than 26,000 transects, data are provided on net distances of shoreline movement, shoreline change rates, and uncertainty values. CZM has incorporated these shoreline change data into MORIS, the Massachusetts Ocean Resource Information System, and has developed a customized Shoreline Change Browser within the MORIS web-based coastal management tool available online.

Shoreline positions change constantly in response to wind, waves, tides, sea level change, seasonal and climatic variations, human alteration, and other factors that influence the movement of sand and other material within a coastal system. The loss (erosion) and gain (accretion) of coastal land is a visible result of the way shorelines are reshaped in the face of these dynamic conditions. The information below explains the process of shoreline change, discusses its impacts, summarizes the Shoreline Change Project, and explains how to interpret and apply the shoreline change data.

The Shoreline Change Project presents both long-term (approximately 150-year) and short-term (approximately 30-year) shoreline change rates at 50-meter intervals along ocean-facing sections of the Massachusetts coast. In a broad sense, this information provides useful insight into the historical migration of Massachusetts shorelines and the locations of erosional hot spots. Care must be used, however, when applying this information to a specific property or section of coastline. Due to the multitude of natural and human-induced factors that influence shoreline positions over time, correct interpretation of the data requires knowledge of coastal geology and mapping and the other forces that affect shorelines. CZM recommends consulting with a professional when applying the Shoreline Change Project data for land-use decisions and planning purposes. In no case should the long-term shoreline change rate be used exclusively before the short-term rate, uncertainty associated with each shoreline position, patterns of erosion and accretion, and other contributing factors are understood and assessed.

How and Why Shorelines Change

The sources of sand that created and continue to feed the beaches, dunes, and barrier beaches in Massachusetts come primarily from eroding coastal landforms. For example, material eroded from Atlantic-facing coastal banks of the Cape Cod National Seashore supplies sand to downdrift (i.e., down current) beaches of Cape Cod.

Erosion, transport, and the accretion that results are continuous and interrelated processes. Every day, winds, waves, and currents move sand, pebbles, and other materials along the shore or out to sea. Shorelines also change seasonally, tending to accrete gradually during the summer months when sediments are deposited by relatively low energy waves and erode dramatically during the winter when sediments are moved offshore by high energy storm waves, such as those generated by northeasters.

Shoreline Change and Coastal Property

Given its aesthetic and recreational appeal, the Massachusetts coast has been and continues to be subject to intense development. Much of this development is susceptible to on-going risks from winds, waves, storm surge, flooding, relative sea level rise, and the associated erosion of coastal landforms. Consequently, shoreline change is an important issue in Massachusetts.

While erosion is necessary and natural, it does have the potential to damage coastal property and related infrastructure—particularly when development is sited close to the shoreline, in unstable or low-lying areas. Erosion can expose septic systems and sewer pipes, contaminating shellfish beds and other resources; release oil, gasoline, and other toxins into the marine environment; and sweep construction materials and other debris out to sea. Public safety is also jeopardized when buildings collapse or water supplies are contaminated.

Erosion can result in significant economic and emotional loss in a system of fixed property lines. Attempting to halt the natural process of erosion with seawalls and other hard structures, however, simply shifts the problem, subjecting downdrift property owners to similar or greater losses. Also, without the sediment transport associated with erosion, some of the Commonwealth's greatest assets and attractions—beaches, dunes, barrier beaches, salt marshes, and estuaries—will be threatened and slowly disappear as the sand sources that feed and sustain them are eliminated.

The challenge, therefore, is to site and manage coastal development in a manner that allows natural physical coastal processes, such as erosion, to continue. To meet this challenge, coastal managers, property owners, and developers must work with erosion—not against it—by understanding the magnitude and causes of erosion and applying appropriate management techniques that will allow its beneficial functions to continue.

The Shoreline Change Project

Through the Shoreline Change Project, the ocean-facing shorelines of Massachusetts have been delineated and statistically analyzed to show trends from the mid-1800s to 2009. CZM launched the Shoreline Change Project in 1989 and produced maps for the entire coast with shorelines from the mid-1800s to 1982. In 1997, CZM distributed shoreline change maps with erosion and accretion rates to coastal conservation commissions, helping local decision makers identify coastlines prone to storm damage and erosion. An update of the Shoreline Change Project was completed in 2001 using 1994 National Oceanic and Atmospheric Administration (NOAA) aerial photographs of the Massachusetts shoreline. CZM established an agreement with the U.S. Geological Survey (USGS), the Woods Hole Oceanographic Institution Sea Grant Program, and Cape Cod Cooperative Extension to produce the 1994 shoreline and calculate shoreline change rates. In addition to paper maps, an online shoreline change browser was provided.

CZM then incorporated the shorelines and shore-perpendicular transects with shoreline change rates into MORIS to provide better access to the shoreline change data and encourage the public to browse the data using this online mapping tool. In 2013, through continued collaboration with USGS, CZM released a new shoreline that spans 2007 to 2009. USGS delineated and analyzed this latest shoreline with other shorelines at 50-meter intervals to compute long-term (approximately 150-year) and short-term (approximately 30-year) rates of shoreline change. Other shorelines added as part of this update include a 2000 shoreline derived by USGS that covers most of the ocean-facing coastline, as well as a 2001 shoreline for the South Shore that was delineated by Applied Coastal Research and Engineering. New shorelines and more than 26,000 transects with updated change rates, uncertainty values, and net distances of shoreline movement have been added to MORIS.

How to Interpret the Data

To interpret and apply the shoreline change data, both general shoreline trends and long- and short-term rates must be analyzed and evaluated in light of current shoreline conditions, recent changes in shoreline uses, and the effects of human-induced alterations to natural shoreline movement. In areas that show shoreline change reversals (i.e., where the shoreline fluctuates between erosion and accretion) and areas that have been extensively altered by human activities (e.g., seawalls and jetties), professional judgment and knowledge of natural and human impacts are typically required for proper data interpretation and incorporation of the data into project planning and design.

For example, a group of 10 transects along Sankaty Head on Nantucket indicate a generally stable (close to zero) long-term trend of shoreline change from 1846 to 2009. The beach is not stable, however, as illustrated by the short-term erosion rates of approximately -9.5 feet per year and the approximately 300-feet of erosion experienced in this area from 1978 to 2009. In this particular example, the beach was accreting up until the 1950s, when it began to erode rapidly. The accretion and erosion in essence mathematically "cancel each other out," leaving a long-term shoreline change rate of around zero.

Where the shoreline has been armored with sea walls, revetments, and other structures, the shoreline change data must be looked at very closely to determine the effects of the structures. The natural sources of beach sand for North Scituate Beach were severely diminished by seawall and revetment construction during the 1940s through the 1970s. Consequently, the trend of erosion is not only continuing in this area—it is increasing, from approximately -0.5 to -2.5 feet per year. Transects on Scusset Beach in Bourne show long-term accretion rates of more than 7 feet per year. However, the short-term accretion rates of approximately 5 feet per year are more reflective of the current shoreline trend. The north jetty of the Cape Cod Canal was constructed in the early 1900s and resulted in an initial rapid growth of Scusset Beach, contributing to the higher long-term rates that have since leveled off.

Shorelines were derived from different historical maps, aerial photographs, and LIDAR topographic data sources. Each shoreline was assigned an uncertainty value based on an estimate of errors inherent in the source material and method used to delineate the local high water line. These estimates of total shoreline position uncertainty, which ranged from 38.1 feet for 1800s shorelines to 4.17 feet for LIDAR-derived shorelines, should be considered when analyzing shoreline movement over time and were included in the calculation of uncertainty at each transect. Each transect has values for long- and short-term rates, as well as estimated uncertainty values for those rates. The shoreline change rates should be looked at as a range, particularly for transects with uncertainty values that are greater than the shoreline change rate. For example, for a transect with an erosion rate of -1.0 feet per year with an uncertainty range of ±2.5 feet per year, the range for the shoreline change rate would be +1.5 to -3.5 feet per year—meaning that the area may be either eroding or accreting. To best protect coastal properties in the long term, the most aggressive rate of erosion over the expected life of the building or structure should be used for project design.

StormSmart Coasts - Inventories of Seawalls and Other Coastal Structures

Excerpted from: http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/seawall-inventory/

Many types of structures exist along the coast of Massachusetts to protect buildings and infrastructure constructed prior to coastal management policies and regulations. Historically, coastal land was developed out of economic necessity. Commercial development primarily included piers, wharves, and warehouses. Residential development, roads, and other infrastructure followed due to increasing population demand and the desire to work and live near the ocean. Today, maintenance of coastal structures built to protect public and private development in dynamic coastal areas challenges the Commonwealth, municipalities, and individuals.

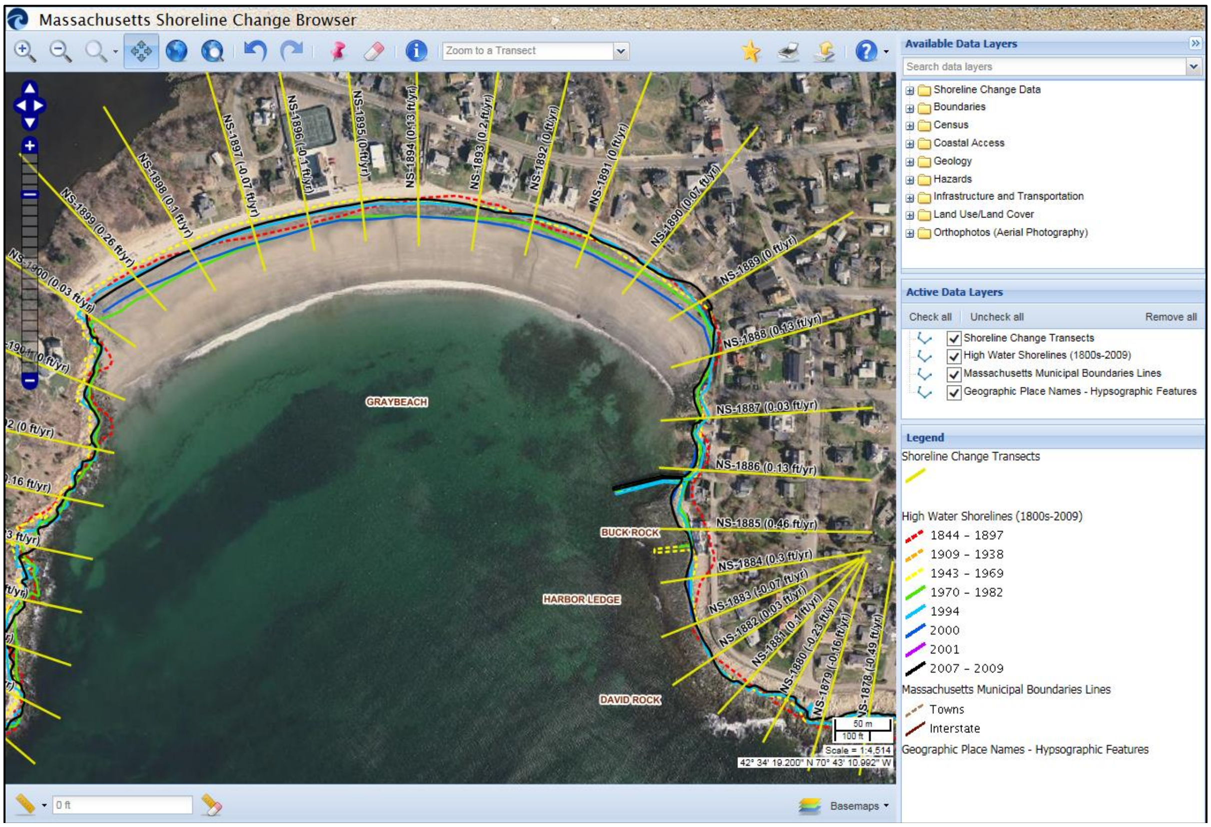

***Figure MA 1**: Screenshot showing GIS-generated historical shoreline positions and rate-analysis transects on a bluff/cliff/beach coastline near Gloucester, MA, obtained from the MA Shoreline Change Browser. Similar data is available through the MORIS Online Mapping Tool.*

To help address these challenges, inventories of both privately and publically owned seawalls, revetments, groins, jetties, and other coastal structures have been developed and are described below. To view both private and public structure data in the Massachusetts Ocean Resource information System (MORIS), see Private and Public Shoreline Stabilization Structures - Data and Online Mapping.

Inventory of Privately Owned Coastal Structures

Prepared for the Massachusetts Office of Coastal Zone Management (CZM) in 2013 by Applied Science Associates, Inc., these data and the technical report document the location and type of coastal structures, such as seawalls and revetments, not included in previous phases of the Massachusetts Coastal Infrastructure Inventory and Assessment Project. These structures were identified using remote sensing techniques and are presumed to be privately owned. The data and report provide a comprehensive assessment of shoreline armoring coast-wide. Nearly 27% of the ocean-facing shoreline is armored by some form of public or private coastal protection.

Inventory of Publicly Owned Coastal Structures

Prepared for CZM and the Department of Conservation and Recreation from 2006 to 2009, the Massachusetts Coastal Infrastructure Inventory and Assessment Project data and reports include condition ratings and estimated repair or reconstruction costs for publically owned coastal structures. These structures were characterized through on-site evaluation.

Figure MA 2*: Screenshot showing GIS-based mapping of private coastal structures on the Massachusetts coast, obtained from the MORIS Online Mapping Tool. Image is extracted from Mapping and Analysis of Privately-Owned Coastal Structures along the Massachusetts Shoreline (2013), Appendix B - Structure ID Generation, which is available at http://www.mass.gov/eea/agencies/czm/program-areas/stormsmart-coasts/seawall-inventory/.*

Section 309 Report: Coastal Hazards

The following information is extracted from*: Massachusetts Office of Coastal Zone Management, Section 309 Assessment and Five-Year Strategy for CZM Program Enhancement FY2016-2020 (May, 2015).* The document is available online at http://www.mass.gov/eea/docs/czm/309/ma-czm-309-strategy-2016-2020.pdf.

For the Section 309 Assessment and Strategy (2016-2020), four areas were identified as "High" Priority" for Section 309 Enhancement Area funding: (i) Coastal Hazards; (ii) Ocean Resources / Energy and Government Facility Siting; (iii) Wetlands; and (iv) Special Area Management Planning. In the prior period covered by the previous Section 309 Assessment and Strategy (FY2011-2015), Section 309 grant funds were expended on the Coastal Hazards Enhancement Area on two major projects:

Shoreline Change Project

In 2011, CZM started work to delineate a new, contemporary oceanfront shoreline. Under contract to CZM, the USGS Woods Hole Coastal and Marine Science Center began to interpret and digitize the mean-high-water shoreline based on aerial ortho-photographs and analyze shoreline change rates. This effort updated the Shoreline Change Project, which was launched by CZM in 1989 to identify erosion-prone coastal areas by producing maps depicting the statistical analysis of historic locations of ocean-facing shorelines from the mid-1800s forward using multiple data sources.

Coastal Hazards Clearinghouse

The goal of this project was to produce a series of fact sheets on options for reducing erosion and storm damage on coastal properties. The fact sheets on Dune Nourishment; Controlling Overland Runoff to Reduce Coastal Erosion; Planting Vegetation to Reduce Erosion and Storm Damage; Bioengineering; and Sand Fencing, provided information on coastal protection approaches and best practices, including both "traditional" as well as "new and innovative" protection alternatives, oriented to certain locations, settings, and conditions.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	462,670	501,352	8.4 %
No. of people in coastal counties	4,783,167	4,924,916	3.0 %
Percentage of people in coastal counties in coastal floodplain	9.7 %	10.2 %	0.5 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

Vulnerability to Shoreline Erosion

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very low (>2.0m/yr) accretion	66.9	8.0 %
Low (1.0 to 2.0 m/yr) accretion	3.8	0.5 %
Moderate (-1.0 to 1.0 m/yr) stable	523.7	63.0 %
High (-1.1 to -2.0 m/yr) erosion	105.3	12.7 %
Very high (<-2.0 m/yr) erosion	131.2	15.8 %

Sea Level Rise: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

Coastal Vulnerability to Historic Sea Level Rise

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very Low	0	0 %
Low	590.7	71.1 %
Moderate	158.1	19.0 %
High	43.8	5.3 %
Very High	38.3	4.6 %

Shoreline Types: D*ata from NOAA's State of the Coast "Shoreline Type" viewer* (~10 % of the Massachusetts coastline is armored)

Surveyed Shoreline Type	% of Shoreline
Armored	11 %
Beaches	21 %
Flats	33 %
Rocky	5 %
Vegetated	30 %

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lakes level change	Y	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise or Great Lakes level change	Y	Y
Other hazards: erosion	Y	Y

In-Depth Management Characterization (Phase II In-Depth Assessment)

Information summarized in tabulated format.

Priority Needs and Information Gaps

Coastal hazards risk reduction continues to be a primary concern of the Commonwealth and CZM. Coastal communities need effective options for managing vulnerability and costs of erosion, flooding, coastal storms, and sea level rise. The top three management priorities where there is the greatest opportunity to more effectively address the most significant hazard risks are:

Promote the use of green infrastructure for coastal resilience

Pressure to further fortify the coastline is building due to coastal storm damages over the last few years. Natural approaches can provide coastal storm damage protection and enhance natural resources. Opportunities to expand the application of green infrastructure exist with CZM's StormSmart Properties fact sheets, and coastal resilience and green infrastructure grant programs.

Increase freeboard of development in high-hazard areas

Elevating buildings above predicted flood elevations can greatly reduce damages during coastal storm events. The Massachusetts Basic Building Code is being updated and there is an opportunity to adopt freeboard requirements for buildings in coastal A-Zones. Communities are also interested in freeboard incentives.

Forecast erosion trends to support managed retreat

Estimates of future shoreline movement require historical observations of shoreline positions and can utilize wave data, sediment budgets, and alongshore features. Process-based shoreline change forecasting can be applied to establish setbacks and rolling easements.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Design standards for mixed sediment nourishment and sills; effectiveness and impacts of green infrastructure applications; flood zone mapping methodologies.
Mapping/GIS/modeling	Y	Coastal A-Zone mapping; sediment transport analyses and budgets; application of the Kalman filter to the MA coast.
Data and information management	Y	Wave data; lidar.
Training/Capacity building	Y	Green infrastructure options and case studies.
Decision-support tools	Y	Continued support of Digital Coast.
Communication and outreach	Y	Fact sheets on green infrastructure effectiveness.
Other	Y	Innovative adaptation strategies.

Michigan https://coast.noaa.gov/czm/mystate/

The Michigan Coastal Management Program was approved by NOAA in 1978, and is administered by the Department of Environmental Quality. Key management authorities of the coastal management program include several parts of the Natural Resources and Environmental Protection Act pertaining to Shorelands Protection and Management (Part 323), Great Lakes Submerged Lands (Part 325), and Sand Dunes Protection and Management (Part 353).

With the world's largest freshwater coastline, Michigan's coastal zone generally extends a minimum of 1,000 feet inland from the ordinary high water mark, with the boundary extending further inland in some locations to encompass important coastal features.

Michigan Coastal Management Program
http://www.michigan.gov/deq/0,4561,7-135-3313_3677_3696---,00.html

Bordered by four Great Lakes, Michigan has the world's longest freshwater coastline. The Michigan Coastal Zone Management (CZM) Program, housed in the Office of the Great Lakes, promotes wise management of the cultural and natural resources of Michigan's Great Lakes coast. The program supports healthy and productive coastal ecosystems, resilient coastal communities, and vibrant and sustainable communities.

Figure MI 1: *Michigan coastal scene (Image: modified from MI Coastal Management Program).*

Michigan's CZM Program was established in 1978 as a state/federal partnership with the National Oceanic and Atmospheric Administration (NOAA). The CZM Program focuses on three central goals:

- Improving the administration of existing state shoreline statutes (e.g., Shorelands Act, Submerged Land Act, Sand Dunes Act and Wetlands Act)
- Providing substantial technical and financial assistance to partners for creative coastal projects
- Improving governmental coordination to reduce delays, duplication and conflicts in coastal management decision-making

Michigan's coastal boundary generally extends approximately 1,000 feet inland from the ordinary high water mark. The boundary extends farther inland in some locations to encompass important coastal features such as coastal wetlands, drowned river mouths, bays, dunes and natural areas. The CZM Program consists of five focus areas, including public access, water quality, coastal habitat, coastal hazards and coastal community development. The CZM Program strives to provide strong leadership and advocacy for coastal resources by fostering environmental stewardship, encouraging innovative methods for understanding and communicating coastal challenges, and serving as partners in economic development.

Public Access

The Great Lakes are vital places for recreation and tourism in Michigan. The CZM Program protects, restores, creates and enhances public access to the Great Lakes using approaches that support coastal communities and foster appreciation of natural resources. The CZM Program supports a variety of projects to ensure the public has adequate access to the Great Lakes while protecting the natural integrity of the coast.

Water Quality

The CZM Program is committed to the protection of high quality waters, which offer important benefits and potential cost savings. Protection, restoration and enhancement of critical coastal resources such as wetlands and beaches are essential for the protection of high quality waters.

Coastal Habitat

The CZM Program is committed to protecting, managing and restoring sensitive coastal habitats, including wetlands and sand dunes. Coastal wetlands serve as spawning and nesting habitat for a variety of animals, help maintain water quality, provide erosion control, and offer recreation and tourism opportunities. Michigan is also home to the world's largest expanse of freshwater sand dunes and the protection of these resources and habitat remains a significant focus for the program.

Coastal Hazards

The CZM Program supports efforts that increase coastal communities' resilience by fostering understanding of the impacts, both natural and human, of coastal hazards and climate change through the development of adaptation strategies. The CZM Program also works with state and federal partners to minimize the loss of life and property caused by dangerous currents through support for creative local efforts that increase scientific knowledge and public awareness of coastal hazards.

Coastal Community Development

The CZM Program promotes wise management of the Great Lakes water and coastal resources through the development of vibrant and resilient coastal communities. Managed well, the coast supports resilient communities with healthy natural ecosystems that provide the economic, social and ecological foundations for a high quality of life.

Shorelands Management

Part 323, Shorelands Protection and Management, of the Natural Resources and Environmental Protection Act, 1994 Public Act 451, as amended is the key state statute providing consumer protection from the natural hazards of coastal erosion and flooding as well as environmental protection of fragile coastal areas. Part 323 is closely integrated with Part 325, the Great Lakes Submerged Lands; Part 353, Sand Dunes Protection and Management; and the Coastal Management Program which provides grants to state and local units of government.

High Risk Erosion Areas

The shorelands of the Great Lakes are a dynamic and quickly changing environment. Lake levels may fluctuate dramatically in response to weather and climate. Wave action, storms, wind, ground water seepage, surface water runoff, and frost are contributing factors to changing and reshaping the shoreline. During periods of low water, property owners are often lulled into believing homes may be safely built closer to the water's edge. Yet longtime residents have many stories about high water levels, the subsequent erosion of the Great Lakes shoreline, and the homes that have fallen into the lake as their foundations have been compromised. This destruction has resulted in severe financial loss to property owners. Public losses to recreation facilities, roads and other public works have also occurred. Structures threatened by erosion may be moved landward, protected by costly shore protection or lost.

The purpose of the High Risk Erosion Area program is to prevent structural property loss in an area of the shoreland that is determined by the department, on the basis of studies and surveys, to be subject to erosion as required by Part 323 of the Natural Resources and Environmental Protection Act, 1994 PA 451 as amended (NREPA) and the corresponding Administrative Rules. High risk erosion areas are those shorelands of the Great Lakes where recession of the landward edge of active erosion has been occurring at a long-term average rate of one foot or more per year, over a minimum period of 15 years. DEQ staff conducted the initial recession rate research of coastal counties between 1980 and 1986; during that time they identified high risk erosion areas in 36 of 41 coastal counties. Recession rates change over time as water levels fluctuate and coastal conditions change. The recession rate research is ongoing and often results in changes to the locations of high risk erosion areas along the shoreline.

The high risk erosion area program increases consumer awareness of the danger of shore erosion and allows staff to provide advice and technical assistance to many citizens living with the dynamic Great Lakes shorelines. Presently about 7,500 individual property owners are affected by setback requirements. All citizens benefit from the program's efforts to reduce the need for public disaster assistance, promote consumer protection, and reduce the loss of natural resources.

Studying the Shoreline

The rates of recession are determined by comparing the location of the erosion hazard line of the shoreline on historical and modern aerial photographs. Depending on the availability of historical aerial photos the studies typically cover the longest possible time period to capture the widest range of water levels and shoreline fluctuations. Additional information from fieldwork, shoreline photos, and online resources, such as the 2012 USACE Great Lakes Oblique Imagery, is used to aid in the determination of the erosion hazard line. The recession rate data are used to calculate the appropriate setback distances for construction. Setbacks are determined for the projected recession of the shoreline 30 years and 60 years into the future. The 30 year setback distance (feet) is for those structures considered readily moveable as defined in Rule R 281.21 (k). If the structure was threatened by erosion it could be moved landward before loss of the structure occurred. The 60 year distance is for non-readily moveable structures such as a septic system. These structures are too large, or not possible, to move. Once a recession rate study is complete the property owners, and their local officials, in the proposed high risk erosion areas are notified and given the opportunity to comment on the proposed designations before they become effective.

Permitting

A DEQ permit is required prior to construction on a parcel in a high risk erosion area regardless of where the structure is proposed on the parcel. Any person or local governmental agency proposing to erect, install, move, or enlarge a permanent structure on a parcel must obtain a permit prior to the commencement of construction. The projects requiring a permit include the construction of a house, garage or addition, substantial reconstruction or restoration of an existing home, the installation or upgrade of a septic system or a commercial building. During the permit application review, the proposed location of the structure will be compared to the required setback distance for the site. Depending on the site, the setback may be measured from the top of the bluff or from the erosion hazard line. The permit application and associated fees are found online as is the ability to track applications.

Local units of government may adopt a zoning ordinance for high risk erosion areas to assume regulatory authority under Part 323 of NREPA which, if approved by the Department, replaces the need for a state high risk erosion area permit. Other state permits such as those required for critical dune areas, wetlands or shore protection may still be necessary from the Department. The Department then monitors the performance of the community and provides technical assistance. Some local units of government adopt zoning ordinances which regulate setbacks but do not assume the authority of Part 323 of NREPA. In those communities a permit is required from the Department and from the local community for construction in a high risk erosion area.

Maps

Currently approximately 250 miles of shoreline are designated as high risk erosion areas along the shorelines of Lakes Michigan, Superior and Huron. Township maps show the locations and setbacks for each of the areas. Local township clerks have lists of the property tax identification numbers available at the time of the high risk erosion area designation. Due to parcel splits the identification numbers may change yet the designation runs with the land so the resulting parcels are also designated and will require a permit for regulated structures.

Additional Information

The Great Lakes shoreline is an actively eroding coast. Some shoreline sectors erode more quickly than others and are designated High Risk Erosion Areas (HREAs). By definition, the HREAs erode at an average rate of one foot or greater per year over at least 15 years. Building a structure too close to the edge of the bluff puts the structure at risk of falling into the lake. Planned development and construction in a HREA helps to prevent the loss of structures. Locating structures safely back from the bluff may also reduce the need for engineered shore protection.

To identify HREAs (Figure MI 2), the MDEQ compares the shorelines on historic and current aerial photos one county at a time by measuring the distance between the old shoreline and current shoreline. Then they calculate the distance (and rate (feet/year)) the shoreline has moved over time. Using this information, the MDEQ calculates the 30-year and 60-year recession distances. Often, the recession distances are also the setbacks for proposed buildings and septic systems. The MDEQ notifies property owners with high rates of erosion on their property so that they may comment on the proposed recession distances before the HREA is formally designated.

Setback distances determined using modern principles of remote sensing and geographic information systems to create and overlay historic and modern digital aerial photographs. The erosion reference feature is identified in each photo. Movement of these erosion reference features is measured at points every 150 feet along the shoreline. The physical change that was measured during the study time period is converted to a rate in feet per year. Areas of similar rates are grouped and the area average is calculated. These rates are multiplied by the required 30 and 60 year time frames, with an additional 15 feet being added to account for the possibility of severe storm events.

Setbacks are measured from the erosion hazard line (EHL) as defined in the administrative rules. Generally, the EHL is a line of stable vegetation or the landward edge of any slumps on the bluff in cases where the bluff is actively eroding. In cases where there is active erosion on the bluff face the EHL may be located as far landward as the top of the bluff. For planning purposes, the top of the bluff is a safe place to measure from because the EHL will never be landward of this feature.

The EHL is a very site-specific feature and is identified on-site by WRD staff every time a permit application for construction in an HREA is reviewed. For planning purposes the top of the lakeward-facing slope or bluff is safe to use as the EHL, because the EHL will never be landward of this feature. In cases where dense vegetation exists down the face of the bluff or bank, the EHL may be located at the lakeward edge of this vegetation depending on the bluff height and slope of the bluff face.

Case Study: Chippewa County High-Risk Erosion Area Update Study

The DEQ, Water Resources Division (WRD), conducted an update of its shoreline recession rate study of the Lake Superior shoreline in Chippewa County. The original shoreline recession rate study was conducted in 1982. Changes in the high risk erosion area (HREA) boundaries and projected shoreline recession distances have been made. Letters explaining the proposed changes and information regarding the opportunities for input were sent to property owners, local officials, and legislators. A Webinar and a local public meeting were held on January 27 and March 4, 2015 respectively. After the public meeting, property owners had the option to appeal the designation of their parcel through an informal appeal process until April 3, 2015. The HREA designations took effect on July 10, 2015 when property owners were notified by certified letter. Some affected property owners have 60 days from the receipt of their designation letter to formally appeal the designation.

The HREA Program identifies rapidly eroding Great Lakes shorelines and establishes setback requirements for construction in these coastal areas to prevent property loss. The proposed changes in the HREAs are the result of a recession rate study conducted on August 20, 2014, to identify changes in the long-term rate of erosion occurring along the Great Lakes shoreline pursuant to R 281.22(22) of the Great Lakes Shorelands Administrative Rules promulgated pursuant to Part 323, Shorelands Protection and Management, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended. The study identified shorelines where recession is occurring at an average rate of at least one-foot-per-year over a minimum of 15 years. A longer study time period was used when technically possible to span a wider range of water levels and shoreline fluctuations.

The Update Study

The erosion hazard line (EHL) as defined in R 281.21(1)(c) means the line along the shoreland that is the landward edge of the zone of active erosion or, for this county, the line where the 604.4 feet, 1985 International Great Lakes Datum, contour on Lake Superior meets the shoreland, whichever is furthest landward. The zone of active erosion means the area of the shoreland where the disturbance or loss of soil and substrate has occurred with sufficient frequency to cause unstable slopes or prevent vegetation of the area. The recession rate study compared the EHL on historical aerial photographs to the EHL on modern aerial photographs. Historic aerial imagery from 1975 was used for most of the shoreline except for an area in Soo Township where 1984 aerial imagery was used. Because the modern imagery was from 2011, the study spanned a period of 36 and 27 years, respectively.

The historic EHL was determined by viewing the vegetation lines along the shoreline on the aerial photograph. The modern EHL was determined using the same method with the added information provided by low-level oblique aerial photographs, 2012 USACE Great Lakes Oblique Imagery, that shows detailed views of the shoreline from an offshore vantage point. An additional resource was the Great Lakes Shoreline Geodatabase, that gives the approximate location of areas of various bluff heights among other attributes. Cross-referencing these resources with the modern imagery was helpful in determining the modern EHL. The shoreline was reviewed and the EHL was determined for all previously designated HREAs and areas of apparent erosion.

Transects were drawn perpendicular to the shoreline at 150 foot intervals along the shoreline and recession rates calculated along the transect lines. Similar rates were grouped into HREAs (Area). Average recession rates were calculated within each Area. Projected recession distances were determined for each Area. Parcel boundaries and owner data was received from the Chippewa County Equalization Department. The 2014 Area and parcel data was compared to the 1982 data to determine designation changes.

Within these hazard areas, placement of new construction requires a permit and must meet setback distances based on projected recession distances when combined with the type of construction and other site-specific conditions. The projected recession distance is the calculated rate of recession for the area over a 30 year [for readily moveable structures, as defined in R 281.21(1)(k)] or 60 year [for permanent structures, as defined in R 281.21(1)(i)] period as determined by R 281.22(2). The required setback distance is based on this rate but may be greater in areas of bluffs over 25 feet in height. Affected parcels were classified under one of the following four categories:

De-designation: These are parcels where the average rate of recession was documented to be one-foot-per-year or greater during the previous study; however, the current study found the long-term rate of recession has fallen below the one-foot-per-year threshold required for HREA designation. The HREA designation is therefore removed, also eliminating the regulations and permit requirements under Part 323.

New: These parcels were not designated during the previous study as being in an area of high risk erosion; however, the current study found the long-term rate of recession has increased to, or is above, the one-foot-per-year threshold required for HREA designation. The properties are designated and subject to the regulations and permit requirements under Part 323 and promulgated rules for HREAs.

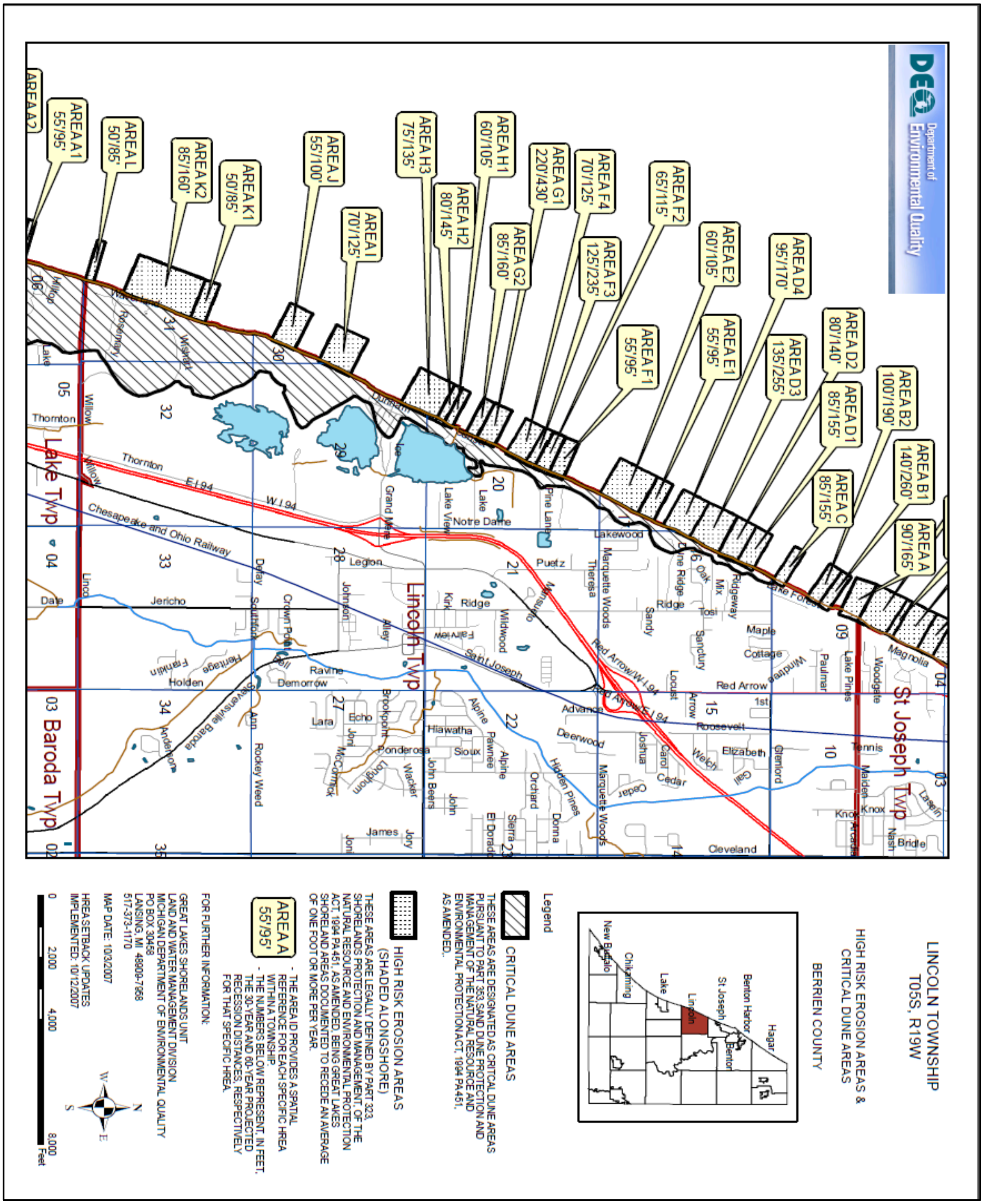

***Figure MI 2**: Typical Michigan DEQ High Risk Erosion Areas (HREAs) and Critical Dune Areas map product (showing Lincoln Township, southwestern Michigan).*

Increase due to study: These are parcels where the average rate of recession was documented to be one-foot-per-year or greater during the previous study and are currently designated as being in an HREA. The current study documented an increase in the long-term recession rate; resulting in an increase in the projected recession distances.

Lower: These are parcels where the average rate of recession was documented to be greater than one-foot-per-year during the previous study and are currently designated as being in an HREA. The current study documented a decrease in the long-term recession rate, but the erosion rate is still at or above one-foot-per-year resulting in a decrease in the projected recession distances.

Findings

There are approximately 78 miles of Lake Superior shoreline in Chippewa County among four townships: Whitefish (Figure MI 3), Bay Mills, Superior, and Soo. During the current study 68% (53.6 miles) of the shoreline was identified as needing study because it was either previously designated or showed signs of erosion. Of the shoreline studied 21% (11.2 miles) was determined to be in an area of high risk for erosion. Of the currently identified areas of high risk erosion 72% (8.1 miles) will be designated for the first time. In 1982, approximately 9.3 miles of Chippewa County shoreline was designated as being at high risk for erosion. Of the originally designated shoreline 34% (3.1 miles) remain designated. Over six miles of shoreline will be de-designated.

The study covered a total of 317 parcels: 79 parcels will be newly designated, one large parcel has areas of both lower and increasing recession rates, 14 parcels will have lower projected recession rates and 14 parcels will have increased rates. A total of 209 parcels will be de-designated and will no longer require that new structures, or their additions, to be setback a specific distance from the erosion hazard line per Part 323. High Risk Erosion Area Update maps for Chippewa County are available online.

Section 309 Report: Coastal Hazards

The following information is extracted from*: Michigan Section 309 Assessment and Five-Year Strategy for Coastal Zone Management Enhancement Fiscal Years 2016-2020 (Draft; 2015)*. The document is available online at http://www.michigan.gov/documents/deq/deq-ogl-czm-309assess-strat-2016-2020_508307_7.pdf.

University of Michigan and Michigan Technological University researchers studied and identified the weather conditions, coastal geomorphology, and other factors that contribute to the formation of transient dangerous currents at Lake Michigan swimming beaches. This multiyear research yielded significant new information supporting the science of Great Lakes currents forecasting.

Michigan Sea Grant (MSG) coordinated risk communication research to develop more effective messaging for beachgoers at Michigan State Parks about dangerous currents hazards, and how to reduce their exposure to these hazards.

MSG developed a Great Lakes dangerous currents website (www.dangerouscurrents.org) presenting a variety of information resources, dangerous current rack card, and other outreach products. MSG also sponsored three regional workshops to educate State and local park personnel and other stakeholders about the different types of dangerous currents, dangerous currents research, fatality and rescue data, and hazard messaging.

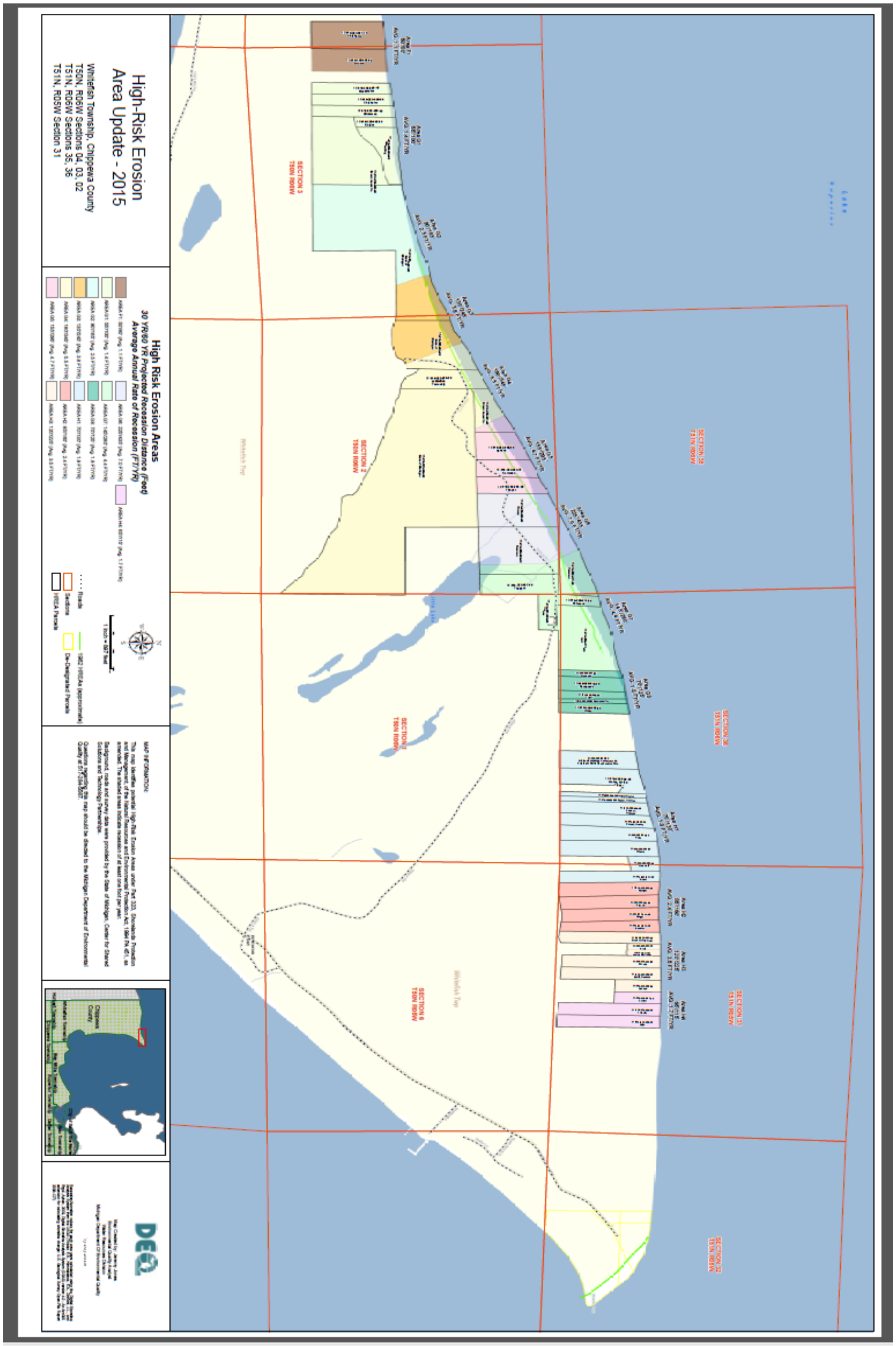

Figure MI 3*: Michigan DEQ High Risk Erosion Areas map for Whitefish County, Chippewa County, Michigan illustrating format for future coastal hazard map products.*

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	254,401	269,519	+5.94 %
No. of people in coastal counties	4,842,023	4,680,503	-3.34 %
Percentage of people in coastal counties in coastal floodplain	5.25 %	5.76 %	+0.51 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

The index does not include data for the Great Lakes states, including Michigan, depicting the vulnerability of the shoreline to erosion. Therefore, data from the MDEQ has been substituted, and the table below has been modified (from template provided in Section 309 guidance) for use within the Great Lakes region. Data shown originates from recession rate studies mandated for the High Risk Erosion Area (HREA) program under Part 323, Shorelands Protection and Management, of the Natural Resources and Environmental Protection Act, 1994 PA 451, as amended (NREPA)

Vulnerability to Shoreline Erosion (Modified for Great Lakes)

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Low or Not Studied (<1.0 ft/yr) stable	3608.37	93.93 %
Moderate (>= 1.0 to <2.0 ft/yr) erosion	158.4	4.12 %
High (>= 2.0 to 3.0 ft/yr) erosion	46.73	1.22 %
Very high (>= 3.0 ft/yr) erosion	27.94	0.73 %

Approximately 233 miles (6.1%) of Michigan's 3,841 mile Great Lakes shoreland is documented as receding at a rate of one foot per year or greater, and therefore is subject to coastal construction setbacks implemented through the HREA program under Part 323, Shorelands Protection and Management, of the NREPA. This represents a reduction of 35 miles of shoreland receding at a rate greater than one foot per year as compared to the 2011 assessment, which identified a total of 268 miles of shoreland above the threshold rate. Presently about 7,500 individual properties are subject to setback requirements under the HREA program.

Other Coastal Hazards: General level of risk in the coastal zone for each type of coastal hazard. The state's multi-hazard mitigation plan is a good additional resource to support these responses.

Type of Hazard	General Level of Risk (H, M, L)
Flooding (riverine, stormwater)	H (high)
Coastal storms (including storm surge)	M (moderate)
Geological hazards (e.g., tsunamis, earthquakes)	L (low)
Shoreline erosion	H
Great Lake level change	H
Land subsidence	L
Saltwater intrusion	-
Other – Dangerous nearshore currents	M

Upper Great Lakes Study
The International Joint Commission's (IJC) International Upper Great Lakes Study concluded in 2012 and resulted in recommendations for a new water level regulation plan for Lake Superior Outflows. The 5-year, $14.6 million study included a Coastal Zone Technical Work Group (CZTWG) to evaluate coastal management implications associated with various regulation plans. Numerous technical reports and products from the CZTWG efforts relate to coastal hazards and potentially serve as resources for assessment and strategy development.

University of Michigan – Graham Institute Water Levels Integrated Assessment
The aforementioned IJC study identified that adaptive management options toward dealing with water level variations, such as local shoreland management, potentially provide for different localities to address impacts and issues tailored to their geography, development and shoreline uses. Location-specific shoreland management options have not been widely adopted in Michigan to date. Implementation of such policies can be difficult due to the variability and uncertainty in water levels as well as difficulties in properly considering local conditions and objectives along with political constraints.

The University of Michigan Graham Sustainability Institute is commencing an integrated assessment initiative to develop information, tools, and partnerships to help decision makers address challenges associated with Great Lakes water level variations. While the scope of the integrated assessment is broad, it is anticipated that associated coastal hazards impacts will be addressed to some extent through this effort. The integrated assessment is scheduled to conclude in 2017. The MCZMP will monitor this initiative to ensure that information, knowledge, and tools developed are properly leveraged within the MCZMP's section 306 efforts, and potentially within a 309 strategy.

High Risk Erosion Area Update Studies
The MDEQ continues to reassess recession rates on a county-by-county basis to account for changing physical conditions, and to incorporate up-to-date technology in the recession rate studies associated with the HREA Program under Part 323 of the NREPA. Four county-wide studies were conducted during the assessment period with overall results trending toward significant decreases in the number of regulated properties and in the length of designated shoreline. When recession rates decrease to less than one foot per year, the MDEQ will de-designate the HREA, which correspondingly decreases the number of regulated properties. Approximately 35 miles of shoreline was removed from designation as HREA since 2011, and, therefore, properties along these shoreline areas are no longer subject to coastal construction setbacks under the HREA program. These decreases are partly attributable to the recent prolonged period of relatively low water levels on Michigan's Great Lakes. Generally, beaches accrete or build in profile during low lake levels, which tends to promote lakeward establishment of vegetation on beaches and foredunes. The current HREA administrative rules emphasize the change in location of this vegetation line over time in the calculation of shoreline recession rates. While the HREA studies include study periods of no less than 15 years and the MDEQ considers historic water levels during data (aerial photographs) selection, modern aerial photographs showing the prolonged low-water conditions can significantly affect the recession rate results. Recession rate studies during periods in the lake level cycle when the vegetation line is temporarily advancing lakeward, and ephemeral beach features have accreted, often leads to lower recession rates than those calculated in previous studies for the same stretch of shoreline.

The hazard threat due to erosion remains significant in many locations and with water levels recently returning to normal or above-normal water levels, those areas of shoreland mapped during low-water conditions may have underestimated the potential risk that will be present under high-water conditions. Updating recession rate studies in an expeditious manner under higher water conditions will be key toward reducing this potential under-estimation caused through the low-water studies, and may even be necessary for stretches of shoreline recently studied.

FEMA/USACE Great Lakes Coastal Flood Mapping Study

The Federal Emergency Management Agency (FEMA) has initiated a coastal analysis and mapping study to produce updated Digital Flood Insurance Rate Maps for coastal counties around the Great Lakes including those in Michigan. This storm surge study is one of the most extensive coastal analyses to date, encompassing coastal floodplains in eight states. Ultimately, the study will update the coastal storm surge elevations for all of the Michigan's Great Lakes shoreline. This new coastal flood hazard analyses will utilize updated 1-percent-annual chance still water elevations obtained from a comprehensive storm surge study conducted by the US Army Corps of Engineers.

An updated coastal flood study will provide a better estimate of coastal flood hazards and risk for the Great Lakes. The current, or effective, Flood Insurance Rate Maps are outdated primarily due to the age of data and methodologies, many of which date back to the 1970s. Major changes in National Flood Insurance Program policies and methodologies have occurred since the effective dates of many Flood Insurance Studies in the area, creating the need for an update that would reflect a more detailed and complete hazard determination. Additional information is available at: http://www.greatlakescoast.org/great-lakes-coastal-analysis-and-mapping/

City of St. Joseph, Michigan Coastal Engineering Study

Although not statewide in scope, this 2012 study prepared by Edgewater Resources, LLC and Abonmarche Consulting, Inc. for the City of St. Joseph, provided the foundation for a first of its kind ordinance creating an overlay zoning district for an identified stretch of coast within the City where a fixed setback line was created, lakeward of which the construction of new structures is prohibited to prevent the need for shoreline protection structures that cause unnatural erosion and irreversible damage to the shoreline and adjacent property. Additional information is available at: http://greatlakesresilience.org/stories/michigan/st-joseph-protects-public-trust-groundbreaking-ordinance

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	N	Y
Climate change impacts, including sea level rise or Great Lake level change	N	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y

Climate change impacts, including sea level rise or Great Lake level change	N	Y

Hazards mapping or modeling programs or initiatives for:

Sea level rise/Great Lake level change	N	Y

HREAs in Michigan, as defined under Part 323, are those shorelands of the Great Lakes and connecting waters where recession of the zone of active erosion has been occurring at a long-term average rate of one foot or more per year.

Under the Flood Risk Area provisions of Part 323, Shorelands Protection and Management, of the NREPA, new structures in the 100-year floodplain of the Great Lakes must be elevated to prevent property damage. All of Michigan's 41 coastal counties have designated flood risk areas mapped and regulations in effect, which is the same number of counties identified in the 2011 Assessment. The Flood Risk Area Program continues to be operated mostly at the county level, and MDEQ staff provides periodic technical assistance and monitoring. All 41 counties participate in the National Flood Insurance Program and have local zoning requirements which meet or exceed Flood Risk Area Program standards.

The MCZMP provided financial support and technical assistance toward several site-specific projects focused on moving built infrastructure away from eroding shorelines. Such projects include managed retreat efforts at Muskallonge Lake State Park and McLain State Park as well as a project with the City of Marquette to plan for moving a 3,000 foot section of roadway away from the eroding shoreline of Lake Superior. The project at McLain State Park best exemplified the MCZMP's recent efforts to strengthen the technical assistance component of the program, as the MCZMP played a key role in the site analysis by conducting a detailed bluff recession rate analysis for the park. The recession rate study is providing the foundation for recommended setback areas and no-build areas which will be incorporated into the park master plan. These projects are also significant in that such projects have not often been needed over the past 15 years or so, during the prolonged low water level period. The three projects mentioned are located on Lake Superior, and their need has been exacerbated by recent upward trends in water levels. Should water levels continue their upward trend, it is anticipated that the need for similar efforts will increase.

In-Depth Management Characterization (Phase II In-Depth Assessment)

As outlined in the Phase I assessment, recent Great Lakes water levels have trended upward resulting in increased shoreline erosion and flooding concerns. All of the Great Lakes with shoreline in Michigan have current water levels above average and projections for the summer of 2015 that remain above average. While future water levels are uncertain, recent trends and the prospects of higher levels command increased effort towards coastal resilience of both erosion and flooding impacts. Great Lakes level change itself is of critical importance; however, such change is the norm for the Great Lakes and is not itself a hazard. Rather, flooding and erosion hazards which are exacerbated by higher lake levels require primary consideration.

Recent shore erosion impacts to infrastructure are not widespread; however intermittent reports of shore erosion damage at public lands such as McLain and Muskallonge Lake State Parks as well as the abandonment of a private residence in Berrien County along the southeastern Lake Michigan shore indicate that the threat associated with shore erosion has increased relative to the threat level of the past decade and a half.

A 2014 survey of local planners in the Great Lakes region reported bluff and shoreline erosion as the highest rated (67%) coastal storm hazard that moderately or greatly impacts their local community. The on-going Great Lakes flood mapping update study conducted jointly by FEMA and the USACE is filling the need for updated coastal flood information and outreach, however bluff and shoreline erosion studies of similar magnitude and scope are not being conducted at this time. The U.S Army Corps of Engineers is conducting a study of the Great Lakes under the National Shoreline Management Study (NSMS), which may provide insight on coastal erosion issues in the lakes; however, extensive creation of new data resources is not anticipated as part of the NSMS to the extent of those being developed through the FEMA flood mapping efforts.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

Approximately 93% of Michigan's Great Lakes coast is not subject to state-specific regulatory requirements under the state's HREA program, and thus local coastal policies provide the key opportunity to thoughtful system management, fostering prudent community growth in a way that reduces coastal hazard impacts. Therefore, a proposed strategy is to provide technical assistance and community capacity building within pilot communities to develop knowledge about supporting data needs at the local, regional, and statewide levels. The pilot planning or zoning efforts will be supported in 1 - 2 communities in each year of the strategy with an eye towards informing needs and opportunities across various geographic regions and coastal typology regions in the state. Pilot studies over a wide range of coastal typologies will determine similarities and differences in information requirements according to differing physical, ecological, and social settings. The MCZMPs adopted policy represents a key program change by serving as a guide which will be used to replicate the successful results of the pilot throughout the remaining coastal regions after the strategy ends. Two management priorities were identified in the 2015 report are indirectly pertinent to coastal geology issues on the Michigan coast and provide opportunity for the CMP to more effectively address significant hazards.

Steward implementation of local zoning and planning that fosters resilience toward shore erosion while maximizing use of non-structural alternatives

The majority of local coastal units of government in Michigan have local plans and zoning ordinances that do not include coastal resilience components related to coastal hazards. A policy gap analysis is needed - identifying existing local plans and ordinances that contain coastal construction setbacks and/or shore protection siting provisions versus those containing no such provisions. Subsequently, identification of coastal local units of government receptive to strengthening their local shoreland management approaches through planning and implementing zoning approaches is needed. This effort may also consider options to improve state/local coordination and messaging approaches when the State implements updated coastal construction setback requirements under the HREA Program.

Improve geospatial information available for application towards local coastal planning and zoning efforts, and which also fosters development of coastal erosion metrics and status and trends tracking on a statewide basis

Even when local officials desire to implement coastal resilience through planning and zoning efforts they often lack geospatial tools and resources needed to properly guide their efforts. Most local units of government do not have internal expertise on coastal erosion, flooding, and geospatial approaches toward assessing vulnerabilities. Such geospatial resources and decision support tools need to be developed and packaged for application by these local officials. A stakeholder and subject matter expert input process is needed to specify priority information needs, and from those needs identify supporting data sets to be acquired. Examples may include recession rate data (including making existing data more accessible), beach widths, location of erosion hazard line, and built structures. Web-based tools and resources specific to Michigan's Great Lakes coast are also needed to educate about long-term coastal erosion and to guide decision making of coastal property owners to promote best management practices for coastal properties.

Assess feasibility of implementing programs that promote soft-shore approaches towards shoreline stabilization

The use of living shorelines and other soft-shore approaches toward coastal stabilization have expanded greatly on the national level in recent years. While Michigan has significantly advanced the implementation of natural shoreline management approaches on inland lakes, similar advances have not taken place along its Great Lakes coast. The feasibility of various soft-shore management approaches on the Great Lakes coast needs to be assessed from a physical science, ecological, and engineering standpoint as well as from a policy and economic standpoint.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	There exists a need for Michigan-specific legal analysis providing policy options and recommendations for local shoreland management approaches (e.g. local setbacks, easements, planning/ zoning provisions). Research regarding feasibility for soft-shore alternatives, including sand-source availability and economic analyses for beach nourishment and engineered living shoreline options is needed.
Mapping/GIS/modeling	Y	There exists a need for geospatial inventory of local planning and zoning requirements that promote coastal resilience; geospatial inventory of coastal features and infrastructure; and updated recession rate information for many shoreline stretches. Geospatial data for various stretches of the coast and specific coastal management themes have been developed; however, improved integration of data and distribution systems is needed. A data development schema and framework is needed to ensure consistency, usability of data, and integration of regional data sets into a statewide effort. A review of existing distribution platforms (e.g. Great Lakes Shoreviewer) should be conducted; determining whether an existing platform is ripe for expansion into a statewide coastal hazards atlas or if a new platform is needed.
Data and information mgmt.	Y	Continued challenges exist with the State's efforts to maintain up-to-date parcel records for those properties designated as high-risk erosion areas. This complicates the department's task of notifying property owners of changes in designation, and also

		may restrict property owners from quickly and efficiently obtaining knowledge about their property's status with respect to erosion hazards.
Training/Capacity building	Y	Training and capacity building is needed on best management practices for incorporating coastal hazards resilience components into local planning and zoning.
Decision-support tools	Y	Need decision support tools that assist in identifying impacts (downdrift and elimination of recreational beach) of proposed shore protection structures. A decision support tool focused on identifying those stretches of coast suitable for soft-shore protection approaches would be of value.
Communication and outreach	Y	Publically available materials detailing coastal erosion trends along Michigan's Great Lakes Shore are needed as well as resources that assist local officials and the general public with best management practices for eroding properties.

Minnesota https://coast.noaa.gov/czm/mystate
http://www.dnr.state.mn.us/waters/lakesuperior/index.html

The Minnesota Coastal Management Program was approved by NOAA in 1999 and consists of a network of agencies and programs led by the Department of Natural Resources. Key legislation includes the Shoreland Management Act and the North Shore Management Plan. Minnesota's coastal zone includes the area to approximately six miles inland from Lake Superior, following the nearest township boundaries along the shore.

Minnesota Lake Superior Coastal Management Program

The following information is extracted from *Minnesota's Lake Superior Coastal Program, Part V*, available at http://www.dnr.state.mn.us/waters/lakesuperior/feis/index.html. The North Shore Management Plan (Minn. Rules 6120.2800) establishes development standards for "Erosion Hazard Areas" (EHA). EHAs are defined as those areas of Lake Superior's North Shore where the long term average annual rate of recession is one foot or greater per year.

The Erosion Hazard Subcommittee of the North Shore Management Planning Process used the following process to identify EHAs. First, a detailed soil map from the 1978 Coastal Zone Management study was transferred onto a Minnesota Department of Transportation strip map of the North Shore. Then, 199 surveys from a 1986 shoreline erosion survey were transferred to the map. Surveys indicating high erosion rates were tagged for further analysis. Fifty sites were revisited and measurements were made to see how far the erosion had progressed since 1986. From this information, it was determined that many of the erosion problems reported in 1986 were attributed to the extremely high water level and severe storms of the period. Losses of cobble beaches, collapse of sea caves and the erosion of rocky shorelines were identified as outside EHAs. However, areas of high clay banks continued to show signs of failure despite the two intervening years of relatively low, calm water. These are the areas identified as Erosion Hazard Areas on maps in the NSMP.

The more critical areas of clay banks were examined from the water. The area from French River to Split Rock River was covered by boat and pictures were taken of potential EHAs. Field notes, photos, and the 1986 and 1988 videotapes of the shoreline were then used to set the approximate boundaries. The EHAs accurately represent the more severe problems of erosion on the shore. Further studies such as the Natural Resources Research Institute (NRRI) study on recession rates and detailed mapping by local zoning officials have improved the data used to identify and manage erodible areas along the shore.

The standards and criteria of the NSMP require at the time of permitting and/or sale of a property within an erosion hazard area (EHA) that a covenant be recorded against the property stating that it is in an EHA. Prior to all new construction in an EHA, a site development plan shall be required and approved by the local land use authority. Structures and sewage treatment systems shall be set back the annual erosion rate times 50 plus 25 feet from the top edge of the eroding bluff. In the absence of an established long term erosion rate, the setback shall be 125 feet. The setback can be modified by variance if the landowner provides technical data proving a different recession rate or that the erosion hazard, although correctly estimated, can be mitigated by structural protection.

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The following information is extracted from: *Minnesota's Lake Superior Coastal Program, Section 309 Assessment and Strategies for 2011-2015 (the most recent available assessment as of fall 2016).* The document is available online at http://files.dnr.state.mn.us/waters/lakesuperior/coastal enhancement/309as2011.pdf.

Resource Characterization (Phase I Assessment)

Level of risk on the coastal zone for the following hazards

Type of hazard	General level of risk (H,M,L)	Geographic Scope of Risk
Flooding	L (low)	
Coastal storms, including associated storm surge	M (moderate)	Coast-wide
Geological hazards (e.g., tsunamis, earthquakes)	N/A	N/A
Shoreline erosion (incl. bluff and dune erosion)	H (high)	Coast-wide
Sea level rise and other climate change impacts	L	Coast-wide
Great Lake level change and other climate change impacts	M	Coast-wide
Land subsidence	L	Coast-wide
Rip currents	M	Great Lakes

The last shoreline erosion study was completed in 1989. Local decision makers lack confidence in the data accuracy, and perform site visits to make decisions on permits based on visual surveys. Minnesota's coastline is made of steep slopes with clay soils and bedrock. This combination can contribute to flash floods in tributary streams damaging roads, bridges and even whole hillsides. Shallow soils and prominent bedrock features heavily influence streams with surface water creating conditions of very high peak flows and very low base flow conditions, which can lead to significant stream bank erosion. Lacustrine red clay soils in Carlton, St. Louis and Lake Counties are prone to erosion and slumping, and are a major source of sediment to the lake. Minnesota Point, a large bay-mouth bar in Duluth, is subject to dune erosion and flooding during high lake levels. Episodic erosion of low-lying also occurs on cobble beaches along the coast.

MLSCP collected oblique imagery of the coast in 2002 and 2007. The imagery was used to document and draw attention to clay bank erosion, bluff line setbacks, and land use changes. The North Shore Management Board (NSMB) is studying land use changes by comparing 2002 and 2007 imagery. The imagery is also used to study and update density requirements in the Lake County zoning ordinance.

Number of coastal zone communities that have a mapped inventory of areas affected by the following coastal hazards

Type of hazard	Number of communities that have a mapped inventory	Date completed or updated
Flooding	8	www.fema.gov/cis/MN.pdf

Storm surge	0		
Geological hazards (incl. Earthquakes, tsunamis)	0		
Shoreline erosion (incl. bluff and dune erosion)	13		1989: Cook, Lake, and St. Louis Counties
Sea level rise	0		
Lake level fluctuation	0		
Land subsidence	0		

Management Characterization (Phase I Assessment)

Management approaches employed by the state for coastal erosion-related issues

Management categories	Employed by state/territory (Y or N)	Significant changes since last assessment (Y or N)
Building setbacks/ restrictions	Y	N
Methodologies for determining setbacks	Y	N
Repair/rebuilding restrictions	Y	N
Restriction of hard shoreline protection structures	N	N
Promotion of alternative shoreline stabilization methodologies	Y	N
Renovation of shoreline protection structures	Y	N
Beach/dune protection (other than setbacks)	Y	N
Permit compliance	Y	N
Sediment management plans	Y	N
Repetitive flood loss policies, (e.g., relocation, buyouts)	Y	N
Local hazards mitigation planning	Y	N
Local post-disaster redevelopment plans	Y	N
Real estate sales disclosure requirements	N	N
Restrictions on publicly funded infrastructure	Y	N
Climate change planning and adaptation strategies	N	N
Special Area Management Plans	Y	N
Hazards research and monitoring	Y	N
Hazards education and outreach	Y	N

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

Gap or need description	**Type of gap or need** (regulatory, policy, data, training, capacity & outreach)	**Level of priority** (High, Moderate, Low)
Erosion hazard location	Data	H
Elevation data (LiDAR)	Data	M
Erosion rate	Data	H
Oblique coastline imagery	Data	H
Erosion policy	Policy	H
MLSCP Boundary Change	Regulatory/Policy	H
Erosion outreach and education	Outreach & education	M
Climate change	Data	H
Climate change	Outreach and education	H
MLSCP Staffing	Capacity	M
Contractor Training	Erosion hazard minimization training	M

As of 2011, significant changes were pending with the update of the state's shoreland rules (Minnesota Rules 6120.2500-3900). When implemented, the updated shoreland standards will address coastal hazards related to erosion by providing special protection through increased shoreline setbacks, bluff setbacks, preventing alterations to topography, altering bluff vegetation, provisions for shoreland revegetation, stormwater standards, larger lot sizes and maintaining natural shorelines.

New York https://coast.noaa.gov/czm/mystate/

The New York Coastal Management Program was approved by NOAA in 1982, with the New York Department of State serving as the lead agency. The Executive Law Article 42, Waterfront Revitalization of Coastal Areas and Inland Waterways, provides the state with the authority to establish a coastal program, develop coastal policies, define the coastal boundaries, and establish state consistency requirements.

The inland New York coastal zone boundary is variable but generally is 1000 feet from the shoreline in non-urbanized areas. In urbanized areas and other developed locations along the coastline, the inland boundary is usually 500 feet or less from the shoreline, with the boundary possibly extending inland up to 10,000 feet to encompass significant coastal resources. http://www.dec.ny.gov/lands/28923.html; http://www.dec.ny.gov/lands/86541.html

New York Coastal Program

Natural protective features (beaches, dunes and bluffs) within coastal erosion hazard areas provide buffering and protection to shorelands from erosion by absorbing the wave energy of open water. Dunes and bluffs are especially effective against storm-induced high water. They are also reservoirs of sand and gravel for beaches and offshore sandbar and shoal formations.

Certain sections of New York's coastline are especially vulnerable to coastal erosion through natural actions and through human activities. Erosion is the loss or displacement of land along the coastline due to the action of waves, currents, tides, wind-driven water, waterborne ice, or other impacts of storms. It also means the loss or displacement of land due to the action of wind, runoff of surface waters, or groundwater seepage.

In vulnerable areas, coastal erosion causes extensive damage to public and private property and to natural resources and endangers human lives. This has resulted in significant economic losses to individuals, private businesses and the state's economy. Coastal erosion damage has necessitated large public expenditures to remove debris and ruined structures, and to replace essential public facilities and services.

The management of coastal erosion hazard areas helps to protect coastal habitat areas, inland natural resources, homes, businesses, and communities from wind and water erosion and storm-induced high water.

Natural Causes of Coastal Erosion

Coastal erosion is a natural phenomenon, an endless sediment redistribution process that continually changes beaches, dunes and bluffs. Waves, currents, tides, wind-driven water, ice, rainwater runoff and groundwater seepage all move sand, sediment and water along the coast.

Other contributing factors that can significantly increase coastal erosion of a natural protective feature include length of fetch; wind direction and speed; wave length height and period; nearshore water depth; tidal influence; and overall strength and duration of storm events.

Combinations of these factors and events can amplify these effects by increasing water levels; increasing storm rise; increasing the distance waves reach inland; producing damaging waves;

driving ice "plates" along the shore scouring beaches and bluff areas; reducing sand from beaches; and allowing water and wave action further inland intensifying coastal erosion of beaches, dunes and bluffs.

Coastal flooding is caused by ocean water rising above normal tidal elevation. Flooding occurs when strong winds and/or high tides drive ocean water inland through inlets, waterways, channels, and wetlands. Coastal flooding on the Great Lakes occurs when strong wind and storms increase water levels. When coastal flooding occurs, it is a temporary and sudden condition.

Human causes of coastal erosion

Human activities, such as construction, shipping, boating and recreation can increase coastal erosion of sandy beaches, dunes, and bluffs. Even though natural events play a major role in the coastal erosion process, human actions can intensify the effects of these processes and speed up the coastal erosion process. Humans contribute to the coastal erosion process:

- by removing vegetation, exposing bare soil to be easily eroded by wind, wave and precipitation
- directing runoff from streets, parking lots, roofs, and other locations over a bluff edge causing it to erode
- or by constructing "hardened" structures on the shore that block the movement of sand along the coastline, reflect wave energy onto adjacent shorelines, or cause deepening of the nearshore

Many development activities damage or alter natural protective features and the protection these features afford the upland area from coastal erosion and storm damage. These activities include:

- building without considering the potential for damage to property or natural protective features
- activities which destroy natural protective features such as dunes or bluffs and their vegetation
- building structures intended for coastal erosion prevention which may exacerbate coastal erosion conditions on adjacent or nearby properties
- wakes from boats that produce wave action at the shoreline

Building coastal erosion protective structures, either by private or public funds, are extremely costly projects. These structures often are only partially effective over time and may increase the erosion potential to adjacent or nearby properties.

New York's Coastal Waters

- Lake Erie* and the Niagara River
- Lake Ontario* and St. Lawrence River
- Atlantic Ocean* and Long Island Sound*
- Hudson River south of the federal dam in Troy
- East River
- Harlem River
- Kill van Kull and Arthur Kill
- All connecting water bodies, bays, harbors, shallows, and wetlands

The coastlines along Lake Erie and Lake Ontario, Long Island Sound, and the Atlantic Ocean coastline of NYC and Long Island are at risk of coastal erosion from natural and human activities and are regulated. *These are the only areas currently mapped as coastal erosion hazard areas that require a Coastal Erosion Hazard Area (CEHA) permit for any regulated activity.

How does DEC Protect Coastal Areas?

Coastal erosion's threat to life and property can be minimized by regulation of land use, development, new construction or placement of structures, and by controlling construction of coastal erosion protection structures in coastal areas designated as coastal erosion hazard areas.

DEC has two programs focused on the protection of coastal erosion: Coastal Erosion Hazard Area (CEHA) permit program and the United States Army Corps of Engineers (US ACE) Civil Works Program. The CEHA program regulates and issues permits for activities within a coastal erosion hazard area. DEC works with US ACE to study coastal erosion problems along coastlines and to develop coastal erosion solutions. These are usually large scale projects that impact entire communities.

How New York State Prevents and Reduces Coastal Erosion

- promoting and preserving the natural protective features such as dunes and bluffs, beaches and nearshore areas of coastal regions
- restricting or prohibiting activities or development in natural protective feature areas
- ensuring new construction or structures are a safe distance from areas of active coastal erosion and the impact of coastal storms
- regulating the placement and construction of coastal erosion protection structures, when justified, to minimize damage to property, natural protective features and other natural resources
- restricting development involving public investment in services, facilities, or activities (for example, extending public water supply and sewer services) which are likely to encourage new permanent development in coastal erosion hazard areas
- requiring publicly financed coastal erosion protection structures intended to minimize coastal erosion damage to be used only where necessary to protect human life or where the public benefits of such structures clearly outweigh the public expenditures
- encouraging administration of coastal erosion management programs by coastal municipalities and establishing procedural standards for local program implementation; and establishing standards for the issuance of coastal erosion management permits

Coastal Erosion Hazard Area Permit Program

Coastal Areas Regulated by the CEHA Permit Program

The Coastal Erosion Hazard Area (CEHA) Permit Program provides written approval of regulated activities or land disturbance to properties within the coastal erosion hazard areas within DEC's jurisdiction. The program also assists certified communities to administer and enforce local programs.

Coastal Law

This program was initiated from the Title 4, Chapter 7 of the Unconsolidated Laws of New York, "Projects to Prevent Shore Erosion", enacted in 1945. The Coastal Erosion Hazard Areas Law (Environmental Conservation Law Article 34) empowers DEC to identify and map coastal erosion hazard areas and to adopt regulations to control certain activities and development in those areas.

The backbone of these regulations is a permitting system aimed specifically at all regulated activities or land disturbance within the coastal erosion hazard areas.

The construction or placement of a structure, or any action or use of land which materially alters the condition of land, including grading, excavating, dumping, mining, dredging, filling or any disturbance of soil is a regulated activity requiring a Coastal Erosion Management Permit. The permit provides written approval by DEC or a local government, whichever has the jurisdiction. DEC is reviewing and updating Part 505 regulations to make it easier for people to understand and comply with the regulations. This will include outreach to stakeholders and a public comment period.

CEHA Jurisdiction

There are 86 coastal communities in NYS that currently fall under CEHA jurisdiction. The law allows local communities to administer their own CEHA program. Forty-two communities have been certified by DEC and have their own coastal erosion hazard area law. The other forty-four communities are managed by DEC.

If you live in a certified community you need to contact your local building or zoning department to learn how to submit the appropriate coastal erosion permit application before construction starts and to obtain any other permits required by your community's local ordinances.

DEC may require other permits for the type or location of activity you are planning. Other agencies (US Army Corps of Engineers, Department of State, Office of General Services) also have jurisdiction within coastal erosion hazard areas, depending on the location and type of activity planned.

Coastal Erosion Hazard Areas (CEHAs)

There are two types of coastal erosion hazard areas: natural protection feature areas (NPFA) and structural hazard areas (SHA).

Natural protective feature areas (NPFA) are areas that contain the following natural features: beaches, dunes, bluffs, and nearshore areas. NPFAs protect natural habitats, infrastructure, structures, and human life from wind and water erosion, along with storm induced high water. Human activities (for example, development or modification of beaches, dunes, or bluffs) may decrease, or completely remove the erosion buffering function of natural protective features.

Structural hazard areas (SHA) are lands located landward of natural protective feature areas (NFPA) and have shorelines receding at a long-term average annual recession rate of 1 foot or more per year. Development within structural hazard areas is limited [by the regulation] to reduce the risk to people and property from coastal erosion and flood damage.

CEHA Coverage

Coastal erosion hazard areas are prone to coastal erosion and have been identified and mapped. The Coastal Erosion Hazard Area (CEHA) maps delineate the boundaries of erosion hazard areas that are subject to regulation 6 NYCRR Part 505. The DEC commissioner issues these maps. Mapped areas currently include the shorelines of Lakes Erie and Ontario, the entire coastline of Long Island, and the Atlantic Ocean coastline of New York City. Maps are also available at Regional DEC offices and at local building departments of certified communities.

Designating CEHA Areas

Natural protective feature areas (NPFA) are mapped by first identifying the most landward natural protective feature (beach, dune, or bluff) using aerial/satellite imagery, LiDAR, and field inspections. The following distances are then used to determine the landward limit of the NPFA.

- Dunes: 25 feet from the landward toe of the dune
- Bluffs: 25 feet from the peak of the bluff
- Beaches: 100 feet landward from the line of permanent vegetation.

Structural hazard areas are those areas located landward of the NPFA, and having shorelines receding at a long-term average annual recession rate of 1 foot or more per year. The inland boundary of a structural hazard area is calculated by starting at the landward limit of the NPFA, and measuring along a line which is perpendicular to the shoreline horizontally landward. This distance is determined by multiplying the long-term average annual recession rate by 40.

The maps that are currently available were created in the late 1980's. The maps are currently being evaluated and revised. This process involves: re-evaluating the currently mapped coastline to determine any changes that have occurred in the natural protective features, comparing historical imagery to current imagery to determine long term shoreline recession rates, and updating the location of both the NPFA and SHA lines. For more information about the map revision process, visit the CEHA Map Revision Process web page.

The areas of Lake Erie and Lake Ontario, Long Island Sound, and the Atlantic Ocean will all have their maps updated. Public hearings will be scheduled for public comment in each area that is revised.

Disputes

Any person who owns real property within a designated coastal erosion hazard area may appeal that designation. The commissioner will decide such appeal within 30 days after receipt of a complete appeal application and, if necessary, will adjust the coastal erosion hazard area boundaries accordingly. The only acceptable basis for a CEHA appeal is either: (1) the long-term average annual rate of shoreline recession was incorrectly established; or (2) the area was erroneously identified as a natural protective feature area or its NPFA was incorrectly identified

CEHA Revision Process

The New York State Department of Environmental Conservation (DEC) is required to review the boundaries of New York State's Coastal Erosion Hazard Areas every 10 years, pursuant to Article 34 of the Environmental Conservation Law (ECL). In reviewing the boundaries of the Coastal Erosion Hazard Areas, ECL Article 34 and Title 6 of the New York Codes, Rules, and Regulations (6 NYCRR) Part 505 direct the Department to identify and map coastal areas subject to erosion, as well as landforms (such as beaches, bluffs, and dunes that protect coastal lands) and development susceptible to the adverse impacts of erosion and high water. Properties located within a Coastal Erosion Hazard Area are subject to regulation under ECL Article 34 and 6 NYCRR Part 505, which limit coastal development in order to protect these sensitive areas.

DEC is currently evaluating and revising the CEHA boundaries. Technologies such as high resolution oblique and orthoimagery, combined with LiDAR topographic data and field checks, have allowed for more accurate mapping than was previously possible. Orthoimagery and LiDAR data will be used to revise the maps using ESRI ArcGIS software, and the maps will be substantiated through the use of oblique imagery and field checks.

Types of Data Used in the CEHA Map Revision Process

Airborne LiDAR is used for the CEHA mapping (Figure NY 1). The LiDAR being used for the CEHA map revision process has been acquired by several different sources, including the United States Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration (NOAA) and the New York City Department of Information Technology & Telecommunications (DoITT). Additional information about LiDAR can found at the USGS Center for LiDAR Information Coordination and Knowledge (http://lidar.cr.usgs.gov/).

Orthoimagery used for CEHA revisions is typically aerial imagery that has been gathered from a sensor mounted on an aircraft or a satellite. The imagery is then orthorectified, a process that removes distortion and creates a spatially accurate image that can be used to make horizontal distance measurements (Figure NY 2). The orthoimagery used for CEHA map revision was acquired by USACE, DoITT, New York State Department of Environmental Conservation (NYSDEC) and Dewberry Engineers Inc.

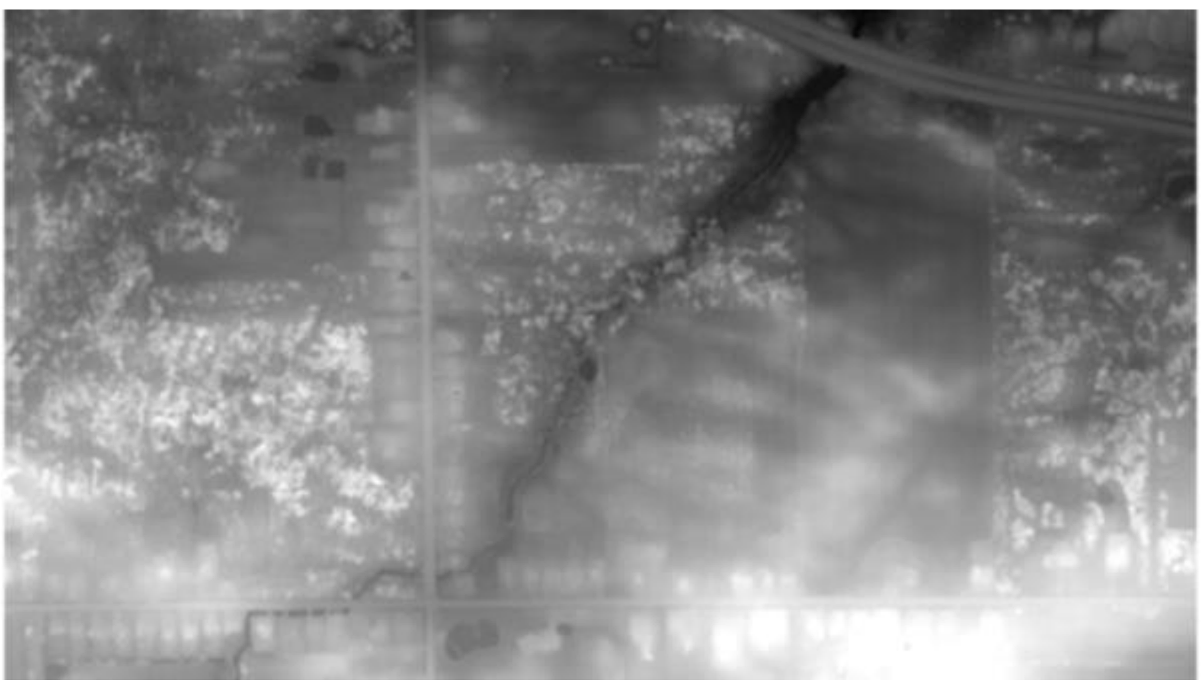


Figure NY 1*: Example of a LiDAR derived Digital Elevation Model (DEM) using data collected by the USACE. Differences in elevations are visually represented by how dark or light an area is.*

Oblique imagery is aerial imagery that is taken at an angle to the land, usually about 45 degrees (Figure NY 3). Oblique imagery allows for a less obstructed view of coastal features when compared to orthoimagery that can sometimes be obscured by vegetation, shadows, and shoreline structures. The oblique imagery used for CEHA map revision was acquired by USACE, NYSDEC, and Dewberry Engineers Inc.

Figure NY 2: *Example of aerial photo orthoimagery from Chimney Bluffs State Park in Huron, NY.*

Figure NY 3: *Example of oblique imagery at Chimney Bluffs State Park, Huron, NY (see Figure NY 2).*

The CEHA Map Revision Technical Process

The CEHA maps are comprised of two distinct zones, the Natural Protective Features Areas (NPFAs) and the Structural Hazard Areas (SHAs). The process for evaluating and revising these two areas are separate, but have some shared elements.

The NPFAs protect New York State's natural protective features (NPFs): nearshore areas, beaches, dunes, and bluffs. In order to ensure the accuracy of the proposed revised CEHA maps, the location and extent of these NPFs must be known. To do this, the LiDAR data is evaluated along transects (paths perpendicular to the shoreline on which measurements are made) placed every 50 meters. Elevation data is extracted along each of these transects, and that elevation data is used to determine the extent of the NPFs. After each NPF is properly identified, the most landward NPF is determined, and used to delineate the NPFA. Field checks are then conducted to verify the proper position of the NPFA in any areas of concern.

The SHAs are regulated areas landward of the NPFAs. SHAs are only delineated in highly erosive shoreline areas with a yearly erosion rate greater than 1 foot/year. The purpose of defining SHAs is to limit permanent (non-movable) construction in areas where damage due to erosion has a high probability of occurring during the life of the structure.

The locations of the SHAs are determined by comparing the shoreline location from historic imagery from the 1970s and 1980s with present day data. The difference in shoreline location between the two time periods determines the shoreline recession rate. If this historic shoreline recession rate is calculated to be greater than 1 foot per year at a given transect, the erosion rate is then rounded to the nearest ½ foot and delineated as a SHA. Areas with recession rates less than 1 foot per year are **not** rounded up to 1. The landward extent of the SHA is determined by beginning at the NPFA line, and extending landward a distance equal to the rounded (to the nearest half-foot) annual erosion rate x 40.

Anatomy of a Proposed Revised CEHA Map

Figure NY 4 and Figure NY 5 are two examples of the proposed revised CEHA maps. The map components are briefly described below; the numbers in the images correspond to the numbers listed in the description of the map components.

Description of Map Components

1. Title Block. The Title block includes:
    - Map Location- City/Town/Village/Borough, and County
    - Certification Date
    - Photo Number (name of orthoimagery photograph used on map)
    - Sheet Number
2. Scale - in both feet and meters. Only maps printed on 11x17 paper are scalable.
3. North Arrow
4. Legend
5. Revisions Table - contains records of any map revisions after certification date.
6. Landward Limit of Structural Hazard Area
7. Landward Limit of Natural Protective Feature Area
8. Historic Shoreline Recession Rates
9. Most Landward NPF Label Line

10. Jurisdictional Boundaries - City/Town/Village/Borough/Reservation
11. Match Lines - match lines assist in orientation of map panels. If match lines from adjacent map panels are superimposed, the panels will display the correct orientation with respect to one another.

Section 309 Report: Coastal Hazards

The following information is extracted from*: New York State Coastal Management Program, 309 Assessment and Strategies 2016-2020 (May 2015)*. This document is available for review online at http://www.dos.ny.gov/opd/pdf/Draft%20309%20Submission%20May_19_2015.pdf

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	732,626	826,513	12.8 %
No. of people in coastal counties	15,836,223	18,848,340	19.0 %
Percentage of people in coastal counties in coastal floodplain	4.6 %	4.4 %	-4.35 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

Vulnerability to Shoreline Erosion

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very low (>2.0 m/yr) accretion	52.27	6.9 %
Low (1.0 to 2.0 m/yr) accretion	0	0 %
Moderate (-1.0 to 1.0 m/yr) stable	439.08	58.2 %
High (-1.1 to -2.0 m/yr) erosion	115.20	15.3 %
Very high (<-2.0 m/yr) erosion	148.40	19.6 %

Sea Level Rise: Data from NOAA's State of the Coast "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

Coastal Vulnerability to Historic Sea Level Rise

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very Low	208.94	27.7 %
Low	491.61	65.1 %
Moderate	54.41	7.2 %
High	0	0 %
Very High	0	0 %

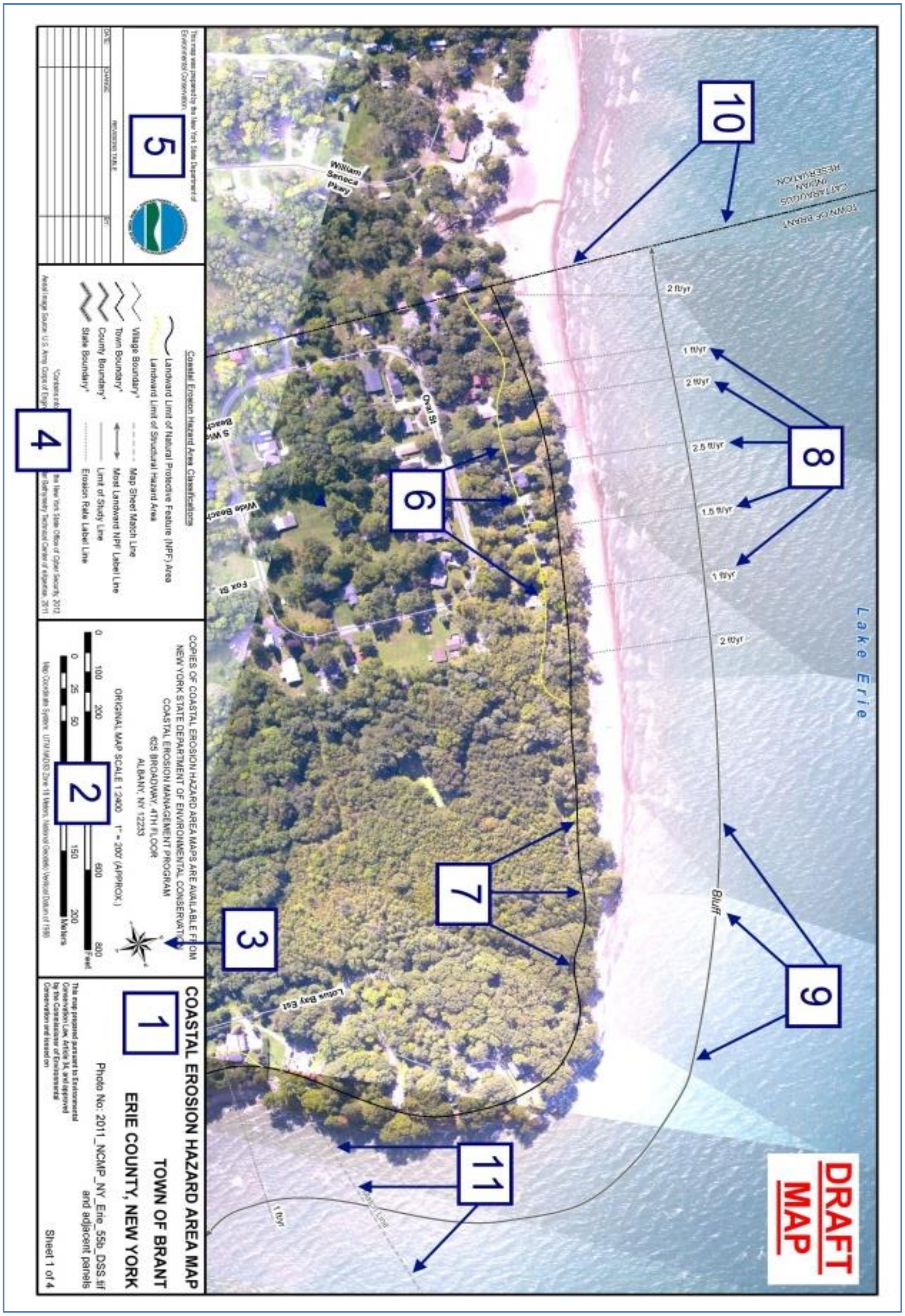


***Figure NY 4**: Example of a proposed revised CEHA map with several map components labeled. The map components are described in the "Description of Map Components" list above.*

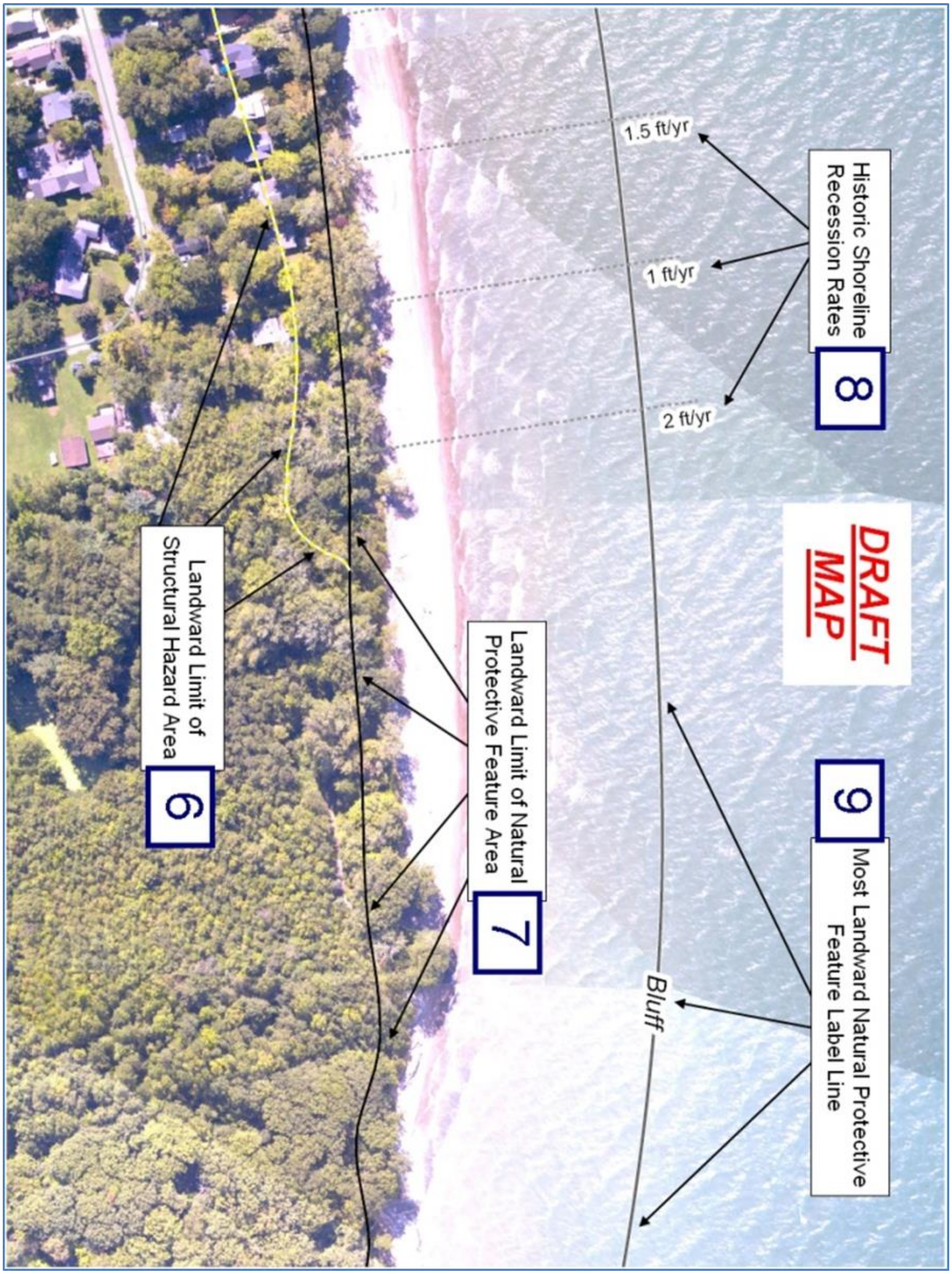


***Figure NY 5**: Close-up section of a proposed revised CEHA map with map components labeled.*

Other Coastal Hazards: General level of risk in the coastal zone for each type of coastal hazard. The state's multi-hazard mitigation plan is a good resource to support these responses.

Type of Hazard	**General Level of Risk (H, M, L)**
Flooding (riverine, stormwater)	H (high)
Coastal storms (including storm surge)	H
Geological hazards (e.g., tsunamis, earthquakes)	L/M (low/moderate)
Shoreline erosion	H
Sea level rise	H
Great Lake level change	M
Land subsidence	L
Saltwater intrusion	H

The New York State Energy Research and Development Authority (NYSERDA) produced an updated climate report in October 2014 titled: Climate Change in New York State – Updating the 2011 Climate Risk Information Supplement to NYSERDA Report 11-18 (Responding to Climate Change in New York State). This brief report summarizes a re-examination of regionally downscaled climate models, with updated data sets. It contains revised projections of certain climate parameters. Findings include small increases in the upper end of the original 2011 projections for temperatures, extreme precipitation events and sea level rise. There are also recommendations for additional studies to refine uncertainties, to track progress in global greenhouse gas mitigation and climate modeling, and to produce better forecasts for regional microclimate areas.

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise/Great Lake level change	N	Y
Other hazards	N	Y

For the purposes of the Coastal Erosion Hazard Area regulations (Chapter 6, New York Codes, Rules and Regulations (NYCRR), Part 505) development, or redevelopment in the event of 50% or greater damage from storms or erosion, is prohibited from mapped coastal erosion hazard areas as follows:

Dunes: 25-feet landward of the landward toe of the dune.
Bluffs: 25-feet landward of the receding edge of the top of the bluff.
Beaches: 100-feet landward of the place where there is a marked change in material or physiographic form, or from the line of permanent vegetation, whichever is most seaward.

An additional area designation "*Structure Hazard Areas*" would be characterized as "High" erosion areas: Where the long-term average annual erosion rate is 1 foot per year or greater, the extent of these areas begins at the edge of the bluff or landwardmost point of active erosion and extends landward 40 times the average annual erosion rate.

In-Depth Management Characterization (Phase II In-Depth Assessment)

The Section 309 Assessment and Strategy (2016-2020) identified three top management priorities where the coastal management program could improve its ability to more effectively address significant hazard risks. *Priority 1* is to revise New York state's coastal federal and state policies to encompass new requirements for flood resilience, including projected water level changes due to sea level rise, in conformance with new statutory requirements**.** *Priority 2* is to develop guidance on the use of natural resources, natural processes and nature-based shoreline treatments to reduce natural hazard risks. This will help improve resilience through incorporation of natural resources and natural processes in decision-making and planning. The guidance will also support application of revised coastal policies by integrating community resilience with management of natural protective features into coastal planning and decision-making.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	-
Mapping/GIS/modeling	Y	Risk assessment mapping to support planning for Great Lakes region and streams/rivers/tributaries. Shoreline geomorphology reach characterization for all of New York's shoreline. Shoreline conditions/structures inventory, particularly south shore of NYC, Nassau and Suffolk Counties and Great Lakes region.
Data and information mgmt.	Y	Regional storm risk frequency/geographic impacts distribution; regional down-scaled climate projections.
Training/Capacity building	Y	DOS staff training in: resilience science; climate change projections for resilience planning; increased local government and stakeholder capacity building; model resilience codes for local governments; best management practices for resilience.
Decision-support tools	Y	DOS risk assessment tool modified for application in Great Lakes and riverine conditions; community resilience assessment tools; guidance on natural resources and natural processes for resilience;

		guidance on climate change vulnerability assessments for planning purposes.
Communication and outreach	Y	Adaptive and resilient measures options and/or success stories.

Long Island Resilience Planning

For Long Island regional resilience planning for coastal hazards, cumulative and secondary impacts, and SAMP enhancement areas, the NYS CMP has identified priority needs and gaps for coastal communities. Existing GIS information for NY's coastal areas, including existing shoreline types/conditions, is insufficient for regional resilience planning. Information on in-water structures is especially lacking. Decision-makers need accurate maps, analytical tools and assessment of conditions to predict future shoreline positions and inundation areas, and identify potential damage to community assets and ecosystem health.

While the existing state coastal policies prioritize non-structural shoreline management measures and conservation of natural protective features, they do not establish performance guidelines or geographic applicability. In addition, recent pilot projects utilizing hybrid shoreline management structures are yielding new information about performance and site constraints. Organized guidance on protective capacity, geographic eligibility, and site constraints of nature-based shoreline management measures is needed.

Better guidance on shoreline management and the benefit of living shorelines in striving for resilient communities can assist communities and staff in determining the most appropriate management action for a specific locality. Living shorelines can expand shoreline management performance to include habitat conservation, natural sediment and hydrologic processes, tidal exchange, nutrient cycling, and runoff filtration and can better meet regulatory and planning objectives that are more compatible with ecosystems and natural processes than conventional shoreline armoring.

Ohio https://coast.noaa.gov/czm/mystate/

The Ohio Coastal Management Program was approved by NOAA in 1997, with the Ohio Department of Natural Resources serving as the lead agency for the networked program. The coastal management program incorporates state laws, regulations, and programs within forty-one management policies that are organized around nine issue areas. Ohio's coastal zone is quite varied and lies within nine counties bordering Lake Erie and its tributaries. The boundary width ranges from about one-eighth of a mile to 15 miles depending on features such as wetlands and bluffs.

Ohio Coastal Management Program

The Ohio Coastal Management Program (OCMP) sets forth management goals for Ohio's portion of Lake Erie, the coast and watershed in order to preserve, protect, develop, restore, enhance and balance the use of the state's valuable and sometimes vulnerable coastal resources. The Ohio Department of Natural Resources is the lead agency in administering the networked program, which means many partners work together to achieve the program's goals. (http://coastal.ohiodnr.gov/ocmp)

The Ohio Coastal Management Program's 41 management policies are organized into nine issue areas. The policies outline state laws, regulations, and initiatives that are related to Lake Erie. The OCMP also designates a Coastal Management Area, outlines the Coastal Management Assistance Grant and Coastal and Estuarine Land Conservation programs, addresses shoreline erosion, public access and energy facility siting, and sets forth provisions of the Federal Consistency Certification authority.

Ohio is one of thirty-four U.S. states and territories with a coastal program approved and funded by the National Oceanic and Atmospheric Administration in accordance with the Coastal Zone Management Act of 1972. Ohio's program was federally approved on May 16, 1997, and has been updated several times.

OCMP Issue Areas and Policies

The 41 policies found in Part II Chapter 5 of the Ohio Coastal Management Program Document are divided into nine issue areas. Information specific to Coastal Erosion and Flooding Policies 1-5 and the Ohio Coastal Management Document can be accessed at: http://coastal.ohiodnr.gov/ocmp

Coastal Erosion in Ohio

Extracted from: http://geosurvey.ohiodnr.gov/lake-erie-geology/erosion-and-research/erosion-problems

Coastal erosion does not happen only along the east and west coasts of the United States. Because most humans live where the earth is stable, many people are surprised to learn that there are settings in Ohio where land can disappear rapidly. The following points address some misconceptions about coastal erosion in Ohio.

Coastal erosion is not a new problem. William W. Mather, Ohio's first state geologist, noted in 1838 that certain portions of the coast had lost 130 feet over the previous 42 years. Geologist Charles

Whittlesey wrote in 1867 that on the Cleveland waterfront between 1796 and 1842 "there had been a general encroachment of two hundred and five feet."

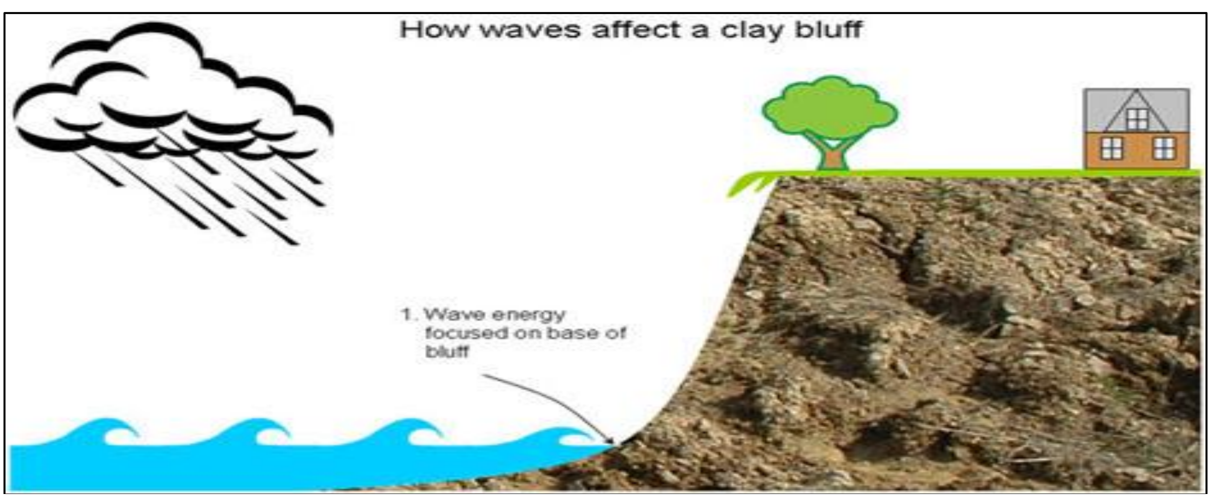
Coastal erosion is not a rare problem. Of the thousands of Ohio homes on the Lake Erie waterfront, nearly half are within 50 feet of the top of the bluff and a quarter are within 25 feet of the top of the bluff. Many were further from the bluff when they were built.

Coastal erosion does not affect only lakefront landowners. All Ohio taxpayers are affected because the State is the largest landowner along the Ohio shoreline. Public parks, swimmers, boaters, anglers, utilities and infrastructure are all subject to the costs and damage of coastal erosion. Reduced property tax revenues and increased insurance costs are borne by many, even those who do not live on the coast. The economic losses caused by coastal erosion can exceed tens of millions of dollars.

Coastal erosion is not always slow. Erosion rates have been as high as 110 feet per year. Coastal erosion can be dangerous. In Ohio, three fatalities in recent decades are known to have resulted when eroded shoreline materials collapsed suddenly. Good, fact-based information on the severity of erosion in a particular area can be hard to find. The ODNR Division of Geological Survey has studied Lake Erie coastal erosion for decades. We have the best information on where coastal erosion is occurring in Ohio and why. The following discussion addresses why the Ohio coast is eroding and what information is available about it.

The Erosion Problem

Erosion begins with Lake Erie waves. Storm waves are the most destructive, pounding against the shoreline and breaking down the materials that make up the shore. Where the shore is a low bank, it can be washed away entirely or become flooded. Waves weaken the base of a higher clay shoreline until the base of the bluff—the slope that rises from the shore to where the upper land flattens out—washes away or collapses. When deprived of its natural base, the bluff becomes overly steep, standing at an unstable angle that it cannot sustain. It responds by slumping, or settling down to a more natural, stable angle. The settling can be sudden or gradual, but as the slope settles, the top of the bluff moves farther from the shoreline. The following schematic diagrams (Figure OH 1) illustrate the process.



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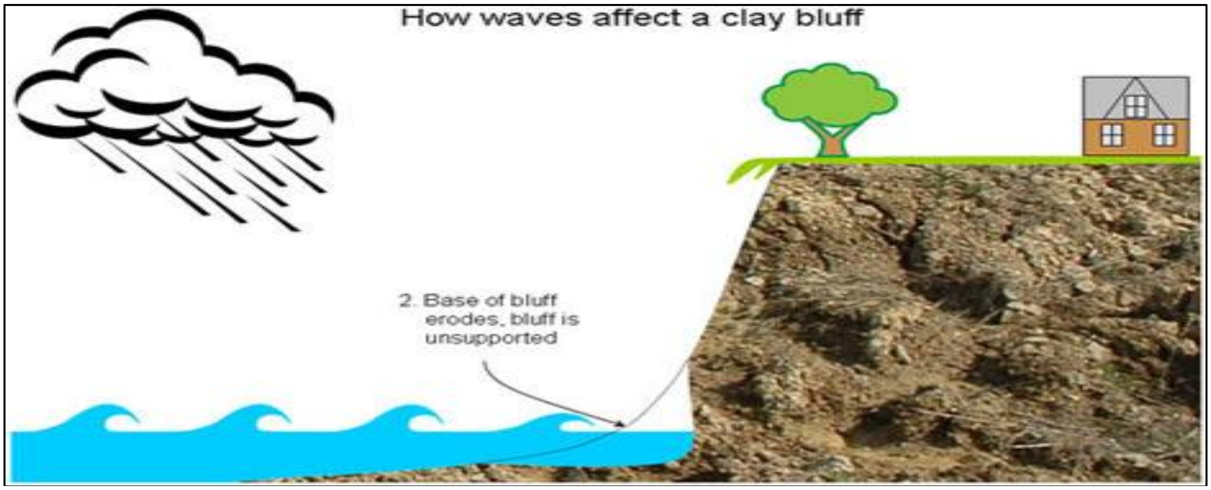

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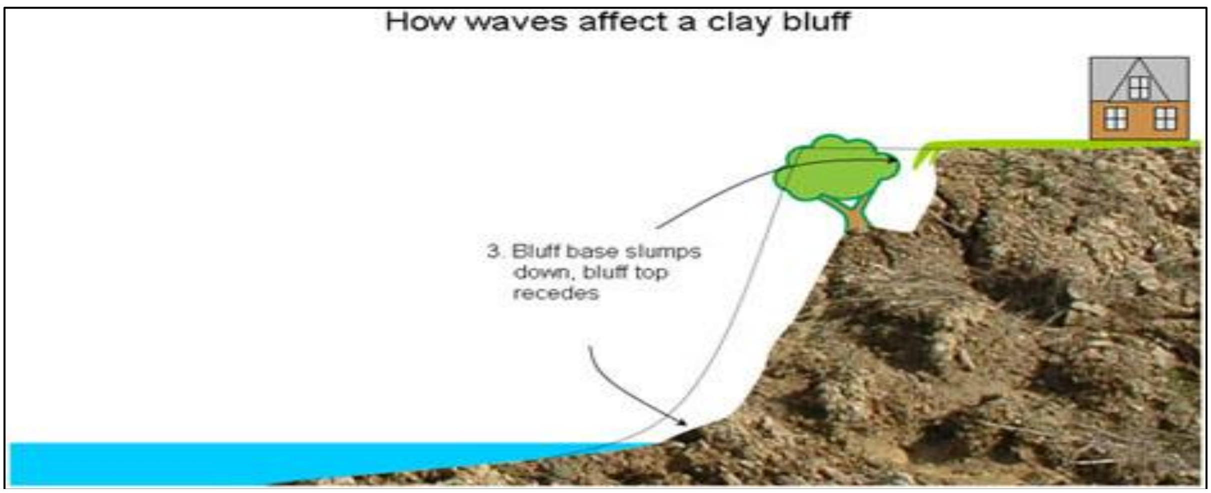


(c)

Figure OH 1*: Schematic diagrams (a-c) used to illustrate generalized sequential steps involved in coastal bluff erosion on the Ohio Lake Erie coast (Image: modified from geosurvey.ohiodnr.gov).*

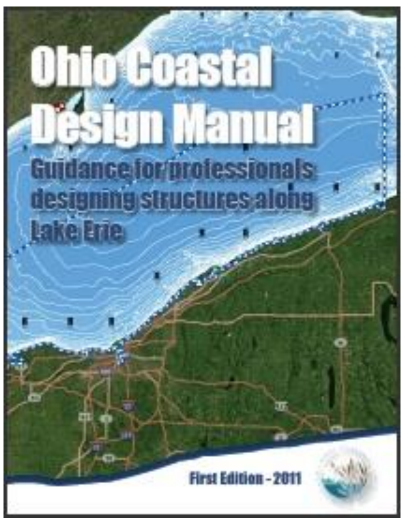
Even a rocky shore is vulnerable to wave attack. Rather than softening and washing away, the toe of a rocky bluff gradually crumbles as waves cut a notch into the bluff base. Eventually the notch erodes far enough into the rock that the upper portion of the bluff, now unsupported, suddenly collapses. This takes much longer than the failure of a clay bluff—maybe years—but the collapse is sudden and can occur with little warning. Natural cracks in the rock accelerate the process.

These forms of erosion tend to be episodic. A bluff may appear stable, losing only a few feet over many decades and giving an impression of permanence. Then, perhaps during a storm, several feet can collapse in a few hours. Whether the bluff is clay soil or shale bedrock, several stories high or low enough to step over, the result of erosion is that the top of the bluff—perhaps the edge of someone's back yard—recedes farther inland.

Waves are only one factor in erosion. Groundwater seepage, freeze-thaw cycles, and lake ice also contribute. Lake levels, which determine how high up the bluff waves can reach, can increase erosion rates as they rise or decrease them as they fall. In addition, the natural beaches that once protected the shore from wave attack are mostly gone, with 44% of the shoreline having no beach at all. Because waves and gravity never cease, erosion cannot truly be stopped. Seawalls, breakwalls and other structures can buy time, but any structure needs ongoing maintenance to stay effective and maintenance is expensive. Many landowners find erosion occurs more quickly than they can raise the funds to control it.

The issues surrounding coastal erosion are complex: What causes erosion at a particular property? What are the most effective measures to prevent it and what other effects will those measures have? How much will such measures cost and how do property owners pay for them? There is no single answer for all properties, but an important starting point is knowing how quickly a shoreline is eroding. The Coastal Erosion Area program was conceived to help landowners, local planners, lenders, real estate professionals and others make wise decisions regarding shoreline recession by actually measuring the amount of erosion that occurs.

Ohio Coastal Design Manual



The ODNR Office of Coastal Management has prepared print and online versions of the Coastal Design Manual to promote better projects along the Ohio shore of Lake Erie including Maumee Bay and Sandusky Bay.

The manual demonstrates how structures along the shore of Lake Erie are designed and how coastal engineering principles are best applied to achieve a balance between landowners' needs for erosion control and lake access and the need to protect our lake's natural resources. The manual is available online at: http://coastal.ohiodnr.gov/design

The Ohio Coastal Design Manual focuses on the design of the types of structures most commonly constructed in Ohio; therefore the guidance only applies to Ohio's unique coastal environment. The companion to this design manual is the Lake Erie Shore Erosion Management Plan (LESEMP) that addresses how the conditions along Lake Erie vary, and which types of erosion control are best suited for specific locations and conditions along the lake. The LESEMP identifies the types of structures or controls that would function best along a section of the shore, and this design manual shows how those structures should be designed and constructed.

The purpose of this manual is to illustrate the engineering and surveying processes needed to develop safe, sound and successful erosion control and lake access projects along Ohio's Lake Erie shore. Engineers, surveyors and contractors should find the manual a valuable resource for planning projects and working with landowners. For the lakefront property owner, this manual can be a means of better understanding the design, surveying and construction processes.

The policies and guidelines included in the Ohio Coastal Management Program Document and the Ohio Revised and Administrative codes pertaining to design of coastal structures, along with the application and guidance on the application process for shore structure permits and submerged land leases, are all available on this website. The importance of meeting these requirements as well as those of all federal, state and local agencies involved in authorizing projects on Lake Erie cannot be overstated.

Lake Erie Shore Erosion Management Plan (LESEMP)

(http://coastal.ohiodnr.gov/erosion)

The Lake Erie Shore Erosion Management Plan (LESEMP) is being developed as part of an effort to assist property owners along the Lake Erie coast by providing free technical assistance to address erosion issues. The LESEMP Map Viewer is available at: http://coastal.ohiodnr.gov/erosion

Why is an erosion control program necessary?

Coastal erosion is a continual process, affecting all of the shore at some point in time. In response to the wide-ranging erosion locations and rates, private and public shore property owners along Ohio's 312-mile Lake Erie coast have constructed a wide variety of erosion control measures. Some of these erosion control measures are properly engineered and constructed. Others are less appropriate or adequate for the site conditions and can exacerbate erosion onsite or on nearby shores.

Recognizing the need to encourage the best possible erosion control options, the Ohio DNR Office of Coastal Management is developing the Lake Erie Shore Erosion Management Plan. The LESEMP aims to promote successful means of controlling erosion by developing erosion control recommendations that are based on regional site conditions.

About the Shore and Erosion

A detailed description of the LESEMP is online at http://coastal.ohiodnr.gov/erosion and provides information on many coastal-issue topics.

LESEMP Regions and Reaches

Lake Erie's coast is divided into "regions" and each region is further divided into "reaches" which are stretches of shore with similar site conditions. LESEMP identifies the causes of erosion in each reach then outlines the most likely means of successful erosion control based on reach-specific erosion issues, geology and habitat. LESEMP's objective is to simplify the decision process while enhancing the effectiveness of solutions to erosion related issues. The LESEMP does not contain any regulatory oversight provisions. Factsheets for regions, and for each reach within a region, are available for download.

Section 309 Report: Coastal Hazards

The following information is extracted from*: Ohio Coastal Program Enhancement Plan: Coastal Zone Management Act S309, Assessment and Strategy 2016–2020 (Draft, 2015).* The document is available at https://coastal.ohiodnr.gov/portals/coastal/pdfs/cpe/Sect309_2016-20DRAFT.pdf

The Ohio Coastal Management Program has made significant strides toward accomplishing the strategies and advancing the 309 enhancement objectives identified under the Section 309 Enhancement Program since the last assessment. The following efforts have been completed since the last assessment and strategy.

Lake Erie Shore Erosion Management Plan (LESEMP)

The Office of Coastal Management has made significant progress towards and will continue development of a plan for local communities and individual property owners to use in addressing Lake Erie based erosion and flooding concerns while minimizing impacts to the shore and nearshore habitats and resources along Ohio's Lake Erie coast. The regionally based plan addresses topics such as sand resources, beach preservation, structural and non-structural solutions to erosion problems, effects of armoring the shore, impacts of federal harbors, engineering design guidance, habitat enhancement, and public education. The plan utilizes information available from existing erosion studies, master plans and comparable efforts undertaken by federal, state and local agencies and identifies gaps in available information. Additionally, the plan will incorporate information from projects initiated as a result of the gap analysis.

Development of the plan relies heavily on public outreach and collaboration with Ohio Coastal Management Program partners before, during, and after the development of recommendations for each region of the Lake Erie shore. Outreach includes public meetings with stakeholders, the availability of print and on-line resources, individual technical assistance site visits with property owners and the continued development of the LESEMP-specific web site and on-line GIS Map Viewer. The Ohio Lake Erie coast has been divided into 9 regions. To date, 7 of the 9 regions have been completed and 3 of the completed regions are undergoing re-formatting to increase the overall effectiveness of the LESEMP document.

Coastal Design Manual

The Coastal Design Manual (Manual) serves as a complement to the Lake Erie Shore Erosion Management Plan. The Manual provides technical design and surveying information for Lake Erie coastal projects to property owners, design consultants and contractors. The increased understanding of the methodologies to use when designing a coastal structure should lead to better proposals that are more likely to be approved in a shorter time period.

The first edition of the Manual, completed in 2011, focused on the design process for coastal structures including a summary of required existing site condition information, basic coastal engineering and surveying methods and design examples for revetments, seawalls and access structures. The second edition of the Manual will address design guidelines for breakwaters, groins, piers, beach nourishment and monitoring and by-pass of littoral material. The second edition of the Manual will be available in print and on-line versions and will incorporate updates to the first edition. The second edition is 90% complete.

Sand Resources study

A GIS product has been developed by the ODNR Division of Geological Survey that enables the Office of Coastal Management to assess potential volumes of sand resources entering the littoral system through erosion of bluffs and correlate the volume to the rate of littoral drift and impacts of shore perpendicular structures such as Federal Harbors on available sand resources. The GIS product was developed as an outcome of the Textural GIS for Lake Erie Bluffs project. Findings from the project are being incorporated into LESEMP reach documents as Regions are being re-formatted. In addition, a Lake Erie Nearshore Habitat fact sheet was finalized and posted online as a complement to the Lake Erie Shore Erosion Management Plan documents. While the study of sand resources was initially identified as a Section 309 Enhancement Grant strategy, the Textural GIS project was accomplished with Section 306 funds.

Resource Characterization (Phase I Assessment):

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	118,540	122,788	+3.6 %
No. of people in coastal counties	2,646,263	2,534,282	-4.2 %
Percentage of people in coastal counties in coastal floodplain	4.5 %	4.8 %	0.3 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

Vulnerability to Shoreline Erosion

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very low (>2.0 m/yr) accretion	no data	no data
Low (1.0 to 2.0 m/yr) accretion	no data	no data
Moderate (-1.0 to 1.0 m/yr) stable	no data	no data
High (-1.1 to -2.0 m/yr) erosion	no data	no data
Very high (<-2.0 m/yr) erosion	no data	no data

Sea Level Rise: Data from NOAA's State of the Coast "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

Coastal Vulnerability to Historic Sea Level Rise

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very Low	n/a	n/a
Low	n/a	n/a
Moderate	n/a	n/a
High	n/a	n/a
Very High	n/a	n/a

2010 Coastal Erosion Area maps provide an update to 1998 Coastal Erosion Area Maps utilized for the State of Ohio Enhanced Hazard Mitigation Plan (Rev January 2011). The 2010 mapping revised the designated Coastal Erosion Areas based on erosion measured between 1990 and 2004. The percentage of shoreline miles affected by a Coastal Erosion Area designation decreased from 1998 to 2010 from 36% to 12%, respectively. Factors that contributed to the decrease in designated miles of shore include average to low water levels during the 2010 mapping period, increased erosion protection and mapping methodology.

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/		

redevelopment in high-hazard areas	N	N
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	N	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	N	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise/Great Lake level change	N	Y
Other hazards	Y	N

Shoreline erosion is classified as a high hazard based on rates of coastal erosion. High-hazard areas are defined as described in Ohio Revised Code Section 1506.06 and Ohio Administrative Code Sections 1501-6-10 through 13. At least once every ten years ODNR must review and may revise the Coastal Erosion Area designations per Ohio Revised Code Section 1506.06 (E). The mapping is useful in determining areas along the coast where higher erosion rates are likely over the next 30 years if no additional erosion control measures are installed. The most recent mapping was finalized in December 2010.

In-Depth Management Characterization (Phase II In-Depth Assessment)

Erosion and flooding have been identified as the most significant coastal hazards within the Ohio coastal zone based on a variety of factors and information, including institutional knowledge gained from reviewing applications for Shore Structure Permits and Coastal Erosion Area Permits, answering technical assistance questions regarding erosion and flooding on a daily basis, conducting site visits to properties across the coast on a regular basis, reviewing historic aerial photography, assisting with the identification of Coastal Erosion Areas, educational backgrounds of staff, professional development/training, in-house development of the Coastal Design Manual and Lake Erie Shore Erosion Management Plan, and other tasks associated with the monitoring and documentation of erosion and flooding issues along the Lake Erie shore.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

OCMP has identified three management priorities where there is opportunity for the CMP to address the most significant hazard risks.

Coastal Erosion

An opportunity exists for updating the Coastal Erosion Area maps in an effort to provide the latest, most accurate information to coastal property owners and stakeholders. Additionally, an assessment of the predictive capability of the Coastal Erosion Area maps can be completed through a comparison of the 1998, 2004 and 2014 planned mapping.

Coastal Erosion Mitigation Impacts

An opportunity exists for this priority to identify and measure the number, types and effectiveness of erosion control measures along the Lake Erie coast. Such an effort could include developing insights into the effectiveness of different types of erosion control measures under varying site conditions.

Sand Resources

An opportunity exists to encourage the use of fewer hard structures and more native vegetation, including dunes and aquatic vegetation, in the management of sand resources. A study of monitoring and bypass operations has potential to provide information that could reduce/eliminate impacts of groins and detached breakwaters on the littoral system.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Information related to species abundance and diversity associated with shoreline type and vegetative cover. Mitigation impact assessment.
Mapping/GIS/modeling	Y	An update to the Coastal Erosion Area mapping is needed. The current designation is based on erosion between 1990 and 2004. An inventory of shoreline structures and shore type would be useful in assessing regional conditions and identifying locations for future studies or enhancement projects.
Data and information mgmt.	Y	A tool that connects regulatory records and resource management data geospatially to assist with characterization of the shore on site-specific and regional levels to be used in making regulatory decisions and planning for studies and enhancement projects.
Training/Capacity building	Y	Living shoreline and sand resource management educational opportunities.
Decision-support tools	Y	See Data and Information Management need above.
Communication and outreach	Y	A strategy for disseminating information to Lake Erie stakeholders.

As part of this Section 309 cycle, OCMP plans to finalize updated Coastal Erosion Area Maps and assess the predictive capability of the mapping methodology in designating coastal erosion areas. The assessment of the methodology used to designate coastal erosion area maps will utilize data from three mapping periods, 1973-1990, 1990-2004 and 2004-2015, to identify areas where the mapping methodology accurately predicted future erosion rates and where it did not. The information gleaned from this assessment will be used to draft proposed changes to the mapping methodology to increase the predictive capability of future mapping efforts.

Oregon https://coast.noaa.gov/czm/mystate/
http://www.oregon.gov/LCD/OCMP/Pages/index.aspx

The Oregon Coastal Management Program, approved by NOAA in 1977, consists of a network of agencies with authority in the coastal zone. The Oregon Department of Land Conservation and Development serves as the lead agency. The primary authority for the coastal management program is the Oregon Land Use Planning Act and the 19 statewide planning goals. Oregon's coastal zone extends from the Washington border on the north to the California border on the south. It extends seaward to the extent of state jurisdiction as recognized by federal law (the Territorial Sea, which extends three nautical miles offshore), and inland to the crest of the coastal mountain range except to the downstream end of Puget Island on the Columbia River, to Scottsburg on the Umpqua River, and to Agness on the Rogue River.

Oregon Coastal Management Program

The Oregon Coastal Management Program (OCMP) develops and employs planning tools, information technologies, and information resources to help conserve and develop coastal resources. (http://www.oregon.gov/LCD/OCMP/docs/general/programoverview.pdf)
Significant hazards-related programs in Oregon include:

Natural Hazards Assessment and Planning

The OCMP assists coastal planners to identify and plan for coastal hazards to prevent property damage and avoid loss of life. The OCMP also works with the Oregon Department of Geology and Mineral Industries (DOGAMI) and Oregon Sea Grant to identify and communicate information on natural hazards such as shoreline erosion and tsunami inundation. DOGAMI has conducted a thorough analysis of the physical processes that cause erosion along Oregon's dune-backed and bluff-backed Pacific coastline. An empirical and equation-based approach was used to identify active erosion hazard zones and to tackle the almost intractable problem of predicting the future extent of high-, moderate-, and low-hazard zones in Lincoln and Tillamook Counties (Allan & Priest, 2001; Priest & Allan, 2004): (http://library.state.or.us/repository/2013/201308161542125/); (http://www.oregongeology.org/pubs/ofr/p-OFR.htm). The protocol has been adopted by others for use in coastal erosion adaptation planning, excellent examples of which are the 2013 erosion adaptation plan prepared for the town of Neskowin, Tillamook County (https://www.oregon.gov/LCD/OCMP/docs/Publications/NeskowinAdaptationPlanFinal.pdf), and the evaluation of erosion hazard zones for dune-backed beaches in Tillamook County (http://www.oregongeology.org/pubs/ofr/p-O-14-02.htm).

Oregon Coastal Atlas and Information Services

The OCMP serves a wide variety of coastal data and information on the Oregon Coastal Atlas (http://www.coastalatlas.net/), and provides web-based information services for ocean planning and management activities (http://www.oregonocean.info). The Coastal Atlas includes the Ocean Shores Data Viewer (Figure OR 1) designed for those working on coastal land-use issues to view, overlay, evaluate, and interact with digital ocean shores data more efficiently. This Viewer provides access to the statewide Goal 18 Beachfront Protection Structure (BPS) eligibility inventory, as well as the existing BPS inventory. Also included in the Viewer are data sets covering tsunami inundation areas, DOGAMI coastal erosion hazard zones, and FEMA flood mapping. The Ocean

Shores Data Viewer was designed and built by local level government users for local level government uses. Originally developed in Minnesota, where it acquired the name "GeoMoose," it was adopted in Oregon in 2010 by the Oregon Local Government Web Mapping Consortium (http://www.coastalatlas.net/index.php/tools/planners/67-ocean-shores-viewer).

OCMP also maintains an online database of imagery, data, and video on the Oregon Shore Zone website (http://www.oregonshorezone.info/). ShoreZone is a coastal habitat mapping and classification system in which georeferenced aerial imagery is collected specifically for the interpretation and integration of geological and biological features of the intertidal zone and nearshore environment. The mapping methodology is summarized in significant detail online at http://www.oregonshorezone.info/docs/OregonProtocol_Final_July2014.pdf. The data summary report provides information on geomorphic and biological features of 2,633 km of shoreline mapped for the 2011 coastal survey of Oregon. The habitat inventory is comprised of 3,223 along-shore segments, averaging 817m in length.

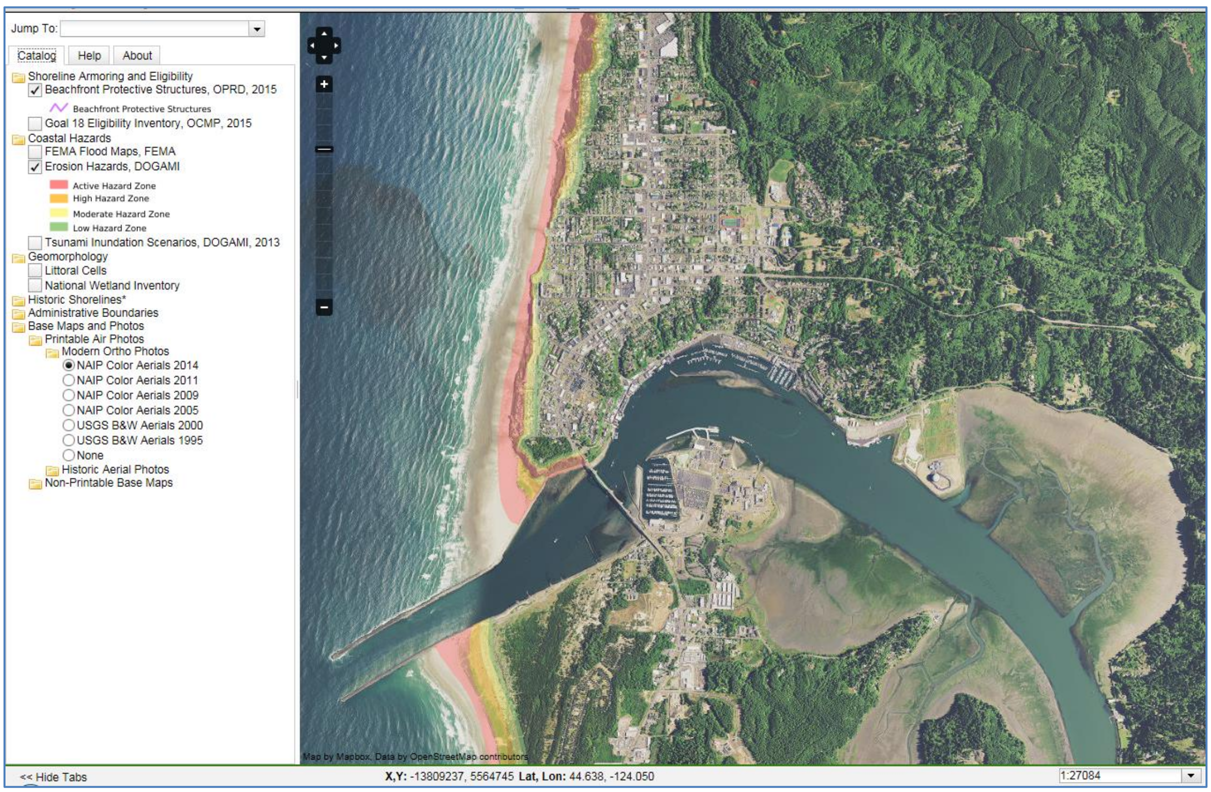


***Figure OR 1**: Screenshot of the Ocean Shores Data Viewer from the Newport area (Lincoln Co., OR) showing a typical format, and the mapped and predicted Erosion Hazard Zones.*

Beneficial Uses of Nearshore Sediment

The OCMP actively works with the Lower Columbia Solutions Group on regional solutions to sediment management issues at the mouth of the Columbia River. More information is available at http://www.lowercolumbiasolutions.org/index.php?option=com_content&task=category&sectionid=5&id=27&Itemid=39.

Climate Change

The OCMP has begun to work with scientists, Oregon Sea Grant, and other agencies to assess the effects of climate change on the Oregon coast and to assist coastal local governments to plan for those effects.

Shoreland Processes and Hazards

Oregon's coastline is the result of the dynamic, powerful natural forces of weather, climate, ocean waves and currents, and tectonic evolution. Existing development on the Oregon coast largely occupies the available less-hazardous sites. New development is increasingly proposed for more hazardous areas such as steep slopes, ocean bluffs, landslide-prone sites, and low-lying areas subject to ocean flooding and coastal erosion (http://www.oregon.gov/LCD/OCMP/Pages/ShorHaz_Intro.aspx).

OCMP recognizes that the Oregon coast is subject to two principal types of coastal hazards. Catastrophic hazards are regional in scale and scope, such as the massive Cascadia Subduction Zone earthquakes that occur every 300-1000 years, with consequent severe ground shaking, subsidence, landslides, liquefaction, and tsunamis. Catastrophic events are inherently difficult to predict and have only recently become a principal concern for coastal communities. Chronic hazards are more local in occurrence and impact, and may result in damage to life and property that, although sometimes dramatic, is limited in scope and severity. Chronic hazards include river and ocean flooding, beach erosion, wave attack, coastal sand inundation, and mass wasting along coastal bluffs. The wide distribution and frequent occurrence of chronic hazards makes them a more immediate concern.

Along bluff-backed and slide-backed shorelines, processes of mass wasting (or gravity-driven landslides) are the primary controls on shoreline stability and result in gradual through rapid bluff recession. Oregon distinguishes between bluff-backed and slide-backed shorelines on the basis of differences in the scale of slope movement. Simple surface *sloughing* is the dominant process along bluff-backed shorelines. Complex deep-seated *landsliding* and *slumping* are the dominant processes along slide-backed shorelines.

Numerous factors affect slope stability by increasing driving forces and/or reducing resisting forces, with material composition being a primary control. Soft bluff-forming sandstones, mudstones, and unlithified sediments are highly susceptible to slope movement. Prolonged winter rains saturate these porous bluff materials, both loading the slope and lowering cohesive strength, to further decrease slope stability. The geometry and structure of bluff materials also affects slope stability. They define lines of weakness and control surface as well as subsurface drainage. By removing sediment from the base of bluffs and by cutting into the bluffs themselves, processes of wave attack may also affect slope stability. The extent to which the beach fronting the bluff acts as a buffer is important in this regard.

Human activities affect the stability of coastal landforms. For example, jetty construction and maintenance dredging are factors that affect shoreline stability for long time periods and large geographic areas. Examples of human activities that affect shoreline stability over shorter time periods and smaller geographic areas include those associated with development, such as grading and excavation, surface and subsurface drainage alteration, vegetation removal, and vegetative and structural shoreline stabilization. With the exception of the latter two, these activities tend to be a particular concern along bluff-backed shorelines. Along bluff-backed shorelines, graffiti carving can be added to the list of human activities that affect shoreline stability and are associated with heavy recreational use.

Oregon cities and counties are required to account for areas with natural hazards in comprehensive plans and associated ordinances. Planning for coastal hazards is guided by Statewide Planning *Goal 17: Coastal Shorelands*, and *Goal 18: Beaches and Dunes*. These goals require local governments to identify and plan for the dynamic and potentially hazardous nature of coastal shorelands, particularly along the ocean.

The purpose of *Goal 17: Coastal Shorelands* is "to conserve, protect, develop, and, where appropriate, restore the resources and benefits of all coastal shorelands." In addition to its conservation objectives for protecting various shoreland habitats, Goal 17 aims to reduce hazards to human life and property. Local governments are required to identify the location of areas subject to geologic and hydrologic hazards within the Coastal Shorelands planning area. More information is available at http://www.oregon.gov/LCD/docs/goals/goal17.pdf. Local governments are required to delineate a Coastal Shoreland planning area that includes lands subject to ocean flooding and within 100 feet of the ocean shore or within 50 feet of an estuary or coastal lake, and adjacent to areas of geologic instability related to or impacting a coastal water body.

Oregon Coastal Management Activities

Assessing Coastal Hazards

The Oregon Department of Geology and Mineral Industries (DOGAMI) has completed detailed coastal erosion and hazard maps and analyses (Coastal Hazard Risk Maps) for the ocean shores of Clatsop, Tillamook, Lincoln, and portions of Curry and Coos Counties. The DOGAMI maps, overlaid on aerial photos, delineate areas of Active, High, Moderate, or Low hazard risk on the ocean shore. Risk zones account for topography, ocean processes and sediment transport that cause erosion of bluff-backed and dune-backed environments.

Beach monitoring and Mapping

DOGAMI carries out the "Oregon Beach and Shoreline Mapping and Analysis Program" (http://www.oregongeology.org/sub/nanoos1/index.htm) to document the spatial variability of beach change at various time-scales (i.e. seasonal, multi-year and long-term). The program purpose is to provide high-quality scientific information about changes to the shore and beach that can be used by coastal managers, city and county planners, the geotechnical community and the public-at-large to plan for ocean shoreline change. This program is central to state efforts to understand the coastal effects of future storms, impacts from El Niño, and to predict long-term change.

Managing for Coastal Hazards

Statewide Goal 18 limits construction of shoreline protective structures to development that existed prior to January 1, 1977. Because it is often difficult to determine whether a property was “developed” at that time, the Oregon Department of Land Conservation and Development (DLCD) has developed a GIS-based tool (Shoreline Protection Structure Eligibility Tool) to help local governments determine whether a parcel is eligible for shorefront protection. The tool is available for most of the Oregon coast.

A Model Code for Chronic Coastal Hazards

The DLCD has prepared a model ordinance in an effort to further assist local governments to address increasing chronic coastal hazards. The code language, or portions thereof, is intended to be used as an overlay zone and should be modified as needed to fit with applicable zoning codes. This model overlay zone is intended to be used with DOGAMI risk zone maps and analyses but could be modified to be used with other credible regional hazard maps and analyses. The model should provide opportunities for innovative options for coastal hazards management within chronic coastal hazard erosion areas. Further information on this initiative is available online at www.oregon.gov/LCD/OCMP/docs/Publications/ModelCoastalHazardsOverlayZone.pdf.

Assessing Shoreline Conditions

DLCD also offers an online document, *Appraisal of Chronic Hazards Alleviation Techniques*, which can be used by local governments in assessing natural hazards mitigation options. It is available online at http://www.oregon.gov/LCD/docs/publications/achatx.pdf.

Littoral Cell Planning

Sediment transport, and the erosion or accretion of beaches, are controlled by the configuration of littoral cells along the Oregon coast. These cells, bounded by rocky headlands on either end, appear to have a relatively fixed sand budget that may move within the cell but is rarely lost. DLCD promotes littoral cell planning as a key to successfully recognizing and accounting for risk from hazards along the ocean shore. A littoral cell management plan is a comprehensive, integrated, area-wide hazard management strategy that accounts for geology, sediment characteristics and volume, length, riverine inputs, presence of dunes or bluffs and the unique characteristics of each cell. These plans are focused on reducing risk to new and existing oceanfront development and include geologic inventories, a chronic hazards management strategy, and implementation mechanisms.

Hazard and beach monitoring and mapping

DOGAMI plans to increase ocean shore monitoring and mapping to fill knowledge gaps and enhance its data base for future decision making efforts.

Section 309 Report: Coastal Hazards

The following information is extracted from: *Oregon Coastal Management Program, Coastal Zone Management Act S309: Assessment and Strategy 2016-2020 (June, 2015).* The document is available at http://www.oregon.gov/LCD/OCMP/docs/Grants/309_Assessment_and_strategy_Final_June 2015.pdf.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	72,334	80,450	10.0 %
No. of people in coastal counties	611,645	653,112	9.3 %
Percentage of people in coastal counties in coastal floodplain	11.8 %	12.3 %	0.5 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion.

Vulnerability to Shoreline Erosion

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very low (>2.0 m/yr) accretion	10	1.0 %
Low (1.0 to 2.0 m/yr) accretion	0	0 %
Moderate (-1.0 to 1.0 m/yr) stable	543	97 %
High (-1.1 to -2.0 m/yr) erosion	6	1 %
Very high (<-2.0 m/yr) erosion	0	0 %

Sea Level Rise: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," on the vulnerability of the state's shoreline to sea level rise.

Coastal Vulnerability to Historic Sea Level Rise

Vulnerability Ranking	Miles of Shoreline Vulnerable	% of Coastline
Very Low	345	61 %
Low	213	38 %
Moderate	0	0 %
High	0	0 %
Very High	0	0 %

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lakes level change	Y	Y

Hazards mapping or modeling programs or initiatives for:		
Sea level rise	N	Y
Other hazards	Y	Y

In-Depth Management Characterization (Phase II In-Depth Assessment)

Shoreline erosion is the most significant chronic hazard affecting Oregon's coast, and is ranked as the #2 coastal hazard in the Assessment & Strategy 2016-2020 report. Large segments of Oregon's ocean coast are extensively developed with residential and commercial uses and attendant infrastructure. The pressure for additional oceanfront development and re-development is also substantial. Much of this existing and future development will be subject to risk from shoreline erosion. These erosion-related risks are documented in several recent DOGAMI reports (e.g., http://newportoregon.gov/dept/pln/documents/DOGAMI_Report.pdf).

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

OCMP has identified two management priorities where there is opportunity for the CMP to improve its ability to effectively address the most significant hazard risks. These are:

Tsunami Resilience

Increase resilience to tsunami of at-risk coastal communities through the implementation of land use planning based management strategies and measures.

The Tsunami Inundation Map Series provides Oregon coastal communities with greatly improved information on the level and extent of risk from both distant and Cascadia tsunami events (http://www.oregongeology.org/pubs/tim/p-TIM-overview.htm). The OCMP has produced guidance for the use of these maps by local governments for land use planning and evacuation facility planning. The next step in addressing this management priority is to provide support and direct technical assistance to communities in applying and integrating these concepts into local comprehensive plans, public facility plans and development codes.

Land Use Management Measures

Implement improved land use management measures in areas subject to chronic ocean shore hazards (i.e. shoreline erosion, sea level rise, ocean flooding).

Risk from chronic hazards in ocean shore areas continues to be a significant issue in Oregon. Although all local governments have hazard area development policies and regulations in place, most of these provisions are based on hazard information that is outdated, and therefore do not adequately address the nature and severity of coastal hazards as currently understood. Recent map products delineating ocean shore risk zones and the development of the OCMP model code for chronic coastal hazards provide a basis for the implementation of improved management policies and regulations.

The OCMP has identified priority needs and information gaps to address the coastal management priorities identified above:

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Oregon's policies which limit the placement of ocean shore hardening have been effective. Additional research is needed to evaluate their efficacy for

		future conditions, and to identify cumulative effects for key littoral cells where development potential is highest. This information is presently lacking. Analysis/research/coordination on the use, effectiveness and impacts of alternative soft solutions to riprap. This may help to evaluate the need for amendments to current state policy on erosion-control structures.
Mapping/GIS/modeling	Y	Mapping of future total water levels (sea level rise) for purposes of long-term resilience planning. Completion of time/distance evacuation modeling for communities subject to tsunami inundation hazard. The analyses are critical in facilitating efforts to plan for tsunami-evacuation facilities improvement. Completion of erosion risk zone mapping for the balance of Oregon's ocean shoreline. Erosion zone mapping now covers only the north and central coast. There is a need to complete up-to-date mapping and classification of dune system landforms for Oregon. Current state planning and regulatory standards rely on accurate morphological classification of these land forms, and current mapping is outdated and inadequate for this purpose.
Data and information mgmt.	N	
Training/Capacity building	Y	There is a need to assist in building capacity at the local government level to support implementation of improved management measures. Capacity needs include: Provision of additional expertise to local partner jurisdictions through training and/or technical support. Additional local staff time/resources to address and implement coastal hazard planning.
Decision-support tools	N	
Communication and outreach	Y	There is a continuing need to raise awareness among local officials, decision makers and the public regarding of the nature and extent of coastal hazards. Specific measures needed include: Additional OCMP and partner agency (e.g. DOGAMI) staff resources dedicated to direct outreach and education on the importance of hazard related

resilience measures, and on tools available to address hazard issues.

Resources for developing OCMP hazard resilience modules that the OCMP communication and outreach staff could present to state and local officials, state agencies, NGOs and the public (including students in primary, secondary, and higher education).

Pennsylvania https://coast.noaa.gov/czm/mystate/
http://www.dep.state.pa.us/river/czmp.htm

The Pennsylvania Coastal Management Program, approved in 1980, is administered by the Pennsylvania Department of Environmental Protection (PA DEP). The coastal management program comprises two widely separated coastal areas: the 76.6-mile (123 km) Lake Erie shoreline and the 112-mile (180 km) stretch of coastline along the Delaware Estuary.

Coastal Resources Management Program

The Pennsylvania Coastal Resources Management Program (CRMP) relies on a network of state authorities. The Pennsylvania coastal zone along Lake Erie varies from 900 feet wide in urban areas to over three miles wide in rural areas; and the Delaware River Estuary boundary extends inland from a distance of 660 feet in urbanized areas to 3.5 miles in rural areas.

The coastal zone is the area where the land meets the sea and includes both coastal waters and adjacent shorelands. These areas face increasing pressure from development, shoreline erosion, biodiversity losses and nonpoint source pollution. Pennsylvania has two coastal areas: the coastline along Lake Erie and the coastline along the Delaware Estuary.

The Lake Erie coastal zone is located within Erie County and includes the shorelines of major tributaries. The coastal zone also extends to the middle of the lake to the boundary with Canada, and inland an average of 1.4 miles (Figure PA 1). The Lake Erie coastal zone also contains Presque Isle State Park and hosts one of the state ports (Erie) for international shipping.

The Delaware Estuary Coastal Zone lies within Bucks, Philadelphia, and Delaware counties. The coastal zone also contains islands, marshes and shorelands of tributary streams that are tidally influenced. The combined facilities of the Delaware Estuary comprise the largest freshwater port in the world.

The CRMP mission is to protect and enhance fragile natural resources by reducing conflicts between competing land and water uses while representing a comprehensive approach to managing the impacts of development and other activities on coastal areas.

The PADEP Compacts and Commissions Office coordinates and implements the CRMP to execute sound coastal management program policies in Pennsylvania's two coastal areas. CRMP receives funding from the National Oceanic and Atmospheric Administration (NOAA) to administer the CRMP and provide grants to local governments, state agencies and nonprofit organizations to undertake projects in the coastal zones. Since the program's federal approval in 1980, the Pennsylvania CRMP has provided over $50 million in funding for coastal zone projects that advance program policies.

Program Policies

- Coastal Hazard Areas: Pennsylvania's coastal hazards are defined as bluff recession along Lake Erie and coastal flooding in both coastal zones.

- Dredging and Spoil Disposal: This economically vital activity must be carefully managed to avoid adverse effects on navigation, flood flow capacity, public interest, and environmental quality. (Note: CRMP funds cannot be used to pay for actual dredging operations).
- Fisheries Management: The strong demand for recreational fishing in both coastal zones requires efforts to protect and improve stocks of popular game-fish species.

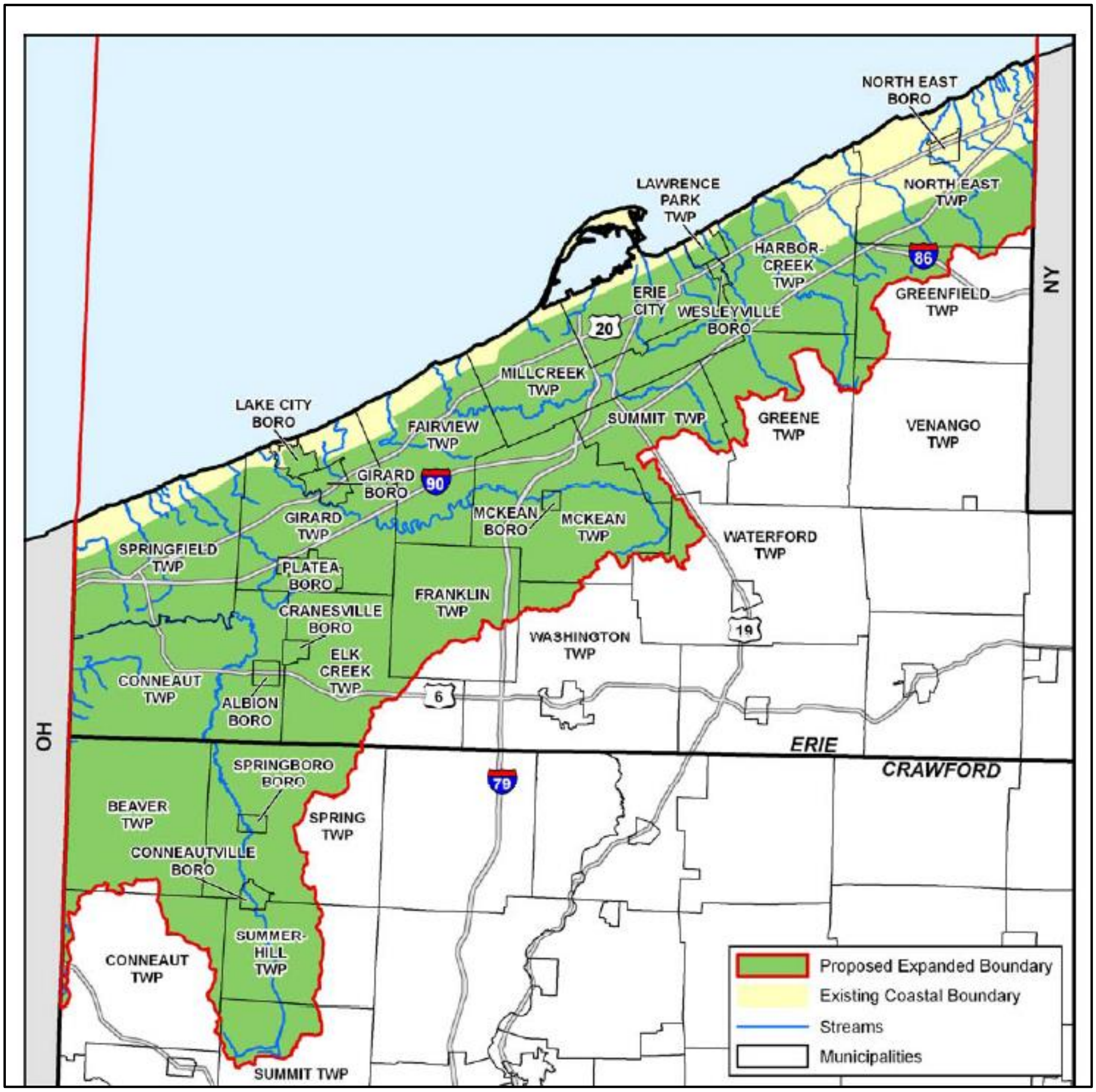


Figure PA 1*: The Lake Erie coastal zone in Erie County, PA, showing the existing coastal zone and a recent proposed watersheds-based coastal zone (Image: modified from Pennsylvania CRMP).*

- Wetlands: This policy involves the protection, enhancement and creation of coastal wetlands in order to maintain benefits for wildlife habitat, flood control, water quality, water flow stabilization and environmental diversity (biodiversity).
- Public Access for Recreation: Efforts are required to meet the public need for boating, fishing, walking, picnicking, sightseeing and other recreational pursuits associated with the waterfront.

- Historic Sites and Structures: This policy includes preservation, restoration and enhancement of coastally significant historic sites and structures within the coastal zone.
- Port Activities: The development and enhancement of coastal port infrastructure is an important aspect of the economic vitality of the waterfront.
- Energy Facilities Siting: Energy-producing facilities are vital to our society but improper siting (placement) can be damaging to fragile coastal ecosystems.
- Intergovernmental Coordination: This policy includes intergovernmental efforts to protect Pennsylvania's coastal resources, especially the quality of our air and water.
- Public Involvement: Efforts are required to increase awareness, provide information and create opportunities for public participation in a variety of coastal issues.
- Ocean Resources: Efforts directed toward the research, study, and/or management of non-native (invasive) aquatic or terrestrial plant and/or animal species.

Lake Erie Bluff Recession Control Point Monitoring

The CRMP actively monitors approximately 130 established control points along Pennsylvania's Lake Erie shoreline (the actual number may change due to control points being abandoned or new control points established). These control points are used to determine local annual rates of bluff recession, help identify Bluff Recession Hazard Areas, and help determine minimum bluff setback distances in accordance with the Chapter 85, Bluff Recession and Setback regulations. A municipal guidance document is available online from CRMP to aid municipalities in promulgating and implementing local zoning ordinances that satisfy Chapter 85 requirements.

A control point is a fixed marker, such as a buried steel pin or existing utility pole, from which a direct measurement to the bluff crest is made. The control points are located approximately every one-half kilometer along the bluff crest from the Ohio to the New York borders. Direct measurements from the control points to the bluff crest are taken every four to five years, with the assistance of Global Positioning System technology. Records of the measured distances from the fixed control points to bluff crest are maintained by the Department. At locations where the bluff line is actively receding, that measured distance gradually decreases from year to year. Over time, an average rate of bluff recession at that location emerges from the collected data.

The first control point was established in 1975 in an effort to begin monitoring the stability of bluff conditions along Lake Erie. The control point program began in earnest in 1982, when 47 control points were established along the bluff crest. An additional 69 control points were established in 1986 and 1987. Changes in land use and on-site construction activities sometimes necessitate the need to move control points or cause the control points to be lost. The control point management and measurement program is an on-going process.

Section 309 Report: Coastal Hazards

The following information is extracted from: *Section 309 Assessment and Strategy of Pennsylvania's Coastal Resources Management Program (2015).* The document is available online at http://www.depgreenport.state.pa.us/elibrary/GetDocument?docId=5204&DocName=3010-BK-DEP4491 Section 309 Asessment and Strategy of PA Costal Resources Mgmt Prgm_ FINAL.pdf (sic).

Coastal Hazards were considered a medium priority in the 2010 assessment, and were elevated to a high priority during the 2015 assessment. Pennsylvania's CRMP has a long history of providing expertise and mitigating damage from shoreline and bluff erosion along the Lake Erie coast. In the

Delaware Estuary, flooding throughout the coastal plain has been a long-standing problem and priority among local partners. Recent climate trends and forecasts indicate an increased frequency of heavy precipitation events and larger more powerful storm systems, which will exacerbate flooding problems. Sea level rise will add additional threats. CRMP's assessment found that the program needed to focus more on climate adaptation issues and help build internal and local capacity for climate adaptation and resiliency planning. The proposed strategy is presented at the end of the 2015 assessment document (see Section 309 link above).

Resource Characterization (Phase I Assessment)

While Pennsylvania's two coastal areas share many problems and opportunities consistent with all coastal communities, they are also unique in many ways. The assessment for coastal hazards largely analyzes the Delaware Estuary (DECZ) and Lake Erie Coastal Zones (LECZ) independently.

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer, summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure since 2000.

LECZ Population in the Coastal Floodplain – Lake Erie

	2000	2010	Percent Change 2000-2010
No. of people in coastal floodplain	5,168	8,566	+65.8 %
No. of people in coastal counties	280,843	280,566	-0.10 %
Percentage of people in coastal counties in coastal floodplain	1.8%	3.0%	+2.2 %

Shoreline Erosion Data from *NOAA's State of the Coast* "Coastal Vulnerability Index" indicate the vulnerability of the state's shoreline to erosion.

Pennsylvania was not included in NOAA's State of the Coast —Vulnerability Index referenced above.

Sea Level Rise Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to sea level rise.

Pennsylvania was also not included in the National Assessment of Coastal Vulnerability to Sea-Level Rise (Thieler, E.R., and Hammar-Klose, E.S., 1999. *National Assessment of Coastal Vulnerability to Future Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast*. USGS Open-File Report 99-593).

However, Pennsylvania's Delaware Estuary is included in an interactive Sea Level Rise Viewer available at NOAA's DigitalCoast (http://coast.noaa.gov/digitalcoast/tools/slr). This viewer does not categorize vulnerability, but does offer a sliding scale of sea level rise that visually shows inundation. It is a CRMP goal to have our tidal shorelines included in future national efforts assessing vulnerability to sea level rise.

Other Coastal Hazards: General level of risk in the coastal zone for each type of coastal hazard. The state's multi-hazard mitigation plan is a good additional resource to support these responses.

LECZ Type of Hazard	General Level of Risk (H, M, L)
Flooding (riverine, stormwater)	H (high)
Coastal storms (including storm surge)	H (shoreline and bluff erosion)
Geological hazards (e.g., tsunamis, earthquakes)	L (low)
Shoreline erosion	H

Great Lake level change	H
Land subsidence	N/A
Saltwater intrusion	N/A
Other – Invasive species	H*

Bluff Recession Control Point Monitoring

CRMP maintains 136 control points along the Lake Erie bluff shoreline to measure and calculate bluff recession. Measurements from fixed monuments to the bluff crest at specific bearings are taken every four years. The last cycle was completed in 2010 and 2011(western county 2010, eastern county 2011). Measurements for this cycle are currently in progress. The Erie County average recession rate is 0.61 feet per year. The table below shows the results from 30+ years of monitoring as of 2011, from west to east:

Township	Average Recession Rate (ft/yr)
Springfield	0.99
Girard	0.87
Fairview	0.52
Millcreek	0.31
Erie	0.47
Lawrence Park	0.32
Harborcreek	0.44
North East	0.48

Federal Emergency Management Agency Region III Coastal Analysis and Mapping

The Federal Emergency Management Agency (FEMA) has begun a coastal analysis and mapping project that will be used to update Digital Flood Insurance Rate Maps. Bucks, Philadelphia, and Delaware Counties are included in the spatial areas subject to storm surge propagating up the Delaware River. An overview of the coastal analysis and mapping project can be found at http://www.r3coastal.com/. FEMA is also conducting a Great Lakes Flood Study that includes Erie County (https://www.rampp-team.com/documents/pennsylvania/watershed/Erie/GreatLakes_factsheet.pdf).

FEMA is currently conducting coastal studies in Delaware, Philadelphia, and Erie counties. Information specific to Pennsylvania's individual county coastal analysis and mapping studies, including fact sheets on methodologies, current status, and projected completion dates, can be found at: https://www.rampp-team.com/pa.htm.

Pennsylvania Climate Impacts Assessment Update (2013)

This 2013 report is an update to the 2009 document Pennsylvania Climate Impacts Assessment and Economic Impacts of Projected Climate Change in Pennsylvania. The documents were prepared by Penn State University specifically for Pennsylvania DEP to fulfill obligations directed in the Pennsylvania Climate Change Act, Act 70 of 2008. The initial efforts focused on summarily quantifying greenhouse gas emissions and trends and did not deal specifically with the management of climate change impacts, related coastal hazards, or strategies for adaptation. The Pennsylvania Climate Change Advisory Committee has moved toward increasing emphasis on adaptation and resiliency. The report, subsequent updates, and related information are available from the PA DEP webpage at http://www.dep.pa.gov/Pages/default.aspx.

Pennsylvania Climate Adaptation Planning Report: Risks and Practical Recommendations

This 2014 report was the culmination of a multi-year effort that included significant public input. Work groups from private and public sectors were formed to evaluate individual sectors. The purpose of the Climate Adaptation Planning Report is to identify practical implementation strategies for the built environment and natural resources. This is the first statewide effort in addressing the need for climate change adaptation planning in Pennsylvania. One outcome of the proposed strategy presented in this document is for CRMP to play a more significant role in representing the unique coastal areas in these statewide efforts. The Climate Adaptation Planning Report will be incorporated into the next version of the Pennsylvania Climate Change Action Plan. The Pennsylvania Climate Adaptation Planning Report can be found online at: http://www.elibrary.dep.state.pa.us/dsweb/View/Collection-10796.

Erie County Hazard Mitigation Plan

Erie County updated their comprehensive Hazard Mitigation Plan in 2012. All 38 municipalities within the county participated in the update as well as PA DCNR, PA Lake Erie Watershed Association, and the PA Coastal Resources Management Program. The 2012 Erie County HMP ranked winter storms, flooding, and environmental hazards (hazardous materials release) as the three top high-risk categories. The coastal related hazards coastal erosion, invasive species, and landslide were ranked in the low-risk category.

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	N	N
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y (minimal)	Y (minimal)
Hazards mapping or modeling programs or initiatives for:		
Sea level rise/Great Lake level change	N	N
Other hazards (LECZ-bluff recession)	Y	Y

Amendment to the Bluff Recession and Setback Act of 1980

CRMP is responsible for implementing the Bluff Recession and Setback Act (Act 48 of 1980) (BRSA) which restricts new development and limits improvements to existing development within formally designated Bluff Recession Hazard Areas (BRHAs). The designation of the BRHAs is a public, regulatory process guided by CRMP-led scientific studies of the average long-term bluff recession rates. Those long-term average recession rates are determined by a combination of on-the-ground monitoring and GIS analysis of recent and historical aerial photography. Future long-term averages will likely include LiDAR as well as on-the-ground monitoring and historical aerial photography. Long term recession rates for the entire county are approximately 0.6 feet per year, but individual municipalities and specific bluff reaches may erode quicker or slower than the county average. The formal adoption of the BRHA's are by reference to the CRMP studies within the Title 25, Chapter 85 Bluff Recession and Setback regulations (companion regulations to the BRSA). In July of 2012, the Pennsylvania General Assembly passed, and Governor Tom Corbett signed, Act 72 of 2012 — an amendment to the BRSA that redefined BRHA's to permanently exclude any areas where the toe of bluff was greater than 250 feet from the shoreline of Lake Erie.

The Bluff Recession and Setback Act applies to bluffs along the Lake Erie coast. It defines the Bluff Recession Hazard Area (BRHA) as the area or zone where the rate of progressive bluff recession creates a substantial threat to the safety or stability of nearby existing or future structures or utility facilities. The term shall not include any area where the horizontal distance, measured perpendicular to the shoreline, between the shoreline and the bluff toe is in excess of 250 feet and such area shall not be subject to any Environmental Quality Board regulations or municipal bluff setback ordinance (Bluff Recession and Setback Act, Act 48 of 1980).

In-Depth Management Characterization (Phase II In-Depth Assessment)

Flooding

Flooding was listed as a high-risk category in the Erie County Hazard Mitigation Plan (2012). Since 1994 the county has documented at least 64 flood or flash flood events, more than 100 windstorm events (≥50 knots), and more than 150 winter storms. Each of these storm types are a frequent, annual occurrence within the Lake Erie Coastal Zone. Shortened lake ice-seasons and decreased total ice coverage as a result of climate change could extend the lake-effect snow season and increase the severity of individual lake-effect snow events.

More frequent and more intense storms could increase shoreline erosion rates, bluff erosion, property losses, and wind and flooding related structural damage. Higher Great Lakes water levels can exacerbate coastal flooding from storms and increase bluff instability and erosion. CRMP implements the Commonwealth's Bluff Recession and Setback Act and has a 35-year history of providing local support, technical support, and research. At this time, Lake Erie water levels are near their long-term averages. Official seasonal water level forecasts for the Great Lakes are issued jointly by the US Army Corps of Engineers - Detroit District and Environment Canada's Great Lakes-St. Lawrence Regulation Office (http://www.lre.usace.army.mil/Missions/GreatLakes/Information/GreatLakesWaterLevels/WaterLevelForecast.aspx).

Current predictions indicate that the lake level will rise slightly in the short term, and remain close to the long term averages for the six-month forecast period. Generally, the current consensus is that climate change will lead to lower lake levels in the future. Regardless of the level, it can be assumed that Lake Erie water levels will continue to fluctuate and bluff erosion management benefits from accurate lake level predictions. Shoreline and bluff erosion will remain a focus for the coastal program. Coastal Hazards was selected as a high priority by 45% of LECZ stakeholders.

Bluff Recession and Setback Act

The intention of the Bluff Recession and Setback Act (BRSA) is to manage development in way that limits the risks to structures and property within the designated hazard areas, not to manage or prevent bluff recession itself from occurring. Although human activities can exacerbate bluff recession, it is a natural process that is inevitable over time. The most recent bluff recession related property damage assessment was conducted in 1987 and covered only a time span of two years of elevated lake levels. No comparison to property damage trends prior to the passage of the BRSA was conducted. If possible, a study to analyze trends in bluff recession-related property damage prior to the passage of the BRSA and progressively through its 35 years of implementation would be beneficial. No such study has been conducted.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

The top two of three management priorities identified in the 2015 report are directly pertinent to coastal geology issues on Pennsylvania's Lake Erie coast and provide opportunity for the CRMP to more effectively address significant hazards.

Resiliency and adaptation planning that considers a changing climate

Resiliency and climate adaptation has not been a high priority for the Pennsylvania Coastal Resource Management Program. The program needs to build its internal capacity to better assist and facilitate local measures to strengthen resiliency and adaptation efforts. Traditional significant hazards, such as flooding in the urbanized flat landscape of the coastal plain, appear to be problems that will be exacerbated by climate change. In addition to building internal capacity, there is a need to promote local buy-in and better network with other agencies and partners.

Bluff and shoreline erosion of the Lake Erie shoreline

Bluff and shoreline erosion along the Lake Erie coast remain a significant concern for Pennsylvania's coastal program. Littoral sediment dynamics specifically for Pennsylvania's coast, including dynamics associated with Conneaut Harbor in Ohio, would help in addressing bluff erosion and the design of shoreline protection structures. The potential impacts of climate change on Great Lakes water levels and bluff and shoreline erosion also warrants additional consideration. Better understanding of littoral drift, especially as it pertains to Conneaut Harbor, will permit identification of potential mitigation measures that would address the high bluff erosion rates downdrift in Pennsylvania.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Better understanding of littoral drift, especially as it pertain to Conneaut Harbor and the potential for mitigative measures that would address the high bluff erosion rates downdrift in Pennsylvania.
Mapping/GIS/modeling	Y	None listed for the Lake Erie Coastal Zone.
Data and information mgmt.	Y	National efforts on vulnerability assessment due to sea-level rise have failed to include Pennsylvania. Need to bring attention to this shortcoming.
Training/Capacity building	Y	Better understanding climate impacts, including sea-level rise, for both internal CRMP staff and local officials and stakeholders.
Decision-support tools	N	n/a.
Communication and outreach	Y	Communication and outreach with municipal officials to better align CRMP resources with local needs.

Washington https://coast.noaa.gov/czm/mystate/
http://www.ecy.wa.gov/programs/sea/czm/index.html

The Washington Coastal Management Program (CZMP), approved by NOAA in 1976, was the first approved program in the nation. The Department of Ecology serves as the lead coastal management agency. The primary authority for the coastal management program is the Shoreline Management Act of 1971.

Washington Coastal Zone Management Program

Washington CZMP defines the state's coastal zone to include the 15 counties with marine shorelines. The CZMP applies to activities within these 15 counties as well as activities outside these counties, which may impact Washington's coastal resources. Most, but not all, activities and development outside the coastal zone are presumed to not impact coastal resources.

The Shoreline Management Act

The Shoreline Management Act (SMA) and implementing regulations establish the foundation of Washington's CZMP. The SMA establishes a planning program and regulatory permit system initiated at the local level under state guidance. While the Washington Department of Ecology is designated as the lead state agency, local governments exercise primary authority for implementing the SMA.

Each local government's planning program consists of a shoreline inventory and a Shoreline Master Program (SMP) to regulate shoreline uses. The inventory covers land and water uses, generalized ownership patterns, and natural shoreline characteristics. The shoreline master program is essentially a land use plan for shoreline areas with distinct environmental characteristics. SMPs include basic goals and objectives, shoreline environmental designations, and regulations. Local governments develop their shoreline plans in accordance with SMA guidelines but are tailored to the specific needs of the community. More than 200 cities and all 39 counties have shoreline master programs.

The Shoreline Master Program (SMP) Guidelines (WAC 173-26-231) specifically address shoreline stabilization measures. Non-structural and structural measures in the Guidelines are not explicitly defined but summaries of each stabilization measure are provided. Puget Sound is emphasized, while measures for the outer coast, lakes, and rivers are not provided (http://www.ecy.wa.gov/programs/sea/shorelines/stabilization/index.html). SMP planning guidelines for soft stabilization are also available (https://fortress.wa.gov/ecy/publications/documents/1406009.pdf).

The SMP Guidelines require vegetation conservation standards in SMPs, with buffers and setbacks required for residential development. Ecology expects that most SMPs will include buffers (or setbacks with vegetation conservation requirements) to protect the ecological functions of the shoreline. Ecology distinguishes between buffers and setbacks as follows (http://www.ecy.wa.gov/programs/sea/shorelines/smp/handbook/Chapter11.pdf):

> Shoreline buffers typically are naturally vegetated areas adjacent to water bodies that protect the ecological functions of the shoreline and help to reduce the impacts of land uses on the water body, as described in the scientific literature. Buffers provide a transition between the aquatic and upland areas. Buffers are generally recognized as a "separation zone" between a

water body and a land use activity (e.g., residential development) to protect ecological processes, structures, and functions and mitigate the threat of a coastal hazard on human infrastructures.

Shoreline setbacks are the distances separating two features such as a structure and the water, or a structure and the buffer. Natural native vegetation may or may not exist within a setback. A setback from a buffer protects the buffer from the impacts related to use of the structure, such as maintenance of a house. Setbacks also help to assure that development is located a safe distance from bluffs, river banks, and other natural features, including buffers. Setbacks are measured from the landward edge of a shoreline buffer or the OHWM, or in certain circumstances, from the top of a steep bank or unstable slope. Major structures cannot be built, but some uses such as gardens or sheds may be allowed within the setback.

Shoreline and Bluff Erosion

Washington's coastal areas experience both shoreline erosion and landslides, natural processes that are due to changing environmental conditions. Large storm waves erode beaches, and normal wave action can carry sand away. Beach erosion also results from a decrease in the sediment supply that feeds beaches (https://fortress.wa.gov/ecy/publications/documents/0006029.pdf).

Puget Sound Bluff Erosion

Bluff erosion occurs naturally on Puget Sound (Figure WA 1). Many bluffs are naturally unstable because of soil, slope, and water conditions. Bluff erosion is affected by geology, waves, and weather. All three factors vary within the Puget Sound region, so bluff erosion rates can range from a fraction of an inch to more than two feet per year. The erosion rate for a bluff can be regular over the years, or it can change from near zero for decades to tens of feet in a matter of seconds. Once steepened to an unstable angle, bluffs can continue to erode without wave action. High glacial bluffs are subject to continuing erosion. Usually this process is not considered significant until people move onto the bluff or the shorelines nearby. To keep land, people often build bulkheads and other structures. Such structures, however, may remove a major source of beach building materials. Erosion can increase downdrift of the structures and beaches can become steeper and/or lower in elevation. Most slope failures are directly related to the buildup of water in the soil. Development activities, such as clearing vegetation and modifying site drainage, and adding on-site septic systems, can make erosion worse. Increases in landslide frequency and magnitude within a watershed as a result of poor land use management, such as road building on steep, unstable slopes, result in harmful downstream impacts (Managing Washington's Coast, 2001; https://fortress.wa.gov/ecy/publications/documents/0006029.pdf).

The public costs of addressing landslides in developed areas are great in terms of emergency response, damage to infrastructure, and litigation as witnessed by the City of Seattle in 1996-1997. The landslides on Hunter's Point and Rolling Bay are not unique. Hundreds of similar sites exist throughout the coastal zone but have not been identified and may not have slid in recent decades. The risks will increase as population expands into landslide-prone areas, such as our steep slopes and coastal bluffs. The possibility of increasingly wetter winters underlines concerns.

Puget Sound Feeder Bluffs

Protection of the significant coastal sediment-supply role of unconsolidated bluffs is an ongoing component of Washington's coastal management efforts. Coastal mapping as part of the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) and partners since 2001 subdivided the shoreline of Puget Sound into five broad geomorphic categories, namely: 1) beaches, 2) rocky shores, 3) deltas, 4) estuaries and lagoons, and 5) artificial shorelines (http://www.pugetsound nearshore.org/index.html). Subsequently, the Washington Department of Ecology's Feeder Bluff Mapping Project (completed in 2013) used the PSNERP classification system as a starting point to map all coastal landforms with an emphasis on beaches and, in particular, coastal bluffs (http://www.ecy.wa.gov/programs/sea/shorelines/FeederBluffs/coastalLandforms.html); (http://www.ecy.wa.gov/programs/sea/shorelines/FeederBluffs/pdf/FeederBluffMappingCGS2013.pdf); (Washington Coastal Atlas; https://fortress.wa.gov/ecy/coastalatlas/tools/Map.aspx).

***Figure WA 1**: Eroding bluffs at Point Roberts, Whatcom County, WA. Sediment eroded from the bluff face is deposited at the base of the slope as colluvial debris (or talus) where it can be readily transported to adjacent beaches (Image: modified from Washington Department of Ecology).*

Puget Sound has over 1,400 miles of beaches, most built of sand and gravel from nearby bluffs. Some bluffs, due to their height, erosion rate, exposure, or composition may be more significant sources of beach sediment than others. Knowing where these feeder bluffs are located is important information in long-term coastal management. In 2013, the Feeder Bluff Mapping Project completed the identification of feeder bluffs throughout Puget Sound. Further information is available at http://www.ecy.wa.gov/programs/sea/shorelines/FeederBluffs/index.html.

Washington describes feeder bluffs as *eroding coastal bluffs that deliver a significant amount of sediment to the beach over an extended period of time and contribute to the local littoral sediment budget*. About 426 miles (about 17%) of Puget Sound's shoreline currently consists of bluffs mapped as Feeder Bluffs or Exceptional Feeder Bluffs. Within individual counties, the extent of feeder bluffs varies significantly principally due to differences in geology and in the level of development. Knowledge of the location of feeder bluffs and their relationship with adjacent beaches and littoral drift cells informs shoreline management, particularly in efforts to prioritize protection and restoration. The Feeder Bluff Mapping Project was specifically developed to identify significant feeder bluffs and their distribution both regionally and within local drift cells.

In Washington, most building on feeder bluffs occurs at the top of the bluff, near or landward of the crest. This presents challenges, because it requires safely developing property while also protecting the natural functions of the bluff (coastal sediment supply). The challenge becomes how to allow some level of development while maintaining the long-term function of the feeder bluff. Ultimately, the objective is to allow safe, suitable development without eventually needing to preserve property by armoring or any other form of erosion control. Two considerations guide appropriate development on feeder bluffs. The first is the rate of erosion and the mechanism of slope failure, since these will determine minimum setbacks. The second is the ability to remove or relocate at-risk structures in the future. A combination of large setbacks and rigorous standards for relocating structures may allow for development on these sites without jeopardizing the long-term health of the shoreline. In general, erosion rates are relatively slow on Puget Sound so reasonable setbacks can provide many decades or more of safety, with the caveat that a greater threat at some sites may be associated with a large slope failure, and not due to chronic erosion (http://www.ecy.wa.gov /programs/sea/shorelines/FeederBluffs/management/building.html).

Structures built on the face of the bluff are inherently vulnerable to ongoing erosion and slope failures. Maintaining them may require stabilization that reduces or eliminates natural erosion and sediment delivery. In general, such development will become more difficult in the case of rapidly eroding bluffs and slopes with deep-seated instabilities. A realistic understanding of erosion rates and slope failure mechanisms may allow for certain types of structures, such as stairways or drainpipes, to be built without jeopardizing the long-term function of the feeder bluff. In general, these should be constructed to allow continued erosion and to be easily relocated if damaged or threatened.

Structures built at the toe of the bluff, such as bulkheads and revetments, eliminate the ability of the bluff to erode naturally and are inconsistent with the function of feeder bluffs. Landslides may continue to occur behind a seawall and some of this material may reach the beach, but over time, the effect is to reduce sediment delivery.

Landslide Hazards

The Department of Ecology maintains a website on landslide hazards in Puget Sound (http://www.ecy.wa.gov/programs/sea/landslides/index.html) that allows property owners to view 1:24,000-scale mapped bluff-stability information (Figure WA 2). The maps indicate the relative stability of coastal slopes as interpreted by geologists based on aerial photographs, geological mapping, topography, and field observations from the early and mid-1970s. Shorelines and steep slopes are dynamic areas and many landslides have occurred since that time that are not reflected on the maps. Subsequent human activities and changes in environmental conditions may have increased or decreased the stability of some areas. Further information is available on the Washington Coastal Atlas (https://fortress.wa.gov/ecy/coastalatlas/).

Coastal slopes in Washington are categorized into several broad geomorphic categories (Figure WA 2) that are defined as follows:

- Stable (S): Stable slopes generally rise less than 15 % in grade, except in local areas of low groundwater concentration or competent bedrock. Stable slopes include rolling uplands and lowlands underlain by stable material such as unweathered till and/or peat deposits which, although inherently weak, have no significant slope.

- Intermediate (I): Intermediate slopes are generally steeper than 15 % except where conditions such as weaker material and/or abundant groundwater exist. Identified areas include slopes of sand and gravel, till, or thin soils over bedrock which have no known failures.

- Unstable (U): Unstable slopes are considered unstable because of geology, groundwater, slope and/or erosional factors. They include areas of landslides and talus too small or obscure to be individually mapped.

- Unstable Recent Landslide (Urs): Identifies recent or historically active landslide areas. [Note that the Urs designation is based on investigations carried out in the late 1970s; subsequent landsliding is not reflected on these maps].

- Unstable Old Landslide (Uos): Identifies post-glacial but prehistoric landslide areas.

- Modified (M): Modified slopes are highly modified by human activity and include areas of significant excavation or filling. Slope response to a combination of natural processes and human activities may be unpredictable.

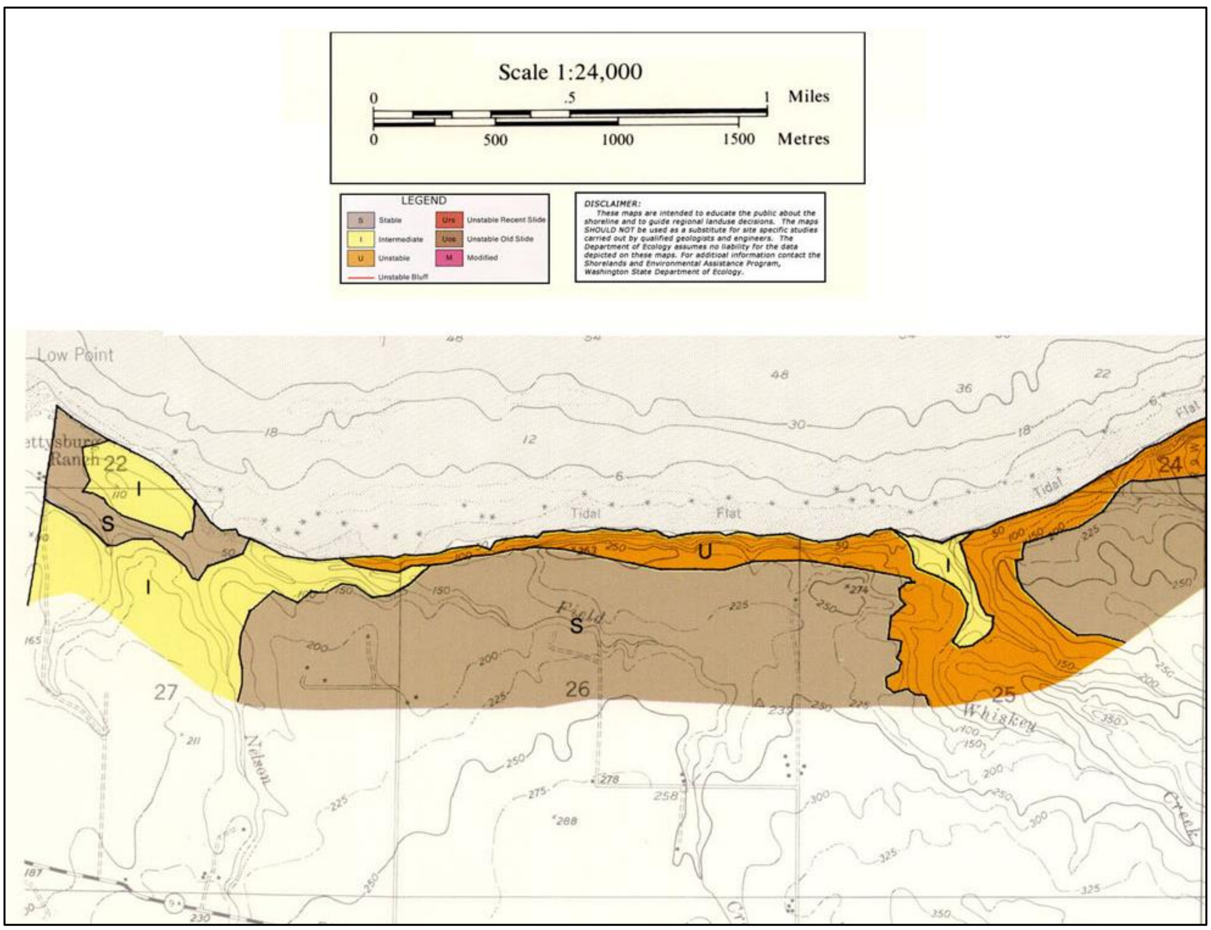


***Figure WA 2**: Screenshot of a typical coastal slope-stability map, from Clallam County, Puget Sound, WA, showing typical information provided on relative slope stabilities.*

Washington Coastal Atlas

The WCZMP provides a variety of coastal data and information on the Washington Coastal Atlas site (https://fortress.wa.gov/ecy/coastalatlas/tools/Map.aspx). The Atlas consists of 122 selectable and viewable map layers organized in several broad categories: Shoreline; Ocean Resources; Administrative/Regulated; and Land Cover. The Shoreline category contains the principal geo-features data (Figure WA 3). Locations of oblique shoreline imagery from 1976, 1992, 2000, and 2006 are shown (point features) with a relatively coarse spacing (approx. 750-2000 ft). Littoral drift cells (line features) show general longshore-current flow directions (but not sediment-transport volumes) that are useful in sediment budget analyses. Coastal landforms (line features; focused on Puget Sound) highlight zones of erosional bluffs, the locations of significant and exceptional feeder-bluff sectors, and the littoral transport sectors that link the two. The coastal landforms category also maps the shoreline by composition: bedrock, delta, artificial, and low-energy shoreline. Historic shorelines (line features) show select positional data (1852-1926) on features such as the low-tide line, the bluff toe, and the bluff crest in the Puget Sound area. Slope-stability data from the Puget Sound area (polygon features) are derived from the 1970s-era landslide hazard data described above.

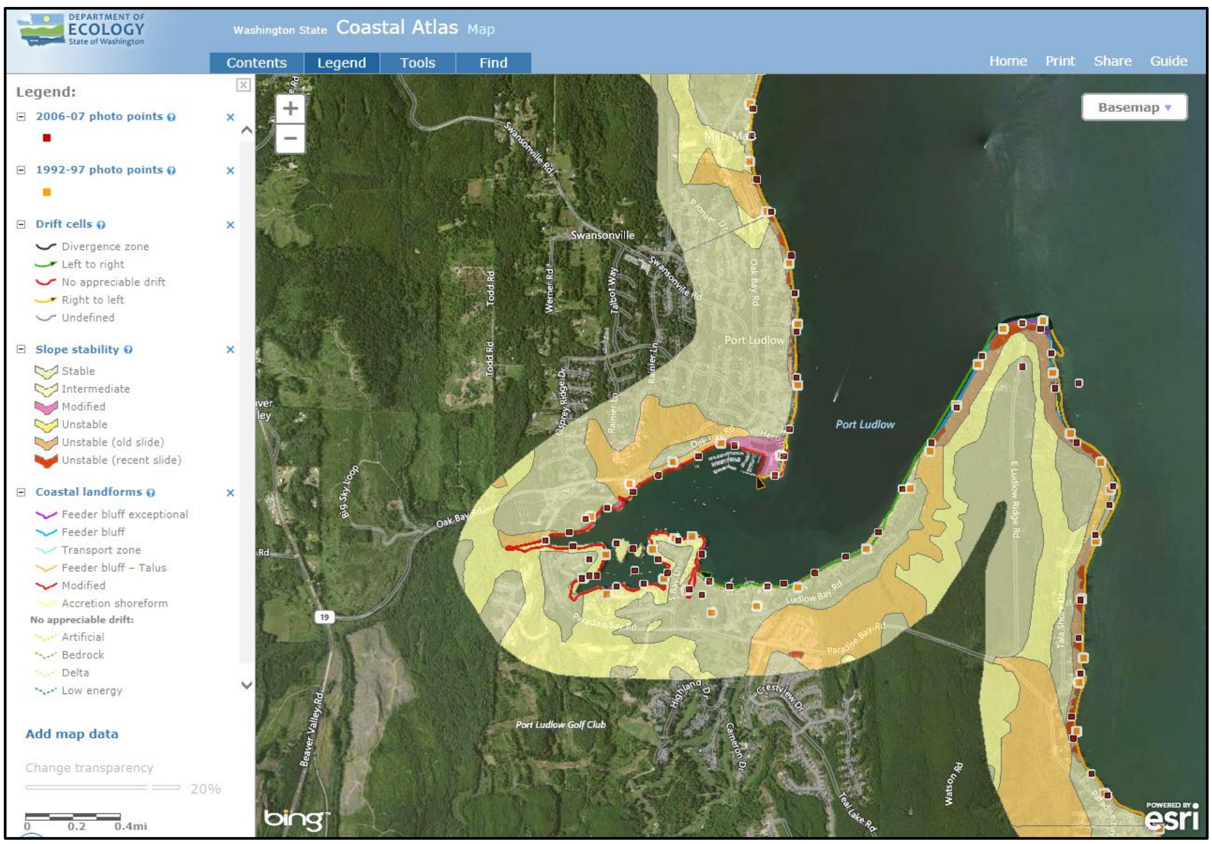


Figure WA 3: Screenshot of a typical image from the Washington Coastal Atlas showing mapped coastal geo-features. Oblique shoreline-imagery locations (1976, 2006), littoral-drift cells, slope-stability swaths, and coastal landform types are shown. Image is from the Port Ludlow area, Jefferson County (Puget Sound), WA.

Section 309 Report: Coastal Hazards

The following information is extracted from: *Washington Coastal Zone Management Section 309 Assessment & Strategy, 2016-2020 (July, 2015).* The document is available for review at https://fortress.wa.gov/ecy/publications/documents/1506013.pdf.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer and summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure. People located within the state's coastal floodplain as of 2010, and changes since 2000.

Floods are a significant hazard in Washington State. From 1980 through 2011, the State had 22 Presidentially-declared flood disasters – 1997 had the highest number of declared flood disasters in the country. For the entire state, ten of the fourteen coastal counties were listed as jurisdictions at greatest risk. WCZMP has increased attention along marine shorelines in recent years as a result of coastal storm surge and overbank flooding. Coastal flooding commonly occurs when winter storms coincide with high tides and is often accompanied by severe wind and wave damage.

Population in the Coastal Floodplain

	2000	2010	% Change
No. of people in coastal floodplain	209,477	251,243	20 %
No. of people in coastal counties	4,070,515	4,615,192	13 %
Percentage of people in coastal counties in coastal floodplain	5.1 %	5.4 %	0.3 %

Shoreline Erosion: Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to erosion. (Note: the customary data in this section has been replaced by a narrative)

Washington's outer coast is divided into two sections when analyzing shoreline change: (i) the Columbia River littoral cell (CRLC) which extends north from the mouth of the Columbia River to Point Grenville, and (ii) the Olympic Peninsula region which stretches from Point Grenville to La Push. While areas north of Port Grenville are experiencing some erosion, much of the research within the last twenty years has been focused on southwest Washington due to the influence of the Columbia River and large scale changes to the natural system. This has resulted in limited data for areas north of Point Grenville. Though most of the CRLC has featured an accretional trend, increased awareness has been placed on localized erosion events due to corresponding impacts on coastal communities.

The seasonal exchange of beach sediment on the southwest Washington coast is large. Beaches may decrease in elevation by about 0.5 m during the winter season and the shoreline may retreat landward by 20 to 30 m. This seasonal change is primarily due to seasonal variability in wave characteristics and water levels in the Pacific Northwest. During the high-wave conditions of the winter season, sediment is transported northward and offshore while during the low-wave conditions of the summer season, sediment is transported back onshore and southward. As a result, the net change over a full annual cycle is small relative to the seasonal variability.

Beach erosion is tied to Columbia River sediment supply in the CRLC. Washington's southwest coast continues to respond to large scale engineered structures by experiencing dramatic beach progradation. Localized chronic and episodic erosion continues to have significant impacts on coastal communities such as Westport, Willapa Bay and Cape Shoalwater, Point Brown Ocean Shores, Cape Disappointment State Park, and Wahkiakum County. Recent storms have increased attention to these long-term issues, however management decisions to sufficiently address areas of concern remain largely unchanged.

Puget Sound has approximately 2,500 miles of marine shoreline, subject to a variety of coastal hazards. These include widespread bluff erosion, landslides, flooding, and severe storms. Anticipated sea level rise is expected to aggravate erosion and flooding during coming decades. Earthquakes, to which this region is highly susceptible, may trigger tsunamis, landslides, liquefaction, and subsidence, and would have devastating effects on coastal areas.

Erosion affects most of Puget Sound's shoreline and includes bluff retreat and landslides, erosion of spits and barrier beaches, and erosion of historically filled lands. While erosion of bluffs is also a natural process that is the basis for many natural land forms, it poses significant concerns where development lies close to the water's edge and can threaten residences, parks, industrial facilities, hazardous waste sites, and urban waterfronts. Managing erosion on Puget Sound is challenging because of the adverse impacts of erosion structures (armoring) on beaches and nearshore habitats. Bluff erosion is a significant source of sediment to beaches and stabilization can negatively impact this beneficial process. In addition, shoreline armoring can affect beach ecology by reducing spawning habitat for some fish species, by eliminating the deposition and accumulation of organic material along the upper beach, and by altering riparian habitats.

Landslides

Landslides commonly occur on slopes and in areas where they have occurred before. Much of the landslide threats on the outer coast of Washington are located adjacent to the U.S. 101 Highway corridor along the Pacific Coast from Astoria, OR to Olympia, WA. Dormant and relict deep-seated landslides in the Willapa Hills are a concern because of their large size and impact on commerce and utility corridors for the rural coastal communities in this part of the State.

Landslides are a major hazard on Puget Sound, where much of the shoreline consists of high bluffs composed of weak geologic materials. Landsliding is largely associated with heavy winter rainfall and elevated groundwater levels and can be aggravated by poor development practices associated with land clearing and drainage. Landslides pose the greatest risk to sites where development has occurred near the top edge of coastal bluffs, within historically active landslide complexes, and at the toe of unstable slopes. New geologic mapping, aided by the widespread availability of LIDAR data, has greatly improved geological understanding of the distribution of landslide-prone areas in the region, but to date there has been little work to translate this into useful products for identifying and addressing coastal hazards.

Landslides were a significant element of federal disaster declarations in early 1997. Record precipitation levels in the winter of 1998-99 led to reactivation of many very large, deep-seated landslides throughout the region, including one on the Thurston County shoreline that resulted in more than thirty condemned homes. In March 2013, a very large landslide in the Ledgewood neighborhood on Whidbey Island gained national media coverage. Continuing coastal landslides along the railroad grade north of Seattle (a passenger corridor) recently led to the development of a Landslide Mitigation Action Plan. The devastating March 2014 Oso landslide (which killed more than 40 people) did not occur on the coast, but occurred in a geological setting similar to the Puget Sound shoreline and underscores the need to better understand landslide hazards in coastal settings.

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	N	Y
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise/Great Lake level change	N	Y
Other hazards	Y	Y

For the FY 2016-2020 assessment and strategy cycle, Coastal Hazards is designated as an Enhancement Area of National Importance. Coastal Hazards received "High Priority" ranking in four of the six most recent WCZMP Section 309 Assessment reports dating back to 1992. As an outcome of this, Washington completed a Coastal Erosion Management Study (CEMS) which addressed Puget Sound coastal erosion management, the impacts of shoreline armoring, and policy alternatives to minimize the adverse effects. CEMS followed three research threads: (i) appropriate engineering and geotechnical approaches to erosion management and bluff stabilization; (ii) the adverse environmental effects of those practices; and (iii) public policy alternatives.

Subsequently, the Department of Ecology carried out an inventory and characterization of alternatives to traditional shoreline armoring. Over thirty beach nourishment projects in Puget Sound were documented, illustrating a wide variety of techniques. Reporting of the project provided the consulting community, local governments, and resource managers with information on the design and management of beach nourishment projects, and other adaptive management alternatives to armoring. Results of these efforts were also incorporated into the Shoreline Master Program (SMP) Guidelines Rule adopted in December 2003.

Coastal Hazards Resilience Network

Through a NOAA Coastal Resilience Grant, the WCZMP has partnered with Washington Sea Grant in the development of a network dedicated to improving regional coordination and collaboration through effective partnerships among hazard and climate change practitioners to make Washington's coastal communities more resilient to natural hazards. A key goal of this effort is to strengthen local capacity to improve resilience to coastal hazards. To achieve this goal, the agencies have worked with coastal communities through the Federal Emergency Management Agency (FEMA) Risk MAP (Mapping, Assessment, and Planning) process to identify vulnerabilities or high priority areas where further coordinated assistance is needed to support more informed planning decisions. As such, the Department of Ecology and Sea Grant are facilitating coordinated agency research and potential management alternatives to solve short-and long-term erosion issues in Pacific County and Ocean Shores.

In-Depth Management Characterization (Phase II In-Depth Assessment)

The Section 309 Assessment and Strategy (2016-2020) identified the four most significant coastal hazards on the Washington coast as (i) Flooding; (ii) Shoreline erosion; (iii) Landslides, which occur in focused areas along the outer coast, but are more prominent in the Puget Sound due to poor development practices a) near the top edge of coastal bluffs, b) within historically active landslide complexes, and c) at the toe of unstable slopes; and (iv) Geologic hazards due to tsunami and seismic risk, which are equally great along the ocean and Puget Sound shorelines. The Washington State Integrated Climate Response Strategy (2012) notes that climate change will impose additional pressures on coastal environments, already subject to the above hazards, as they continue to experience environmental stressors from human activities and population growth (https://fortress.wa.gov/ecy/publications/documents/1201004.pdf).

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

The top three management priorities where there is the opportunity for WCZMP to effectively address the most significant hazard risks are:

Understanding the role of the WCZMP in reducing hazards and coordination among management authorities

The challenges posed by coastal hazards and climate change cross traditional boundaries of government agencies, politics, and geography. Not all of the four significant hazards within the Washington coastal zone (identified above) are a high priority for the WCZMP. It is important for the WCZMP to first understand its role in reducing hazards and coordinate and collaborate with other agencies to align policies, practices, and resources to improve the efficiency and effectiveness of coastal hazards resilience planning.

Shoreline Master Program Guideline improvements to better address coastal hazards

The primary approach to addressing coastal hazard threats in the WCZMP is through local SMPs. However, guidelines can be improved to (i) better assist communities in preventing or minimizing threats to existing populations and property from episodic and chronic coastal hazards; and (ii) to direct future public and private development and redevelopment away from hazardous coastal areas.

Considering additional impacts of climate change

Coastal communities are facing existing coastal hazard stressors that will be exacerbated under changing climate conditions. Sea level rise in particular will have a significant impact in areas along of Washington's coast. However, further understanding is needed to determine what information is needed for actionable decision making and planning.

The WCZMP has identified priority needs and information gaps to address the coastal management priorities identified above:

Priority Needs	Need? (Y/N)	Brief Explanation of Need/Gap
Research	Y	Developing consistent yet regionally-and locally-appropriate coastal hazards information. FEMAs Risk MAP process is providing data and information to communities. However, this does not include erosion and the impacts of future conditions due to climate change such as sea level rise. One challenge communities face is variability in vertical land movement such that regional projections of sea level rise by the National Research Council are not local enough to assess and analyze. Another need is for more robust erosion and shore change monitoring with the incorporation of projected climate conditions. Staff currently have limited capacity to even monitor shoreline profiles and changes.
Mapping/GIS/modeling	Y	Once research is conducted to gather locally specific information, then communication of that information will be needed.
Data and information mgmt.	Y	Multiple agencies conduct research and assessments on coastal hazards in the state, however, there is no central source for cross-hazards information, data, and mapping.
Training/Capacity building	Y	The Padilla Bay NERR is beginning to provide more training to planners and coastal managers on hazards and climate impacts. However, training opportunities are needed (i.e., vulnerability assessment, incorporating hazard mitigation and adaptation into planning tools) for other important audiences to improve preparedness and resilience.
Decision-support tools	N	Technology is improving which is providing better estimates of natural hazard impacts. However, these new tools are expensive and local governments lack the capacity to understand and decide which tools are most helpful to support their planning decisions. It is still unclear what information is needed at the local level for actionable decision making/planning.
Communication and outreach	Y	Through the WCZMPs existing efforts on coastal hazards, communication and outreach are important parts of public awareness and informed decision making. We continue to explore new ways to connect with communities, but additional resources are needed to support communication strategies. More specifically, a program website on coastal hazards that provides guidance to homeowners on awareness

		and responsibility to reduce risk, is needed.
Capacity	Y	Coastal Hazards are a new priority for our program beyond the Program Improvements already committed through 309 efforts. As a *designated area of national importance*, this emphasis is likely to remain a high priority for our program and additional resources could greatly benefit work on our strategy.

Wisconsin https://coast.noaa.gov/czm/mystate/

The Wisconsin Coastal Management Program, approved by NOAA in 1978, is administered by the Department of Administration, Bureau of Intergovernmental Relations. The coastal management program is a networked program implemented in partnership with the Wisconsin Coastal Management Council, with representatives from local governments, state agencies, Native American tribes, and interest groups. The council sets the policy direction for the program. The Wisconsin coastal zone comprises the 15 counties fronting Lake Superior, Lake Michigan, and Green Bay.

Wisconsin Coastal Management Program Objectives

The Wisconsin Coastal Management Program follows the premise that coastal management means achieving a balance between natural resources preservation and economic development (https://doa.wi.gov/Pages/LocalGovtsGrants/CoastalManagement.aspx). The program works to achieve the following objectives:

- Improve the implementation and enforcement of state statutes, policies, regulations and programs affecting the Great Lakes.
- Improve the coordination of activities undertaken by federal, state and local governments on matters affecting key coastal uses and areas.
- Strengthen the capacity of local governments to undertake effective coastal management.
- Advocate the wise and balanced use of the coastal environment.
- Inform the public about coastal issues and increase opportunities for citizen participation in decisions affecting the Great Lakes.

Wisconsin's Coastal Zone

The boundaries of the coastal zone subject to the Wisconsin Coastal Management Program extend to the state boundary on the waterward side and, on the inland side, include the 15 counties with frontage on Lake Superior, Lake Michigan, or Green Bay. Maps are available showing Wisconsin's coastal counties, Lake Superior and Lake Michigan basins, and the National Oceanic and Atmospheric Administration's (NOAA) Coastal and Estuarine Land Conservation Plan areas.

Coastal Natural Hazards

Natural Hazards were the backbone focus of the Wisconsin Coastal Management Program (WCMP) when it was created due in part to high lake levels in the early 1970s. Natural hazards continue to be a priority for the WCMP. Since 1994, WCMP has been updating methodologies and data to understand, visualize and develop mitigation measures to deal with shore erosion in the Great Lakes.

- Current work focuses on developing and implementing shoreline and bluff erosion policies for Wisconsin's coasts. The WCMP seeks to accomplish this through expanding technical tools, providing education and outreach, and cooperating with coastal communities and other agencies.

- WCMP coordinates with partners (Wisconsin Department of Natural Resources, University of Wisconsin (UW) Sea Grant, Wisconsin Emergency Management, UW-Madison) through the Coastal Natural Hazards Work Group.
- WCMP coordinates with other federal partners with interest in shore erosion such as Corps of Engineers, Federal Emergency Management Agency (FEMA), and others.

Section 309 Report: Coastal Hazards

The following information is extracted from: *Wisconsin Coastal Management Program: Needs Assessment and Strategy 2016-2020 (2015).* The document is available for review online at https://coast.noaa.gov/czm/enhancement/media/wi309-2016.pdf.

- WCMP staff organized and chaired Coastal Natural Hazards Work Group meetings. Work group members come from diverse organizations – including UW Sea Grant, Wisconsin Emergency Management, University of Wisconsin-Madison Departments of Engineering and Geology, Association of State Floodplain Managers, Ozaukee County, and Wisconsin Department of Natural Resources. The Work Group meets several times a year to discuss current and emerging issues, share information, and collaborate on projects.

- WCMP staff organized a series of outreach meetings, titled "Great Lakes Coastal Processes and Best Management Practices." WCMP staff and Coastal Hazards Work Group members presented at the workshops.

- Section 309 funding was used to determine appropriate setbacks for two counties on Lake Superior. Northwest Regional Planning Commission worked with Iron County and Douglas County to complete the shoreline analysis and calculate setbacks.

- Enhancement funds were used for an examination of high bluffs and the effect of stabilization at Concordia University in Mequon, Wisconsin.

- The City of Oak Creek used enhancement funding to conduct a bluff stabilization study as part of its redevelopment efforts for the city's lakefront. The study helped the city to make decisions on what to do with an eroding bluff as it developed a larger plan for the site. Coastal Hazards Work Group members helped review the plans.

- The University of Wisconsin collaborated with the City of Port Washington to address failing bluffs by updating recession rates and developing guidelines. The efforts included well-attended public outreach sessions.

- The University of Wisconsin-Superior used enhancement funding to develop a map and analysis of landslides caused by the June 2012 flood within the Red River, Pokegama River, and Nemadji River watersheds and create a landslide hazard risk map for the Red River breaks watershed. The project resulted in improved understanding of the effect of upland management on water quality and property.

- In an ongoing project, the Association of State Floodplain Managers is using enhancement funding to analyze "hot spots," unstable bluffs on Lake Michigan. Recently mapped photos have shown that, since 1976, some previously unstable bluffs have since stabilized. Identifying the areas that are active and understanding why some areas have and some have not stabilized may help locals and landowners to determine where and whether to build. Enhancement funds were used to classify and map oblique photographs from the 1970s and 2007 into a GIS database for a previous stage of this project.

- In another current effort that has received enhancement funding, University of Wisconsin Engineering staff are examining the effects that coastal structures in the Great Lakes have on shoreline evolution.

Resource Characterization (Phase I Assessment)

Flooding: Data from *NOAA's State of the Coast* "Population in the Floodplain" viewer, summarized by coastal county through NOAA's Coastal County Snapshots for Flood Exposure since 2000.

Population in the Coastal Floodplain

	2000	2010	Percent Change 2000-2010
No. of people in coastal floodplain	116,258	125,277	+7.75 %
No. of people in coastal counties	1,992,393	2,049,934	+2.89 %
Percentage of people in coastal counties in coastal floodplain	5.84 %	6.11 %	+0.27 %

Shoreline Erosion Data from *NOAA's State of the Coast* "Coastal Vulnerability Index" indicate the vulnerability of the state's shoreline to erosion.

No information.

Sea Level Rise Data from *NOAA's State of the Coast* "Coastal Vulnerability Index," indicate the vulnerability of the state's shoreline to sea level rise.

No information.

Other Coastal Hazards: General level of risk in the coastal zone for each type of coastal hazard. The state's multi-hazard mitigation plan is a good additional resource to support these responses.

Type of Hazard	General Level of Risk (H, M, L)
Flooding (riverine, stormwater)	H (high)
Coastal storms (including storm surge)	M/H
Geological hazards (e.g., tsunamis, earthquakes)	L
Shoreline erosion	H
Great Lake level change	M (moderate)
Land subsidence	M
Saltwater intrusion	L (low)

- State of Wisconsin Hazard Mitigation Plan – The State of Wisconsin Hazard Mitigation Plan assesses Wisconsin's vulnerability to natural hazards. It outlines roles for state agencies and details a strategy to reduce vulnerability.
- Wisconsin Coastal Atlas – This web-based tool is a resource for sharing diverse coastal data and resources to encourage informed decision-making. It has sections for maps, tools, geospatial data, and tools related to Wisconsin's Great Lakes.

- Wisconsin Shoreline Inventory and Oblique Photo Viewer – This online tool allows users to examine photos from 1976-78 and compare them to corresponding photos from 2007-2008 to assess changes to the shoreline. GIS layers for shore structures, beach protection, and bluff conditions for each timeframe allow for more detailed analysis of shoreline and bluff changes. Recent analysis of the data has evaluated "hotspots," areas of active bluff erosion.
- Great Lakes Coastal Resilience Planning Guide – Another online resource, this tool provides in-depth case studies on hazards and climate change.
- Wisconsin Initiative on Climate Change Impacts – The Wisconsin Initiative on Climate Change Impacts released its first comprehensive report in 2011. The report includes sections on Coastal Resources and Water Resources.
- NOAA Great Lakes Coastal Storms Program: Great Lakes Planning and Mitigation Needs Assessment of Coastal Storm Hazards – A survey of planners and other stakeholders on coastal storm hazards. Of 186 respondents, 42% were from Wisconsin. Bluff and shoreline erosion was identified as the top coastal storm hazard.
- NOAA Coastal Services Center/Coastal Storms Program: 2013 Shoreline Change Workshop: Perspectives on the Great Lakes – A report on the results of this workshop explores priority gaps and needs related to the Great Lakes shoreline. Visualization tools, bathymetry/topography data, and observational data and monitoring stations were identified as gaps for future lake levels. Demonstration projects for alternatives to shoreline armoring, bathy/topographic data, and policies were identified as gaps for bluff erosion/failure. Key takeaway included the need for visualization projects, need for translating science to policy and outreach, and need for bathy/topographic data.
- FEMA flood mapping – The Federal Emergency Management Agency (FEMA) is undergoing coastal analyses and mapping studies to provide updated Digital Flood Insurance Rate Maps for coastal counties in the Great Lakes Region. The effort is not complete, but development standards in the region may be affected in the near future.

Management Characterization (Phase I Assessment)

Management Category	Employed by State or Territory (Y/N)	CMP Provides Assistance to Locals that Employ (Y/N)
Statutes, regulations, policies, or case law interpreting these that address:		
Elimination of development/ redevelopment in high-hazard areas	Y	Y
Management of development/ redevelopment in other hazard areas	N	N
Climate change impacts, including sea level rise or Great Lake level change	N	N
Hazards planning programs or initiatives that address:		
Hazard mitigation	Y	Y
Climate change impacts, including sea level rise or Great Lake level change	Y	Y
Hazards mapping or modeling programs or initiatives for:		
Sea level rise/Great Lake level change	Y	Y

Coastal Hazards continue to be an area of high importance to Wisconsin. There are significant development pressures on Wisconsin's coastal shoreline. Coastal flooding has impacted areas in the Lake Superior region as well as the southeast region of the state in recent years. Communities are concerned about the effects of fluctuating lake levels. Discussions with planners, local decision-makers, Wisconsin Emergency Management staff, and members of the Wisconsin Coastal Natural Hazards Work Group (with participants from University of Wisconsin-Madison Geology and Engineering, Association of State Floodplain Managers, Wisconsin Emergency Management UW-Sea Grant, Wisconsin Department of Natural Resources, NOAA Coastal Storms Program, and community planners) have made it clear that WCMP should pursue opportunities to address coastal hazards.

Statutes and Regulations

In July of 2015, Wisconsin passed its biannual budget. One of the provisions of the budget will change shoreland zoning on a county level. Counties will no longer be allowed to create shoreland zoning ordinances that are more restrictive than state standards. This is a significant change that affects more than hazards-related areas, but in a hazards context, in the past, WCMP encouraged counties to adopt shoreland zoning ordinances as a way to enact more restrictive setbacks on erodible shorelines, especially in high bluff areas. Presumably, existing county standards will immediately be void where they are more restrictive than state standards. Counties won't be able to use shoreland zoning to enact setback standards: the state standard is 75-feet from the ordinary high water mark. Counties will be unable to use shoreland zoning for a more restrictive standard (such as 75 feet from the bluff edge). The budget provision was unexpected. There may be room for counties to enact bluff setbacks through their Land Use Ordinances or other means. Other future outcomes are unclear.

Hazard Mitigation

Flooding impacted communities in the Lake Superior region, leading to hazard mitigation efforts. Some of the efforts in the area were funded by the WCMP. Section 309 funds were used in mapping landslides and other failures in watersheds in the area. The results of the funding will hopefully be used in land-use planning efforts in the region. Section 309 funding was also been used in the City of Milwaukee to develop green infrastructure policies to reduce flooding impacts. The guidelines are being used by the City in development decisions. In addition, WCMP 306 funding is being used in a project to review several Southeastern Wisconsin communities' existing ordinances and local codes that need to be revised to better address coastal flooding through green infrastructure. WCMP organized and presented at a series of outreach meetings titled, "Great Lakes Coastal Processes and Best Management Practices" workshops. Section 309 funding was used for the workshops.

Climate Change Impacts

The Wisconsin Initiative on Climate Change Impacts (WICCI) produced a report titled "*Wisconsin's Changing Climate: Impacts and Adaptation*." The report provides broad recommendations for decision makers, including a section on coastal impacts. The effort was led by the University of Wisconsin-Madison.

Great Lake Level Change

WCMP co-mentored a Coastal Management Fellow who developed "Wisconsin's Coasts in Transition," an online tool that allows users to examine land cover changes at the municipal level. WCMP partnered with University of Wisconsin Sea Grant in hosting a series of public forums on low lake levels. One of the workshops was directed to the Wisconsin Legislature, and the others were public-outreach workshops.

In-Depth Management Characterization (Phase II In-Depth Assessment)

Coastal erosion, flooding, and coastal storms present significant risks to public safety and property. The Wisconsin Coastal Hazards Work Group has identified these areas (along with changing lake levels) as the most significant coastal hazards. The 2011-2015 Needs Assessment and Strategy for Enhancements to the Wisconsin Coastal Management Program identified flooding and shoreline erosion as having a high general level of risk and Coastal storms as having a medium/high level. NOAA Great Lakes Coastal Storms Program's "Great Lakes Planning and Mitigation Needs Assessment of Coastal Storm Hazards" asked respondents to rate coastal storm hazards; Bluff and shoreline erosion rated as number one with overflow of combined systems as number four and stormwater flooding of residential and commercial developments as numbers four and five. Coastal Erosion and flooding (with associated storm effects) are discussed in the State of Wisconsin Hazard Mitigation Plan.

Methodologies for Determining Setbacks

The Coastal Hazard Work Group has led developments in determining setbacks. In particular, the group has coordinated with Bayfield County zoning staff to develop a new setback ordinance for the county. WCMP provided funding for the efforts, which included incorporating LIDAR data into building setback requirements. The work also included on-the-ground site visits, public outreach, training, website development, and revisions to ordinance language. The outcome is currently a voluntary standard that will provide better protection of the county's shoreline.

Promotion of Alternative Shoreline Stabilization Methodologies

WCMP funded a report titled "Managing Coastal Hazards in Wisconsin's Changing Climate." In addition to detailing coastal hazards and risk management on Wisconsin's shores, the report provides recommendations. One is to restrict shore protection structures and encourage non-structural options. The Coastal Hazards Work Group and WCMP will use the report and its recommendations in future efforts.

Local Hazards Mitigation Planning

Wisconsin Emergency Management has coordinated with communities in developing and revising their Hazards Mitigation Plans and updated the State of Wisconsin Hazard Mitigation Plan. WCMP participated in some of the efforts. In addition, Bay-Lake Regional Planning Commission produced a report titled "A Guide to Hazard Mitigation Planning for Coastal Communities in Wisconsin," which was funded by WCMP. The guide assists communities with addressing coastal hazards issues within their hazard mitigation plans.

Hazards Research and Monitoring

Research and monitoring efforts in the past few years have included final efforts to develop and provide public research for a bluff stability model for southeastern Lake Superior. WCMP funded the project. WCMP also funded the University of Wisconsin-Madison efforts to investigate lakebed down cutting in Lake Michigan. The work resulted in a much clearer understanding of erosion of the near shore lakebed and increased public awareness of bluff recession.

The WCMP also funded projects that resulted in oblique geolocated photographs of Wisconsin's coasts. Older oblique photos were digitized and geolocated, and a GIS database built to allow comparison between the sets. The work resulted in a database that allows users to analyze change to the state's shoreline.

Priority Needs and Information Gaps (Phase II In-Depth Assessment)

Three management priorities identified in the 2015 report are directly pertinent to coastal geology issues and provide opportunity to more effectively address significant hazards.

Policy refinement/development

Development of local regulations addressing coastal hazards is needed. Recent changes to shoreland zoning necessitate review of existing ordinances and, potentially, development of new policies to address setbacks on eroding shorelines. This management priority includes reviewing existing ordinances, zoning, and other regulations to incorporate new information and data as well as development of new regulations. This management priority also includes refining and developing guidance documents for addressing coastal hazards, such as (where appropriate) living shorelines.

Mapping/research

Mapping of shoreline erosion and predictions, modeling for changing lake levels, and research on nearshore processes are all areas where WCMP can assist. Enhancement funding has assisted in these areas in the last few years; WCMP has an opportunity to continue developing models and tools for coastal hazard management.

Targeted outreach

There is a need for outreach to homeowners, local planners, and permitting staff (state and local). WCMP is in a good position to coordinate outreach efforts between researchers and other hazards professionals and local decision makers and landowners.

Priority Needs	**Need?** (Y/N)	**Brief Explanation of Need/Gap**
Research	Y	Need for more research on sediment transport, nearshore habitat, and potential effects of climate change. Need research on potential effects of the recent changes to shoreline zoning: what counties rely on shoreland zoning to establish setbacks and what counties are interested in developing other means of protecting their shorelines as well as what the options are (if any) for counties that want to adopt regulations.
Mapping/GIS/modeling	Y	Need for improved modeling (e.g., HAZUS modeling is by Census block and may not reflect actual losses/risks); modeling on effects of climate change; mapping of nearshore habitat, sediment transport.
Data and information mgmt.	Y	Need to make data available to managers; need to make data and other information available to land owners; data gaps on historic permits – difficulty in tracking this information down and need to digitize; need more data on impacts of coastal structures, particularly on the Lake Michigan Shoreline.
Training/Capacity building	Y	Training/education of consultants and local decision-makers for identifying hazardous areas, ensuring

		appropriate setbacks, and use of non-structural shoreline stabilization methodologies (where appropriate); training of permitting staff; training of homeowners in best-management practices and in evaluating consultants and proposed development plans.
Decision-support tools	Y	Technical tools to help communities address development and plan for hazards; new and improved visualization tools needed for planning efforts; need to integrate existing technology into useful tools (e.g., LIDAR of bluffs and bathymetric LIDAR could be used to make profiles fixed in space on a region-by- region basis); improvement needs for existing tools (e.g., missing data for Oconto County).
Communication and outreach	Y	Education of elected officials; education of landowners especially new homeowners; making information available to locals.

Chapter 3: State of Knowledge on the Coastal Setting, Geology and Stratigraphy of Pennsylvania's Lake Erie Bluffs and Nearshore Waters

Introduction

Coastal cliffs (consisting primarily of consolidated materials or "bedrock"), bluffs (primarily unconsolidated materials) and banks (<1.5 m in height in Pennsylvania, and consisting of unconsolidated materials) are pervasive landforms along the world's coastlines, accounting for ~80% of global coasts (Figure 3.1; Emery and Kuhn, 1982). Approximately one quarter of the entire US Great Lakes coastline consists of cohesive bluffs and banks (Pope et al., 1999). This type of coast is very susceptible to present-day processes of weathering and erosion, and to future climate-influenced changes in bluff geotechnical properties and lake levels that directly affect bluff stability. Recent literature on climate change in Pennsylvania and the Great Lakes Basin suggests that increased precipitation in winter and spring, more frequent heavy downpour events, and less frozen precipitation may characterize regional climate over the next several decades (Lofgren et al., 2002, 2011; Karl et al., 2009; Shortle et al., 2013). This trend may lead to increased bluff instability due to increased erosion of the bluff face by surface runoff. Increased precipitation may also lead to increased water retention (mass) within the bluff, and on the bluff face within vegetation and soil mats. Conversely, an expected increase in regional evapotranspiration and a consequent reduction in surface-water inflows to the Great Lakes Basin may lead to lowered Lake Erie water levels, which should have a bluff-stabilizing effect because bluff-toe erosion by waves will be reduced (see Chapter 4).

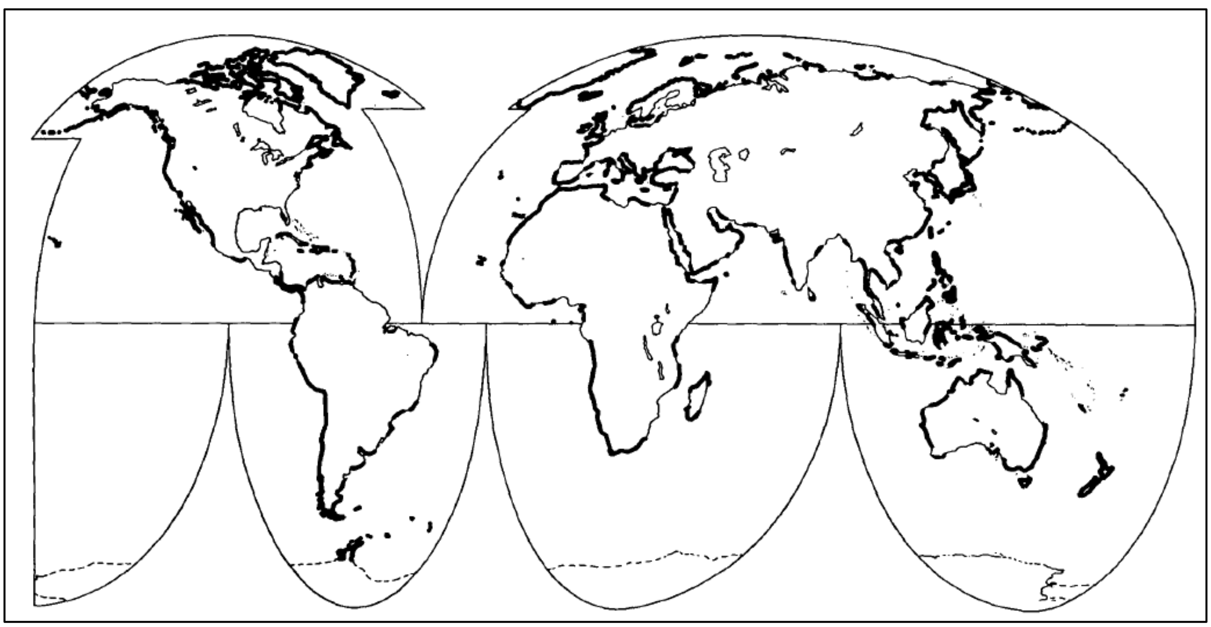


Figure 3.1: *Global distribution of coastal cliffs and bluffs. Low banks (typically <1.5 m in elevation) are excluded from this map. Cliff and bluff coasts are generally subject to less urban-development pressures than low-relief coastlines such as beaches, coastal plains, and deltas (Image: modified from Emery and Kuhn, 1982).*

The expected precipitation trends may also lead to increased recharge of Pleistocene surficial aquifers on the Pennsylvania coast, and therefore to an increase in groundwater pore pressures, storage, and discharge at the bluff over time. In sandy and silty aquifers exposed at the bluffs, increases in groundwater content will likely lead to a decrease in bluff stability as water tables rise and reduce internal friction. Although uncertainty exists in regional climate modeling, the predicted climate trends suggest hydrodynamic processes (waves, ice, currents) may become less important as drivers of bluff instability through the end of the century. However, subaerial processes (linked with surface water and groundwater) may become more important drivers. This process duality makes predicting changes in the loss of bluff-adjacent agricultural, forested, and urban land over time more challenging.

The Upper Great Lakes Setting of the Pennsylvania Coast

Lake Erie possesses the highest proportion of cohesive bluff coastline in the upper Great Lakes, where 12% (1960 km) of the US/Canadian coastline consists of cohesive bluffs and banks (Geomorphic Solutions, 2010). Lake Erie, where 44% (630 km) of the coastline is cohesive, is second only to Lake Michigan (32%; 760 km) in the total number of kilometers of cohesive bluffs (Geomorphic Solutions, 2010). A recent classification of Lake Erie coastal morphology was conducted as part of the US Army Corps of Engineers' Lower Great Lakes Erosion Study (LGLES; Stewart, 1999; Geomorphic Solutions, 2010), where the coast was categorized by the type of shoreline morphology, and by the type and abundance of coastal engineering structures present. That study found that approximately 41% of the entire Lake Erie perimeter consists of low banks through tall bluffs dominated by unconsolidated glacial till and lacustrine sediments (Figure 3.2; Stewart, 1999). The second-most common shoreline category on Lake Erie was classified by the Army Corps of Engineers study as "artificial," at 23%. Approximately 12% of the Lake Erie shoreline consists of consolidated, commonly Devonian, bedrock with the most common lithology being shale. Shale and thin sandstone strata are significantly more resistant to wave attack than the Quaternary-age cohesive tills, lacustrine sediments, and beach-ridge sands that otherwise make up Lake Erie bluffs.

The LGLES shoreline classification scheme also generated a kilometer-by-kilometer spreadsheet geodatabase for the shoreline. This database was subsequently updated by Cross et al. (2016) who used a GIS approach to examine long-term bluff retreat along the southern US coast of Lake Erie. In general, the LGLES study shows that the sand content in both homogeneous (where the bluff consists of a single lithology) and composite bluffs (where the bluff is defined by multiple lithologies) ranges from 0-20% (~41% of bluffs and banks) to a maximum of 20-50% (~57% of bluffs and banks) lakewide. Bluffs and banks with sand contents in excess of 50% are rare (~2%; Morang et al., 2011). Offshore, approximately 42% of the adjacent nearshore lakebed consists of bedrock. This general coastal morphology is characteristic of the entire Pennsylvania coast to the west and east of Presque Isle: within Presque Isle Bay, bedrock is covered by a significant veneer of muds, silts, and sands. Nearshore bedrock occurring within the zone of wave breaking (less than 5-10 m water depth) can significantly reduce the rate of adjacent bluff retreat. This is because nearshore downcutting of the lakebed is reduced which in turn limits the wave heights and thus wave energy stress that may be directed at the bluffs. Approximately 46% of the Lake Erie perimeter is associated with a nearshore that consists of cohesive till, cohesive lacustrine clay, and cobble or boulder lags over cohesive materials (Stewart, 1999). These three lithologies are more susceptible to wave-induced downcutting during both high and low lake levels when compared to nearshore areas characterized by bedrock.

Figure 3.2: *Example of a cohesive bluff coast (bluff, beach and nearshore), near Port Alma on the Canadian coast of Lake Erie. Note the wave-cut notch at the toe of the bluff, evidence of slumping and gully development, and the absence of a resistant shale bedrock toe. This site is located across Lake Erie from the Pennsylvania coast (Image: modified from Geomorphic Solutions, 2010).*

In Pennsylvania, cohesive bluffs locally overlie up to 7 m (23 ft) of basal shale bedrock, particularly on the lake front east of Presque Isle. With the exception of the Presque Isle peninsula (a beach-ridge strandplain), the entire coast is classified as a cohesive coast in the LGLES scheme (Stewart, 1999). Given the relatively developed and urban nature of the Lake Erie coastline, bluff retreat is understandably a pressing issue for the residents of its perimeter states and provinces. For Pennsylvania, the susceptibility of the coast to erosion is further enhanced because the entire Lake Erie shoreline is a northwest-facing, windward coast subject to larger fetches and wave energies than the bluff-dominated coasts of neighboring Ohio, Michigan, and Ontario. In contrast, the New York coast of Lake Erie is notably different from that of Pennsylvania in that only about 20% of its coast consists of cohesive bluffs (Geomorphic Solutions, 2010).

Geologic Framework

The Pennsylvania bluff coast is characterized by unconsolidated bluffs and banks ranging in elevation from 1.5 to 55 m above lake level (175.5-229 m above mean sea level (MSL)). Depending on location, the unconsolidated bluff sediments may rest upon as much as 7 m of Devonian bedrock that often forms a resistant bedrock toe. The bluffs are intersected by numerous stream mouths, many of which are incised into Devonian bedrock. Small ephemeral springs drain modern actively eroding rotational slumps and ravines while perennial springs drain larger, well-vegetated Holocene bowls. In Harborcreek and North East, narrow beaches are present along 65-70% of the coast. They have a maximum width of 34 m (updrift of marinas), a median width of 4 m, and a modal width of 1 m (Foyle and Naber, 2011).

Landward of the bluffs, an elevated coastal plain consists of a low-gradient, lakeward-sloping, paleo-lacustrine plain that extends several kilometers inland. Inland, it abuts a late Pleistocene paleo-shoreline (typical elevation ~213 m MSL) that marks the lakeward edge of the Warren beach ridge complex, which is in turn backed by the older, higher-elevation, Whittlesey complex (Schooler, 1974). Both of these complexes formed during short still-stands of lake level during the latest Pleistocene during a long-term drop in the level of Lake Erie (Holcombe et al., 2003). The coastal plain eventually terminates 5-10 km inland against the toe of a coast-parallel glacial-moraine escarpment at a typical elevation of ~245 m MSL. The crest of the escarpment (typically at ~450 m MSL) marks the southern edge of the Lake Erie drainage basin in Pennsylvania. Near North East, the Warren beach-ridge complex (crest elevation ~229 m MSL) progrades over the underlying paleo-lacustrine plain, extending to the bluff edge. This sandy and gravelly complex is up to 15 m in thickness, is notably devoid of significant surficial drainage, and causes the highest bluff-top elevations in Erie County to occur in this sector. The beach-ridge complex formed as the latest Pleistocene coast prograded lakeward and northeastward over a transgressive shoreface that is now stranded 20-40 m above present lake level as a paleo-lacustrine plain. The result is that along this part of the Harborcreek and North East coast, a lakeward-thickening sandy wedge adds as much as 15 m of additional sand and gravel (in a recurved spit geometry) to the finer-grained subjacent lacustrine and glacial till section.

Offshore, Devonian-age shale and sandstone bedrock crops out as a shallow stepped wave-cut platform in the surf zone and nearshore. The inner nearshore (<5 m depth) dips to the north-northwest with a typical nearshore gradient of ~1:100 while Devonian strata dip gently southward. For a distance of ~10 km west of Presque Isle, the outer nearshore (5-10 m depth) extends further offshore along eastern Fairview and Millcreek townships due to sediment cover. Shallow bathymetry limits surf zone wave height during storm events and fosters partial dissipation of wave energy before waves reach the beach and bluff. Two dominant bedrock joint sets, oriented NE-SW and NW-SE, are developed in the eastern half of the county (Figure 3.3; Foyle and Naber, 2013). Onshore at the bluff face, enhanced groundwater transmissivity in these joints leads to heightened pore pressures that can contribute to localized failures in overlying bluff sediments (Richards et al., 1987). Knuth and Lindenberg (1995) note that joints in bedrock along the eastern coastal reach (described in Chapter 1) have been widened by waves to produce indentations that are as much as 15 m wide and extend as much as 7 m inland (Figure 3.3). In these small coves, sand often forms pocket beaches. A bedrock toe or ledge is prevalent along the base of the bluffs in the eastern coastal reach. In easternmost Erie County, bedrock gradually plunges below lake level and the bluffs transition into low-elevation banks. In Erie County's western coastal reach, bedrock lies primarily at or below average lake level (Figure 3.4).

Bluff Stratigraphy

Detailed information on bluff stratigraphy in Erie County is scarce, is focused on a small number of specific research sites, and it not easily compilable from the unpublished literature. Therefore, these data should as much as possible be incorporated into a GIS database to make them, and any data collected in the future, easily accessible and queryable. Information on nearshore substrate properties for the Pennsylvania coast is even more scarce and poses a significant limitation for any future modeling of bluff stability to estimate future locations of the bluff crest. The Ohio DNR Office of Coastal Management maintains the LESEMP Map Viewer (http://coastal.ohiodnr.gov/erosion) where coarse-resolution nearshore substrate coverage extends eastward into Pennsylvania waters.

Figure 3.3: *Typical appearance of coastal bluffs in western Harborcreek Township. Pronounced irregularities in the bluff crest trend are caused by preferential erosion at joints and faults in the Devonian Bedrock. Bedrock makes up the lower ~50% of these low bluffs that are capped by glacial till (Knuth and Lindenberg, 1995). In the nearshore, larger fault/joint traces trend towards the "4:30" and "7:30" clock positions (Imagery collected in April 2015 and available from Pennsylvania DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 3.4: *Typical appearance of bluff failure along high bluffs in western Erie County. Small rotational slumps occur in lacustrine sands at the top of the bluff; and debris slides occur in glacial tills in the lower half. The bedrock toe is absent. Erosion-mitigation efforts (left side) involve slope re-grading and placement of rip-rap at the bluff toe (Imagery collected in April 2015 and available from Pennsylvania DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

The principal sources of detailed site-specific geology are limited to studies completed by D'Appolonia (1978), Knuth (1983, 1985, 1987, 2001), Buyce (1987), Amin (1989, 1991, 2001), Knuth and Lindenberg (1994, 1995), Highman and Shakoor (1998), Knuth (2001), Urban Engineers (2004), Wetland and Coastal Resources, Inc. (2004), Baird (2010), Foyle and Naber (2011), Foyle (2014), and Cross et al. (2016).

While the above publications may provide detailed stratigraphic information at specific locations across coastal Erie County, the number of research/study sites remains small. Extrapolation of stratigraphy and geotechnical properties between sites, and to other sites, is thus not yet feasible. This is because of (i) variability in till, lacustrine, and strandplain stratigraphy along the coast; (ii) along-coast variability in geotechnical properties and hydrogeologic framework; and (iii) the large spacing between existing study sites. Trying to correlate bluff stratigraphy between sites further apart than 50-100 meters remains a challenge on the Pennsylvania coast due to data scarcity. More generalized geologic and coastal-engineering summaries, and a broad-scale classification of bluff and nearshore materials, are available in Carter et al. (1987) and Stewart (1999). The former study also categorized the Lake Erie coast into hazard-risk zones on the basis of susceptibility to coastal erosion: western Erie County was classified as a moderate-risk zone while eastern Erie County was predominantly a low-risk zone. Visualization of the of Erie County bluffs is possible using the online PA DEP oblique aerial photo database that has acquired imagery of the coast for the past several years (Figures 3.3 and 3.4; www.dep.pa.gov). In general, bluffs on the Pennsylvania coast consist of most or all of four principal stratigraphic units that underlie coastal Erie County:

- Devonian shale bedrock that crops out at and below lake level in western Erie County and in the nearshore to 7 meters above lake level in eastern Erie County
- two late Pleistocene glacial till units
- laminated and non-laminated lacustrine clays, silts and sands
- latest Pleistocene strandplain sands and gravels deposited during former highstands of lake-level and similar in appearance to modern Presque Isle

Carter et al. (1987) show that the Pennsylvania coast from the Ohio state line to Presque Isle (the western coastal reach of Knuth, 2001) is effectively a cohesive coast dominated by glacial tills with variably-thick overlying proglacial lacustrine sands. Bluffs are locally capped by highstand strandplain deposits (the Warren paleoshoreline) near Lake City. Shale bedrock crops out at lake level locally, such as east of Walnut Creek, and bluffs range in elevation from low banks (~1.5 m) to 30 meters. Narrow beaches front nearly the entire western coastal reach and are best developed at stream mouths where bluff re-entrants allow land elevations to gradually drop towards lake level. Beaches are generally narrow due primarily to a known lack of natural sediment transport around the tip of the Conneaut breakwaters just west of the Ohio state line (Knuth, 2001). Were it not for periodic artificial sand bypassing across the Conneaut breakwaters (Morang et al., 2011), littoral drift from Ohio into Pennsylvania would approach 0 m^3/yr. Narrow beaches also occur because sand and gravel concentrations in the bluffs are low (typically <25%), and because localized sediment starvation occurs on the downdrift sides of shore-protection structures.

In Presque Isle Bay and from Presque Isle east to the New York state line, the bluffs have a similar stratigraphy to the western reach but typically rest on as much as 7 m of resistant Devonian shale with sandstone interbeds that provides a bedrock toe for the bluff. Bluffs are locally capped by thick sandy to gravelly highstand strandplain deposits in the North East area (geomorphically similar to those at Lake City). Because of the bedrock toe, wave-induced erosion of unconsolidated bluff materials is reduced and beaches are thus less prevalent than in western Erie County. Slow rates of wave-induced erosion of the relatively resistant bedrock toe mean that most of the bedrock toe retreats as a low near-vertical (>60 degrees; Foyle and Naber, 2011) cliff that fosters wave reflection, downward-directed wave shear stress, lake-bed scour, and consequently a limited opportunity for beach accumulation given a pre-existing shortage of littoral sand supply.

The nearshore sediment budget also plays a role in the reduced prevalence of beaches in eastern Erie County. Knuth (2001) estimated that none of the bluff-supplied 60,000 m^3/yr of littoral sand and gravel leaving the eastern end of the western coastal reach bypasses the terminus of Presque Isle. Littoral sediment is trapped in deep water (depths >8 m) east of Presque Isle to build the large subaqueous platform upon which the Presque Isle strandplain migrates along-coast (Foyle and Norton, 2006). Additional sand also gets trapped along the north side of the baymouth's north jetty and in the offshore federal navigation channel. This deprives the eastern coastal reach of a significant volume of material that could otherwise be used in beach building. The entire eastern coastal reach receives only ~27,000 m^3/yr of bluff-derived sediment suitable for beach building (Knuth, 2001). As is also the case for the western coastal reach, streams entering the coastal zone and the Lake Erie nearshore supply insignificant quantities (<5%) of sand and gravel to the littoral zone (Knuth, 2001). The bluff sediment inputs to the littoral zone derived by Knuth (2001) assumed parallel bluff retreat over an 18-year observation period that used DEP control point surveys. While this assumption of parallel retreat is applicable for many bluff morphologies globally over long timescales, it may not hold true at such short timescales. The sediment budget numbers may thus be overestimates (in the eastern coastal reach where a bedrock toe is present) or underestimates (in the western coastal reach where a bedrock toe is absent). For comparison, Nummedal et al. (1984) used a wave energy power approach, based on wave climate, to estimate potential littoral sediment input and estimated that ~30,000 m^3/yr of beach-suitable material arrives at the west end of the Presque Isle Peninsula, about half that of the Knuth (2001) estimate.

Because site-specific information is critical to meaningful bluff stability analyses and hazard mitigation planning, the scarcity of available and detailed (multiple property-parcel scale) geotechnical data for the nearshore and bluffs represents a significant data-gap that needs to be filled, both in Pennsylvania and on the majority of Great Lakes cohesive coastlines. Natural variability in bluff and nearshore geotechnical properties is the norm and this influences their susceptibility to erosion by wave shear and impact stresses, longshore current-induced stresses, and sand abrasion. For example, Kamphuis (1987) noted that the shear strength of 22 Great Lakes cohesive-sediment samples was highly variable. Kamphuis (1990) found that tills on the Ontario coast of Lake Erie are generally too strong to be eroded by wave generated shear stresses alone, but that lower shear stresses could initiate erosion where granular abrasives are present (Trenhaile, 2009). Davidson-Arnott and Ollerhead (1995) found that subaqueous vertical erosion rates in lakebed tills of western Lake Ontario due to down-cutting were as high as 3 cm/yr at depths of less than 3 m. Critical shear stresses (stresses above which erosion can occur) for cohesive clays in the southern Great Lakes are highly variable (0.53 Pa to 20 Pa; Coakley et al., 1986; Zeman, 1986; Kamphuis, 1990; Trenhaile, 1990; Bishop et al., 1992) and the characteristics at one site do not necessarily translate to a different nearby site. However, because the nearshore substrate along the Pennsylvania coast is dominated by Devonian shales with thin interbedded sandstone layers, wave-generated nearshore shear stresses as an erosive agent are expected to be particularly ineffective. When modeling bluff stability to determine a bluff-top location where the Factor of Safety value (USACE, 2003) indicates minimal bluff failure risk, accurate data on geotechnical properties are needed. Such data include material shear strength, age, composition, jointing, and compaction; and the variation in these parameters in three dimensions with bluff stratigraphy and geographic location.

Relatively complete, bluff stratigraphic sections that include strata representative of the entire coast occur between Twelvemile Creek and Sixteenmile Creek in eastern Erie County. At one site near North Brickyard Road, the bluff face (from toe to crest) consists of up to 2.5 m of Devonian bedrock that may be mantled with slump debris; approximately 10-14 m of Quaternary grey glacial tills (one or two units) containing thin and discontinuous gravel horizons; approximately 10-15 m of brown lacustrine nearshore sands and silts; and approx 5-7 m of brown-tan upper-shoreface and beach-ridge sands and gravels. (Figure 3.5). A classic "SA>M" bluff geometry (Emery and Kuhn, 1982; see Chapter 4, Figure 4.1) is developed at this site and along much of the eastern coastal reach because the bluff is commonly shielded from wave (M "marine" or hydrodynamic) attack by a bedrock toe and subaerial (SA) processes dominate. Bedrock-controlled shallow nearshore bathymetry and gentle nearshore gradients enhance wave-energy dissipation across the nearshore and thus reduce the amount of wave energy expended at the bluff. Hydrodynamic processes driving bluff retreat are therefore less significant than subaerial processes. Because surface runoff at the bluff edge is rare at this and other sites due to vegetation cover, terrain slope, and soil permeability, it is likely that (i) groundwater discharge is a major subaerial process effecting bluff retreat, and (ii) any spatial variation in groundwater discharge at the bluff face should show a positive correlation with bluff retreat rate.

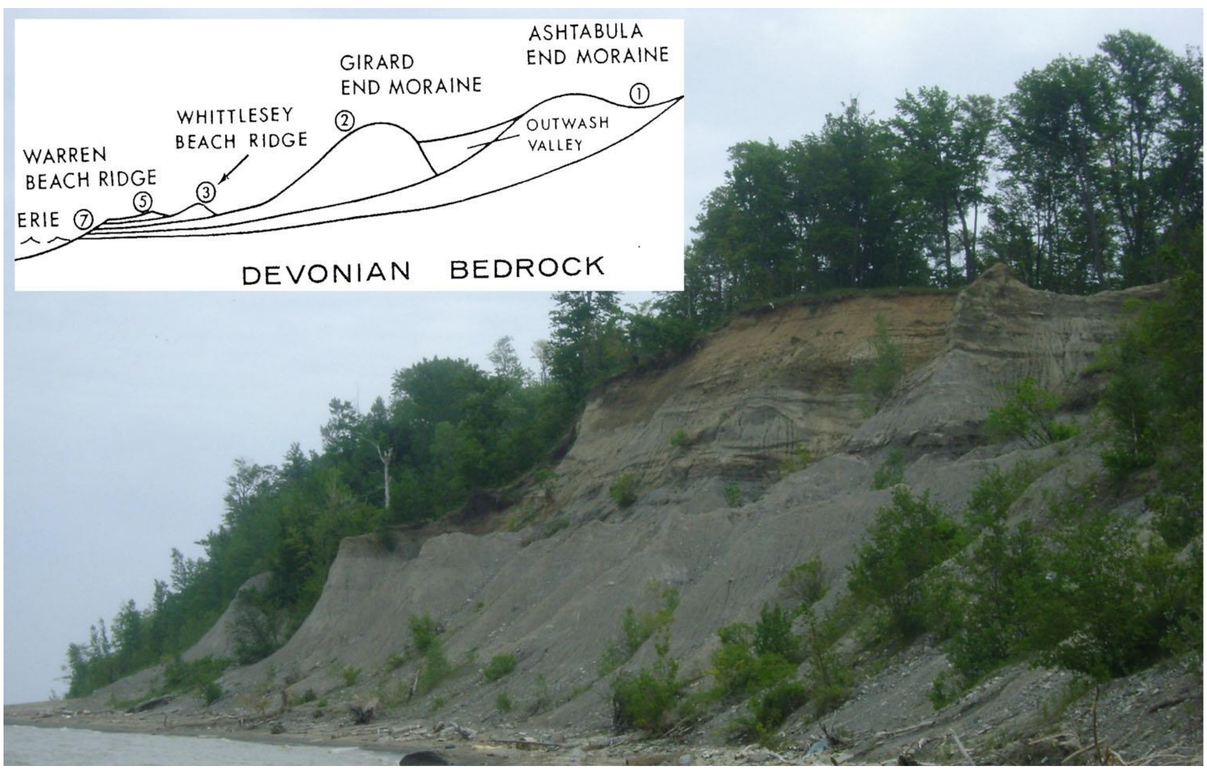


Figure 3.5: *Typical appearance and stratigraphy of a tall eroding bluff in eastern Erie County near North East. The entire stratigraphic sequence is developed, but the bedrock toe is masked by talus debris. The schematic insert (from Schooler, 1974) shows the generalized lakeward-stepping geologic framework for the Erie County coast that includes bedrock and glacial tills (which characterize the lower half of the bluff); and a well-layered lacustrine section with capping beach-ridge strandplain sediments (which characterize the upper half of the bluff). The base of the pale tree-trunk on the left side of the image marks the approximate contact between the glacial tills and lacustrine sediments (Image: modified from Foyle, 2014).*

Devonian Bedrock

Bedrock occurring along the Erie County coast consists of members of the Upper Devonian Canadaway Formation. The Northeast Shale member is exposed at the lake shore to the east of Elk Creek, while the Girard Shale member is exposed at the mouth of Elk Creek and locally to the west at and below lake level (Knuth et al., 1981; Knuth, 2001; LERC, 2008). These Devonian rocks consist of grey shales and thin (< 0.1 m) interbedded sandstones (Sevan and Braun, 1997; Berg et al., 1980) and directly underlie Pleistocene glacial tills and pro-glacial lacustrine sediments. There is a several-hundred million year gap in the rock record across the unconformity (erosional surface) separating the Devonian from the Quaternary. Bedrock elevation at the bluff face ranges from ~174 m to ~181 m MSL or 0 to 7 m above average lake level. The erosional unconformity between bedrock and overlying glacial till has gentle along-coast topography but has more significant topographic relief inland in the shore-normal direction due to stream incision over the past ~10,000 years. Locally, streams have cut through over 70 m of lacustrine, glacial, and bedrock materials with long-term average down-cutting rates of 7 mm/yr during the Holocene. Additional relief on the unconformity likely occurred due to glacial scour and pro-glacial lake processes active during the pre-Holocene (Foyle and Naber, 2011). Bedrock relief is important along the Pennsylvania coast because retreating bluffs may progressively intersect either higher- or lower-elevation regions of bedrock that are presently buried landward of the bluff face.

Bedrock bedding dips gently southward ($0 - 15^0$) beneath coastal Erie county. Schooler (1974) showed that the top-bedrock unconformity generally increases in elevation southward, being overlain by as much as 20 m of Pleistocene sediment at the bluffs but just 1-3 m along the southeastern edge of the lacustrine plain 2 km inland. A Quaternary isopach map by Richards et al. (1987) shows that the Quaternary cover varies in thickness along the coast. It is commonly 8 - 30 m thick, being thickest where paleo-strandplain sand- and gravel-rich landforms are well developed near Lake City and North East. Gas well logs indicate that the Devonian-Quaternary unconformity has an average downward slope of ~1^0 (1.5:100) to the northwest from an elevation of ~290 m MSL beneath the glacial escarpment near I-90. In many cases, bedrock at the bluff face stabilizes the bluff because (i) the southward bedding dip within the rock layers reduces the incidence of lakeward-directed bedrock slides and (ii) the bedrock toe limits wave impact on unconsolidated bluff materials. Knuth (2001) and Foyle and Naber (2011) reported that the Northeast Shale exhibits two dominant sets of joints, oriented at N 40^0 E and N 55^0 W (Figure 3.6). Small normal faults are also common, with displacements of less than 20 centimeters, as well as small thrust faults with drag folds. Hapke et al. (1990) and Knuth et al. (1981) note that bedrock joints are responsible for a headland-cove and pocket-beach shoreline morphology between the City of Erie and Sixmile Creek to the east. The face of the bedrock toe at the base of the glacial till along most of the eastern coastal reach, and along the western coastal reach where bedrock occurs above lake level, slopes steeply lakeward at $60\text{-}90^0$.

Quaternary Glacial Tills

Unconsolidated glacial till of latest Pleistocene age (17,000-22,000 years old) unconformably overlies bedrock and is the depositional record of as many as eight glacial advances into Pennsylvania that occurred during the past 2 million years (Figure 3.7; Thomas et al., 1987). On the south side of Presque Isle Bay, at a remediated bluff-failure site, these deposits consist of medium-stiff gray silt with little sand (24% sand, 76% silt and clay; Urban Engineers, 2004). These percentages are in general agreement with those observed by D'Appolonia (1978), Amin (1989), and Knuth (2001) elsewhere on the coast. The glacial tills have a high moisture content, poor drainage characteristics, a hydraulic conductivity (k) of ~$5x10^{-5}$ cm/s, and a Standard Penetration Resistance of 26-100 blows/m (Urban Engineers, 2004).

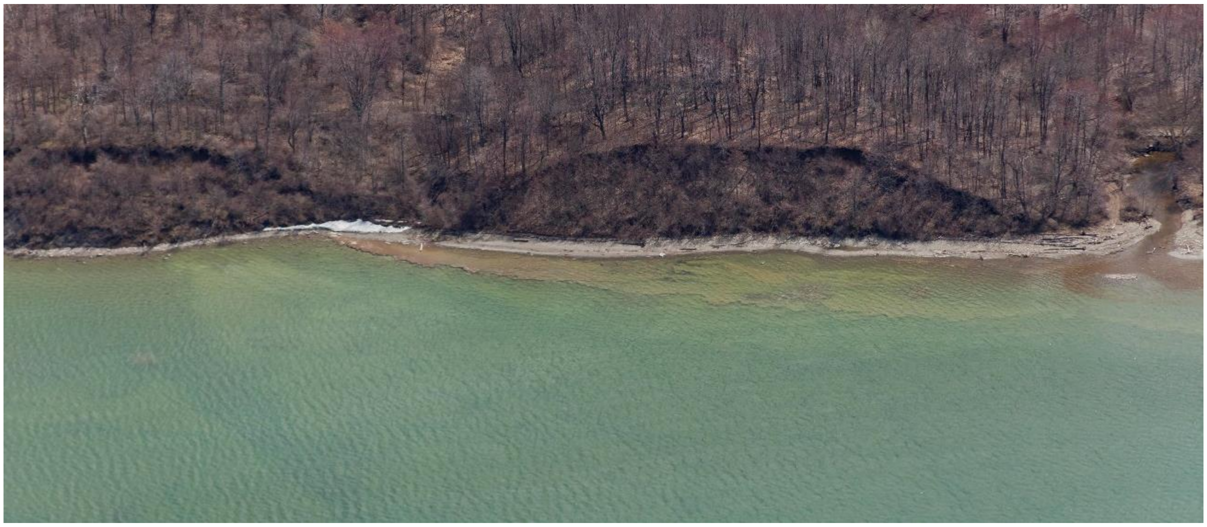


Figure 3.6: *Typical appearance of coastal bluffs in western Erie County, just east of Conneaut, OH. A Devonian bedrock toe is absent in this area, but shale crops out on the lake bed below lake level in the foreground. Two large faults or fractures cross the nearshore bedrock surface (dark linear features) which indicates minimal nearshore sediment coverage. The features extend lakeward of the bluff face, trending towards the "4:30" clock position (Imagery collected in April 2015 and available from Pennsylvania DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Elsewhere, Knuth (2001), reporting on mapping in the western and eastern parts of the county, notes that the glacial till is most often composed of an upper unit and a lower unit with an indistinct contact between the two. The upper till unit is sometimes thinly stratified and is characterized by stiff to very stiff cohesive yellow-brown to gray clayey silt to silty clay with some gravel-shale fragments. The lower till is similar but is a very stiff to hard well-bonded gray, clayey silt to silty clay, with flat angular shale fragments and occasional cobbles and boulders. It is up to 40 feet thick along most of the Pennsylvania coast but thins significantly near the New York state line. The two till units are likely to have significantly different geotechnical properties given their sedimentological differences (cohesiveness, grain size) and because the lower unit often has prominent vertical jointing that will induce failure mechanisms that will not necessarily occur in the upper till unit. In general, the till bluff face slopes lakeward at $35\text{-}45^0$ and has abundant rills and gullies cut by surface runoff and bluff-face seepage in areas where vegetation is scarce (Figures 3.7 and 3.8).

Quaternary Lacustrine Sands and Silts

The glacial tills are capped by a transgressive erosional surface (Catuneanu, 2006), cut by a relative rise in lake level during the latest Pleistocene. This low-relief erosional unconformity has up to 5 m of local relief and is overlain by transgressive lacustrine deposits (Schooler 1974; Sevon and Braun 2000; Knuth 2001). The erosional contact, because it also marks a significant change in hydrogeologic properties between the adjacent glacial and lake sediments (compaction, porosity, permeability), is very commonly the part of the bluff where large rotational slumps bottom out (i.e., where the failure surface daylights), particularly in eastern Erie County. The overlying lacustrine strata consist of loose, low shear strength, brown sand (83% fine sand, 17% silt and clay; Urban Engineers, 2004) on the south shore of Presque Isle Bay, have a moderate to high moisture content with a k value of ~$1x10^{-4}$ cm/s, and have a Standard Penetration Resistance of 10-33 blows/m. Elsewhere, Knuth (2001) describes this unit as consisting of soft to very stiff yellow-brown to gray, finely interbedded, clayey silts to silty clays with fine sand or silt partings and occasional shale fragments, deposited in a proglacial lake setting. Sevan and Braun (1997) state that the lacustrine deposits are the result of deposition of thinly interbedded clayey silt and silty clay in a proglacial lake setting. This sequence of lake sediments is inferred to be capped by a basal surface of forced regression (Catuneanu, 2006; Foyle, 2014) cut by a relative stillstand or fall in lake level. This surface is in turn overlain at the coast by the latest-Pleistocene age Warren (and perhaps, Whittlesey) beach-ridge complexes which are ancient analogs of the modern Presque Isle strandplain (Figure 3.5). D'Appolonia (1978) and Knuth (2001) state that ~76% of the unconsolidated (till and lacustrine) sediments in Pennsylvania bluffs are too fine to remain in the littoral system to facilitate beach building and are instead transported offshore to enhance deep-water silt and clay deposition.

Figure 3.7: *Oblique aerial photo showing the typical appearance and stratigraphy of eroding high bluffs in eastern Erie County near North East (and near the location of Figure 3.5). Curved and sharp bluff edges at the headwall scarps of four active rotational slumps can be seen on either side of a large vegetated Holocene bowl that contains a blue-roofed building and a beach-access trail. Note the spring-fed stream exiting the active slump to the west of the beach-access trail. It is sourced by groundwater from the unconfined aquifer in the upper lacustrine/beach-ridge section of the bluff (tan colored). Glacial tills (grey color) occupy the lower two-thirds of the bluff. The flat plateau inland of the bluffs is part of the beach-ridge complex associated with the Warren paleoshoreline (Imagery collected in April 2015 and available from the Pennsylvania DEP Coastal Resources Management Program at http://www.dep.pa.gov).*


(a)


(b)

Figure 3.8: *Close-up ground photo (a) of the bluff face from the active slump on the left side of Figure 3.7 shown in (b). Clinoform bedding is developed in the lacustrine section (top third of the image) that unconformably overlies glacial till which has small rills and gullies developed. Two till units are present in the lower half of the image, separated by a horizontal erosional surface marked by gravels (near base of image). Groundwater discharge from this high-permeability erosional surface is the cause of iron-oxide staining and a wet surface appearance on the lower till unit (Images: modified from Foyle, 2014; and PA DEP-CRMP at http://www.dep.pa.gov).*

Quaternary Beach Strandplain Silts, Sands and Gravels

Pennsylvania's Lake Erie bluffs range in height from 1.5 to 55 m. The highest bluffs in both the western and eastern reaches of Erie County occur where the lacustrine sequence is capped by beach strandplain deposits. The latter are associated with the Warren paleoshoreline in the central portion of each reach (Figure 1.11) near Lake City and North East. The strandplain unit is described by Knuth (2001) as a sequence of loose to medium-compact, yellow brown to grayish brown, stratified sands and gravels. These ancient beach deposits, dominated by sand and gravel, contain layers comprised entirely of well-rounded pebbles that mark former beach foreshore positions. In eastern Erie County, groundwater flow rates through this unit are significant, and localized zones of focused groundwater flow in high-permeability layers can cause sapping and piping at the bluff face. This process is believed to be a strong contributing factor to the development of large rotational slumps, which tend to be volumetrically best developed in this upper section of the bluff.

Holocene Soils

Soil classification at 1:12,000-scale by the Natural Resources Conservation Service (NRCS, 2015) shows that modern soil characteristics landward of the bluff crest do not vary significantly along the coast. However, there are local differences in soil characteristics between historically wooded and farmed areas, areas where highstand strandplain deposits are developed or not developed, and along lacustrine-plain sectors. This variability can affect bluff stability, stream flow, runoff, and groundwater recharge. This is because the degree of soil development and thickness influences the infiltration rate for precipitation. Soils can therefore influence how much precipitation is directed to surface runoff, to groundwater recharge, and to evapotranspiration. Soil composition also influences vegetation (species, plant density, root development, etc.) and therefore impacts the degree of bluff stabilization fostered by root development. In eastern Erie County, the principal soil types present are well drained (Ksat=2.5-50 cm/hr) loamy fine sands that dominate areas within 500m of the bluff crest, and moderately well drained (Ksat=0.2-0.5 cm/hr) fine sandy loams that dominate in areas more than 500m from the bluff crest.

Substrates, Water Content, and Bluff Failure Mechanisms

Each of the unconsolidated stratigraphic units along the coast has distinct geotechnical properties (e.g., angle of repose, degree of compaction, surface micro-topography, shear strength, etc.). These properties control how a stratigraphic horizon, and the bluff face as a whole, visually appears and which type of failure mechanism is most likely to occur (Figure 3.9). Vadose zone sediments (above the water table) at the top of the bluff often have the steepest slopes, usually 80-90^{0} with root-stabilized overhangs (90-120^{0}) occurring along short stretches (<50 meters) of bluff top. Earth falls (individual grains to blocks of several cubic meters) are the most common failure mechanism at this upper bluff location. Limited rill and gully development suggests that overland flow is an unimportant contributor to bluff instability on the upper bluff in these sandy sediments above the water table.

Below the elevation of the water table (in the phreatic zone), large (tens to hundreds of cubic meters) rotational and translational earth slumps (Varnes, 1978) are the most significant failure mechanisms (Figures 3.7, 3.9, and 3.10). They most commonly originate within the saturated sediments of the strandplain and lacustrine sections of the bluff. The headwall scarp marking the top of the failure surface of these slumps typically extends to the bluff top, while the toe of the failure surface typically daylights at or in the top of the glacial till (Figure 3.10). Daylighting of the slip plane at the sand-till contact suggests that pore-water pressures are high at the base of the lacustrine section, partly due to the large contrast in hydraulic conductivity between it and the less permeable, more-cohesive, underlying glacial till section. Erosional chutes occur in the underlying glacial till when a rotational slump or debris fall on the upper bluff supplies debris that abrades the lower bluff during downslope transport. Subsequent groundwater seepage into these chutes can allow further development of topography. Distant from active and paleo-slumps, bluff face sections may fail gradually over time via thin (<0.3 m) earth flows, thin translational earth slumps, sheet wash, and soil creep that often build small debris fans on the beach (Figure 3.9).

Based on a review of the PA DEP database of oblique coastal aerial photography, translational slumps (Figures 3.9 and 3.10) appear to be more common along the western coastal reach while rotational slumps (Figure 3.7) appear more common along the eastern coastal reach. The reason for this is unknown, but is likely due to differences in geotechnical properties and bluff stratigraphic geometry. The translational slump mechanism may also be favored when the bluff toe is over-steepened by wave attack which is most likely to occur in the western coastal reach where bedrock is often absent from the bluff profile. Stepped benches extending tens to hundreds of meters along-coast with headwall heights of meters are typical dimensions. These failures, unlike rotational slumps, do not necessarily deliver as much debris to the bluff toe, beach, or lake. They have the appearance of sequential and organized (but incomplete) slump activity where benches often remain relatively intact (Figure 3.10). The benched topography has the benefit of adding transverse topography to the bluff profile that reduces the opportunity for development of incised rills and gullies fed by surface runoff. For property owners, this type of failure in western Erie County is more likely to result in less landward retreat of the bluff crest during a failure event, but also to result in a greater along-coast impact. This contrasts with the rotational slump response (Figure 3.7) of greater headwall retreat but lesser along-coast extent that is more common in eastern Erie County. This latter mechanism is more prevalent in tall bluffs where bedrock is present in the bluff profile and where groundwater focusing at seeps and springs higher in the profile appears more prevalent.

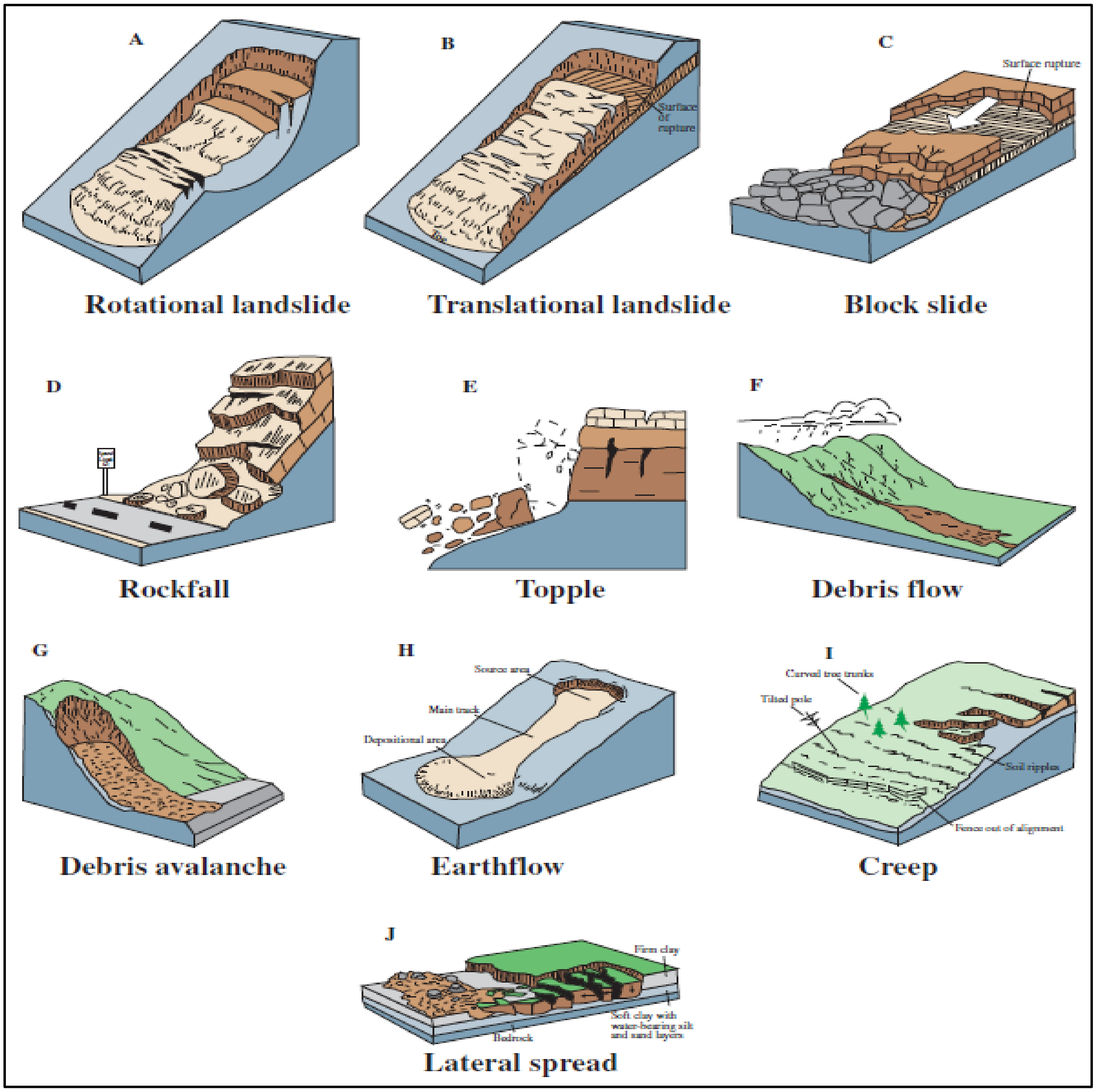


Figure 3.9: *Schematic summary diagram showing a general classification scheme for common bluff failure mechanisms (landslides). The scheme is based on material composition, the rate of movement, and the internal water content of the materials involved in the failure (Image: modified from Highland and Johnson, US Geological Survey Fact Sheet 2004-3072, 2004).*

Figure 3.10: *Oblique aerial photo showing a translational slump (slide) with a relatively linear bluff-crest headwall. The failure is developed in bluffs consisting of glacial tills and overlying lacustrine sands in western Erie County. Three sloping headwall scarps and two intervening sub-horizontal benches are visible. The lowermost headwall scarp at the shoreline also shows more recent earth flow and soil creep activity (Imagery collected in April 2015 and available from the Pennsylvania DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Littoral Sediment Budget for the Pennsylvania Coast

About 24% of the Pennsylvania coast is protected by coastal engineering structures placed in the nearshore, on the beach, or on the lower to mid bluff (Stewart, 2001). Coastal structures are significant because they interact with the supply, movement, and accumulation of sandy littoral sediments moving in the littoral zone. Morang et al. (2011) noted that a comprehensive coastal sediment budget was lacking for the Pennsylvania coast and that developing such a budget would be a key aspect of improving regional sediment management. A subsequent USACE sediment budget model for the US coast of Lake Erie (Cross et al., 2016) improved understanding of sediment budgets for Pennsylvania and for the region as a whole. In general terms, Pennsylvania's bluff coast is a sand-starved system due to the small volumes of sand supplied to and moving within and through the system. The entire coastal system can be defined by three large littoral cells that lie offshore of the western coastal reach, the central coastal reach (or Presque Isle strandplain), and the eastern coastal reach (Chapter 1; Knuth, 2001; Morang et al., 2011).

The breakwaters at Conneaut Harbor, Ohio, define the updrift end of the western littoral cell. Long-term average sediment transport around the Conneaut jetties towards the Pennsylvania coast is considered to be minimal (Knuth, 2001). Morang et al. (2011) estimated that littoral sediment transport across the OH-PA state line may have been as high as 4,500-11,000 m^3/yr during the 1990s. Ohio DNR (Figure 3.11) used bluff retreat rates (1990-2004) and general bluff composition data (e.g., a sand and gravel content of 19%) to estimate that each kilometer of Ohio bluff coast supplies an average of ~475 m^3/yr of littoral (sandy) sediment to the Ohio littoral zone (Jones and Hanover, 2014). This suggests that the ~1.5-2 km of Ohio coast east of Conneaut is supplied with

~1000 m^3/yr of littoral sediment from bluff retreat alone. This volume, supplemented by natural and anthropogenic bypassing of sand around Conneaut Harbor, then moves along the Pennsylvania coast. Because much of the bluff coast along Erie County's western coastal reach is similar (geotechnical properties; hydrodynamic forces; composition) to that of the eastern Ohio coast, a "back of the envelope" estimate suggests that bluff erosion along Pennsylvania's western coastal reach alone may supply ~17,000 m^3/yr of sandy material to the littoral system west of Presque Isle. This means that ~18,000-29,000 m^3/yr of sandy material derived from bluff retreat may exit the downdrift (eastern) end of the western littoral cell (at the west end of Presque Isle) during an average year. This volume would be augmented by any additional sand supplied from Pennsylvania streams, and by onshore transport of shale debris generated by nearshore erosion processes.

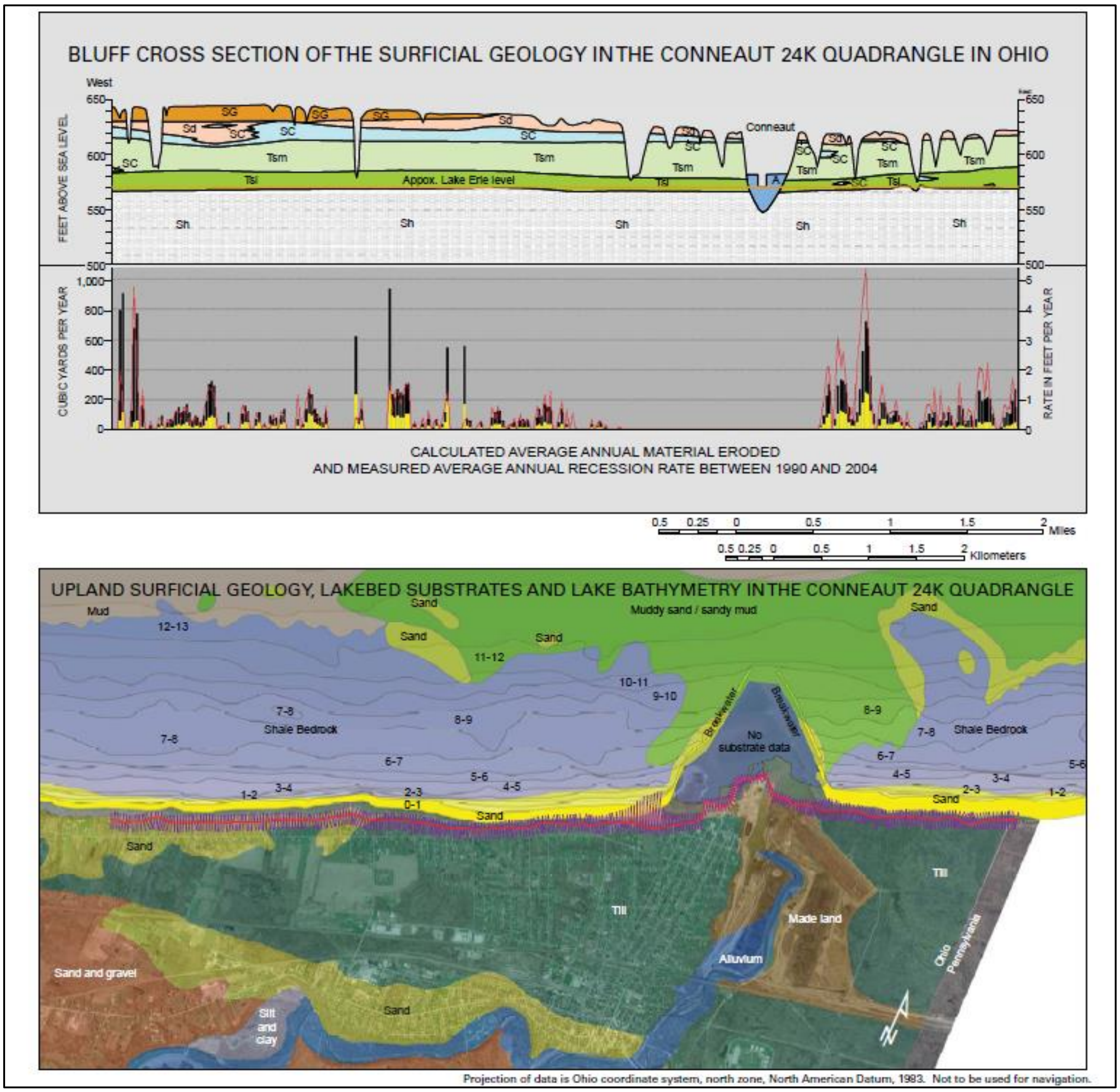


Figure 3.11: *This Ohio DNR image shows bluff-face stratigraphy, annual bluff retreat rates (1990-2004), sediment volumes input to the littoral zone, lake-bed and onshore geology, and bluff transect locations (33 m spacing) used for bluff mapping (Image: modified from Jones and Hanover, 2014; and Ohio DNR at http://geosurvey.ohiodnr.gov/Portals/geosurvey/PDFs/GeoNotes/GeoNote9.pdf).*

Morang et al. (2011) estimated bluff-sediment inputs along Pennsylvania's western coastal reach over three multi-decade time periods using bluff-retreat data: 1875-1938, 1938-1973/1978, and 1973/1978-2006. They estimated that the volumes of littoral sediment arriving at the west end of the Presque Isle strandplain for those three periods were 47,000 m^3/yr, 61,000 m^3/yr, and 39,500 m^3/yr, respectively. These volumes are interesting because of their variability: the three time periods corresponded to extended periods of lake regression (a ~0.75 m fall; rate ~12 mm/yr), transgression (a ~0.75 m rise; rate ~20 mm/yr), and a subsequent regression (a ~ 0.5 m fall; rate ~16 mm/yr). These volumes are also larger than those derived using the Ohio DNR approach above. However, they support the general contention that bluff retreat rates are commonly lower during falling and low lake levels than during rising and high lake levels. This is particularly true for coasts not protected by a bedrock toe and where hydrodynamic forces are therefore significant. A complicating factor in interpreting these numbers is that the Ohio coast saw a progressive increase in hard stabilization during the 1875-2006 time period (Fuller and Gerke, 2005).

The Erie harbor jetties at the east end of the Presque Isle peninsula define the downdrift end of the central (Presque Isle) littoral cell. The jetties and associated navigation channel are significant barriers to littoral sediment transport towards the eastern coastal reach. Nummedal et al. (1984) calculated that potentially 110,000 m^3/yr of littoral sand arrives at this area and at the adjacent Gull Point sand spit and shallow nearshore. Because nearshore sediment supply entering the west end of the Presque Isle littoral cell has been estimated to range from 30,000-61,000 m^3/yr (Nummedal et al., 1984; Knuth, 2001; Morang et al., 2011; Cross et al., 2016), a significant quantity of the sand arriving at the terminal end of this cell is derived from erosion along Presque Isle. This includes erosion of sand supplied by periodic beach nourishment (Foyle and Norton, 2006).

Littoral sediment transport along the eastern littoral cell is dependent on inputs from bluff retreat, nearshore (shale bedrock) erosion, and small streams. Bluff retreat along the eastern coastal reach is approximately two times slower than along the western coastal reach due to the presence of a relatively resistant shale bedrock toe (Chapter 1). Nearshore bedrock erosion rates should be similar to rates in the western coastal reach because nearshore slopes are similar which means similar areal coverages of lake bed are susceptible to wave shear stresses and abrasion forces. Stream sediment inputs on a per-stream basis should also be similar to the western coastal reach because the geomorphology is generally similar. However, the volumes of sand and coarser material presently supplied by streams in Erie County are not well known (see Buxton et al., 1982 for a discussion on New York streams). Data on littoral transport volumes in the eastern littoral cell are consequently scarce. Morang et al. (2011) estimated that late-1990s littoral sediment transport at the downdrift end of the cell was ~12,000 m^3/yr, similar to the volume that enters the Pennsylvania system at the Ohio state line.

Littoral sediment transport volumes on the Pennsylvania coast are of sufficiently low magnitudes that, when possible, artificial sand bypassing should be considered for any large coastal structures (e.g., marinas) that trap littoral sediments. Periodic artificial bypassing has already been conducted updrift of the western coastal reach at Conneaut Harbor, and near the downdrift end of the eastern coastal reach at North East marina near the PA-NY state line (Morang and Melton, 2001).

Chapter 4: State of Knowledge on Bluff Stability in the Great Lakes Basin and Lake Erie

Introduction

Cohesive coastal bluffs retreat due to a combination of natural and anthropogenic physical, chemical, and biological mechanisms. These mechanisms are active on and landward of the bluff crest, across the bluff face, and at the bluff base over a range of time and space scales (Foyle and Naber, 2011). In general, rates of bluff change are about 1-2 orders of magnitude lower than rates of change routinely recorded on sandy-beach coasts. Globally, a varying combination of subaerial (terrestrial) and hydrodynamic (marine or lake) factors influence the retreat of unconsolidated bluffs and rocky cliffs on the world's coasts (Emery and Kuhn, 1982; Sunamura 1983, 1992; Shih and Komar, 1994; Komar, 1998; Hampton and Griggs, 2004; Mickelson et al., 2004; Brown et al., 2005; Young et al., 2009a). In addition, groundwater processes in cliff retreat can be regionally important and have been discussed by Sterrett and Edil (1982), Laity and Malin (1985), Higgins and Coates (1990), Cherkauer and McKereghan (1991), Brien and Reed (2007), and Foyle (2014). Figure 4.1 illustrates typical bluff profiles found on the world's coastlines (Emery and Kuhn, 1982) while Figure 4.2 illustrates bluff failure mechanisms common on Great Lakes and oceanic coasts.

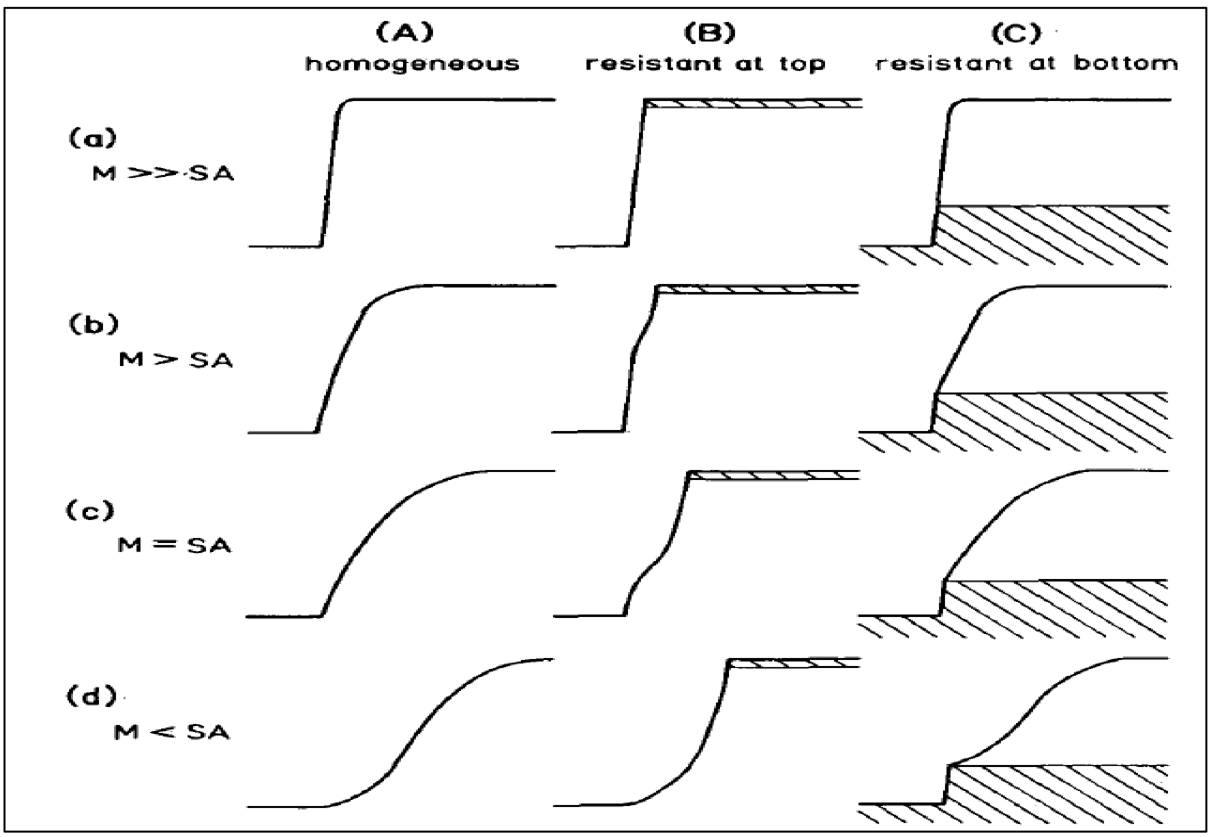


Figure 4.1: *Matrix showing general morphologic profiles of global cliffs and bluffs. Columns A-C denote general bluff stratigraphy: unconsolidated materials (no pattern) and bedrock (diagonal pattern). Rows a-d denote the relative importance of hydrodynamic processes (M) active at the bluff toe, and subaerial processes (SA) active on, within, and above the bluff. Bluffs along Erie County's western coastal reach are typified by Types A-a through A-c. Bluffs in the central and eastern coastal reaches are typified by Types C-a through C-d (Image: modified from Emery and Kuhn, 1982).*

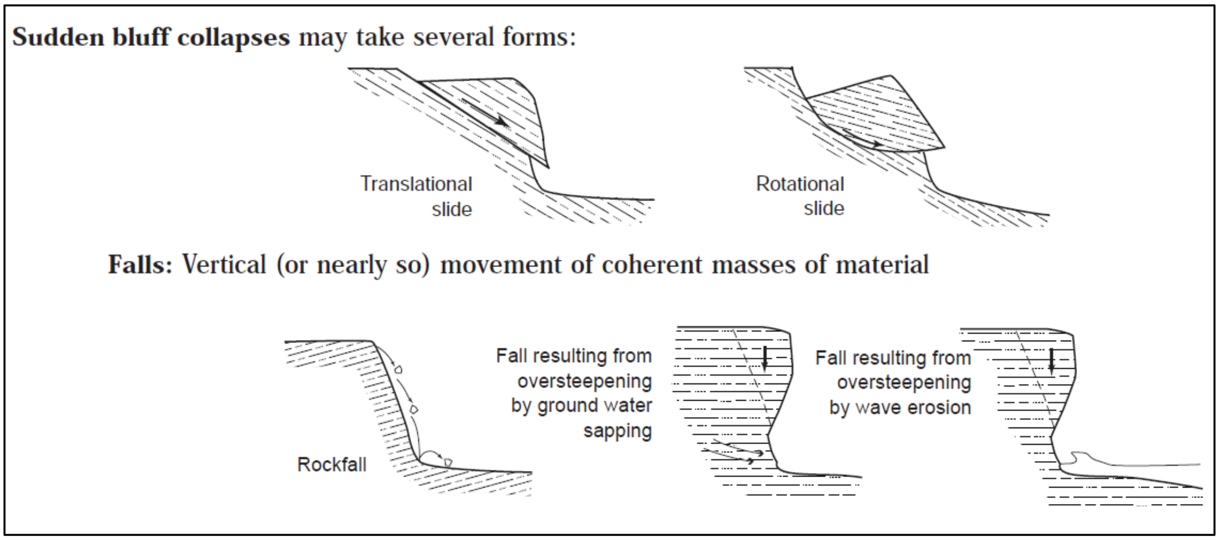


Figure 4.2: *Common, large volume, bluff failure mechanisms that occur on ocean, Great Lakes, and Lake Erie coasts (Image: modified from Johnsson, 2003).*

Factors that influence bluff retreat spatially and temporally along the Pennsylvania coast, as well as coastal cliff retreat in general, are summarized in Table 4.1. In Erie County, non-watershed related factors show along-coast variability, the principal factor being the presence (in eastern Erie County) or absence (in western Erie County) of a bedrock toe at the base of the bluffs. The degree of development of capping beach-ridge strandplain deposits also varies along the coast: they are locally present in the central parts of both the western and eastern coastal reaches, near Lake City and North East, respectively. These deposits are associated with the tallest bluffs and large rotational slumps. Along-coast variations in surface watershed size and relief, groundwater recharge volumes, topographic shielding of the bluff face from runoff, and groundwater fluxes at the bluff face, likely also play significant roles in along-coast variability in bluff-change rates. These factors are discussed in detail in the groundwater process study reviewed later in this chapter.

General Model of Bluff Retreat on the North American Great Lakes

On the Great Lakes, the general model of bluff erosion (Figure 4.3) is one of simple parallel profile retreat when observations are averaged over decades (Philpott, 1984; Davidson-Arnott, 1986; Bishop et al., 1992; Davidson-Arnott and Ollerhead, 1995; Trenhaile, 2009; Davidson-Arnott, 2016). This type of conceptual model assumes the bluff coast is in some form of dynamic equilibrium with hydrodynamic and subaerial processes over a time period of centuries to millennia. It is also assumed that there is an absence of stratigraphic complexity in the profile, that geotechnical properties are non-varying along the profile, and that bedrock is not present at the coast. However, under real-world conditions, these assumptions are almost always not met and this results in the wide range of bluff profile geometries that can be observed geographically (Figure 4.1). Conceptually, the coastal profile erodes vertically in the nearshore and horizontally onshore because the nearshore and bluff components of the bluff system are in dynamic equilibrium with a number of hydrodynamic and subaerial forces. Different types of bluff response occur at rates that may be slower than, match, or are faster than, changes occurring in the hydrodynamic and subaerial forcing mechanisms. For example, Baird (2003) and Brown et al. (2005), on the basis of modeling studies, noted that it takes at least 50 years for a bluff profile to return to dynamic equilibrium following a typical increase in lake level.

Hydrodynamic factors	Base-of-bluff factors	Bluff face and internal factors	Hinterland factors
Wave energy flux	Bluff engineering	Slope, height, strength	*Winter snow and ice cover*
Seiche, tide, storm and seasonal lake level change	*Beach volume, morphology, and composition*	Composition, dip and strike of internal layering	Land slope, orientation and topography
Storm surge height, duration and frequency	*Presence of logs/large debris/ coastal structures*	*Bedrock toe strength, height, relative dip*	*Bluff crest road/foot traffic*
Width of winter nearshore ice complex	*Wave energy shielding by deltas and bathymetry*	Groundwater sapping, piping	*Anthropogenic water additions near bluff*
Nearshore bathymetry	*Littoral sediment supply*	*Seasonal runoff and freezing*	Hydraulic conductivity (*k*)
Lake ice stress on bluff toe	*Presence/absence of beach sand and gravel*	*Bluff orientation (wind, waves, sun)*	*Land use: low-density urban, forest, agricultural*
Nearshore substrate composition	*Presence/absence of folds, joints, and faults*	Internal aquifer heterogeneity	Runoff:infiltration ratio
Regional long-term change in lake level	*Bedrock freeze–thaw weathering*	*Vegetation; wildlife nesting and burrowing*	Water table slope, orientation and topography
		Groundwater discharge through the bluff face	Volume of rainfall intercepted/m of coast

Factors most responsible for along-coast (spatial) variability in recession rates are shown in normal font, and those less responsible in italic font.

Table 4.1: *Principal hydrodynamic (ocean, lake) and subaerial (terrestrial, subsurface) factors contributing to bluff change on the Pennsylvania coast. Few process studies to date make it difficult to determine the importance of each process in space and time (Image: modified from Foyle, 2014).*

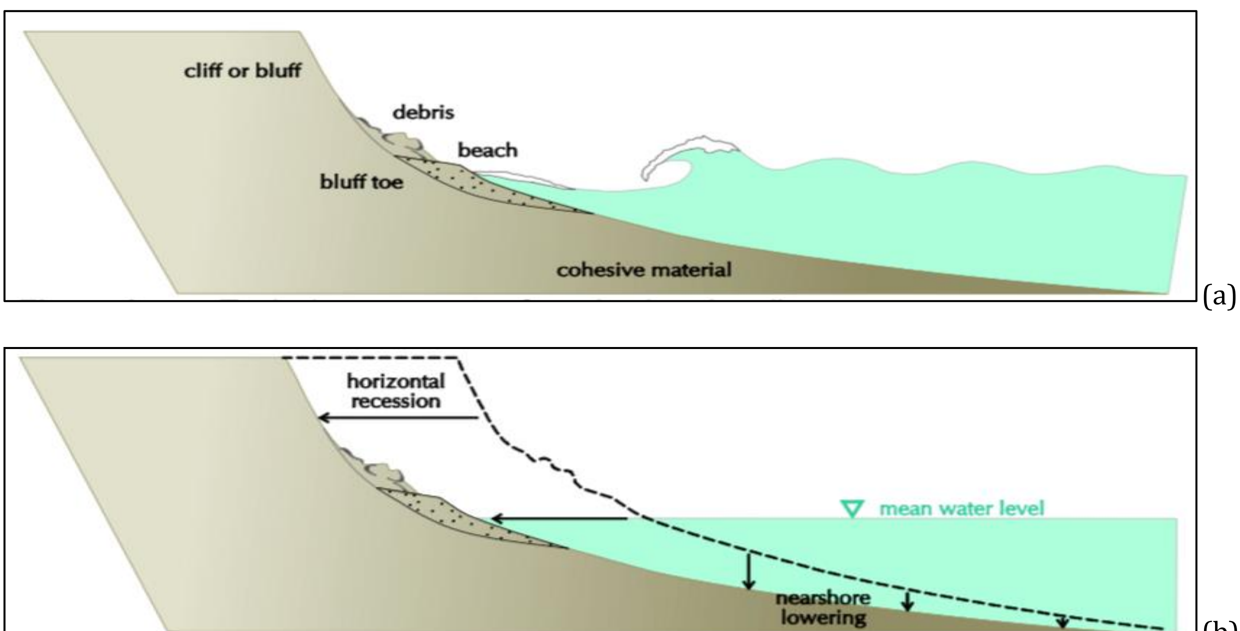


Figure 4.3: *Schematic diagram showing (a) the typical components of an unconsolidated (cohesive) coastal zone in the Great Lakes Basin where bedrock is absent and (b) the fundamental model of simple parallel bluff retreat. In this model, the nearshore and the entire bluff profile consist of cohesive materials without any stratigraphic complexity or variability in geotechnical properties (Image: modified from Geomorphic Solutions, 2010 and Davidson-Arnott, 2010).*

The generalized sequence of processes involved in the parallel-retreat model when averaged over long time periods is as follows:

- nearshore downcutting in water depths of less than 8-10 m
- bluff-toe erosion via abrasion, wave impact, and joint expansion
- bluff-face failure via several possible mechanisms ranging from soil creep to rotational slump
- accumulation of a protective colluvial debris apron following the slope failure
- reduction in the rate of bluff-face retreat because the slope has been reduced
- erosion of the colluvial apron by wave attack, longshore currents, and wave swash/backwash
- resumption of toe erosion

This general model is most likely not the norm for the Pennsylvania coast because the bluffs and nearshore on the Pennsylvania coast of Lake Erie are physically different than most other areas on the Lake Erie perimeter (Figure 4.4). The lower part of the bluff and/or the nearshore is often composed of resistant bedrock, and there is a shortage of littoral sediment in the coastal system. This means that wave shear stress on the lake bed, and abrasion of the lake bed and bluff toe by sand-charged waves and surf-zone currents (i.e., hydrodynamic processes), are less significant compared to locations such as the Lake Michigan coast of Illinois and the Lake Erie coast of Ontario.

Figure 4.4: *Map of Lake Erie showing the prevalence of cohesive coastlines as defined by the IJC International Upper Great Lakes Study (IUGLS). Pennsylvania is distinct from New York and Ohio based on its large percentage of cohesive coast compared to other coastal types (sandy, wetland, bedrock) (Image: modified from Geomorphic Solutions, 2010).*

At these other Great Lakes locations where glacial till defines both the bluff and nearshore lakebed, shear stresses due to waves and currents, and abrasion when there is a littoral sand supply, result in hydrodynamic forces being very effective at causing nearshore downcutting and bluff abrasion (Robinson, 1977; Nairn, 1986; Skafel and Bishop, 1994; Davidson-Arnott and Langham, 2000). Work by Davidson-Arnott and Langham (2000) suggests that weathering of the till lakebed during quiet periods can lead to enhanced erosion during storm periods. These processes in turn allow larger waves to reach the bluff, causing notch-cutting and over-steepening of the lower part of the profile, particularly if a volumetrically large beach is not present to limit wave run-up. Bluff-face failure is then more likely to occur, particularly when subaerial processes contribute to instability (Carter and Guy, 1988; Wilcox et al., 1998; Jibson et al., 1994; Trenhaile, 2007; Amin and Davidson-Arnott, 1995; Geomorphic Solutions, 2010). Subaerial processes are often a combination of:

- weathering during quiet periods which reduces the strength of the bluff-face
- rill and gully incision caused by natural and anthropogenic surface runoff
- rain-drop impacts, displacing individual sediment grains on the surface
- freeze-thaw or wet-dry cycling
- spring ice melt events, allowing infiltration of precipitation and reducing bluff-face strength
- groundwater discharge at the bluff face, reducing bluff cohesion
- tree toppling, etc.

Zuzek at al. (2003) proposed that bluff-failure mechanisms in the Great Lakes Basin can be grouped into two general categories. Shallow translational slides commonly occur in homogeneous bluffs, while rotational slumps tend to characterize composite bluffs with more complex stratigraphy (Figure 4.5). This finding concurs with similar findings by Quigley at al. (1976); Sterrett and Edil (1982); Eyles et al. (1986); Carter and Guy (1988); Amin and Davidson-Arnott (1995); and Chase et al. (1996). The Zuzek et al. (2003) model in Figure 4.5 is most applicable to bluff coasts with a cohesive, erodible, nearshore and can be expected to differ for coasts with bedrock nearshores.

Translational slides have a tendency to fail at a relatively consistent rate over time so that average annual retreat rates (AARRs) are likely to be similar for any comparative time periods in excess of a decade (Figure 4.5). Conversely, rotational slumps have a tendency to fail in a more punctuated manner so that AARRs for specific time periods will likely be more variable. Figure 4.5 shows that most of the bluff-crest retreat for the rotational slump scenario occurs between Time 2 and Time 3. Minimal bluff-crest retreat occurs during Time 1-2, and Time 3-4 even though the bluff slope is changing significantly. This is important for the Erie County coast because large bluff failures along the western coastal reach may be more likely to exhibit translational behavior while large bluff failures along the eastern coastal reach may be more likely to exhibit rotational behavior. This has implications for perceptions of retreat rates and retreat periodicity by the general public.

Also significant in the Zuzek et al. (2003) model is that the failure mechanisms can be characterized by a bluff failure cycle that may influence rates of measured bluff retreat during a monitoring period. A steeper initial bluff slope (for example, at the start of a monitoring program) is more likely to exhibit larger AARRs than a less-steep initial slope over the subsequent monitoring period. This phenomenon occurs because (i) steeper bluffs are in general more likely to fail than less-steep bluffs that are near a stable slope angle; and (ii) less-steep slopes may need significant over-steepening by wave-induced toe erosion before they fail and cause a significant landward jump of the crest. Brown et al. (2005) suggest that such failure cycles may have a period of ~50 years.

Review of Prior Research on Pennsylvania Bluff-Change Rates and Processes: Rate-of-Change Studies

Prior bluff research on the Pennsylvania coast has primarily focused on monitoring bluff retreat in order to acquire data that can be used to (i) estimate future bluff-crest locations, and (ii) help define construction setback requirements. There has been very limited research on the process-response characteristics of Lake Erie bluffs, and this represents a data-gap that should be addressed to improve hazard management. In addition, geotechnical data for the bluff sediments in Erie County are extremely sparse because, historically, the larger focus of coastal research on the Lake Erie coast has been on beach erosion, land loss, and navigation issues associated with Presque Isle, Pennsylvania's only beach strandplain. In addition, quality records from water-well and gas-well drilling, which are common sources of subsurface information, are focused on Devonian bedrock targets and not on the overlying Quaternary unconsolidated strata of which bluffs are primarily composed. As a result, information on unconsolidated Quaternary sediments was either not collected, or was recorded in cursory form, because the emphasis was on tracking the depth to the Quaternary-Devonian bedrock unconformity (which impacts drill-casing requirements). Record-keeping standards have also changed over time with the result that the data-content deteriorates progressively for older wells. The most thorough geotechnical analysis of bluff materials for slump-remediation purposes was conducted as part of a slump-remediation project on the south side of Presque Isle Bay (Urban Engineers, 2004), data from which are briefly reviewed in Chapter 3.

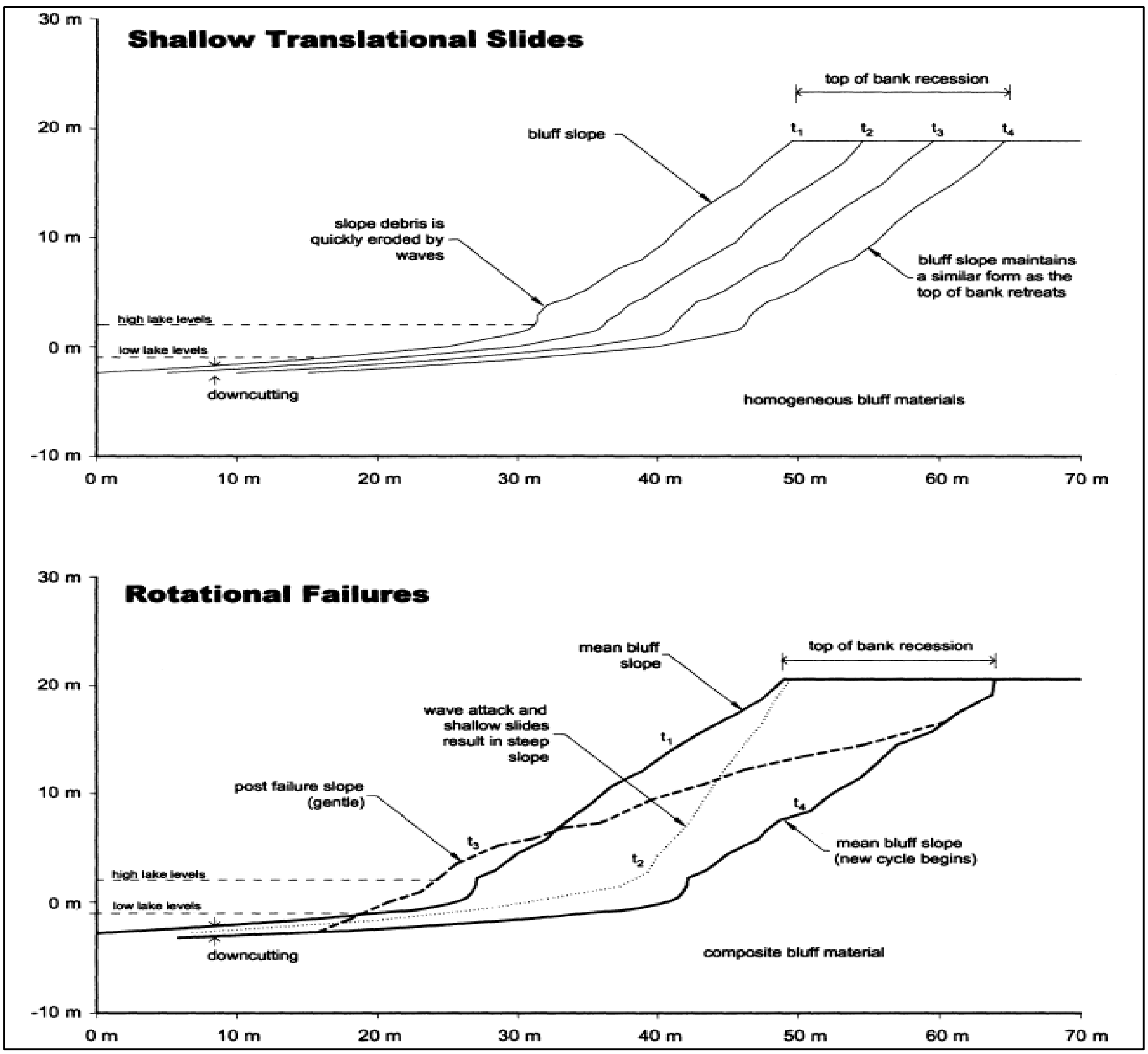


Figure 4.5: *Schematic diagram showing two principal failure modes for unconsolidated bluffs in the Great Lakes Basin: (a) shallow translational slides and (b) rotational failures (slumps). Note the relative bluff-crest positions during time steps 1 to 4 (Image: modified from Zuzek et al., 2003).*

Based on studies completed to date, long-term bluff retreat rates (over decades) along the Pennsylvania coast of Lake Erie grossly average about 0.25 m/yr with significant spatial and temporal variability. PA DEP, specifically, notes that the average based on the most recent control point monitoring (for the whole coast) is 0.16 m/yr (0.54 ft/yr). The municipal averages range from 0.1 m/yr (0.30 ft/yr in Millcreek Township) to 0.3 m/yr (0.96 ft/yr in Springfield Township). These rates of change are comparable with lake- and ocean-coast rates elsewhere in the US. They are relatively small when compared to the magnitudes of the possible errors inherent in some of the older methods used to measure those rates. Pope et al. (1999) compiled a regional-scale map of bluff change (1:2,000,000 scale) for the entire Great Lakes shoreline and reported bluff recession rates on the Pennsylvania coast that ranged from 0-1 m/yr.

The PA DEP Coastal Resources Management Program began monitoring bluff retreat using transects at established ground-control points beginning in the mid-1970s. Original monitoring work was begun by PA DEP (formerly DER) in 1974 and is reported in Knuth and Crowe (1975). In that study, prior to the establishment of long-term monitoring control points, recession rates were estimated using photogrammetric analysis of historical aerial photographs from 1938, 1950, 1959, 1969, 1974, and 1975. These rates were then used to delineate initial construction setback areas for the Lake Erie coast. The scale of imagery for all years but 1974 and 1975 was a relatively coarse 1:20,000, with the scales of the 1974 and 1975 imagery being 1:14,000 and 1:24,000, respectively (Knuth and Lindenberg, 1995). The 1938-1975 dataset was analyzed using eighty-nine transects along the western and eastern coastal reaches, resulting in a sample point approximately every 0.67km. Knuth and Lindenberg (1995) reported that recession rates for the 37-year record varied from 0.04 m/yr (0.13 ft/yr) to 1.4 m/yr (4.39 ft/yr). With anomalies removed from the data, the average retreat rate for eighty transects along the coast was 0.27 m/yr (0.87 ft/yr).

Long-term control-point monitoring transects were established by PA DEP beginning in 1982 and 1986 in order to field-map bluff crest positions. Georeferenced control points were established at ~500m intervals along the coast. In the 1982 study, a geotechnical component also collected information on bluff height, bluff angle, bluff shape, shape of the crest, general stratigraphy, beach topography, and nearshore bathymetry. Distances from control points to the bluff crest continue to be measured on average every four years using a measuring tape and compass bearing (Knuth and Lindenberg, 1995). Because the errors in this direct field-survey method are likely small (<0.05 m/yr), calculated multi-decade bluff-change rates are likely to be very accurate, but applicable only at and near the widely spaced locations from which they are collected. Knuth and Lindenberg (1995) note that the data generated by PA DEP monitoring has not been as usable as it should be because of inconsistencies in reporting and because data from areas between the widely spaced control points were not collected even if change was significantly different from that seen at the nearby control point transect.

In a study to determine sediment contributions to Lake Erie by eroding bluffs, Knuth (2001) delineated fourteen bluff segments along the Pennsylvania coast excluding the central (Presque Isle Bay) coastal reach. The segments average 4.25 km in length (range: 3.5 – 6.2 km) and were defined on the basis of similarity in bluff characteristics (slope, height, beach development, stratigraphy, etc.). Segments 1-8 lie in the western coastal reach (Ohio state line to the west end of Presque Isle; 35.5 km) while segments 9-14 cover the eastern reach (Presque Isle Bay entrance to the New York state line; 28.6 km). Historical data from this study are shown for context in Figure 4.6 and Table 4.2 where average bluff retreat rates are organized by PA DEP control-point transect and by transect groups (coastal segments) for the entire coast excluding Presque Isle Bay.

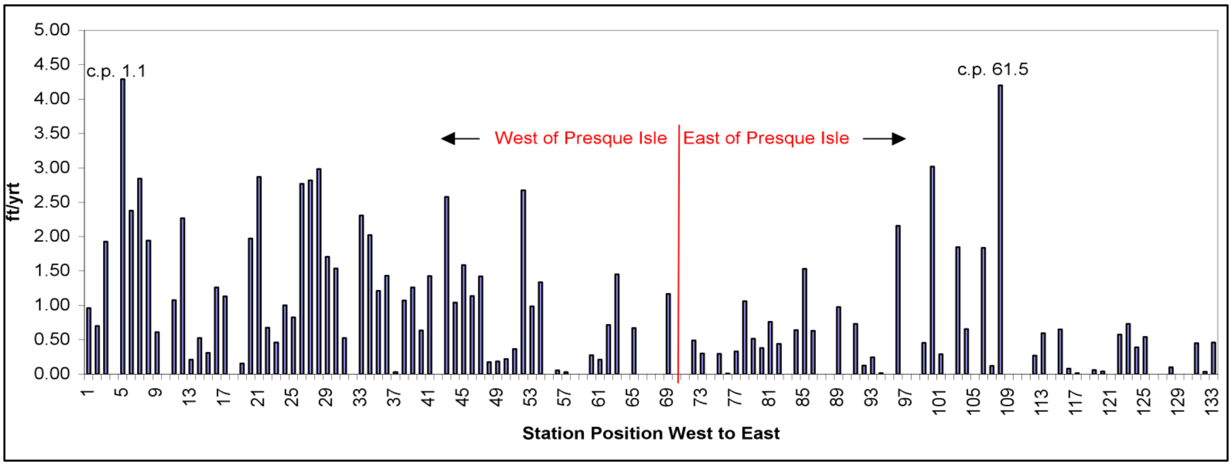


Figure 4.6: *Historical (1982-1998) average bluff-crest retreat rates by transect (ft/yr by PA DEP control point) for Erie County. Rates are derived from 18 years of data coverage, collected every ~4 years from transects spaced at ~0.5 km intervals. A known difference in retreat rates between western and eastern Erie County is apparent (Image: modified from Knuth, 2001).*

Seg	Cont. Pt.	Length		Ave. Rec.
	Range	feet	meters	Rate m/yr
1	*0.0-2.0*	14000	4267.20	0.666
2	*2.5-7.5*	15800	4815.84	0.285
3	*8.0-13.5*	16000	4876.80	0.502
4	*14.0-17.0*	16000	4876.80	0.328
5	*15.5-21.0*	12000	3657.60	0.366
6	*21.5-25.5*	15000	4572.00	0.288
7	*26.5-29.5*	11600	3535.68	0.056
8	*30.0-33.5*	16200	4937.76	0.125
9	*44.1-48.0*	15900	4846.32	0.115
10	*48.5-53.0*	17000	5181.60	0.265
11	*53.5-59.0*	16400	4998.72	0.207
12	*59.5-64.5*	20400	6217.92	0.234
13	*65.5-69.0*	12800	3901.44	0.082
14	*69.5-73.5*	11400	3474.72	0.088

Table 4.2: *Historical (1982-1998) average annual bluff retreat rates (m/yr) from Knuth (2001) for 14 coastal segments on the Lake Erie coast excluding Presque Isle Bay. Each segment rate represents the average of several transect (PA DEP control point) rates shown in Figure 4.6. These 16-yr averages are derived from bluff-crest measurements between 1982 and 1998. Retreat rates west of the Presque Isle reach (Segments 1-8) are notably greater than those to the east (Segments 9-13) (Image: modified from Knuth, 2001).*

Subsequently, Pennsylvania CRMP utilized historical aerial photography from 1938, 1959, and 2000 to determine rates of bluff retreat along the entire Pennsylvania coast. Over the six-decade period, crest retreat averaged 0.18 m/yr (PA CZM, 2004). That study sampled the aerial photo data using transects spaced at ~33 m (100 ft) intervals with the goal of predicting future bluff-top position for coastal zone planning purposes. The results of that study were ultimately used as the most recent basis for updating BRHA designations. The study used several related datasets to calculate rates of bluff recession and identify potential BRHAs: (i) high-altitude aerial photography;

(ii) low-altitude oblique-angle aerial photography; (iii) beach-level bluff face photography; (iv) on-site inspections; and (v) historical data from PA DEP control point monitoring. However, as described by Moore (2000), mapping linear features on older aerial photos, such as bluff edges on the 1938, 1959, and 2000 era photos, is susceptible to errors. These are associated with photo rectification (reported as 0.86 m for the 2000 photos), radial distortion (potentially +/-0.11 mm at photo scale), tilt (potentially +/-0.68 mm at photo scale), and digitization of the feature of interest on the hard-copy photo or the on-screen version (potentially +/-0.23 mm at photo scale). Consequently, with aerial photo scales of 1:20,000 (1938, 1959) and 1:3,600 (2000), the total spatial errors associated with the annual bluff-change rate in the PA CZM (2004) study may be quite large, as high as +/-0.36 m/yr when annualized (Foyle and Naber, 2011).

Figure 4.7 shows a typical map product from the PA CZM (2004) study wherein rates of bluff change were derived for a time period of as long as 62 years (using aerial photography from 1938, and aerial photography and control-point monitoring data through 2000). The bluff sampling interval is relatively coarse at 33 m (100 ft) and is partly why the line-segment trace of the bluff crest on the project maps does not closely track the typical curvilinear bluff crest geometry seen in the aerial photo (1996) underlays (Figure 4.7). The well-inland location of the predicted 2050 bluff crest on the Springfield Township coast shown in Figure 4.7 reflects the relatively high average long-term rates of bluff retreat in this area where bedrock is absent from the toe of the bluff.

Engle and Malone (2008) utilized 1998 and recent but low-quality 2006 LiDAR data on a 10 km stretch of coast in western Erie County (near Elk Creek) to map short-term bluff retreat rates. Results showed that retreat averaged 0.16 m/yr in that area. The bluff edge in that study was prone to positional and interpolation errors in the LiDAR data and generated TIN surfaces, as well as to a small bluff-edge digitization error. Because the 1998 and 2006 data had horizontal errors of +/-0.8 m and +/-1.5 m, respectively, summing the errors in quadrature (Hapke and Reid, 2007) results in annualized rate errors that may be as high as +/-0.2 m/yr.

Hapke et al. (2009) utilized 1938 aerial photos from the PA CZM (2004) study with 1998 and 2006 LiDAR data to estimate bluff-retreat rates along the entire coast over an almost seven-decade time frame (Figure 4.8). The authors are careful to point out that the results of the pilot study, which was part of the US Geological Survey NACCH program (Chapter 2), are not intended for predicting future rates of retreat. Due to limitations in temporal data overlap, the area studied covered just 32 km of a 60-km stretch of Lake Erie coastline. The average rate of coastal bluff retreat over 6-7 decades was 0.3 ± 0.1 m/yr, based on data averaged from 1,595 individual transects spaced at 20 m intervals. Retreat rates generally were lowest where a bedrock toe was present, and highest adjacent to sites of human activities (e.g., groynes, jetties; extensive irrigation on the bluff plateau). Their bluff edge picks were subject to positional, DEM-interpolation, and bluff-edge digitization errors associated with the 1998 LiDAR data; and to larger photo rectification, radial distortion, tilt, and bluff-crest digitization errors for the 1:12,000-scale 1938 aerial photos.

Hapke et al. (2009) were also able to derive average bluff-retreat rates individually for the eastern and western coastal reaches of Erie County (Figure 4.8). For both reaches, the maximum rate of calculated bluff retreat was ~1 m/yr and occurred where bluffs were highest. For the eastern reach, the average bluff retreat rate was 0.2 ± 0.1 m/yr over a 60-year time period (1938-1998). However, while the eastern reach is ~28.6 km in length, many data gaps for one or both of the end-years resulted in the rates being determined for only 4.7 km of coastline. For the western reach, which is ~35.5 km in length, the average rate of bluff retreat was 0.3 ± 0.1 m/yr over a 68-year time period (1938-2006). However, because of data gaps, bluff retreat rates were calculated for only 27 km of coast.

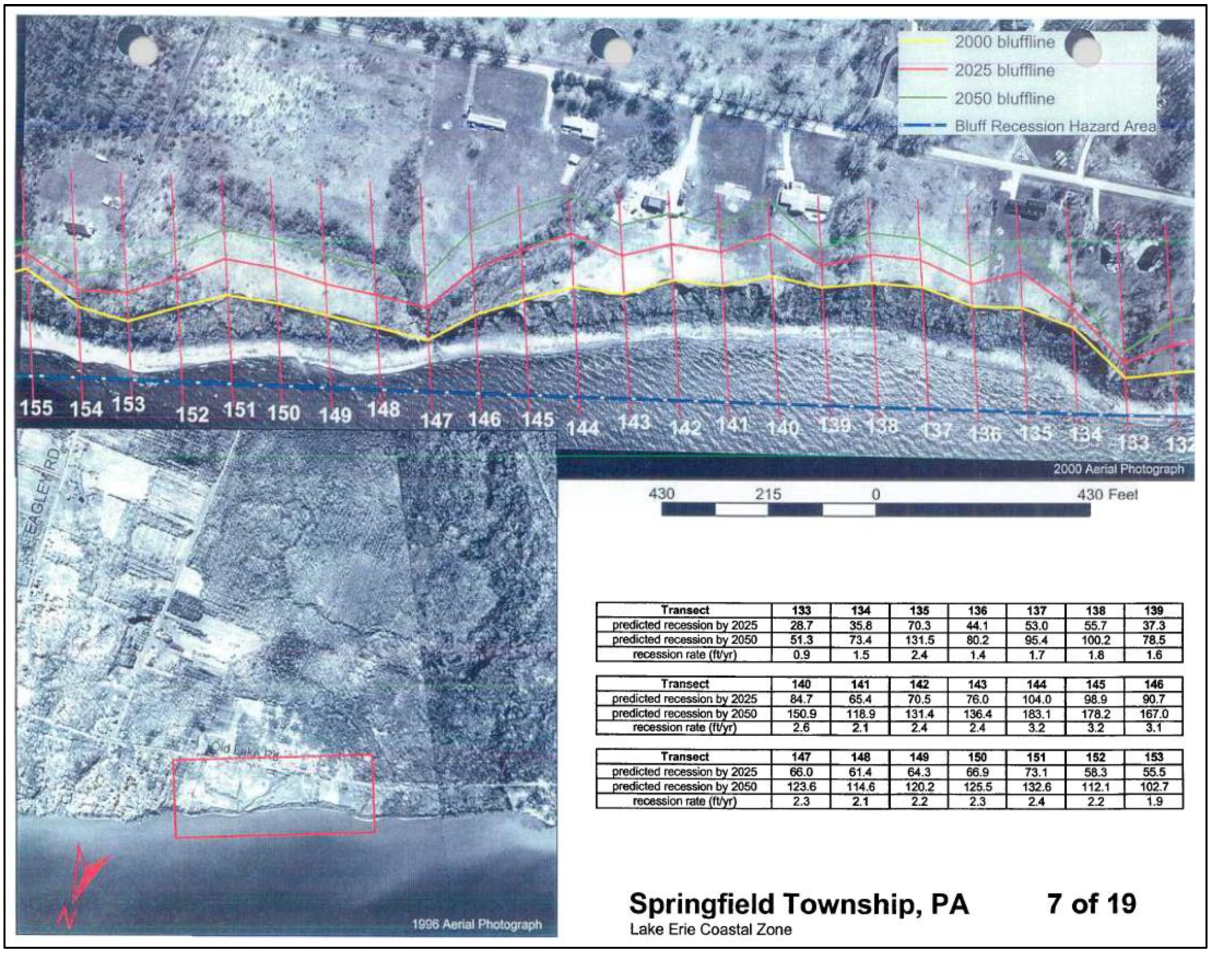
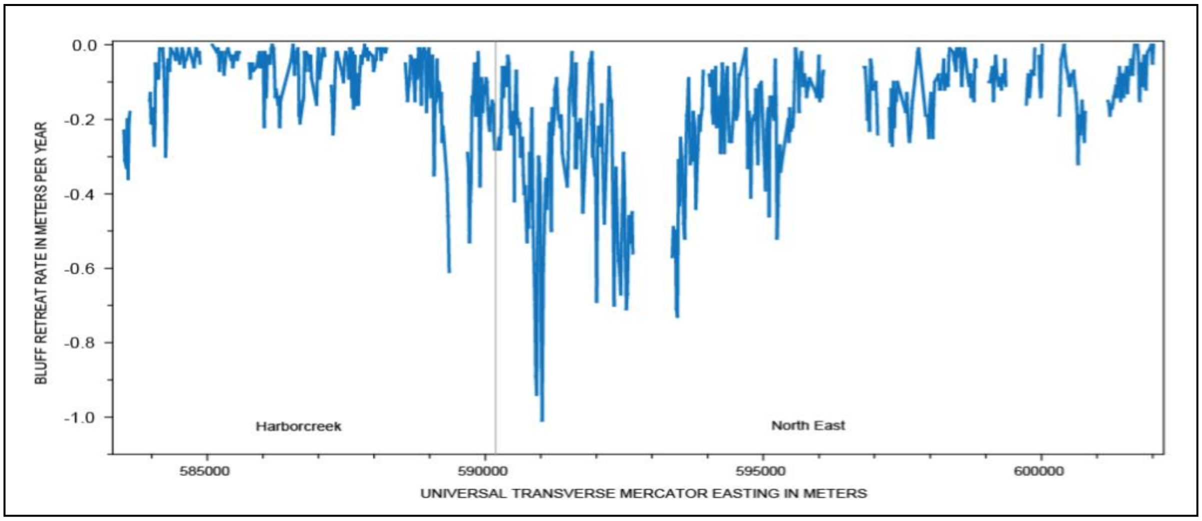
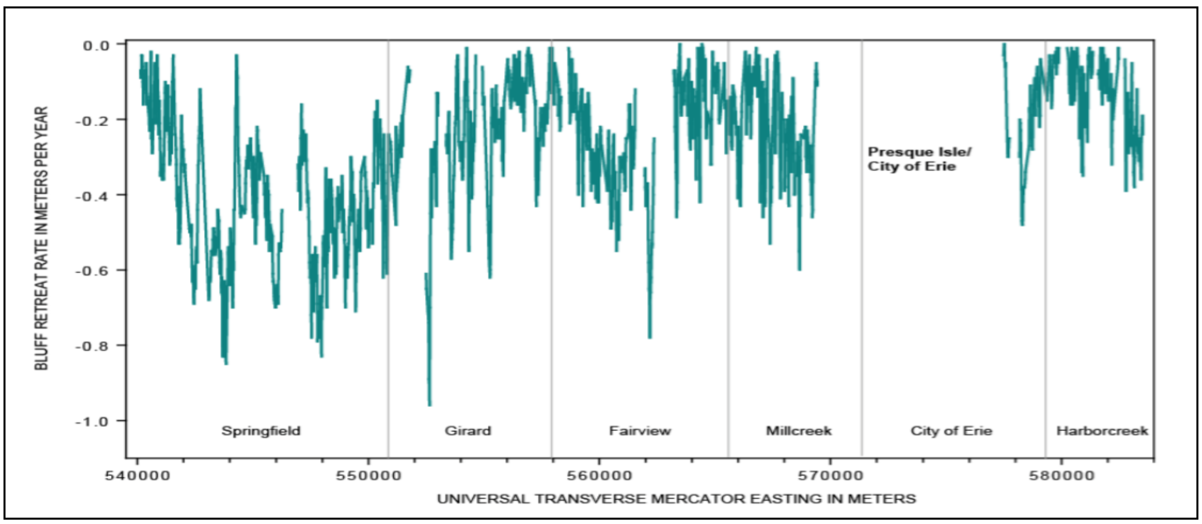


Figure 4.7: *Screenshot of a map product from the PA CZM (2004) study showing location of the bluff crest in the year 2000, and predicted bluff-crest positions in 2025 and 2050 in Springfield Township, western Erie County. The analysis used a 33 m (100 ft) transect spacing for mapping and prediction purposes which explains the unrealistic straight-line segment appearance of the bluff lines (Image: available at Pennsylvania CRMP website at http://www.dep.state.pa.us/river/reference/brha.htm).*

Foyle and Naber (2011, 2013) and Foyle (2014) examined bluff change and the significance of groundwater as a driving process of change over a one-decade period (1998-2007) in eastern Erie County (Figure 4.9). They demonstrated that bluff recession is spatially variable at decade time scales, and that the rates were of comparable magnitude to the longer-term rates of Hapke et al. (2009) in the same area. At the eastern Erie County coastal sites of Foyle and Naber (2011) and Foyle (2014), about 85% of the bluffs exhibited retreat, while 15% showed stability, minor progradation, or minor retreat (partly masked by the mapping methodology). Average-annual change rates had a significant range, from 0.98 m/yr (progradation; due to anthropogenic influences) to -4.3 m/yr (retreat). Large slump events during periods of increased soil saturation can cause over 20 m of bluff recession in less than a month.



(a)



(b)

Figure 4.8: *Bluff-crest average annual retreat rates (m/yr) for (a) eastern and (b) western Erie County. Retreat rates are shown using negative numbers and are derived from a maximum of 68 years of data coverage (1938 aerial photos to 2006 LiDAR) using an EPR (end-point-rate) method within DSAS (Thieler et al., 2005). The difference in bluff retreat rates between western and eastern Erie County remains very apparent over this longer timeframe when compared with the Knuth (2001) study (Image: modified from Hapke et al., 2009).*

In summary, bluff-change studies on the Pennsylvania coast to date have primarily focused on the question of how much (and where) erosion has occurred in the past and is, by extrapolation, likely to continue occurring in the future. Results indicate that, regardless of the time duration covered, there exists a high degree of spatial variability in bluff-retreat rates (Figure 9.10). This is to be expected because bluff stratigraphy and geotechnical properties typically show spatial variation over short distances of 10s to 100s of meters due to changes in materials and in depositional and post-depositional processes (from grain size distributions and sedimentary mega-structures to fracturing and groundwater-induced piping). In addition to spatial variation, the geotechnical properties of the bluffs (such as possible slip plane geometries, shear strength, permeability, compressibility, degree of cohesion, stable slope angle, etc.) can also show temporal variation due to changes in groundwater pore pressures, runoff volumes, snow loading, seasonal rainfall patterns, and degree of beach buttressing. Any generalized models of bluff behavior, therefore, cannot yet be expected to be very accurate at the individual-property scale now, nor in the future, unless the processes and architectures responsible for bluff retreat patterns can be better constrained.

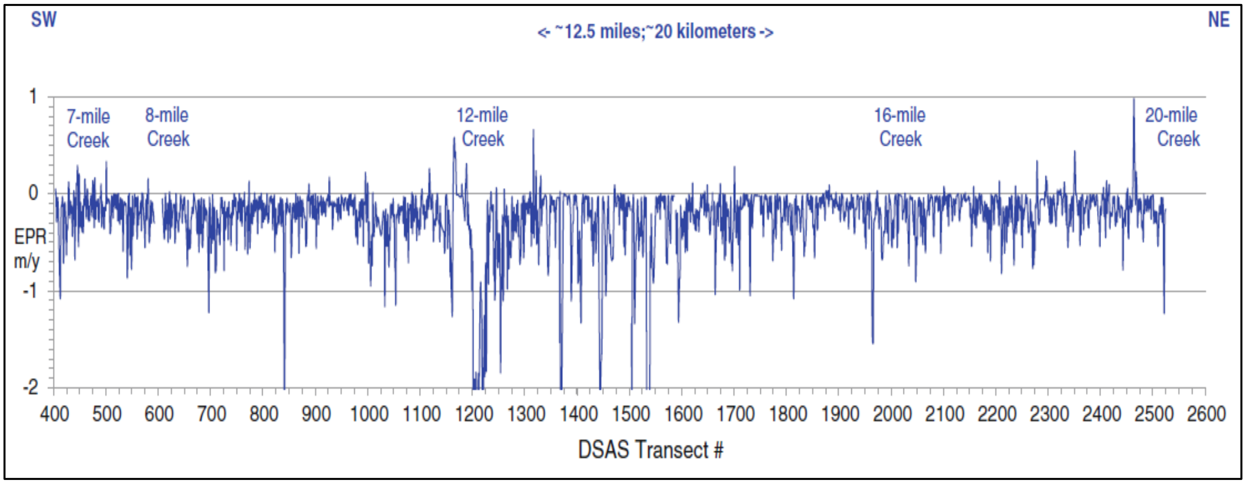


Figure 4.9: *Average annual bluff-crest retreat rates (m/yr) for the coast between 7-Mile and 20-Mile Creeks in eastern Erie County. Retreat rates are shown using negative numbers. Rates are derived from a maximum of 9 years of data coverage (1998 and 2007 LiDAR) using the EPR (end-point-rate) method within DSAS and a 10 m transect spacing. Retreat rates are greatest (most negative) where the bluffs are tallest, which occurs where the Quaternary beach-ridge stratigraphic sequence intersects the coastline near North East, between DSAS Transects 1200 and 2000 (Image: modified from Foyle and Naber, 2013).*

These issues of scale, property, and process continue to pose a conundrum for municipalities both in Pennsylvania and nationwide. An average set of geotechnical properties derived from limited sampling of an entire coast, or of a large sector on that coast, will in all likelihood not match those on the ground where a building setback distance may need to be established. The converse argument is also true, wherein applying lessons learned at a small number of specific sites to larger stretches of coast is not yet practical. Consequently, an increasing number of municipalities (in California, in particular) are beginning to recommend or require a site geotechnical investigation by a licensed civil engineer or engineering geologist when determining construction setbacks on the bluff as part of a construction permit application. Over long time periods, this parcel-by-parcel approach to acquiring data on bluff geotechnical properties is one feasible way to fill in the geotechnical-data gap for any particular municipality's bluff coast. However, the process is slow and dependent on the frequency of construction-permit applications. This approach has the added societal benefit that the costs of such data acquisition are borne by the property developer and not by existing residences elsewhere in the municipality.

To date, process studies and process-response modeling studies on bluffs have been limited, with a tendency to be focused on specific sites where major investments are being considered (e.g., D'Appolonia, 1978). This makes it difficult to determine the importance of non-linear subaerial and hydrodynamic processes over space and time. An ongoing challenge in coastal hazard management generally is thus to correctly identify the governing physical processes, and the relative/absolute importance of those processes, that are responsible for coastal change. Understanding these processes and the specific geotechnical properties that work with or against them, to a degree that permits accurate coastal-change prediction at near property-parcel scales, remains a challenge. In settings including the Pennsylvania coast of Lake Erie, historical retreat rates have been mapped to varying degrees of precision that are dependent on the quality of coastal-change data and on the analytical methods used. In general, both have improved over time, but this has led to a temporary short-term bias in information derived from high-quality data. However, this short-term bias will eventually resolve itself if high quality data such as coastal LiDAR continue to be collected on multi-year cycles. Conversely, improving the accuracy of forecasting future bluff-crest positions is in a state of relative infancy, but recent applications of Bayesian statistics to this and similar problems is proving productive (e.g., Hapke and Plant, 2010).

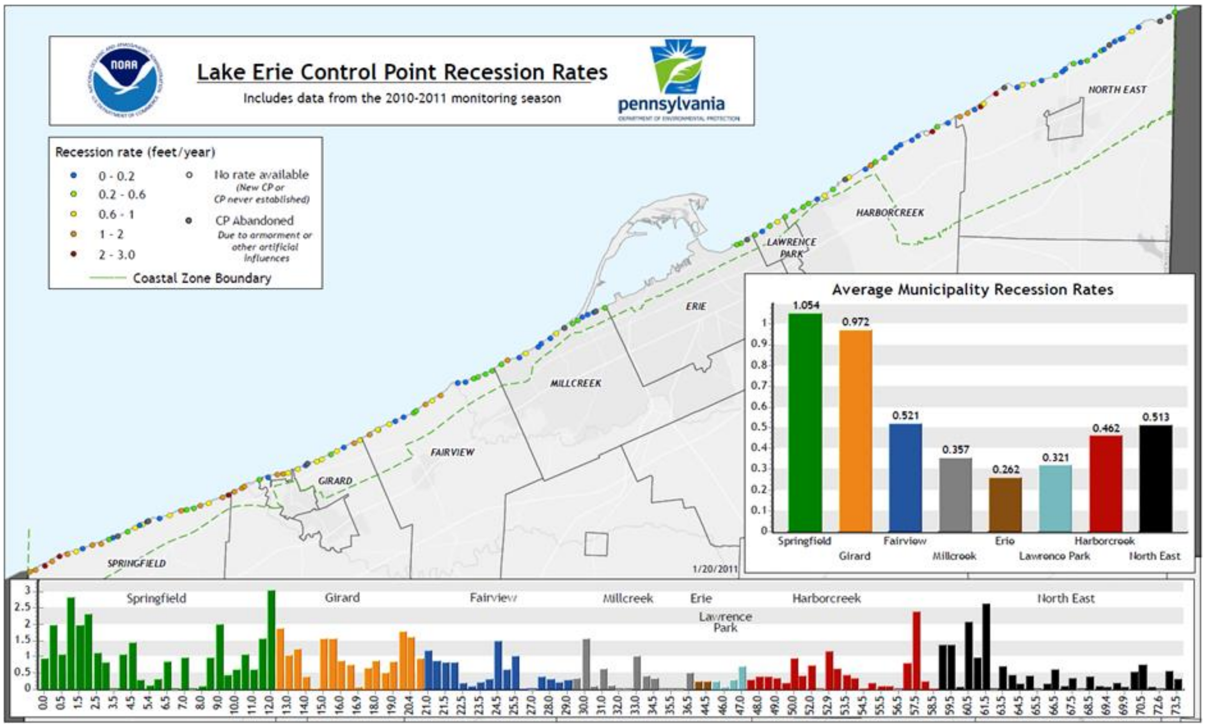


__Figure 4.10:__ Along-coast variability in average annual bluff-crest retreat (recession) rates in ft/yr. The averages are derived from almost three decades (1982-2011) of control-point monitoring of the bluff crest in Erie County by PA DEP (Image: modified from Moore, 2016).

Examination of the dominant forces causing bluff retreat in Pennsylvania is limited to very few process studies with the result that current government-agency statements concerning the causes of bluff change are understandably generalized because they depend on process information from bluff coasts in general. Recent work in eastern Erie County by Foyle and Naber (2013) and Foyle (2014), reviewed below, and elsewhere in the Great Lakes (Cherkauer and McKereghan, 1991) has specifically examined the significance of groundwater discharge at the bluff (and cliff) face as a driver of bluff change for different geomorphic and topographic settings. Other contributing factors, such as those listed in Table 4.1 above, have not yet received much attention on the Pennsylvania coast. Elsewhere in the US, such as in California in particular, the role of groundwater as a driver of bluff instability is recognized. However, its role has not yet been incorporated in modeling because of the difficulty of doing so (see Hapke and Plant, 2010) and because its role is often secondary to the much more significant hydrodynamic driving forces active on the Pacific coast.

Review of Prior Research on Pennsylvania Bluff-Change Rates and Processes: Process Studies

Groundwater Setting

On most coasts, including Pennsylvania, groundwater in the coastal zone is known to influence erosion rates beneficially as well as adversely (Edil and Vallejo, 1980; Lee et al., 2001). On sandy coasts, for example, an elevated water table can result in groundwater discharge on the beach profile, allowing ephemeral drainage networks to develop on the beach face between successive high tides. Additionally, high pore pressures in the shallow subsurface can enhance beach-erosion rates by reducing the shear strength of the sand. Beach dewatering has been tested on several US beaches (e.g., Massachusetts) with some success but has not been widely adopted, partly for aesthetic reasons. Dewatering by groundwater pumping is also an accepted engineering approach used to reduce the risk of landslides in coastal and other steep-slope settings (Chapter 6). A series of groundwater extraction wells is typically installed in the area behind a landslide-prone slope in order to intersect the saturated zone below the water table and extract groundwater to increase sediment shear strength and/or induce "lock-up" of potential slip surfaces. The method was recently considered, but not adopted, for the Ferncliff Beach bluff failure site on Presque Isle Bay (Urban Engineers, 2004) and has been considered for use at numerous locations in New York, California and Washington.

On the Pennsylvania coast, groundwater is suspected to play a large role in bluff failure events, particularly in high-bluff areas where a bedrock toe limits the amount of slope over-steepening (which decreases slope stability) that may occur due to scour by wave forces (Foyle and Naber, 2011, 2013; Foyle, 2014). The effects of increasing groundwater volumes in bluff sediments can be observed following the spring enhanced-precipitation period when increased bluff face seepage and sapping occur due to raised groundwater tables. Large groundwater discharge rates of 3-6 liters/min occur at slump headwall springs which occur at localized sites on the bluff face (Foyle and Naber, 2013). Water discharging through high-permeability zones within the strandplain (beach ridge) sands and gravels near the top of the bluff, or at the contact between the lacustrine sand section and the underlying glacial tills lower on the bluff face also enhances sediment mobilization. Dispersed groundwater discharge at slow rates leads to soil creep and thin translational slides over larger areas of the bluff face (Foyle, 2014).

In Erie County, groundwater is present within both the Devonian bedrock and within the overlying Quaternary glacial tills, lacustrine, and strandplain sediments (Richards et al., 1987; Buckwalter et al., 1996) that constitute the Quaternary aquifer system. Away from joints and faults, the bedrock forms an effective basal aquitard for the aquifers within the unconsolidated Quaternary section. As a result, groundwater may be forced to exit the bluff face at the bedrock/till contact. In bedrock areas with joints and faults, groundwater may be exchanged between unconsolidated bluff materials and bedrock aquifers. The prevalence and significance of jointing and faulting in groundwater exchange (which leads to bluff instability) is not well known on the Pennsylvania coast because these structures have not yet been mapped. Median yields from wells in glacial tills are about five times smaller than the yields of shallow wells in the overlying sandy lacustrine and beach-ridge deposits which can yield 284 liters/min (Richards et al., 1987). In coastal Erie County, water levels in these latter wells are highest in spring and lowest in fall, and lie at a median depth of about 4 m. At the bluff face where these aquifers crop out, groundwater pore pressures in the bluff section below the water table can influence bluff stability positively when pore pressures are low, and inter-grain cohesion is enhanced. Alternatively, there can be a negative effect when pore pressures are high, because inter-grain cohesion is reduced and piping and slumping may occur

(Foyle, 2014). Groundwater flow volumes through the surficial aquifer are typically several times greater in the lacustrine and beach-ridge strata than in the deeper glacial tills and bedrock.

Coastal Zone Groundwater Budget

Long-term mean annual precipitation for coastal Erie County is ~105 cm/yr (NCDC, 2013), which includes approximately 300 cm/yr of snowfall. Analysis of stream flow and precipitation data by Buckwalter et al. (1996) in nearby watersheds showed that about 30% of annual precipitation percolates through the Quaternary aquifers to become stream base flow, 32% becomes surface runoff across the landscape contributing directly to stream flow, and about 38% becomes a combination of evapo-transpiration (23%) and groundwater underflow (15%). The general lakeward-thickening wedge geometry of the coastal Quaternary stratigraphic section in Erie County (Schooler, 1974) suggests that the geometry of the water table at the top of the Quaternary aquifer system mimics the surface topography (Richards et al., 1987; Buckwalter et al., 1996). In general, groundwater divides likely mimic watershed divides and the water table likely dips from beneath the glacial escarpment down-gradient towards the coast and laterally towards stream valleys.

On well-drained beach ridge complexes along the central parts of the western and eastern coastal reaches (which are devoid of significant surface drainage), as much as 77% of precipitation may discharge through the bluff face beneath the water table because surface runoff and base flow are insignificant. The bluff face along different parts of the coast can experience spatial variation in groundwater discharge that is determined by the prevalence of surface drainage systems exiting the coast. Groundwater discharge volumes also show temporal variation depending on season and precipitation inputs, particularly for the shallow flow systems that likely dominate in the unconsolidated coastal-zone stratigraphic section.

Conceptual Hydrogeomorphic Model

Foyle (2014) developed a conceptual groundwater box-model applicable to a 20 km stretch of coast in the Harborcreek – North East area using available data on bluff retreat, climate, and hydrogeologic framework. On the basis of topography, drainage patterns, stream density, soil hydraulic conductivity, and watershed orientation relative to the coast, distinct coastal sectors were identified (Table 4.3). The hydro-geomorphic attributes of a high-elevation beach-ridge sector near North East are significantly different from lacustrine plain sectors immediately to the northeast and southwest.

From that model, bluff retreat rates derived using LiDAR from 1998 and 2006 were positively correlated with inferred groundwater flux patterns at the bluffs. Retreat rates were higher where modeled groundwater fluxes through the bluff face were larger, while retreat rates were lower in sectors with lower groundwater flux (Figure 4.9). In general terms, the tallest bluffs in eastern Erie County occur where beach-ridge (strandplain) sands and gravels of the Warren paleoshoreline are present, and this is where surface drainage patterns are poorly developed and groundwater fluxes are inferred to be large. Conversely, where beach-ridge (strandplain) sands are absent from the bluff top, bluffs are lower, surface drainage patterns are more organized (coast-normal orientation, steeper gradients, more incised), and groundwater fluxes are inferred to be lower. While not yet tested, this conceptual model may be applicable to the entire Lake Erie coast because similarities exist between bluff topographies in eastern and western Erie County due to the localized intersections of Warren-age strandplain paleoshorelines and older lacustrine plains with the modern bluffs. Based on findings from eastern Erie County, the model supports the premise that groundwater fluxes are likely more important in causing bluff retreat along high-bluff sectors than other factors (Tables 4.1 and 4.3). This premise is supported by variability in bluff retreat rates mapped by Hapke et al. (2009) for the western and eastern coastal reaches (Figure 4.8). Their study found that, in general, retreat rates are higher in areas where beach-ridge strata with poorly-developed surface drainage systems are present, and lower where they are absent.

Characteristic	SW Paleo-Lacustrine Plain	Central beach–ridge complex	NE Paleo-Lacustrine Plain
Principal soil types (NRCS 2013)	Berrien fine sandy loam and Ottawa fine sand	Conotton coarse sandy loam and gravelly sandy loam	Wallington silty-sandy loam
Surface drainage	Moderately well drained	Well drained; Ksat = 5–15 cm/h	Poor; Ksat = 0.2–0.5 cm/h
Streams and orientation	Incised; coast-oblique	Absent; short ravines	Incised; coast-normal
Lakeward topo gradient	Very low; 1 %	Very low; 1–2 %	Low; ~7 %
Cross-valley gradients	Moderate; 4 %	N/a; <0.5 % coast-parallel	High; ~15 %
Stream order and pattern	3rd order; dendritic	1st order ravines; dendritic	1st and 2nd order; parallel
Groundwater flow lines	Coast-parallel to oblique	Coast-orthogonal	Coast-parallel
Annual average recession	−0.20 (−0.16 to −0.25) m/year	−0.32 (−0.18 to −0.63) m/year	−0.15 (−0.09 to −0.22) m/year
Relative underflow (*U*)	High (15–77 % of *R*)	High (~77 % of recharge *R*)	Very low (5–15 % of *R*)
Q/*A* at bluff face	20 m^3/m^2/year	35 m^3/m^2/year	13 m^3/m^2/year
Q/*L* at bluff face	309 m^3/m/year	690 m^3/m/year	61 m^3/m/year

Table 4.3*: Summary geomorphic characteristics of beach-ridge and lacustrine plain coastal sectors in eastern Erie County between Seven-mile and Twenty-mile creeks. Similar geomorphic sectors occur in western Erie County. Differing hydrogeologic characteristics in these two types of coastal sector correlate well with LiDAR-mapped rates of bluff retreat (Image: modified from Foyle, 2014).*

Groundwater discharge at the bluff face along lacustrine plain sectors (where beach-ridge strandplain deposits are absent) in western and eastern Erie County is likely dominated by a local component (groundwater recharge from within 1-2 km of the bluff). This component exits through the lacustrine section along with a more distally recharged component that exits the glacial till section which has a significantly lower hydraulic conductivity and hydraulic gradient. As suggested by Richards et al. (1987), the glacial tills may locally gain a small component of bedrock flow at subsurface joints and faults. Precipitation landing on the coastal plain becomes overland flow to streams, percolates and contributes to stream baseflow, and contributes to evapo-transpiration and minor groundwater underflow (to adjacent basins). At the downstream ends of watersheds, valley-axis oriented topographic and water-table slopes are steeper than bluff-oriented topographic and water-table slopes. This will favor groundwater flow lines that are oriented approximately parallel to the coast so that bluff-face discharge of groundwater may thus represent only on the order of 15% of recharge by precipitation (Figure 4.11). It is low because ~85% of precipitation becomes a combination of runoff, stream base flow, and evapo-transpiration while the bluff face acts as an imperfect (leaky) no-flow boundary. This configuration will favor groundwater discharge through the lacustrine strata along valley sides and limit bluff-face discharge which will enhance bluff stability. Bluff discharge will be dominated by water exiting (with lower discharge rates) from the glacial tills lower in the bluff (Figure 4.11a; Foyle, 2014). Bluff retreat rates should be lower as a result.

Along the coast where bluffs are capped by beach-ridge deposits, surface drainage is almost absent. Groundwater discharge through the bluff face should consist of a dominant component from local recharge exiting through the beach-ridge complex and lacustrine sediments, combined with a smaller distally-sourced volume exiting via the glacial tills similar to that in the lacustrine sectors. Because of the lack of surface drainage, and because topographic and water-table gradients are oriented towards the coast due to the absence of a strong fabric of incised valleys, groundwater flow lines are oriented towards the coast and the bluffs no longer behave as a leaky no-flow boundary. Bluff-face groundwater discharge will thus be large and may represent ~77% of recharge by precipitation. Overland flow is largely absent (due to high soil permeability and soil-aquifer connectivity) and contributions to baseflow may approach zero (Figure 4.11b). A high bluff-face groundwater discharge may then be a significant driver of bluff failure because slip-plane development and the effectiveness of sapping and piping processes will be increased (Figure 4.11; Higgins and Coates, 1990; Foyle, 2014).

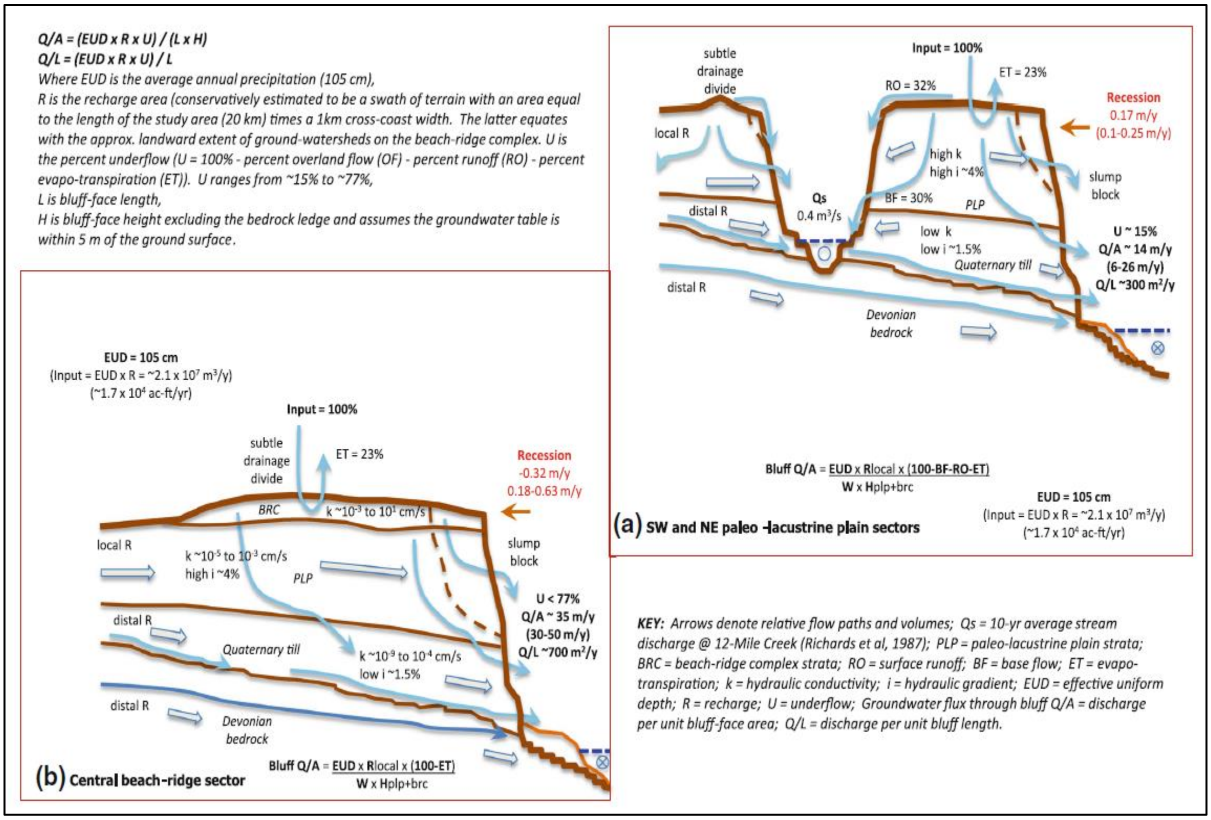


Figure 4.11: *Coast-oblique oriented schematic hydrogeologic box-models for the (a) lacustrine plain and (b) beach-ridge sectors of the Lake Erie coast in eastern Erie County. The relative sizes of slumps indicate the association of smaller-volume slumps with the lacustrine plain sector where bluff-face groundwater discharge rates (Q) are lower (Image: modified from Foyle, 2014).*

The conceptual hydrogeomorphic model found that bluff retreat rates along bluffs with capping beach-ridge deposits average 0.32 m/yr (range: 0.18 to 0.63 m/yr). Where beach-ridge deposits are absent, rates average 0.17 m/yr (range: 0.09 to 0.25 m/yr). Highest retreat rates (greater than 0.5 m/yr) occur mostly along short reaches of bluff at and near active rotational slump areas that are most prevalent where beach-ridge deposits are present (Figure 4.12). Related groundwater-induced sapping and piping (Laity and Malin, 1985; Higgins and Coates, 1990) occur where discharge is locally enhanced. This can be due to (i) lithologic heterogeneity (e.g., internal bar and trough channelform structures) within the beach-ridge complex that focuses groundwater flow and (ii) local topography on the erosional surface that separates the glacial tills from overlying sand-rich lacustrine strata. The latter alters aquifer thickness locally and focuses groundwater flow towards short sections of bluff where the sandy components are thicker. Elsewhere, groundwater focusing can occur when flowlines in otherwise homogeneous aquifer areas become focused towards active slump and ravine features because these intrusions into the groundwater flow field distort equipotential surfaces. Groundwater focusing is known to occur at narrow bays along dolomitic cliffs in the northern Great Lakes where it can cause as much as a 500% amplification of the groundwater discharge at the cliff face (Cherkauer and McKereghan, 1991). Feedback mechanisms allow slumps to evolve either into short ravines if a high-conductivity aquifer zone is intercepted, or into larger slumps in areas of more homogeneous aquifer, respectively. The headwalls of ravines and slumps may eventually intercept a near-bluff groundwater drainage divide that limits further landward growth and promotes stabilization of slumps as mature vegetated bowls.

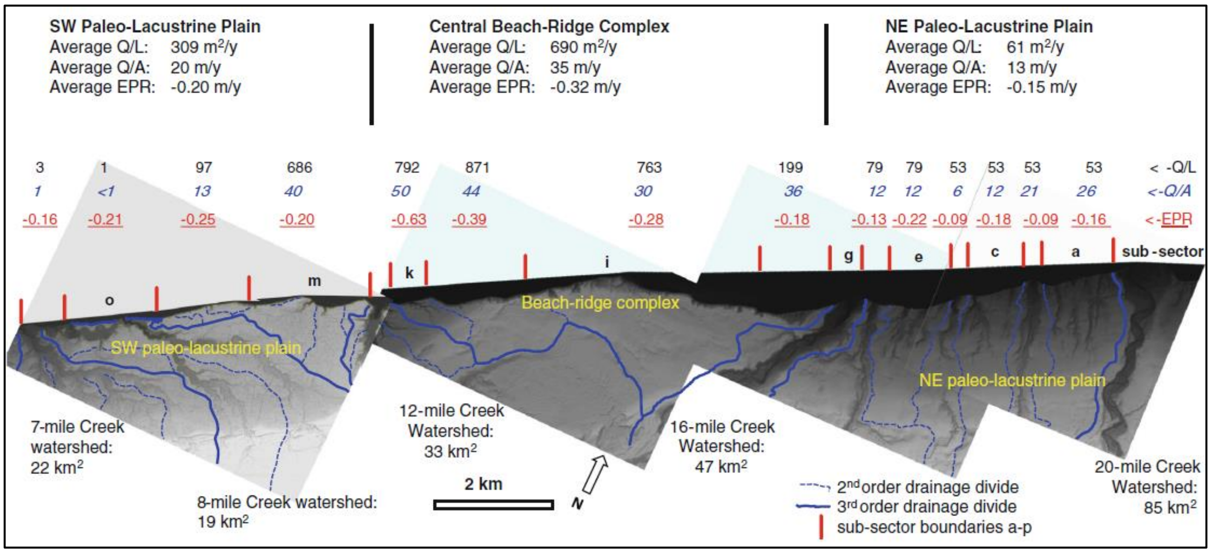


Figure 4.12: *2007 DEM surface showing watersheds and drainage divides developed along the lower coastal plain in eastern Erie County based on the conceptual model of Foyle (2014). Coastal sub-sectors are labeled A through P. Numbers in normal font denote average annual sub-sector groundwater flux (as Q/L; discharge per unit length of bluff) at the bluff face (m²/yr). Numbers in italics denote average annual sub-sector flux (as Q/A; discharge per unit area of bluff) at the bluff face (m/yr). Underlined numbers indicate the average annual sub-sector bluff-change rate (calculated in DSAS using an End-Point Rate (EPR) in m/yr; negative values indicate retreat). Tabulated data show the average Q/L, Q/A, and EPR for the three principal coastal sectors (Image: modified from Foyle and Naber, 2013; Foyle, 2014).*

The 20 km coastline in the Foyle and Naber (2013) and Foyle (2014) studies was also subdivided into 14 sub-sectors associated with specific watersheds (for the lacustrine sectors) and topographic sub-basins (for the beach-ridge sector). This allowed examination of smaller-scale variability in the relationship between groundwater discharge and bluff change rates. Comparing the sub-sectors (Fig. 4.12) showed a strong positive correlation (correlation coefficient $r=0.74$; $p<0.001$) between discharge per unit length of bluff (Q/L) and bluff retreat rate (EPR values), as shown in Figure 4.13, while the correlation between discharge per unit area of bluff (Q/A) and bluff retreat rate is somewhat weaker ($r=0.64$). Significant variability in bluff-retreat rates at the multi-kilometer (coastal sector) and kilometer (small watershed) scales strongly suggests an inverse relation exists between bluff retreat and the degree of surface drainage development. This is to be expected because a better-developed surface drainage network means less precipitation is diverted to groundwater recharge for eventual discharge at the bluff face.

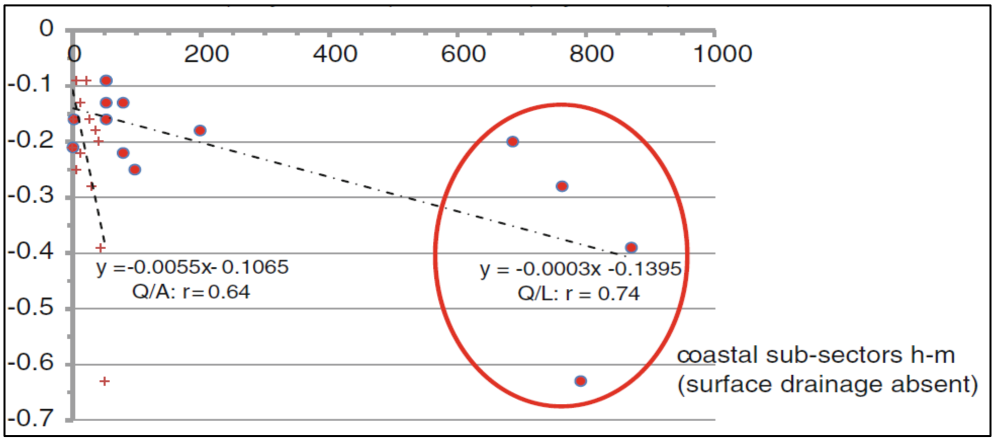


Figure 4.13: *Average annual groundwater discharge/meter of bluff length (X-Axis: Q/L circles) and average annual discharge/meter² of bluff face (X-Axis: Q/A crosses) versus average sub-sector bluff-change rate (Y-Axis: end-point rate (EPR) in m/yr). Subsectors with well-developed surface drainage systems have Q/L values that cluster in the less-negative EPR region of the graph while subsectors lacking surface drainage (sectors H through M from Figure 4.12; beach-ridge areas) cluster in the more-negative EPR region of the graph (Image: modified from Foyle, 2014).*

The study also notes that the moderate to strong "Q/L : bluff retreat rate" correlation coefficient (r=0.74) suggests that additional factors other than variations in groundwater flux through the coastal aquifer may also contribute to spatial variation in bluff retreat. Examination of beach statistics showed that bluff-change rates are only marginally greater where beaches are wider than where they are narrower or absent (r= 0.03). This may simply reflect a cause-and-effect relationship in that actively eroding bluffs supply pulses of sediment to the beaches, a relationship often seen on the Pennsylvania coast. Over time scales of decades, Lee (2008) documented that bluff-crest retreat rates at several sites on the UK North Sea coast and elsewhere are inversely proportional to the volume of beach material present. This relationship is expected because wider and/or taller beaches, particularly when coarse grain sizes facilitate surf infiltration, reduce the velocity and volume of wave run-up that ordinarily drives toe erosion (see also Ruggiero et al., 1996, 2001). Along parts of the Chesapeake Bay coast of Maryland (Chapter 2), bluffs that have been isolated from wave attack by spit and strandplain development are now significantly more stable because the process of toe erosion is no longer active. Among other factors along the Erie County eastern coastal reach, Foyle (2014) noted that bluff retreat showed only a weak positive correlation with bluff height and with agricultural land use. However, these weak correlations likely reflect the co-location of the bluff height and agricultural land-use attributes with the beach-ridge complex where groundwater fluxes are high.

Chapter 5: State of Knowledge on Lake Erie Climate Change and Water Levels

Introduction

Approximately one quarter of the entire US Great Lakes coastline consists of cohesive bluffs and banks (Pope et al., 1999). This shoreline type is very susceptible to present-day processes of weathering and erosion, and to future climate-driven changes in the internal geotechnical properties and external forcing agents that affect bluff stability. Recent literature on climate change in Pennsylvania and the Great Lakes Basin suggests that increased precipitation in winter and spring, more frequent heavy downpour events, and less frozen precipitation may characterize regional climate over the next several decades (Lofgren et al., 2002, 2011; Karl et al., 2009; Cruce and Yurkovich, 2011). These trends could lead to increased bluff instability due to increased erosion of the bluff face by surface runoff and by thin soil-mat creeps. A potential mitigating factor is that an expected increase in evapotranspiration and a reduction in surface-water inflows to the Great Lakes Basin will likely lead to lowered lake levels in Lake Erie (Cruce and Yurkovich, 2011) which would have a bluff-stabilizing effect because toe erosion by waves would be reduced.

The expected precipitation changes may also lead to increased recharge of Pleistocene surficial aquifers on the coast, and to an increase in aquifer storage and discharge over time. In sandy and silty surficial aquifers exposed along the bluffs, resultant increases in groundwater levels and pore pressures will likely lead to a decrease in bluff stability as water tables rise. Overall, climate-driven trends in bluff erosion for the Pennsylvania coast through the end of the century remain difficult to predict. Uncertainty exists because of climate data shortcomings, a lack of climate-model resolution, and feedbacks in climate and earth-surface systems that are not yet sufficiently well quantified.

Recent work over the past decade (Abler et al., 2008; Shortle et al., 2009; Ross et al., 2013; Shortle et al., 2015) on how Pennsylvania climate may change over the next century is reviewed below. While these studies have a thorough (sub-regional) statewide emphasis, specific details on changes pertinent to the Lake Erie coast are not always resolvable. Also, while the capabilities of climate-change modeling and climate prediction at the regional to continental scale are increasing rapidly, the science still has the challenge of down-scaling global circulation models, on which current climate predictions are based, to smaller regional models with a high degree of resolution. Coupled with that challenge is that available earth-system data needed for such specific regional modeling is still imperfect due to shortcomings in data density, geographic distribution of data, and frequency and duration of temporal coverage.

Future climate change in the Great Lakes Basin will impact coastlines and adjacent coastal uplands as the hydrologic balance is altered, groundwater systems respond, and groundwater-influenced stability of unconsolidated coastal bluffs changes. In general, enhanced bluff retreat may be expected for Pennsylvania during wetter climate periods when seasonal water tables would be higher and groundwater flow towards the bluff face would be enhanced (Foyle, 2014). Conversely, reduced rates of bluff retreat may be expected during drier climate periods when the water table is lower and groundwater flow through the bluff is reduced. A recent study by Foyle and Naber (2013) and Foyle (2014) on coastal hydrogeology and bluff-change data for a nine-year period in eastern Erie County shows that modeled groundwater discharge at the bluff face is positively and strongly correlated with variation in bluff-retreat rates.

Recent Research on Pennsylvania Climate Change Pertinent to the Erie County Coast

The Pennsylvania Climate Change Act (2008) directed Pennsylvania DEP to examine the potential impacts of global climate change on Pennsylvania over the next century. The study was conducted by The Pennsylvania State University and presented in two reports: *Pennsylvania Climate Impacts Assessment* (Shortle et al., 2009) and *Economic Impacts of Projected Climate Change in Pennsylvania* (Abler et al., 2009). These reports were subsequently followed by two updates, prepared in 2013 (Ross et al., 2013) and in 2015 (Shortle et al., 2015). What follows below is a brief review of these reports to highlight the general climate-change consequences over the next century that can be expected to impact, directly or indirectly, and over a range of timescales, bluff stability on the Lake Erie coast.

Pennsylvania warmed by just over 1 °C (1.8 °F) over the past 110 years, with a brief cooling period in the mid-20th century. There has been a 10% increase in average annual precipitation across the state, and there has been a 71% increase in the number of extreme precipitation events (heaviest-1%) over the past half-century (Karl et al., 2009). Natural climate cycles, such the North Atlantic Oscillation (NAO), the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Pacific/North American pattern (PNA), all influence Pennsylvania's temperature and (particularly) precipitation (Shortle et al., 2015). These climate cycles are commonly reflected in recurring spatial patterns in sea surface temperature and sea surface pressure, both of which are capable of modifying atmospheric conditions over a range of timescales, ranging from monthly to multi-decadal. The effects of these events on Pennsylvania's precipitation are dominant at periods of about 20 years (Shortle et al., 2015).

In the discussion of past, present, and future lake levels later in this chapter, Lake Erie shows variation in lake levels at similar (~20 yr) periods. This suggests that cycles such as the NAO, ENSO, PDO, and PNA influence lake levels in the Great Lakes Basin, as would be expected. Cyclicity in water levels directly influences the degree of wave impact on the bluff toe along the entire NW Pennsylvania coast and thus the rates of bluff retreat over similar time scales. During periods of higher lake level of sufficient duration to allow a bluff response (years to decades), bluff retreat may accelerate more in western Erie County compared to eastern Erie County due to the lack of a protective bedrock toe in the former area. During periods of lower lake level of sufficient duration, retreat rates may decelerate and approach similar rates for both coastal reaches. Quigley et al. (1977), in a study of the bedrock-free Ontario coast of Lake Erie in the 1960s and 1970s, noted that a rise in lake level (transgression) during a normal 1-2 decade lake-level cycle led to increased wave energy at the bluff toe and enhanced rates of toe erosion. Bluff stratigraphy in their study area west of Long Point, ON, was similar to that of western Erie County, with unconsolidated clayey glacial tills capped by post-glacial sands.

Shortle et al. (2015) show that Pennsylvania's current warming and wetting trends are expected to continue at an accelerated rate. It is projected that by the middle of the 21st century, Pennsylvania will be about 3 °C (5.4 °F) warmer than it was at the end of the 20th century, while annual precipitation is expected to increase by 8%, with a winter increase of 14%. There are expected to be modest but significant increases in annual-mean runoff and small changes in annual-mean soil moisture (Table 5.1). The likelihood of drought is expected to decrease while months with above-normal precipitation are expected to increase (Shortle et al., 2015). Warmer temperatures and increased non-frozen precipitation on the Pennsylvania coast will lead to greater groundwater recharge of the surficial aquifers. This can be expected to increase bluff instability because the usually-beneficial effect of a frozen bluff face and bluff top will not be present as frequently to mitigate rainfall infiltration and higher groundwater pore pressures. There may thus be a seasonal and a durational shift in the timing of most bluff failures (currently, late fall and spring) into the early winter and early spring, respectively.

Property	21st Century Projection
Precipitation	Increase in winter precipitation. Small to no increase in summer precipitation. Potential increase in heavy precipitation events [High confidence for winter, lower for summer]
Snow pack	Substantial decrease in snow cover extend and duration [High confidence]
Runoff	Overall increase, but mainly due to higher winter runoff. Decrease in summer runoff due to higher evapotranspiration [moderate confidence]
Soil moisture	Decrease in summer and fall soil moisture. Increased frequency of short and medium term soil moisture droughts [Moderate confidence]
Evapotranspiration	Increase in temperature throughout the year. Increase in actual evapotranspiration during spring, summer and fall [High confidence]
Groundwater	Potential increase in recharge due to reduced frozen soil and higher winter precipitation when plants are not active and evapotranspiration is low [Moderate confidence]
Stream temperature	Increase in stream temperature for most streams likely. Some spring fed headwater streams less affected [High confidence]
Floods	Potential decrease of rain on snow events, but more summer floods and higher flow variability [Moderate confidence]
Droughts	Increase in soil moisture drought frequency [Moderate confidence]
Water quality	Flashier runoff, urbanization and increasing water temperatures might negatively impact water quality [Moderate confidence]

Table 5.1: *Summary of climate change-related impacts on the hydrologic cycle for Pennsylvania (statewide) through 2100. Changes to the hydrologic cycle can be expected to impact bluff stability due to changes in groundwater levels, groundwater pore pressures, and exchange of water between subsurface and surface reservoirs (Image: modified from Shortle et al., 2015).*

The surface-water system is also expected to change. Over the past five decades, most Pennsylvania streams have shown flashier and higher peak flows, and overall higher stream flows. This has resulted in more energetic stream flow and thus higher erosion potential. Likely consequences of this are higher stream sediment loads, more widespread riverbed erosion, and more bank failure (Shortle et al., 2015). As the present trend of higher, flashier flow is expected to continue, channel down-cutting and bank erosion can be expected to be of increasing concern for streams in the Lake Erie watershed that exit the coastal bluffs in Pennsylvania. During runoff events, perennial streams and over-bluff (surface) runoff can lead to bluff instability. Bluff surface runoff incises rills and gullies that locally increase bluff slopes within the drainage features. Perennial streams will deepen and or widen their channels leading to steeper bank slopes at stream mouths on the coast, leading to an increased risk of bluff failure along the edges of coastal re-entrants. Surface runoff during precipitation events typically co-occurs with, or follows, an infiltration phase that can lead to ground saturation and slope instability or failure as the water table rises. Cruce and Yurkovich (2011) expect that coastal erosion rates will increase for Lake Erie due to more frequent storms and storm surges, and greater coastal wave energies, associated with less lake-ice cover. Additionally, an expected decline in the lake-ice season will likely enhance beach and bluff erosion during winter months.

Significance of Lake Level and Lake-Level Change in Bluff-Retreat Dynamics

Lake Erie water levels constantly change because they are in a state of dynamic equilibrium with the hydrology of the Great Lakes Basin and global climate. Earth-system interactions and feedbacks between the hydrosphere and atmosphere cause lake level to fluctuate at differing rates and magnitudes over a range of human through geological timescales. These timescales range across:

- seconds, due to wind-generated waves with typical wave periods of 3-4 seconds
- hours, due to small astronomical tides with a semi-diurnal tidal range of < 0.1 m, random storms causing coastal storm surges of ~1 m, and seiches with a periodicity of ~18 hours and a range of as much as 3 m
- seasons, due to snow storage and precipitation trends in the basin that cause summer (July) levels to about 0.7 m higher than winter (January) levels
- years, because of high-frequency climatic variability
- multiple years and decades, due to longer-term global climatic changes outside of the Great Lakes Basin such as the PDO, ENSO, PNA, and NAO

Lake level is important because it determines where, how intensely, and for how long, erosive hydrodynamic forces impinge upon the nearshore substrate, the beach (if present), the bluff toe and, under extreme conditions, higher elevations on the bluff face. These forces include wave-induced abrasion and bottom shear stress; longshore and rip currents; erosional wave run-up (swash); hydraulic and air-pressure changes causing joint expansion in bedrock and glacial till at the bluff toe; and wave impact stress on the bluff face, that assume different degrees of significance in different coastal settings. Lake levels are therefore an important contributor to the variability in rates of bluff retreat observed around the Great Lakes Basin, reported as ranging from 0.2 to 2 m/y by Davidson-Arnott (2010). What is not yet fully known are the response times of the bluff profile and nearshore to the physical processes causing change, although some of those relations are known from modeling of specific (though limited) sets of the forcing variables in specific geologic and wave/tidal-regime settings. Modeling work by Baird (2003) as part of the Lake Michigan Potential Damages Study (LMPDS), for example, suggests that cohesive nearshore-bluff coasts need more than 50 years to fully adjust to a typical change in lake level. However, such response times are understood only to the order-of-magnitude scale which is less than ideal.

On the Great Lakes, the influence of lake level is sufficiently significant that it has been modeled when trying to estimate the effects of possible lake-level regulation on Lake Superior and on the St. Lawrence Seaway. For example, the IJC International Upper Great Lakes Study (IUGLS) includes a mandate to determine the potential impacts of various lake-level scenarios on coastal erosion that would result if the outflow of Lake Superior were to be regulated. An overview of the study (Geomorphic Solutions, 2010) notes that while lake levels are known to influence nearshore and bluff behavior, it is not known how accurately existing models quantify the relationships. Models used to estimate bluff response to changing lake levels include the FEPS-COSMOS model (Southgate and Nairn, 1983; Nairn and Southgate, 1993; Baird, 2003, 2004, 2010), the SCAPE model (Walkden and Hall, 2005) and the Trenhaile (2009) model. These models have a primary focus on coasts that do not have bedrock and may not be directly applicable to over 50% of the Pennsylvania coast.

In general, but for complex reasons, the research literature indicates that high lake levels will result in an increase in the rate of bluff-face and bluff-crest retreat (e.g., Quigley at al., 1977). However, the change in rate is not yet predictable, and it is conceivable that retreat may slow or stop if feedbacks in the system result in reduced erosion at the bluff toe, particularly in areas where subaerial processes play a minor role. The latter assumption is unlikely to hold true for the Erie

County coast due to the importance of subaerial processes. However, the time frame of observation is also important, in that the response to a rise in lake level may take years to become apparent, and the change seen over several months or years may be different in magnitude and scale from the response that is seen over years to decades. Conceptually, high lake levels may be accompanied by a decline in nearshore erosion as the wave field "lifts off" the lakebed and allows sediment (bluff derived or littoral) to accumulate in the nearshore below wave base. Alternatively, high lake levels may be accompanied by deepening of the nearshore due to enhanced shear stress and abrasion because there is less attenuation of larger waves during storm events. The complex nearshore response is also partly governed by the geotechnical strength of the material that makes up the nearshore, be it glacial till or bedrock.

Onshore, wave attack at the bluff may increase or decrease in terms of energy delivered per meter of bluff, and in terms of duration and magnitude of energy-delivery events, depending on whether the nearshore has shallowed or deepened. Energy delivered to the bluff also depends on whether a subaerial beach is now smaller (due to submergence) or absent (due to erosion) or larger (due to colluvial sediment supply by more frequent or larger bluff failures). This will dictate the rate of erosion (increased or decreased) occurring at the toe of the bluff which will in turn affect slope stability as the overall bluff slope changes. Material supplied by bluff failure (via soil creep, mud flow, rotational or translational slumps, or debris falls) may temporarily provide a natural protective barrier at the base of the bluff. This will absorb wave energy as the unconsolidated colluvial debris interacts with the littoral current, wave swash, and wave backwash over time. In summary, a rise in lake level will cause a change in bluff stability, particularly in regions where hydrodynamic processes are more important than subaerial processes. Whether that change is large, small, or detectable on a specific coast over specific time frames remains a challenge for observational scientists and modelers.

Low lake levels should in general result in an increase in bluff stability as waves become smaller due to lakebed friction in the nearshore, or as waves become spatially removed from the bluff toe area as the shoreline progrades lakeward. If the fall in lake level is sufficient, all hydrodynamic forcing agents are spatially removed from the bluff and any associated erosional processes that were active at the bluff now become inactive. Then bluff geometry and crest position will become exclusively a response to subaerial processes whose magnitudes will be less than those of the hydrodynamic and subaerial processes combined, other factors being equal. Again, however, time frame is important because climate changes leading to a decline in lake level may also alter the significance of the subaerial processes. For example, a decline in the level of Lake Erie could be induced by warmer seasonal temperatures, allowing evapo-transpiration from the lake to become larger than it was prior to the warming trend due to higher water temperatures and more shallow-water phreatophytes. The warming trend may also lead to changes in the timing and state of precipitation (snow vs rain) falling in the coastal watersheds, in soil moisture content, in surface runoff (duration, frequency, and magnitude), and in groundwater levels and pore pressures. These characteristics may be sufficiently changed that they negate the "reduced erosion" benefit attributable to the drop in lake level.

As in the case of high lake levels, the responses of the coastal system are complex due to the complexity of the variables involved, positive and negative feedbacks that exist between those variables, and the time frames over which observations to map responses are made. What is currently known for Great Lakes bluff coasts is that rates of bluff retreat generally decline during periods of lowered lake level, particularly if the durations of those periods are long. However, lowered lake levels mean that more wave energy is directed at the nearshore substrate as the wave field "sinks into" it (particularly on bedrock-free coasts). Consequently, when lake levels subsequently rise to or above former levels, larger waves than before will now be able to reach the bluff and cause increased erosion of the bluff toe. On bedrock-free bluff coasts, this would suggest that lake-level cyclicity at certain frequencies may lead to more lakebed erosion and bluff retreat than would occur if lake levels were stable. This is a current knowledge gap in bluff-coast science and an opportunity for future research: how does bluff stability compare for decades-long periods of low lake levels, lake-level cyclicity, and high lake levels in large-lake settings?

Lake Level Trends: Cycles and Magnitudes of Transgressions, Highstands, Regressions, and Lowstands

Elsewhere on United States ocean coasts, coastal management agencies are attempting to account for increased rates of sea-level rise (transgression) in hazard planning. Only in Alaska are managers concerned with falling sea level (regression). The effort to account for continued and accelerating rates of sea level rise is occurring in order to begin mitigation planning for increases in erosion in both beach and bluff coastal settings (e.g., Oregon, California, Florida). Typically, on bluff coasts, early approaches to dealing with the expected acceleration in sea-level rise entail adding a numerical "safety factor" to existing bluff-setback calculations (e.g., in California; see Chapter 8).

In the North American Great Lakes, water levels are monitored by NOAA's National Ocean Service (Center for Operational Oceanographic Products & Services) and by the Canadian Hydrographic Service. For the Great Lakes coastlines, NOAA-GLERL maintains an online Great Lakes Water Level Dashboard (https://www.glerl.noaa.gov/data/dashboard/GLWLD.html) that includes almost four centuries of modeled and recorded Lake Erie water level information (covering the time period 1722-2105). For forecasts of future lake level in Lake Erie, the data summarized below show a large range in predicted levels between various authors and models. This is because research on future lake levels is a relatively new endeavor and because much of the non-anthropogenic control on future levels hinges on as-yet-to-be-identified changes in climate in the Great Lakes Basin. Researchers on Lake Superior and the St. Lawrence Seaway have examined the potential beneficial impacts (i.e., a reduction in coastal land losses) if the waterway were to be managed with the goal of reducing or stabilizing water levels.

For context, annual average lake level in Lake Erie in 2015 was 174.32 m IGLD, or 0.18 meters above the long-term (1918-present) average of 174.14 meters IGLD (International Great Lakes Datum; an elevation benchmark used by all water-level gauging stations in the Great Lakes). Lake Erie annual average lake level rose by 0.35 m between 2013 (174.06 m) and 2016 (174.41 m). Figure 5.1 shows Lake Erie water levels over the past century (approximately), along with the long-term average lake level (174.14 m IGLD) for context. Figure 5.2 shows modeled lake levels extending back to 1722 (Wiles et al., 2009). A multi-year cyclicity in lake level is very apparent in both datasets. This reflects annual- and decadal-scale variability within the hydrologic and climate cycles, and longer term climatic variations. Such cyclicity is common across all of the Great Lakes.

Several recent studies have been published that use models to assess the impact that future climates will have on Great Lakes water levels. There is significant variation between these models, which effectively present multi-decade lake-level forecasts. This variation is because of uncertainties in present climate modeling, and because of limitations (temporal and geographical) in the data needed by climate modeling for the Great Lakes Basin and North America. The long-term lake-level projections for Lake Erie beyond 2050 shown in Figure 5.3 are derived from the NOAA-GLERL Water Level Dashboard and rely on modeling by Angel and Kunkel (2010); Lofgren et al. (2011); Hayhoe et al. (2010); and MacKay and Seglenieks (2012).

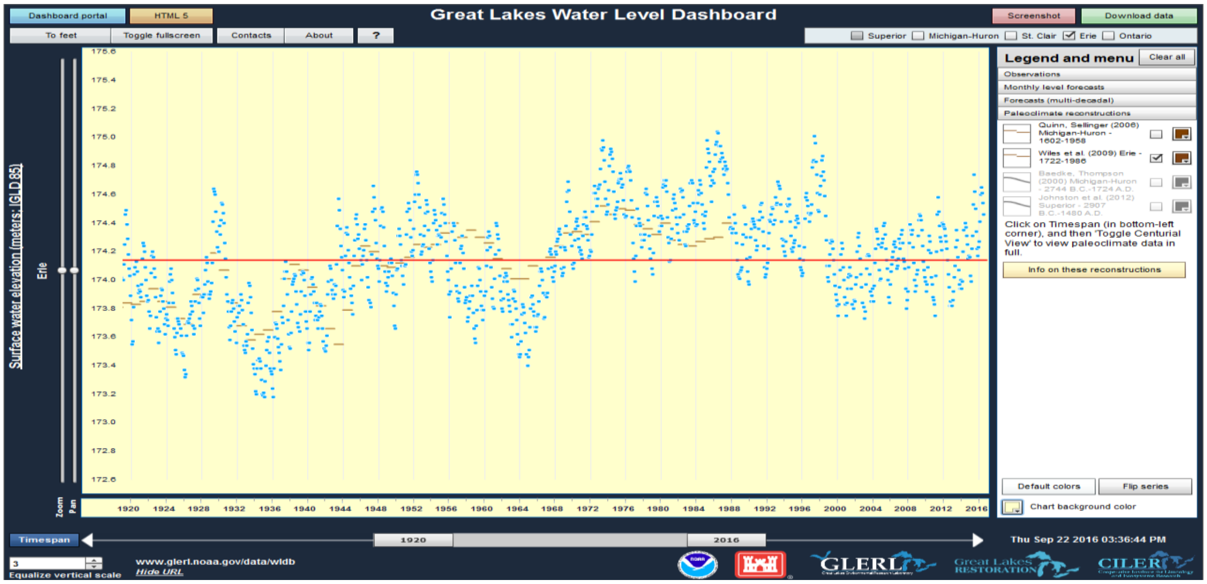


__Figure 5.1:__ Screenshot from the NOAA-GLERL Great Lakes Water Level Dashboard showing the time series of measured Lake Erie levels since 1920, with average lake level (1918-present; 174.14 m IGLD) shown for reference. The short dashed lines show the elevations of recent lake levels as modeled by Wiles et al. (2009) for the entire 1722-1986 time period shown in more detail in Figure 5.2.

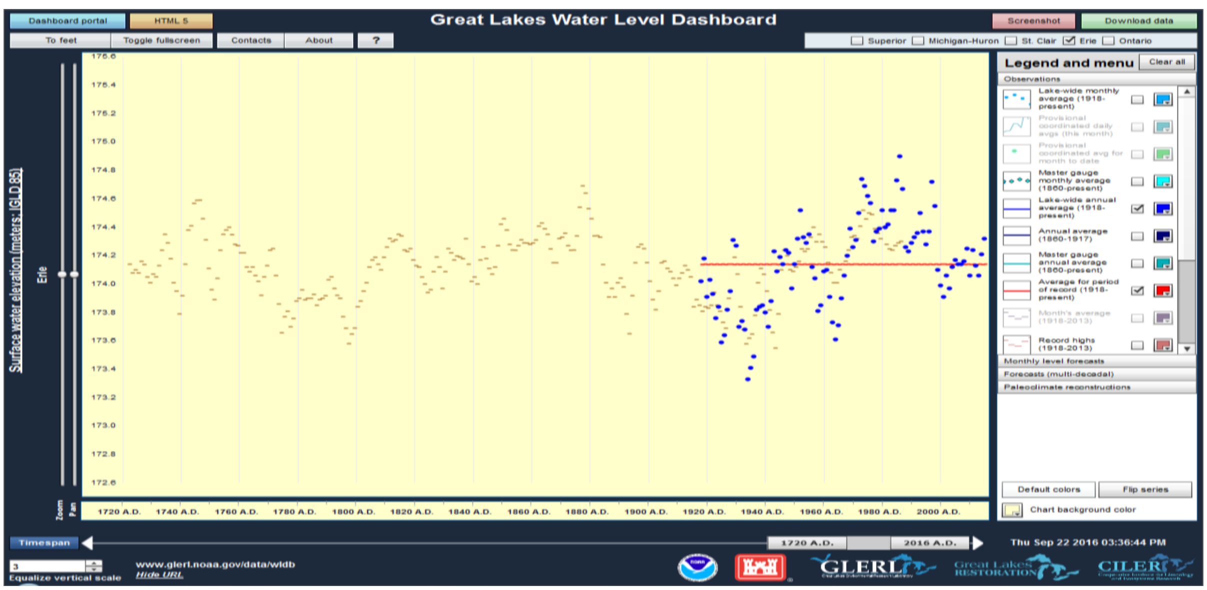


__Figure 5.2:__ Screenshot from the NOAA-GLERL Great Lakes Water Level Dashboard showing the time series of Lake Erie water levels (short dashes) modeled by Wiles et al. (2009) for the 1722-1986 time period. Historical average lake level (1918-present; 174.14 m IGLD; solid line) and the 1918-to-present lakewide annual average lake level (dots) are shown for context.

Modeling by Hayhoe et al. (2010) predicts that Lake Erie levels may fall to 173.89 m IGLD over the next century to a level of about 0.25 meters below the long-term average lake level (Figure 5.3). Angel and Kunkel (2010) predict levels over the same time period to lie in a range between 174 m and 174.4 m IGLD which approximates the normal range of lake levels over the past decade. Four different models run by Lofgren et al. (2011) show predicted levels at the end of this century to have a range of model-dependent possibilities, ranging from 1.45 meters (4.76 feet) below long-term average (at 172.69 m IGLD) to 0.33 meters (1.08 ft) above long-term average (at 174.47 m IGLD). MacKay and Seglenieks (2012) show lake levels lying at 174.34 m IGLD, about 0.2 m above long-term average.

Future lake level is important in the discussion of bluff-retreat patterns over time. Figure 5.3 summarizes the modeled and actual lake levels for Lake Erie for the entire 383-year time period between 1722 and 2105. Annual average lake level historically can be seen to vary by as much as 1.5 meters. The wider range in the forecast levels out through 2105 is partly due to modeling uncertainties and also due to climate-change expectations over the next century. At present, the data suggest that future levels in Lake Erie may be higher or lower than today, with a weighting towards the latter. Probabilities associated with those levels are not yet available but are understandably a goal in long-term climate and water-level prediction in the Great Lakes. In their study of the response of the Great Lakes Basin to climate change, Cruce and Yurkovich (2011) noted that by the end of this century, average Great Lakes water levels are likely to decline. In a review of 23 Global Circulation Models and over 600 climate scenarios, over 75% of the model simulations showed steady or declining lake levels for a higher emissions scenario for all of the Great Lakes. For Lake Erie, 25% of the models showed a decline in lake level of ~1.8 ft by 2080. For a lower emissions scenario, lake levels were projected to change very little from the historic average (Angel & Kunkel, 2010).

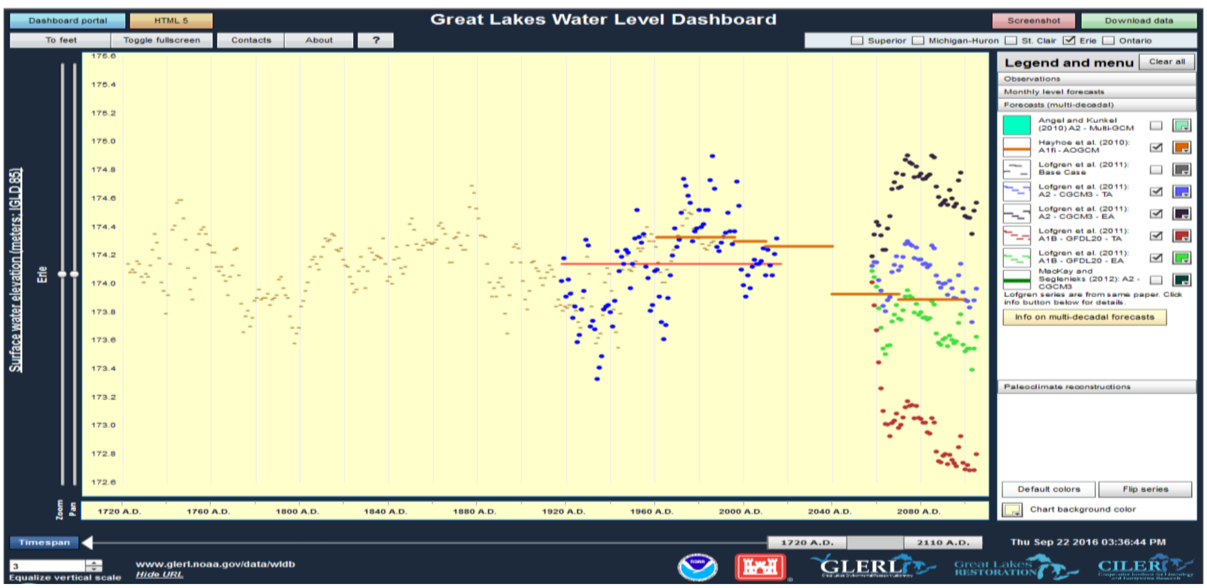


Figure 5.3: *Screenshot from the NOAA-GLERL Great Lakes Water Level Dashboard showing Lake Erie water levels modeled by Wiles et al. (2009) for the 1722-1986 time period (short dashes); historical average lake level (1918-present; solid line); lakewide annual average lake level (1918-to-present; dots); and modeled lake levels beyond 2050 (dots and thick lines). See text for discussion.*

It is important to realize that each lake-level data point shown in Figure 5.3 represents a relatively long time period, on the order of a year. That means that lake processes have the opportunity to interact with the bluff toe, or not interact with the bluff toe, for these time periods that are longer than the normal seasonal periods of high and low water. During transgressions (lake-level rise), wave energy, littoral currents, and winter ice have the opportunity to enhance erosion of the bluff toe and adjacent beaches (if present). During regressions (lake-level fall), wave energy, littoral currents, and winter ice have less opportunity to induce erosion of the bluff toe and beaches and will expend greater energy on the shallow nearshore lake bed. Sustained periods of lower lake level can allow significant down-cutting of the lake bed to occur (if the lake bed consists of cohesive sediments) so that when lake level subsequently returns to a higher level, larger waves and stronger littoral currents will be able to cause enhanced erosion at the bluff toe.

From Figure 5.1, it is apparent that long-term cycles in lake level are significant, particularly because these cycles cover somewhat similar timescales to those used in urban planning and residential structure permitting. For example, from 1934 to 1974, the lake shows a punctuated rise, with smaller intervening declines, of about 2 meters (~6.5 ft). This period of overall transgression can be argued to have in fact extended through the year 2000, a duration of approximately 65 years. This time period overlaps with a time of increasing coastal development in Pennsylvania and nationally. Thus, while larger and more expensive buildings were in general being built closer to the bluff prior to the implementation of the Bluff Recession and Setback Act (1980), the wave-related processes that drive bluff failure were becoming more vigorous due to increasing nearshore water depths as a consequence of transgression. What is not well understood is if Lake Erie bluffs are still responding to this long-term rise (through enhanced retreat rates) or whether they have already reached equilibrium and are returning to a state of lower retreat rates. Research by Baird (2003) suggests the former is more likely due to system process-response times of at least half a century. Knuth and Lindenberg (1995) suggest that it can take as little as a decade for the bluff crest to respond to over-steepening produced by erosion of the bluff base during a prior period of high lake level.

These long-term transgressions allow wave attack on the bluff to proceed for not just a season or a year or two before falling back but for a much longer timeframe of decades. This allows even the relatively slow insidious geologic processes of wave abrasion, current scour, and freeze-thaw to do significant damage to the bluff toe which will in turn lead to enhanced instability as bluff over-steepening occurs. Conversely, periods of regression, even the short interval from 1952 to 1966, should have some beneficial effect on bluff stability on the Erie County coast. Beach area may expand due to reduced erosion by waves such that the backshore increases in volume and limits wave attack at the bluff toe. Shallower water depths in the surf zone mean that there will also be an incremental reduction, due to increased bottom friction, in the wave heights reaching the shoreline and beach. Beaches will also accumulate material as background bluff failures (due to ongoing subaerial processes) supply sediment to the bluff toe. This will provide some degree of buttressing at the bluff toe and will also reduce the average bluff slope, enhancing stability. Also, as the shoreline progrades lakeward with lake-level fall, additional space is made available on the updrift sides of groynes and jetties which will allow larger protective beaches to accumulate.

Figure 5.1 reveals interesting trends in lake level over the past half-century that may be affecting present bluff-retreat rates and potential future retreat rates through the end of the century. Lake Erie levels have on average been lower (by ~0.3 m; ~1 ft) during the 1998-2016 time period than they were during the 1971-1998 time period. If process-response time lags are long (>50 yrs; Baird, 2003), bluff-retreat rates in western Erie County (where there is no protective bedrock toe) may still be high and in equilibrium with the former high lake levels but may begin to decline over the next several decades. This may particularly be the case if Lake Erie levels do in fact fall through the end of the century as suggested by Cruce and Yurkovich (2011) and others. If process-response time lags are shorter (~10 yrs; Knuth and Lindenberg, 1995), then bluff-retreat rates may already be declining in tandem with lower lake levels over the past two decades.

Chapter 6: National and Regional Efforts to Mitigate Bluff Retreat

Introduction

Approximately 34 million people live within the Great Lakes Basin, or ~32% of the Canadian population and ~8% of the US population (MI Sea Grant; miseagrant.umich.edu). About 12 million of those people live in the Lake Erie watershed (EPA.gov). In states such as Michigan, privately owned lakefront property values may reach as high as $30,000 per linear meter of shoreline (nature.org/michigan). Bluff erosion problems are thus an issue for the many parts of the Great Lakes perimeter that are urbanized, intensively farmed, or preserved for public use. As populations continue to move closer to shorelines on the Great Lakes for economic and lifestyle reasons, erosion mitigation will continue to grow as an important focus of coastal management programs over time (Figure 6.1).

Figure 6.1: *Bluff failure in western Erie County (right side of image). Small rotational slumps occur in lacustrine sediments near the top of the bluff, while debris slides and soil creep occur in glacial tills on the lower bluff. Nearby erosion-mitigation efforts (on the left) include slope re-grading and placement of riprap at the bluff toe (Imagery collected in April 2015 and is available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

The goal of erosion mitigation on bluff coasts is to stabilize the bluff face and the position of the bluff crest over multi-decade timescales that match property ownership and mortgage duration timescales. For this to be accomplished in whole or in part requires scientists and engineers to use approaches geared to reduce the effects of:

- surface runoff
- mass loading
- groundwater discharge
- steep slopes

- toe erosion that causes bluff-face steepening
- lakebed downcutting in the surf zone and nearshore

Overview of Mitigation Methods

Mitigation approaches in general fall into two categories: hard stabilization (otherwise referred to as engineering solutions) and soft stabilization (otherwise referred to as bioengineering and biotechnical solutions). Each has advantages and disadvantages from the perspective of the property owner, the municipality, the general public, and environmental agencies. Under CZMA (1972), participating coastal states now have a “toolbox” of preferred mitigation approaches to address bluff-retreat problems. Mitigation efforts are typically directed at one or more of the following components of the bluff system, depending on the erosional processes at a site:

- the nearshore and surf zone
- the beach
- the toe of the bluff
- the bluff face within reach of storm waves
- the entire bluff face
- the bluff interior
- the bluff crest
- the adjacent tableland (upland) landward of the bluff crest

Complete or partial solutions to a bluff erosion problem may span a range of hard- and soft-stabilization options, used individually or in combination. These options range from installation of offshore breakwaters to surf zone lake-bed paving offshore. Onshore, they include placing riprap or revetments at the bluff toe; installing plantings and vegetated structures on the bluff face; mechanically regrading (reducing) the bluff profile; improving drainage on and within the bluff face; and installing subsurface dewatering systems and infiltration barriers on tableland areas. In general, engineering solutions may be used on any part of the bluff profile, from the surf zone lakeward of the bluff toe to the tablelands landward of the bluff crest. Bioengineering and biotechnical solutions are best used on the subaerial parts of the profile, at or landward of the dry beach (backshore). Typically, these latter solutions work best above the reach of storm waves that tend to impact the lowermost 2 m of the bluff face on southern Lake Erie (Amin, 1991; Highman and Shakoor, 1998), or above the bedrock if bedrock comprises the lower part of the bluff. All erosion-mitigation approaches are intended to reduce bluff retreat by addressing specific physical processes on the bluffs such as:

- limiting wave erosion at the nearshore, surf zone, and lower bluff face
- reducing damage due to winter ice formation and movement
- reducing groundwater pore pressures within the bluff
- reducing the volume of surface-water runoff over the bluff face
- absorbing or dispersing the volume of groundwater emanating from seepage faces and springs
- adding or inducing buttressing of the lower bluff face by increasing the beach volume or by adding engineering structures
- removing or restricting mass-loading at or near the bluff crest

Many coastal states and organizations with bluff-retreat problems have established Best Management Practices (BMPs) for their coasts that cover a range of engineering, bioengineering, and biotechnical solutions (e.g., Gianou, 2014). In general, these BMPs show commonalities with Chapters 16 and 18 of the NRCS Engineering Field Handbook (USDA 1992, 1996) that focus on slope and shoreline protection. For example, the Northwest Regional Planning Commission (VT) has produced *The Shoreline Stabilization Handbook for Lake Champlain and Other Inland Lakes* (2004) that reviews, in general terms, the most commonly used solutions to bluff instability on Lake Champlain and other inland lakes. Figures 6.2 and 6.3 show tabulated information for the most common engineering-, bioengineering-, and biotechnical-based stabilization methods. While the handbook was developed for Lake Champlain, the approaches summarized in Figures 6.2 and 6.3 are relevant to erosion problems on the Lake Erie coast of Pennsylvania. This is because many mitigation solutions can be applied across geographies with potentially minor adjustments to compensate for substrate, hydrodynamic, topographic, and climatic conditions (e.g., USDA, 1996; LHBSG, 2013; Keillor and White, 2003; Luloff and Keillor, 2016).

New York DEC and Pennsylvania DEP have similar web outreach documents available for the public (http://www.dec.ny.gov/permits/50534.html; Cross et al., 2007, revised 2017). The PA DEP bluff-vegetation BMP document (Cross et al., 2007) is intended to guide property owners and contractors on the causes of erosion and the best vegetative (bioengineering and biotechnical) methods to use to reduce bluff instability (https://seagrant.psu.edu/section/manuals-plans-proceedings).

Ohio DNR has made the Ohio Coastal Design Manual (http://coastal.ohiodnr.gov/design) available that provides a series of model recommended coastal-engineering solutions for coastal-engineering contractors to emulate (http://coastal.ohiodnr.gov/design/erosioncontrol). Plans are provided for various bluff scenarios typical of Lake Erie that incorporate beach presence or absence; bluff stratigraphy and composition; and bluff height and slope (Figure 6.4). Ohio may be the most proactive state on the Great Lakes in coastal-erosion mitigation planning. It has developed model construction plans and procedures in its Coastal Design Manual to reflect design recommendations in the US Army Corps of Engineers Coastal Engineering Manual. Ohio's proactive erosion management can be partly attributed to the fact that, in the 1990s, ~95% of the Ohio coast was erosional and there were ~2,500 structures located within 15 m of the shoreline (Highman and Shakoor, 1998).

The Erie County Department of Public Safety (ECDPS, 2012) has recommended that residents living near the Lake Erie shoreline be well educated on bluff retreat hazards. ECDPS acknowledges that through proper land-use management practices, bluff retreat can be slowed, but not prevented. Since the majority of bluff retreat-related problems in western Erie County in particular begin at the base of the bluff as a result of wave attack, ECDPS recognizes several measures (revetments, groynes, biotechnical slope protection, dewatering, and vegetative plantings) that can be used effectively to stabilize the bluff shoreline. However, ECDPS also notes that some of these measures are relatively ineffective in stabilizing bluffs where groundwater plays a large role in bluff retreat. The latter situation is most likely to occur along the eastern coastal reach where (i) a bedrock toe partially to completely protects the unconsolidated materials of the bluff from wave attack; and (ii) groundwater discharge is locally high within strandplain sediments.

	Erosion Control Method	Where It Works	Where It Doesn't Work	Neighboring Impacts	Labor/Preparation	Cost
NON-STRUCTURAL	**Re-Vegetation with Native Species** *page 19*	Along embankments, roadways, and steep slopes	Heavy wave action	None	Moderate	Low
	Relocation *page 20*	Where a structure is threatened by erosion along a shoreline and adequate room on site is available	Structures that cannot be moved due to structural integrity or inadequate space on site	None	High	High
	Drainage *page 20*	On banks that have become eroded from surface runoff Works well along roadways	Banks that are eroding due to other forces than runoff	Moderate to None	Moderate	Moderate
STRUCTURAL	**Stone Riprap Revetment** *page 21*	Embankments or shorelines where the underlying soil is stable	Steep slopes or embankments with significant amount of loose soil	Moderate to High	Moderate	Moderate to High
	Gabion Mattress *page 22*	Along embankments and roadways	Steep slopes Heavy wave action	Moderate to High	Moderate	High
	Concrete Wall *page 23*	Along moderate slopes which receive heavy action	Steep slopes Loose soil	Moderate to High	High	High
	Gabion Wall *page 23*	Along moderate slopes which receive heavy action	Steep slopes Loose soil	Moderate to High	High	High
	Bulkheads *page 24*	Unvegetated high banks with a lot of backfill and little wave action	Steep slopes Heavy wave action	Moderate to High	Moderate	Moderate to High
	Groins *page 25*	Long stretches of sandy beach	Rocky soils Heavy wave action	High	Moderate	Moderate
	Breakwaters *page 25*	Heavy wave action, >4 feet Harbors	Minimal wave action	High	High	High

Monitoring and Maintenance	Permitting	Can be Installed by	Advantages	Disadvantages
Moderate	Low to None	Skilled Individuals	• Low costs and labor • Aesthetically pleasing • Grows stronger with age • Provides wildlife habitat	• Limited time of year for installation of native species • High failure rate in first two years • Additional re-seeding may be necessary each year
None	Moderate	Design– Engineer Install– Professional Contractor	• Removes future problems • No monitoring and maintenance	• Costs can be high • Improper setback distance may result in future problems • Requires heavy equipment • Requires significant land preparation
Moderate	Moderate to Intensive	Design– Engineer Install– Professional Contractor	• Re-directs water flow • Drainage structures are barely visible	• Can be expensive • May require significant land preparation • May create problem elsewhere
Moderate	Moderate	Design– Engineer Install– Professional Contractor	• Proven to be successful • Less expensive than other structural methods	• Not aesthetically pleasing • Costs can be high • Creates barrier for fish and wildlife habitat • Weakens with age
High	Moderate	Design– Engineer Install– Professional Contractor	• Can be built without heavy equipment • Supports vegetation	• Not aesthetically pleasing • Costs can be high • Creates barrier wildlife • High maintenance and repair • Weakens with age
Moderate	Intensive	Design– Engineer Install– Professional Contractor	• Strong, durable structure • Works well against heavy waves	• Expensive • Not aesthetically pleasing • Creates barrier for wildlife habitat • Does not support vegetation • Weakens with age
High	Moderate	Design– Engineer Install– Professional Contractor	• Resists heavy waves • Supports vegetation	• Expensive • Not aesthetically pleasing • Creates barrier for wildlife • Weakens with age
Moderate	Moderate	Design– Engineer Install– Professional Contractor	• Holds eroding soil in place • Can support some vegetation	• Expensive • Not aesthetically pleasing • Weakens with age • Labor intensive
Moderate	Not Permittable	Design– Engineer Install– Professional Contractor	• Essentially non-moving shoreline	• Not aesthetically pleasing • Need long reaches • Takes up a lot of space
Moderate	Intensive	Design– Engineer Install– Professional Contractor	• Reduces wave action	• Boat hazard • Environmental hazard

***Figure 6.2**: Technical details, advantages, and disadvantages for common engineering-based bluff-stabilization methods applicable to the coast of Lake Champlain. The bottom half of the image continues from the right-hand side of the top image (Image: modified from The Shoreline Stabilization Handbook for Lake Champlain and Other Inland Lakes, 2004).*

	Erosion Control Method	Where It Works	Where It Doesn't Work	Neighboring Impacts	Labor/Preparation	Cost
BIO-ENGINEERING	**Live Staking** *page 26*	On slopes where erosion is minimal. Commonly used in conjunction with other methods	Badly eroded areas	Low	Low	Low
	Contour Wattling *page 27*	On slopes where erosion is minimal Top of a slope to provide a buffer zone	Badly eroded areas that receive heavy erosive action	Low	Low	Low
	Brush Layering *page 28*	On badly eroded slopes which need to be restored	Loose soils Heavy wave action	Low	Moderate	Low
	Brush Matting *page 29*	On badly eroded slopes which need to be restored	Loose soils Heavy wave action	Low	Moderate	Low
BIO-TECHNICAL	**Erosion Control Matting** *page 31*	Moderate to steep slopes along roadways or on slopes	Heavy wave action	Low	Moderate	Low
	Vegetated Riprap *page 31*	Waterways or inland lakes where the underlying soil is stable	Steep banks with loose soil	Moderate	High	Moderate to High
	Vegetated Gabion Wall *page 32*	Moderate slopes to resist wave action	Steep slopes Loose soil	Moderate	High	High
	Vegetated Gabion Mattress *page 33*	Moderate slopes to resist wave action, ice, and surface erosion	Steep slopes Loose soil	Moderate	High	High
	Vegetated Cribbing (Live Cribbing) *page 34*	Unvegetated slopes with a lot of backfill and little wave action	Steep slopes Heavy wave action	Moderate	Moderate	Moderate to High

Erosion Control Method	Monitoring and Maintenance	Permitting	Can be Installed by	Advantages	Disadvantages
Live Staking	Moderate	Low	Skilled Individuals	• Grows stronger with age • Provides habitat for wildlife • Low costs and labor • Natural appearance • Does not require skilled labor	• Limited time of year for installation • High failure rate in first two years
Contour Wattling	High	Low	Skilled Individuals	• Grows stronger with age • Provides habitat for wildlife • Low costs and labor • Natural appearance	• High monitoring and maintenance • Limited time of year for installation • Requires skilled individuals • High failure rate in first two years
Brush Layering	High	Low	Skilled Individuals	• Restores banks • Grows stronger with age • Provides habitat for wildlife • Natural appearance • Low costs	• More labor intensive • High monitoring and maintenance • Limited time of year for installation • Requires skilled individuals • High failure rate in first two years
Brush Matting	High	Low	Skilled Individuals	• Restores banks • Grows stronger with age • Provides habitat for wildlife • Natural appearance • Low costs	• More labor intensive • High monitoring and maintenance • Limited time of year for installation • Requires skilled individuals • High failure rate in first two years
Erosion Control Matting	High	Low	Skilled Individual(s)	• Restores banks, slopes • Grows stronger with age • Provides wildlife habitat • Natural appearance	• High monitoring and maintenance • Limited time of year for installation
Vegetated Riprap	High	Moderate	Design– Engineer Install– Professional Contractor	• Increased stability with vegetation • More natural appearance • Provides some wildlife habitat	• Costs can be high • Labor intensive • High failure rate for vegetation in first two years • Increased monitoring and maintenance with vegetation added.
Vegetated Gabion Wall	High	Moderate	Design– Engineer Install– Professional Contractor	• Increased stability with vegetation • More natural appearance • Provides some wildlife habitat	• High costs • Labor intensive • High failure rate for vegetation in first two years • High monitoring and maintenance
Vegetated Gabion Mattress	High	Moderate	Design– Engineer Install– Professional Contractor	• Increased stability with vegetation • More natural appearance • Provides some wildlife habitat	• High costs • Labor intensive • High failure rate for vegetation in first two years
Vegetated Cribbing (Live Cribbing)	High	Moderate	Design– Engineer Install– Professional Contractor	• Use of timber creates nice, natural appearance • Provides wildlife habitat • Increased stability with vegetation • Holds eroding soil in place	• Expensive • Labor intensive • High failure rate for vegetation

Figure 6.3*: Technical details, advantages, and disadvantages for common bioengineering and biotechnical bluff-stabilization methods applicable to the coast of Lake Champlain. The bottom half of the image continues from the right-hand side of the top image (Image: modified from The Shoreline Stabilization Handbook for Lake Champlain and Other Inland Lakes, 2004).*

Figure 6.4: *Mitigation of bluff retreat on adjoining properties at a location west of Conneaut, Ohio. These projects involved slope re-grading, vegetative plantings, subtle terracing, a likely installation of a drainage system, and installation of a steel seawall and a filled caisson seawall (with back-fill). The hopper barge may be temporary (Imagery collected in April 2015 and available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

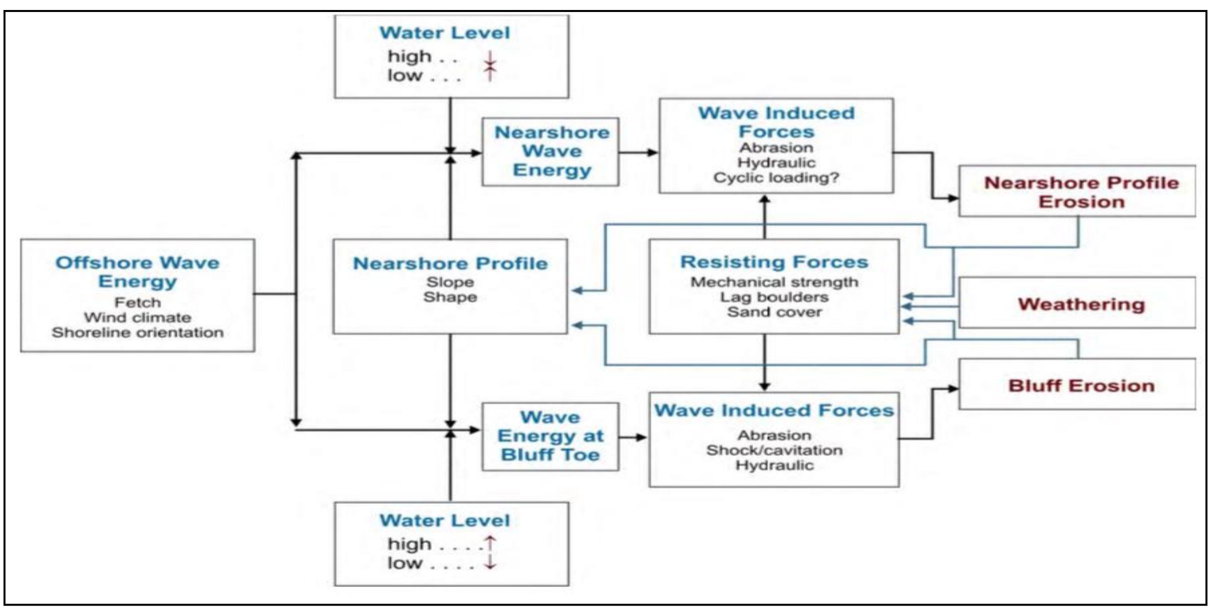


Figure 6.5: *Schematic diagram illustrating linkages between hydrodynamic processes (wave energy) active in the nearshore and at the bluff toe. These wave-related processes, and subaerial and subaqueous substrate weathering, are major drivers of nearshore and bluff-toe erosion on bedrock-free cohesive coasts. Reducing the effects of erosional processes such as these is one goal of bluff-retreat mitigation (Image: modified from Davidson-Arnott, 2016).*

Historically in coastal erosion mitigation, many engineering, bioengineering, and biotechnical solutions that were developed for problems on sandy beach coasts were adaptable, with appropriate modifications, to solving problems on cohesive bank and bluff coasts (as well as inland areas of steep terrain) by simple "technology" transfer. Feedbacks among the resistive and driving forces on the nearshore, bluff-face, and bluff-crest parts of cohesive coasts (Figure 6.5) have a similar degree of complexity to those that exist on beach coasts. Numerous feedbacks in coastal systems allow the opportunity for specific mitigation methods to be used to address specific parts of a complex bluff-retreat problem. When time permits, applying a comprehensive, planned, proactive solution or set of solutions is a better approach (Figure 6.6) than applying a piecemeal (or reactive) solution where the underlying erosion-driving mechanisms are not fully understood or addressed (Figures 6.7 and 6.8).

In general, the application of remediation measures landward of the shoreline (e.g. revetments, rock-filled cribs, and slope re-grading) is technically and economically more feasible that applying measures lakeward of the shoreline (e.g., offshore breakwaters at Forest Park, Lake Forest, IL; submerged sills at North Avenue Beach, Chicago, IL). Figure 6.9 shows an Ohio DNR model coastal-engineering solution for a high Lake Erie bluff scenario where retreat is being driven primarily by hydrodynamic processes (waves). In such cases, appropriate structures placed at the base of the bluff, combined with slope re-grading, are important components of plans to achieve bluff stability. In general, guidance plans such as those provided by Ohio DNR proactively facilitate the work of coastal-engineering contractors involved in erosion mitigation by clarifying expectations and procedures in the permit-design-build process. Equally valuable is the provision of generalized bluff and coastal hazard information for the general public and coastal property owners, such as that provided by Wisconsin Sea Grant (Keillor, 1998; Keillor and White, 2003; Chase et al., 2012; Luloff and Keillor, 2016) and Ontario's Ministry of Natural Resources (OMNR, 2001).

Figure 6.6A: *Example of proactive mitigation of a bluff-retreat problem on the Lake Ontario coast at Lake Bluff, Town of Huron, New York, using a comprehensive approach to address several causes of historical bluff instability. The stratigraphy at this New York site is similar to that of the Pennsylvania coast.*

Figure 6.6B: *Mitigation methods being adopted at this site include toe protection using riprap, slope re-grading to a dual-slope configuration, installation of koir matting and erosion-control matting, vegetative plantings, septic-system modifications, and ground- and surface-water interception drainage (Images: modified from www.lakebluff-ny.org).*

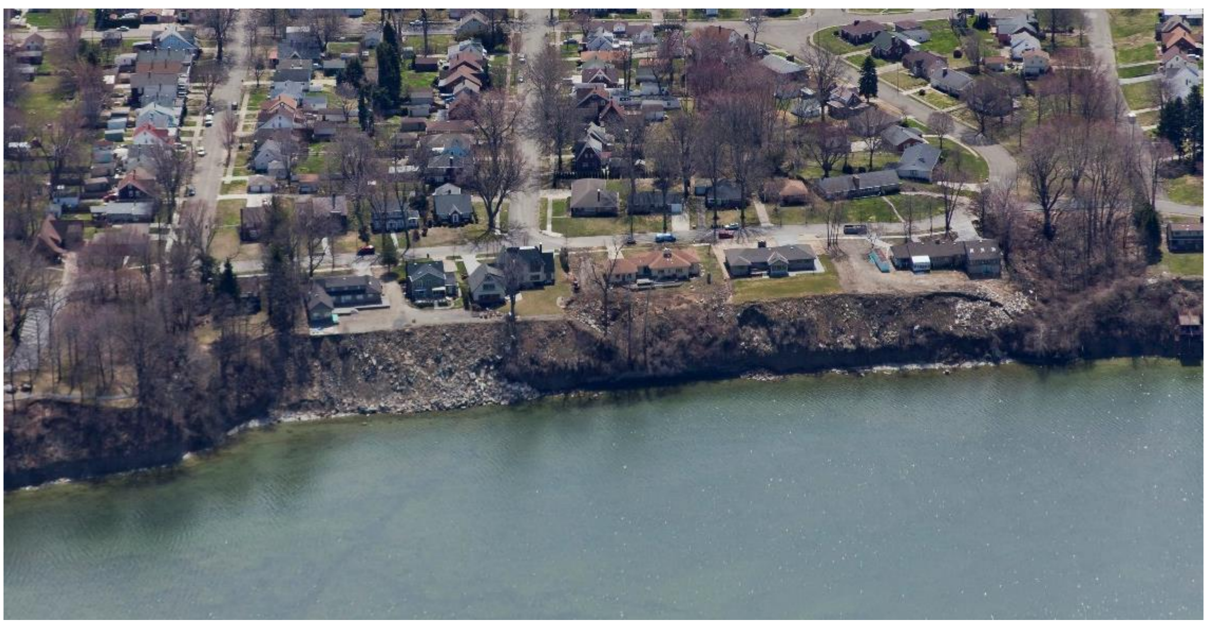


Figure 6.7: *Apparent reactive mitigation of a bluff retreat problem on several adjacent properties in Lawrence Park, east of the City of Erie. Mitigation appears to simply involve the tipping of construction debris onto the existing unconsolidated slope that likely had a wide bedrock ledge at its base. The tall bedrock toe in this area means that wave-induced erosion of the bluffs is less significant here than along the western coastal reach and that groundwater may play a large role. A small rotational slump has already developed in the unconsolidated fill material, adding debris to the base of the near-vertical bluff toe (Imagery collected in April 2015 and available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.8A*: Oblique aerial photograph (from 2009) of the pre-1970s Esplanade Apartments complex, Pacifica, California. The image illustrates chronic bluff failure (debris falls, gullying) in an urbanized setting where five apartment complexes sit atop sandy Pacific coast bluffs. Sufficient time may not have been available at this site to develop a proactive erosion-mitigation plan. Hard stabilization (riprap) placed at the bluff toe is not preventing continuous bluff retreat at the site.*

Figure 6.8B*: Oblique aerial photograph (from 2013) of the Esplanade Apartments complex, Pacifica, California. By early 2016, two of these complexes had been condemned and demolished because bluff erosion had undermined the buildings. The addition of extra riprap, concrete grouting and bluff face-anchoring did not prevent continued bluff retreat (Images: modified from an aerial photo database available from the California Coastal Records Project at Californiacoastline.org).*

Bluff-Retreat Mitigation Trends on Pennsylvania's Lake Erie Coast

Private properties on the bluff coast of Pennsylvania use a large variety of engineering, bioengineering, and biotechnical approaches to stabilizing bluffs. Two general factors other than economics contribute to why a variety of approaches is used: (i) environmental trends and changing regulatory preferences over time; and (ii) variability in coastal-geology (specifically, bluff stratigraphy and elevation) with location on the coast.

Historically, hard stabilization (engineering) at the base of the bluff was the preferred practice in mitigating bluff retreat. Adding riprap, sea walls, bulkheads, or revetment structures at the toe of the bluff helped reduce the amounts of material lost from the bluff. The structures provided buttressing that resisted the pull of gravity on slope material, and protected the lower bluff from wave attack and littoral current scour. Adding groynes allowed the beach area on a specific property to expand sufficiently that destructive wave energy was less likely, most of the time, to reach the toe of the bluff. Groynes also provided an equally important benefit of increasing the beach area for recreational and aesthetic purposes. Similarly, adding sea walls with backfill isolated the bluff toe from wave attack under most conditions, provided buttressing, and allowed an increase in recreational space at lake level if shore-access stairways or trails were installed. Over time, and in common with most coastal states participating in the NOAA Coastal Zone Management Program (https://coast.noaa.gov/czm/), environment-friendly policies and regulations at the state and federal levels resulted in a more recent trend to move mitigation approaches towards the soft-stabilization (bioengineering, biotechnical) end of the spectrum where possible.

Concurrent with this temporal environmental trend, differences in bluff stratigraphy between the eastern and western coastal reaches have indirectly led to a spatial variation in mitigation methods used. There is a preference for bluff-face mitigation approaches along the eastern coastal reach where a bedrock toe is present, and a bluff-toe approach along the western coastal reach where the bluffs are more susceptible to wave-induced erosion. In the eastern coastal reach, the resistant bluff toe may extend as much as 7 m above lake level. This geometry restricts access to the base of the bluff, which in turn reduces choice in mitigation options because waterborne staging becomes expensive. The stratigraphy also disincentivizes placing structures such as groynes and back-filled seawalls that allow a material mass to provide toe support for the bluff. This toe-access problem is particularly the case when a beach is not initially present. Bluff-retreat mitigation in these cases then tends to focus on the bluff face and bluff crest to address bluff failure. This can be fortuitous because in such settings, subaerial processes involving some combination of surface runoff, groundwater discharge, and mass loading are more likely to dominate over hydrodynamic forces as the cause of bluff retreat. Consequently, where feasible, mitigation involving reducing the slope of the bluff face, intercepting surface runoff and groundwater discharge, using plantings and planted structures, and installing low-relief terracing is more likely to occur. However, along the easternmost part of the eastern coastal reach where bedrock dips below lake level, access to low bluffs and banks permits bluff-toe and beach-retention structures to again become more feasible.

In the western coastal reach, the bluff toe (cliff) is often absent and access to the beach can be easier. Because hydrodynamic forces dominate over subaerial forces, structures placed to defend the toe of the bluff become more important in the spectrum of mitigation approaches. The goal of engineering solutions may then be to at least partly replicate the protective effect of the bedrock toe that is absent. As a result, structures such as riprap aprons, sea walls with backfill, bulkheads, and revetments are the mitigation solution of choice. Many of the various structures are scaled to the dimensions of the property given the costs of coastal construction, and many are sufficiently old that they were installed with minimal consideration of impacts to downdrift properties. Where groundwater and/or surface runoff is an issue, slope regrading and installation of drainage systems are employed either separately or in conjunction with toe stabilization.

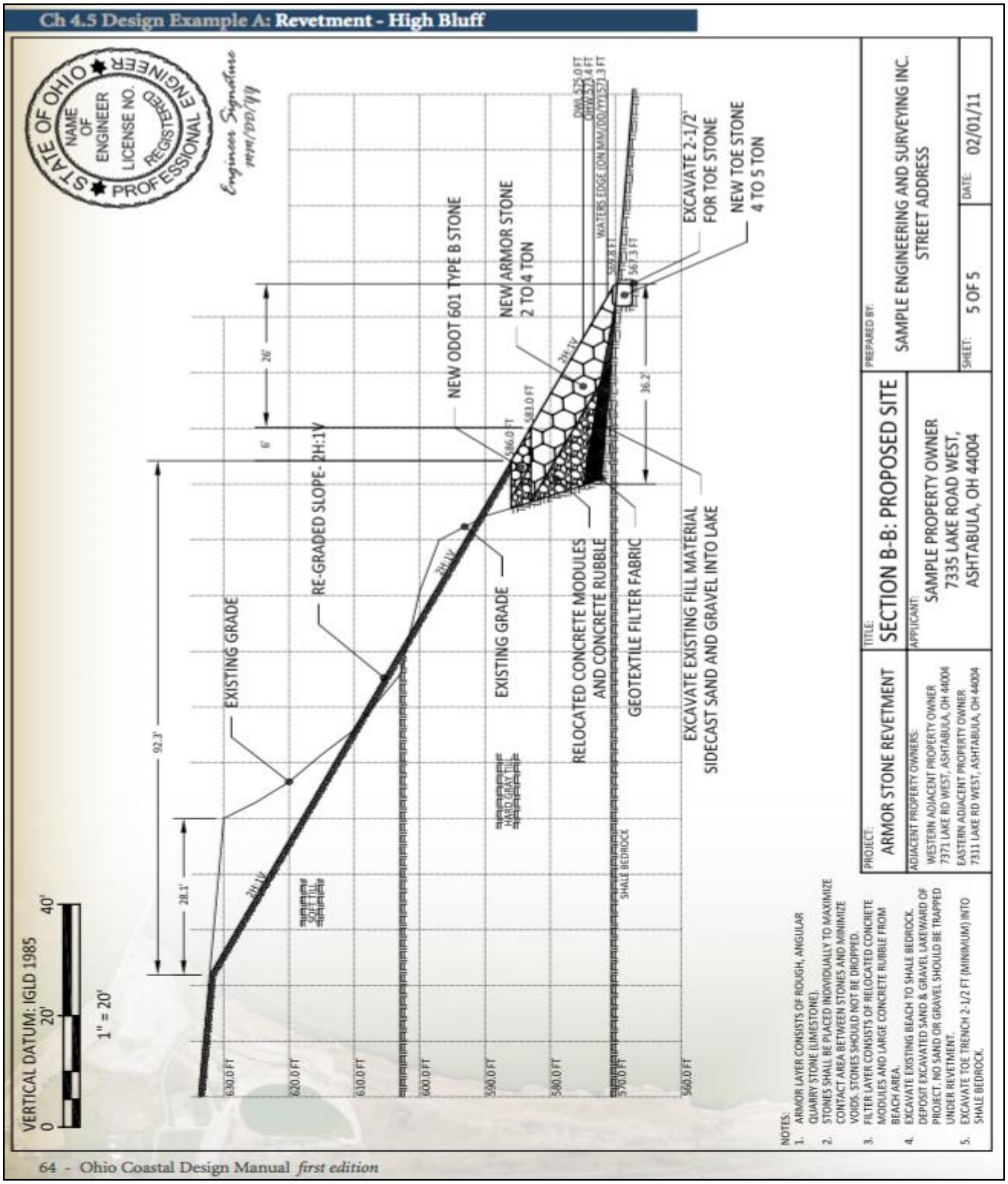


Figure 6.9: *Screenshot of a model revetment + slope regrade solution provided by Ohio DNR for a high-bluff scenario without a bedrock toe. Model plans such as this (section and map views) provide guidance for coastal engineering contractors. Bluff stratigraphy at this site is very similar to that encountered in western Erie County, PA (Image: modified from the Ohio Coastal Design Manual at http://coastal.ohiodnr.gov/portals/coastal/pdfs/designmanual/Ch4_5A.pdf).*

On the Pennsylvania bluff coast, with two exceptions, offshore structures have not been used as an engineering solution for bluff-retreat problems. The two exceptions are associated with the shore-attached breakwater structures that define the marinas at Shades Beach and North East in the eastern coastal reach. While bluff and low-bank protection, respectively, were secondary benefits of these marinas, the two breakwater complexes have allowed beach expansion on their updrift (southwest) sides. This has had the effect of removing wave action from the toe of the adjacent bluffs and banks with consequent benefits to bluff stability. However, sediment bypassing (using trucks and bulldozers) to the downdrift coast has subsequently been needed for at least one of the marinas due to the effectiveness of the breakwaters in trapping part of the small volume of littoral drift moving along the Pennsylvania coast. Offshore breakwaters have, however, been used extensively on the sand-spit coast of Presque Isle to replace the declining benefits of older (failing or subsiding) structures that date from as far back as the late 1800s. The 55-element new breakwater field was constructed in the early 1990s with the partial aim of reducing the volume of periodic beach nourishment that would be needed at Presque Isle State Park (Foyle and Norton, 2006). However, this technology has not yet been adapted to the Pennsylvania bluff coast.

Elsewhere on the Great Lakes, hard stabilization using shore-attached offshore breakwaters has been working successfully for almost three decades at Lake Forest, Illinois (Figure 6.10). At this site, the primary goal was to provide a municipal beach for Lake Forest residents along a coastline that was otherwise dominated by eroding glacial-till bluffs, narrow gravel beaches, and a glacial till nearshore and surf zone. A small safe harbor was also part of the project, similar in design to the one at Shades Beach on the Pennsylvania coast. The project used an arc of five offshore breakwaters connected to shore by steel sheetpile to trap southward-moving littoral drift and ultimately retain a multiple beach-embayment geometry between the breakwater "headlands." Lakeward displacement of the shoreline along the former lakefront bluffs has shifted wave energy away from the bluff toe such that rates of bluff retreat have been reduced significantly. This is an approach that may work on parts of the Pennsylvania bluff coast if the goal is to have benefits other than just bluff stabilization.

While beneficial at the mitigation site, hard stabilization approaches may have adverse impacts on downdrift properties. These most commonly occur because of disruptions to the littoral sediment supply, adverse end-effects associated with the hard structure, and local reduction in littoral sediment inputs caused by the structure. On the Wisconsin coast of Lake Michigan at Concordia University, Lin and Wu (2014) noted from a decade of monitoring that a large bluff-toe revetment with significant slope regrading reduced bluff retreat to zero along the 1000 m structure. However, the structure led to enhanced bluff retreat and lake-bed downcutting over a comparable distance (~1000 m) along the downdrift coast. Thus, while the university bluffs and adjacent infrastructure benefited from mitigation project, private landowners immediately downdrift of the project were adversely impacted.

The eastern shore of the Chesapeake Bay is another example of the use of offshore breakwaters for coastal stabilization where structures have been in place for over a half-century at Kiptopeke State Park, Virginia (Figure 6.11). A former ferry terminal located on a low-bluff sandy coast with well-developed beaches is still being protected by a double offshore breakwater system consisting of WWII-era concrete-hull transport ships. In combination with the former terminal jetties, the beaches have prograded westward (bayward), thus isolating the bluff from wave attack. This site is effectively a scaled-up but more-crude version of the Forest Park project (Figure 6.10) with significantly different project goals. The more recent Forest Park project likely involved more environmental planning, modeling, and coastal engineering design.

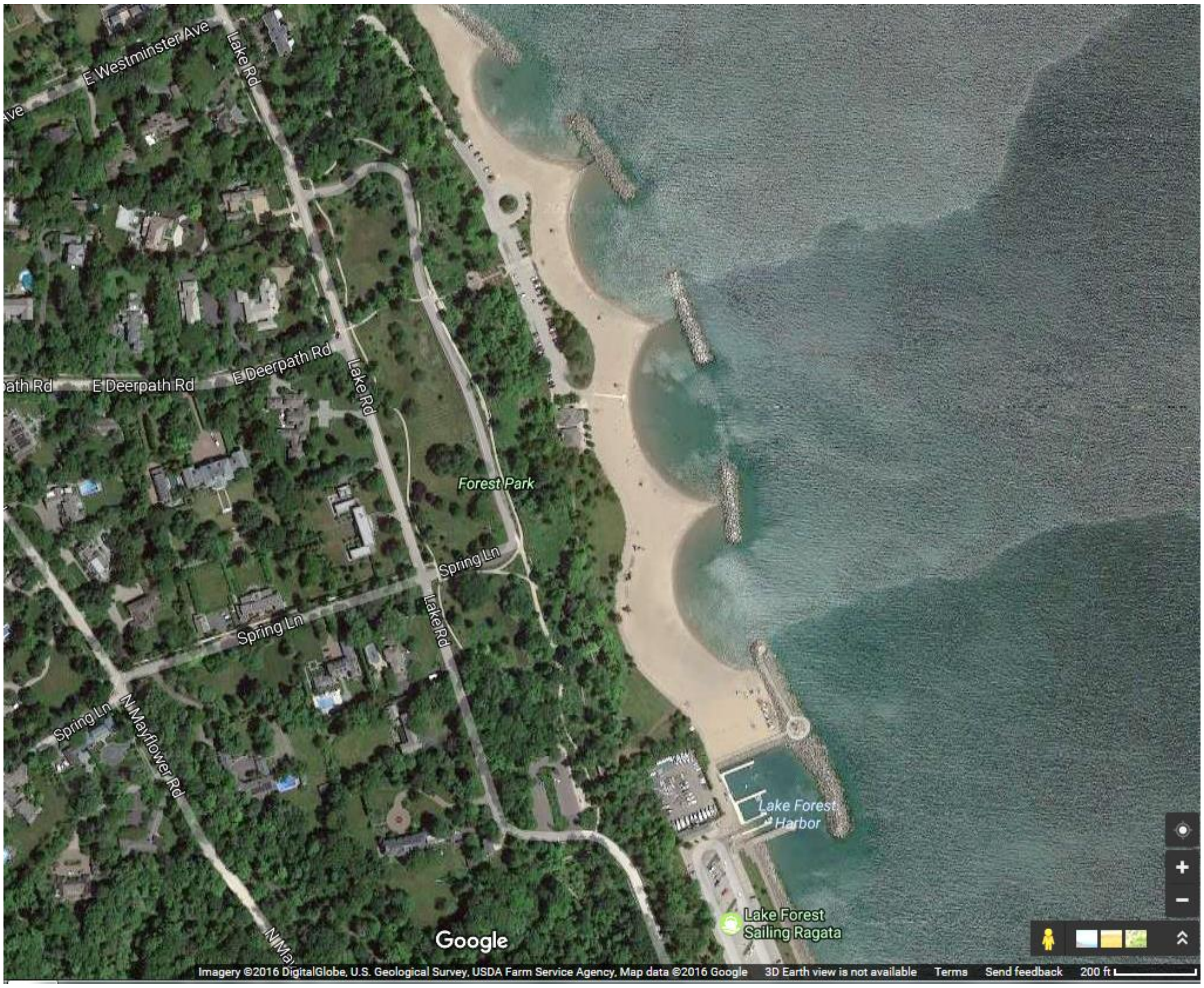


Figure 6.10: *Forest Park, Lake Forest, Illinois, near Chicago. This is an example of an attached offshore breakwater design on the Lake Michigan bluff coast that provides beach resources, a safe harbor, and bluff stabilization. Littoral drift moves from north to south. Note erosion mitigation using bluff slope reduction in the far distance in the lower image (Images: maps.google.com).*

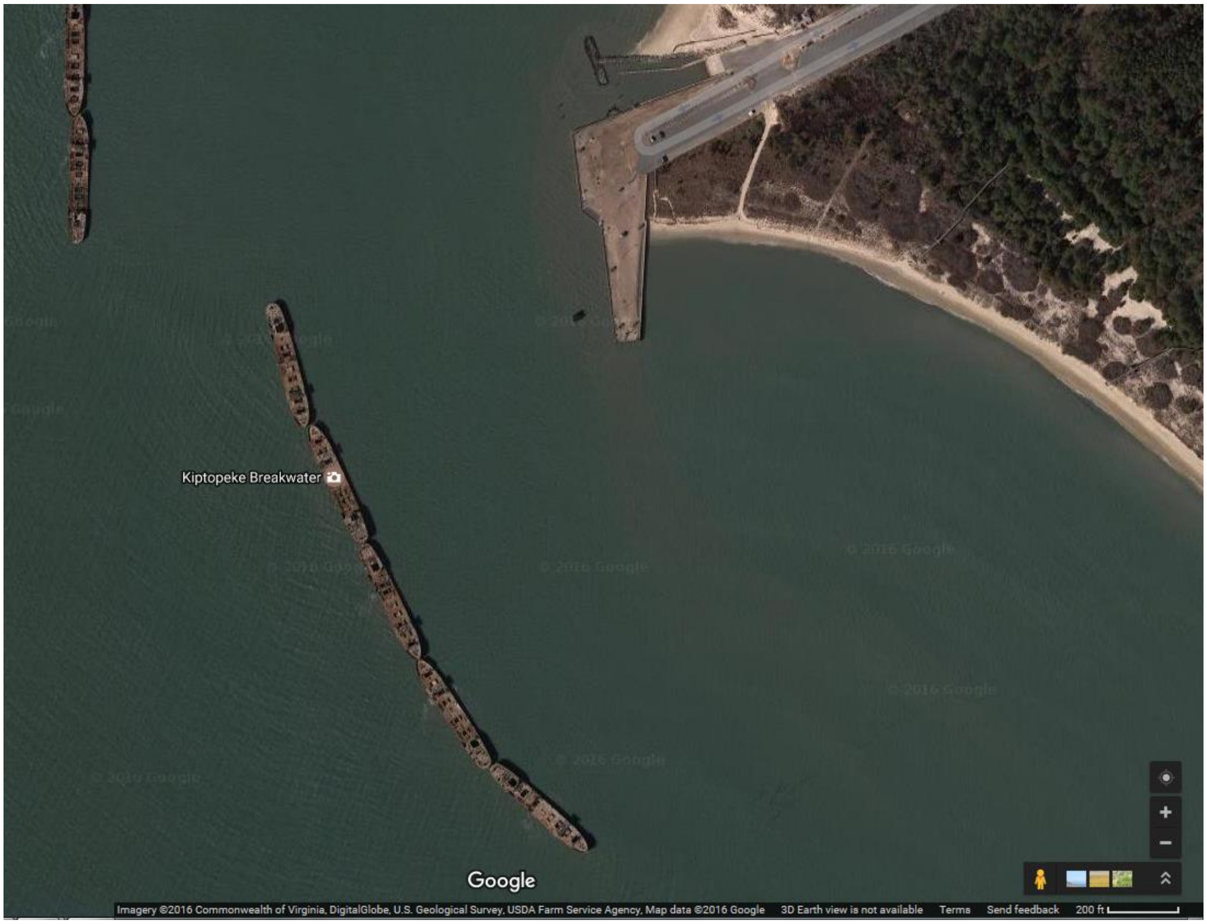


Figure 6.11: *Kiptopeke State Park, Virginia Eastern Shore, Chesapeake Bay. Offshore breakwaters (concrete WWII-era ships emplaced about 1950) protect the beaches and low bluffs. The structures cause wave reflection and diffraction that reduce wave energy density at the shoreline (Image: maps. google.com).*

Aerial-Photo Tour of Bluff-Retreat Mitigation Methods on the Pennsylvania Coast

The following sequence of oblique aerial photographs illustrates common erosion-mitigation methods used on the Pennsylvania coast. Traversing the coast from northeast to southwest, the imagery used here was collected during April 2015. It is available online from the Pennsylvania DEP Coastal Resources Management Program at http://www.dep.pa.gov. Prior and subsequent eras of oblique coastal-zone photography coverage are also available from PA DEP. For the Pennsylvania coast in general, hard stabilization structures at the shoreline and bluff toe dominate the methods used. Soft stabilization methods (bioengineering and biotechnical methods) are notably rare. This can be partly attributed to the fact that much of the erosion being addressed is linked to wave attack at the base of the bluff where bioengineering and biotechnical methods are less resilient. Additionally, more recent efforts involving surface and subsurface drainage systems and slope regrading are more difficult to see at the scale of the photographs, particularly if those projects are more than a few years old.

Figure 6.12: *Stepped concrete revetment and back-filled concrete-cube seawall (bulkhead) in easternmost Erie County. A bedrock toe is absent at this location (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

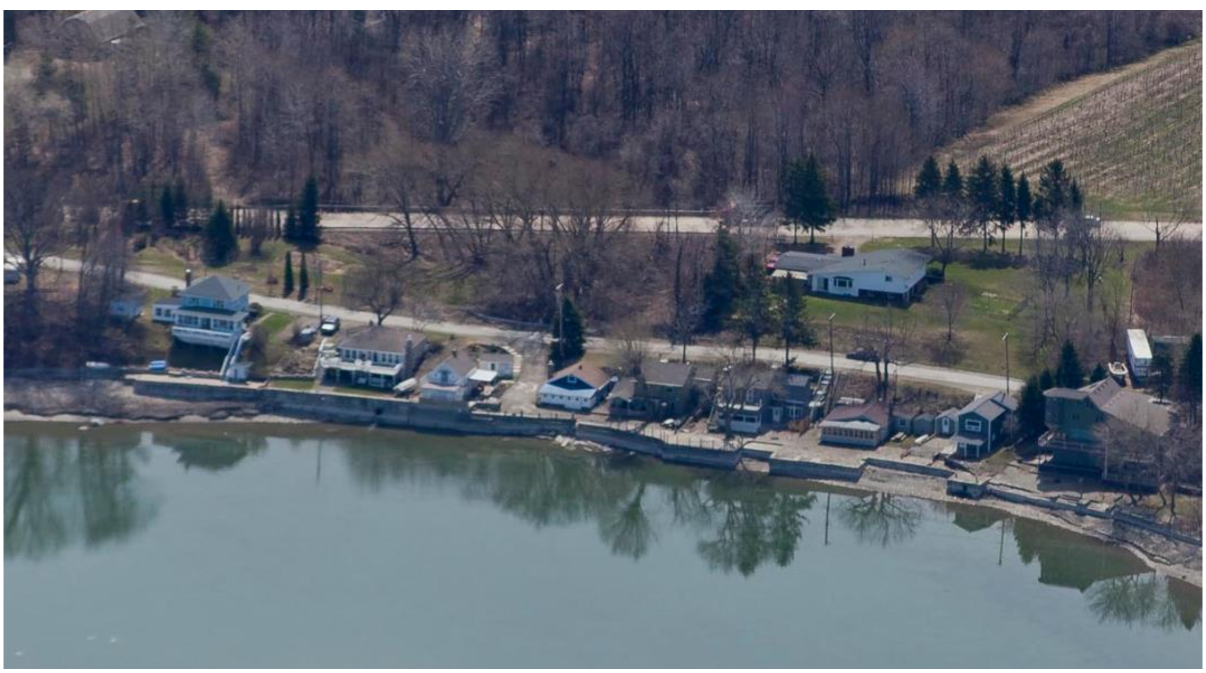


Figure 6.13: *Back-filled concrete-cube bulkheads protect properties built on a low bank east of Twentymile Creek, eastern Erie County (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.14: *Shore-attached breakwaters and low banks at North East Marina, eastern Erie County. Bedrock is below lake level at this location. Artificial sediment bypassing is in progress on the updrift (right) side of the marina and will be moved to the downdrift (left) side (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

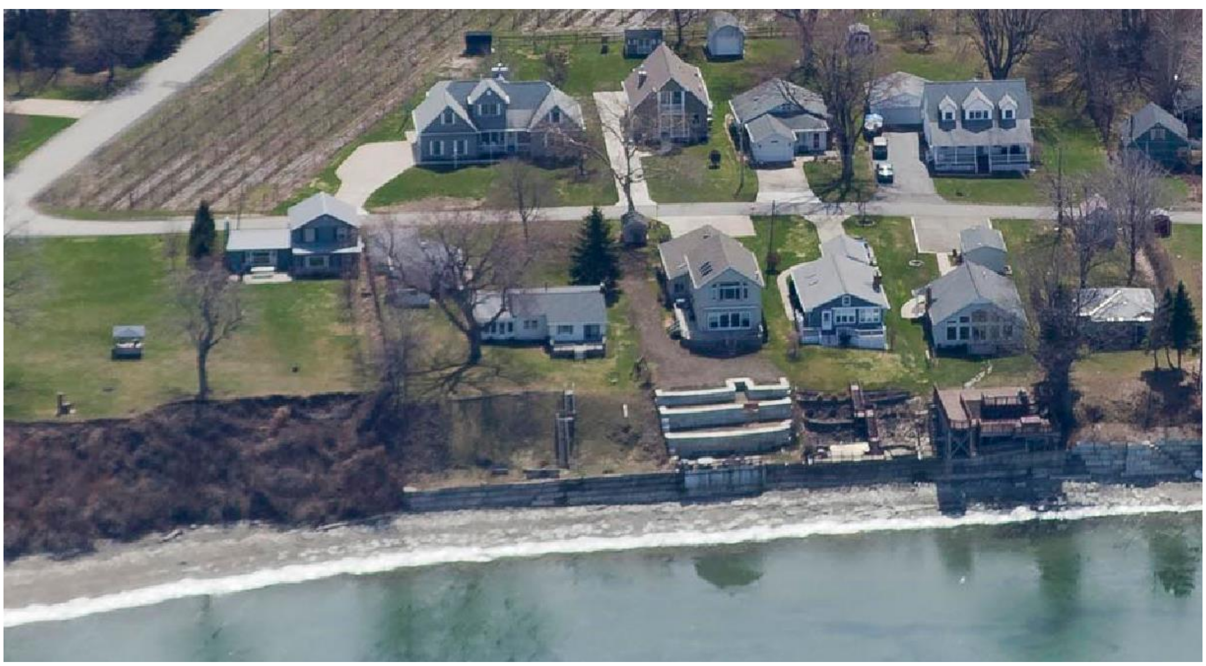


Figure 6.15: *A bluff-toe bulkhead and terracing, using concrete cubes, protect a low bluff in eastern Erie County. A bedrock toe is absent at this location (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.16: *Concrete filled caissons with backfill protect buildings along a low coastal bank east of Freeport Beach at Sixteenmile Creek, eastern Erie County (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.17: *Stacked concrete-cube bulkhead west of Sixteenmile Creek, eastern Erie County. The bulkhead rests on beach or on shallow bedrock beneath the beach (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.18: *Soil slide (or soil creep) east of Eightmile Creek, eastern Erie County. Shallow-rooted vegetation covering the lower glacial till has moved down-slope while a small rotational slump occurs at the bluff crest. There is no evidence of bluff-retreat mitigation at this site where groundwater saturation of the glacial till causes bluff-face instability (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

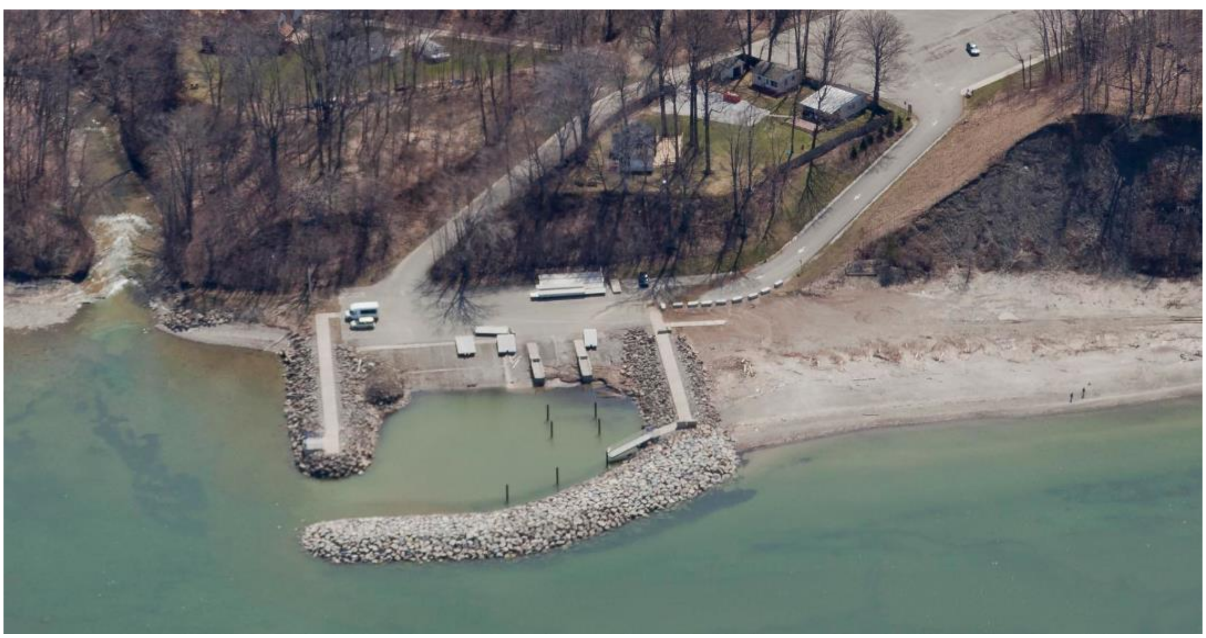


Figure 6.19: *Shades Beach Marina at Eightmile Creek, eastern Erie County. The breakwaters provide protection to the bluff immediately behind the marina basin. A growing beach fillet on the updrift (right) side may be reducing the retreat rate of adjacent bluffs. Slope regrading and a parking-lot drainage system are also part of the site renovations (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.20: *Concrete-cube bulkheads and groynes west of Eightmile Creek, eastern Erie County. Trapping of littoral sand by groynes removes the focus of wave attack from the low bluff (with a steep bedrock-toe) on the updrift sides of the structures (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.21: *Buttressed concrete-cube bulkhead west of Presque Isle peninsula, western Erie County. Stepped buttresses allow lake access from the bulkhead and function as short groynes to allow beach accumulation (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

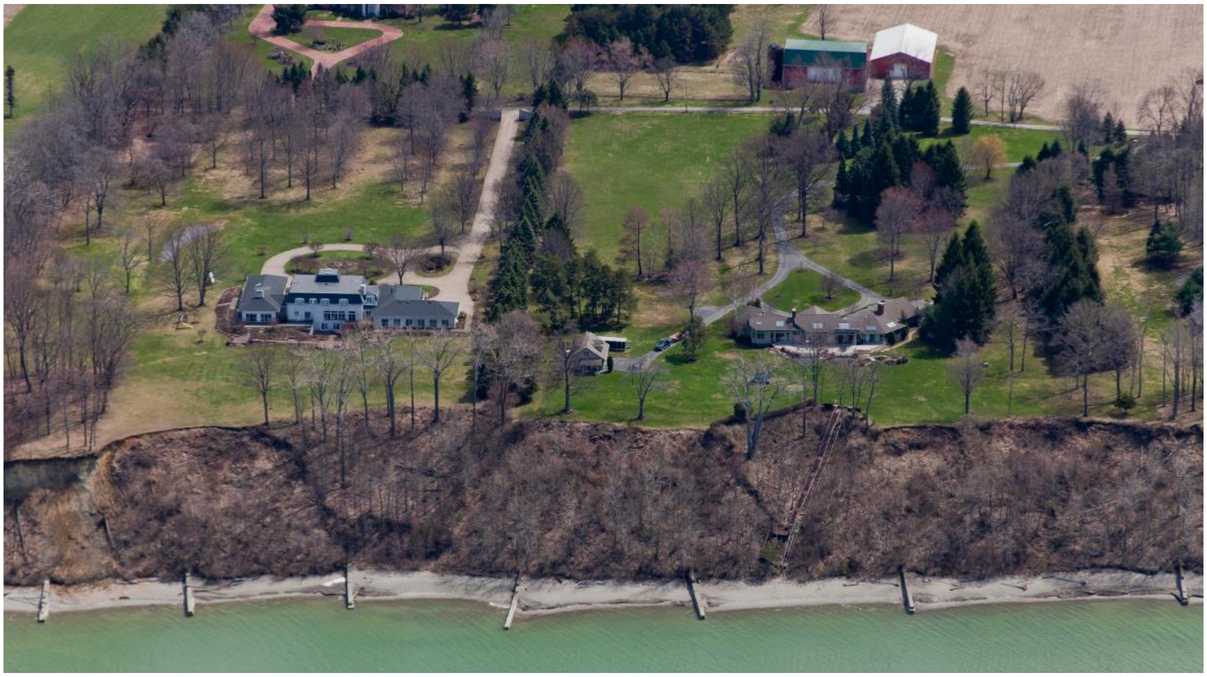


Figure 6.22: *Small non-parallel groyne field in western Erie County. Beach accumulation between the groynes keeps wave energy away from bluff at these two properties (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.23: *High-relief vegetated stone terracing and updrift concrete groyne in western Erie County (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.24: *Concrete and concrete-cube groyne pair with low connecting seawall near Avonia Beach, western Erie County. This approach cordons off the natural beach from fair-weather wave attack that is often beneficial (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Figure 6.25: *Buttressed, dual-level, curvilinear (in plan view) concrete-cube bulkhead resting on beach or bedrock in western Erie County. Stepped buttresses allow lake access from the bulkhead and function as short groynes to allow seasonal beach accumulation (April 2015 imagery, available from PA DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

Chapter 7: Current Trends in Monitoring and Modeling Coastal Bluff Retreat

Overview

Coastal retreat is a pervasive geologic process active on cohesive (clay-rich) bluffs, non-cohesive (sandy) beaches, and rocky cliffs worldwide. For bluff coasts, it remains very difficult to predict the future position of the bluff crest, face or toe at short, intermediate, and long timescales. This is because of prediction and modeling challenges that arise:

- due to the large number of variables that influence bluff retreat rates and magnitudes at any given site (Table 7.1)
- because a bluff failure event will generally increase bluff stability (by reducing the bluff slope) until protective material that collected at the base of the slope gets removed by hydrodynamic forces such as waves, littoral currents, and ice movement
- because bluff behavior along a coast and over time can vary greatly due to changes in internal geotechnical properties that are fundamentally governed by geology and climate (principally hydrology)
- because the more significant factors determining the rate of bluff retreat vary greatly with location on a coast and with time
- because when an unstable bluff fails, the failure-driving forces are often reduced relative to the resistive forces and the bluff enters a more stable phase for an indeterminate period of time
- because the pre-failure condition of the bluff is always a significant factor

Hydrodynamic factors	Base-of-bluff factors	Bluff face and internal factors	Hinterland factors
Wave energy flux	Bluff engineering	Slope, height, strength	*Winter snow and ice cover*
Seiche, tide, storm and seasonal lake level change	*Beach volume, morphology, and composition*	Composition, dip and strike of internal layering	Land slope, orientation and topography
Storm surge height, duration and frequency	*Presence of logs/large debris/ coastal structures*	*Bedrock toe strength, height, relative dip*	*Bluff crest road/foot traffic*
Width of winter nearshore ice complex	*Wave energy shielding by deltas and bathymetry*	Groundwater sapping, piping	*Anthropogenic water additions near bluff*
Nearshore bathymetry	*Littoral sediment supply*	*Seasonal runoff and freezing*	Hydraulic conductivity (k)
Lake ice stress on bluff toe	*Presence/absence of beach sand and gravel*	*Bluff orientation (wind, waves, sun)*	*Land use: low-density urban, forest, agricultural*
Nearshore substrate composition	*Presence/absence of folds, joints, and faults*	Internal aquifer heterogeneity	Runoff:infiltration ratio
Regional long-term change in lake level	*Bedrock freeze–thaw weathering*	*Vegetation; wildlife nesting and burrowing*	Water table slope, orientation and topography
		Groundwater discharge through the bluff face	Volume of rainfall intercepted/m of coast

Factors most responsible for along-coast (spatial) variability in recession rates are shown in normal font, and those less responsible in italic font.

Table 7.1: *Principal hydrodynamic and subaerial factors that influence bluff change both generally and on the Pennsylvania coast of Lake Erie (Image: modified from Komar, 1998; Foyle, 2014).*

Table 7.1 summarizes the principal physical factors that govern behavior of bluff coasts in general. What is not yet known for the Lake Erie coast, nor other specific bluff settings globally, is the relative and/or absolute importance of each of these factors at any specific site or general coastal area. Determining whether a specific bluff retreats because of subaerial processes exclusively, because of hydrodynamic processes exclusively, or because of some combination of these two groups of processes, is extremely difficult to accomplish with any degree of precision. Typically, and often in the field of bluff modeling, an assumption is made on the relative (e.g., a ratio) importance of these two process groups based on local or site data, or on bluff profile geometry. The geometry indicator is easily evaluated because wave-driven bluff retreat tends to produce more-vertical bluff slopes than retreat that is driven by subaerial processes such as runoff and groundwater discharge (Chapter 4, Figure 4.1).

Monitoring and Predicting Coastal Bluff Retreat

Currently, three general approaches are used to estimate the location of a coastal bluff crest at some predetermined time in the future. These comprise (i) deterministic retreat-rate estimates, (ii) process-response models, and (iii) Bayesian probabilistic models.

Deterministic or Observational Retreat-Rate Methods

Deterministic methods utilize mathematical techniques based on the concept that future behavior can be predicted from past behavior of a set of data. These methods ignore the existence of disturbances or external shocks that may alter the data's future pattern. This observational approach thus relies on using an historical record of past bluff positions to obtain average retreat rates in order to estimate where the bluff crest may be located in the future. That is, it simply relies on the forward projection of historical erosion rates. This approach relies on knowing at least one historical bluff-crest location in conjunction with a more recent or present location. Knowing several historical locations as well as the present location of the bluff crest allows either a regression-based average retreat rate or an end-point average retreat rate (EPR) to be determined. The regression-based rate is preferred over the more simplistic EPR when multiple datasets are available. The EPR is determined if the present location, one known historical location, and the time interval between the two are known. Confidence intervals or error bars can be included in the positional and rate information in both cases to convey the degree of uncertainty in the data (Thieler et al., 2009). Increasing the number of known historical positions, and incorporating error bars to account for uncertainty in the position-measurement methodology and the analysis methodology, will yield statistically more valid retreat rates. However, in many coastal areas, data on past bluff positions may be scarce and data quality may be less than ideal.

Improving the data quality, such as switching from identifying bluff-crest positions on unrectified and non-georeferenced aerial photos to identifying them on larger scale ortho-rectified and geo-referenced photos will improve overall accuracy dramatically and is now a quality-control requirement for federal/state-funded coastal monitoring projects that utilize aerial photographs. Automating the identification and measurement tasks as much as possible is another means to improve overall accuracy and consistency of the retreat rates determined. The benchmark automated change-rate method now most widely used in the United States is the GIS-based Digital Shoreline Analysis System (DSAS; Thieler et al., 2005, 2009). DSAS allows the user to define the spacings of virtual rate-change measurement transects that are most commonly in the range of 10 to 20 meters depending on project needs and coastal complexity (Figure 7.1).

Widely practiced in the United States, the deterministic approach is an excellent method for identifying past change rates and locations of coastal features (shorelines, bluff crests, etc.) because it is based on retrospective observations. This is particularly true when using more recent, high-resolution, data and automated analytical methods. However, the method is very limited in its ability to estimate where a future bluff-crest will likely be located because that step involves making assumptions about future change rates and environmental conditions. The limitation exists because the method approaches the problem of estimating the future bluff-crest position by:

- ignoring the underlying processes and geotechnical properties that drive or resist bluff change and that vary over time and space
- assuming that bluff change, because of the position/time averaging process, is linear in the past and will continue to be linear in the future
- assuming that environmental conditions in the past will remain similar in the future

On oceanic coastlines, the latter assumption ignores the considerable impacts on bluff retreat that can be induced by changes in the sign or rate of sea-level change. In common with many other states, Pennsylvania continues to use this observation-based deterministic approach in coastal erosion mapping, largely due to the absence of any widely practiced, more-accurate approach sanctioned by federal agencies such as NOAA and FEMA. When estimating future bluff-crest positions, oceanic states are beginning to acknowledge the effects of ongoing sea-level rise, and expectations of increased rates of sea-level rise, on bluff stability. To date, this is accomplished by adding a safety factor (buffer) or a geometrical adjustment to the future bluff-crest location using aspects of the Bruun Rule (Bruun, 1962; Bray and Hooke, 1997).

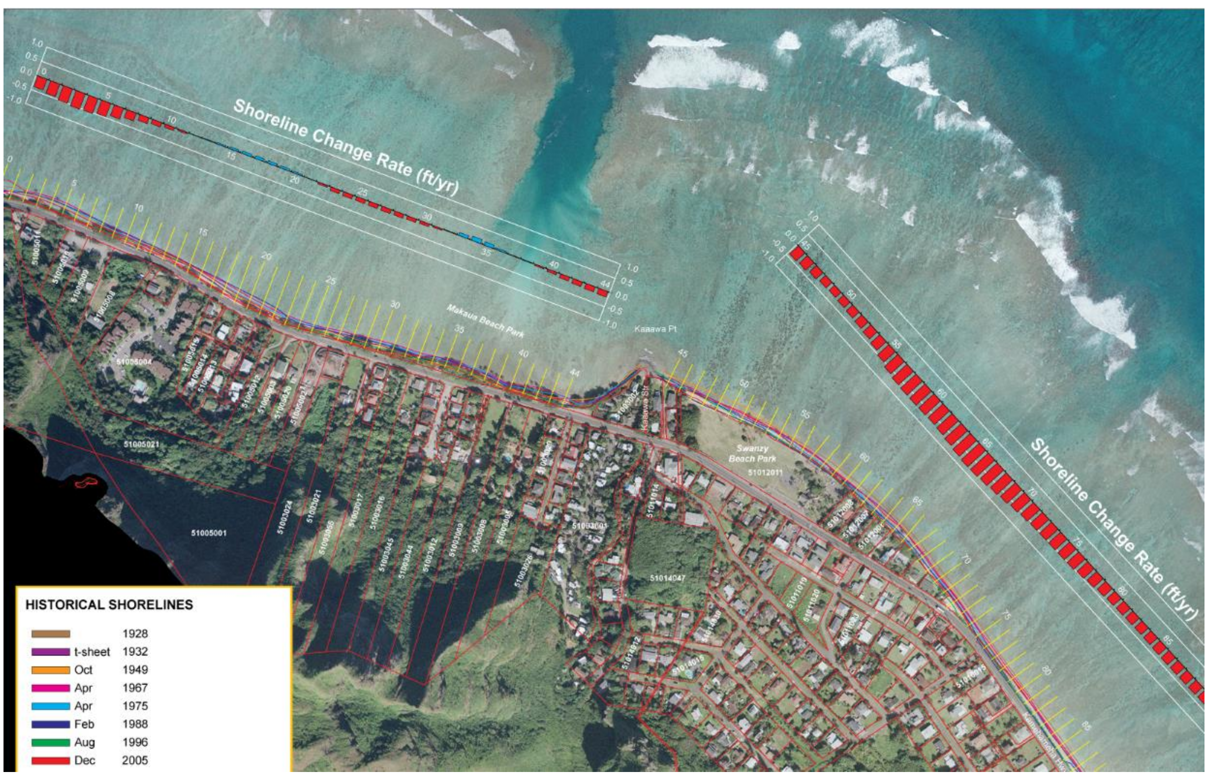


Figure 7.1: *Screenshot of a section of the Oahu, Hawaii, coast showing a typical map product generated by DSAS in GIS. On this non-bluff coast, changes in the low-water shoreline are tracked over time (1928 to 2005; various data sources). Virtual monitoring transects are shown in yellow, historical shorelines by variously colored line features, and coastal-change summaries by bar graph (red is erosion; blue is accretion; maximum erosion rate ~0.24 m/year) (Hawaiian coastal data from ftp://soest.hawaii.edu/coastal/webftp/Oahu/posters/KaaawaSTsmoothTMKPosterRGB72.jpg).*

The accuracy of the retreat rate estimate using past retreat-rate data can be improved by using as much positional data as possible over as long a timeframe as possible (Lee et al., 2001). The general consensus is that this timeframe should be longer than 50 years (Johnsson, 2003; Zuzek et al., 2003). However, the issue then arises that older positional data derived from early ground mapping and aerial surveys recorded at smaller scales yield prior bluff-crest positions that necessarily have large errors associated with them. This issue is partly mitigated when those large errors become less mathematically significant when (i) data are compared over long time periods, (ii) when older data are given a lower weighting than newer (or more accurate) data when being analyzed as part of a larger dataset, and (iii) when change rates are annualized. Fine-tuning the temporal coverage of the positional data is also beneficial and can validate (or not) the use of specific retreat-rate data in estimating future crest positions. For example, bluff retreat rates on both oceanic and lake coasts can be expected to vary depending on whether long-term water levels are rising (transgression) or falling (regression). Retreat rates derived over a longer time period that includes both transgression and regression will yield different values than if the timeframe was limited to one or other water-level scenario. Relying on retreat rates derived during a water-level trend (i.e., transgression or regression) that is likely to change in the future limits the accuracy/validity of using those retreat rates for future coastal planning purposes. Often, this temporal aspect of the data cannot be resolved until the frequency and duration of data coverage is increased. Presently, the data-quality issue is being mitigated slowly over time as more accurate bluff-mapping surveys (e.g., LiDAR and total-station surveys) and analytical methods (e.g., USGS DSAS method; Thieler et al., 2009) become the norm and whose data progressively displace the older data from the comparison window.

Process-Response Models

Process Response Models (PRMs) used in coastal bluff change analysis apply mathematical and engineering principles to attempt to explain how and why a bluff profile (crest, face, and toe) retreats over time and may be expected to retreat in the future. The models attempt to identify a selection of the dominant variables controlling bluff retreat, select the most important variables that should be included, ignore the less important variables in order to reduce model complexity, and identify feedbacks between variables, to model bluff features and behavioral characteristics over time and/or space. Typically, the models are two-dimensional in that they model a bluff profile for a field site with a specific set of assumed, known, or estimated characteristics. The number of bluff-study sites where the modeling approach has recently been or is being used is still relatively small, but this field of endeavor continues to grow with developments in computers and mathematical methods.

A review of recent modeling efforts on the Great Lakes by Geomorphic Solutions (2010) notes that fundamental differences exist between PRMs developed for oceanic versus large-lake coasts. The former coasts are subject to microtidal through macrotidal, diurnal or semidiurnal, fluctuations in water level that shift the zone of attack of hydrodynamic processes landward and seaward and vertically at regular intervals. The former coasts also have long-period oceanic swells, and wave characteristics are quite different from those observed on large lakes where wave periods, heights, and fetches are usually smaller. The coastal morphology of ocean-bluff coasts, in terms of surf morphodynamics, is also much more variable than Great Lakes coasts: lake-bluff coasts are more likely to have narrow reflective beach and nearshore profiles, which permit more wave energy to reach the shoreline and bluff. Conversely, oceanic bluffs may be protected by a wide dissipative beach and shallow nearshore profile which reduces wave energy impinging at the shoreline and bluff. However, even within the Great Lakes, bluff-beach-nearshore systems can show significant variability. Much of the Pennsylvania coast may function similar to a cliffed and reflective oceanic coast because shale bedrock at the bluff and in the nearshore is more resistant (and thus limits nearshore downcutting and wave energy transfer to the shoreline) than cohesive clay and mud coasts. The latter shore types are more prevalent along the Canadian coast of Lake Erie and are likely associated with less reflective conditions. Overall rates of bluff retreat on the Ontario coast should be higher than on the Pennsylvania coast (other factors being equal) because of the weaker, non-bedrock, substrates present and the increased rates of nearshore downcutting that permit a more energetic wave environment at the shoreline. To summarize, bluff-retreat models are very specific in the complex conditions they aim to replicate and thus are often limited in their applicability to the specific sites modeled.

Typically, PRMs can use historical retreat-rate information for calibration purposes when estimating future bluff geometry and position. Alternatively, the models can be run beginning at some historical date (for which the bluff-crest position and/or profile geometry are known) and terminating at a recent survey date to determine how well the model replicates the actual change history. However, in certain regions, historical data on bluff retreat rates, prior bluff crest positions, or profile geometries may be lacking in geographic coverage, or in duration and frequency of coverage. This is most commonly the case for the bluff cross-sectional geometry that is often the feature these models attempt to replicate. The records problem arises because it has historically been more time-consuming or impractical to map or survey an entire bluff profile than to survey where the shoreline, toe and crest are located. In such cases, and until that issue is rectified over time, models can be checked by comparing the modeled outcomes with information on bluff retreat from similar geological settings that may be from the same region (ideally) or more widely dispersed geographically (less than ideal).

Modeling of bluff behavior with PRMs has led to a significant literature collection due to efforts by mathematical geologists, engineers, and process-response modelers over the past several decades. Pertinent papers relevant to Great Lakes coasts include those of Quigley et al., 1977; Sunamura, 1982, 1992; Kamphuis, 1986, 1987, 1990; Southgate and Nairn, 1993; Skafel and Bishop, 1994; Skafel, 1995; Wilcock et al., 1998; Brien and Reed, 2007; Collins and Sitar, 2008; Del Rio and Gracia, 2009; Quinn et al., 2009, 2010; Trenhaile, 2009, 2010; and Castedo et al., 2012, 2013. These papers focus on North American, northern European, and Asian coasts where bluffs have varying degrees of similarity with those of Pennsylvania and the Great Lakes. Over time, models have become more complex and now examine a larger number of interacting variables than did models of the 1970s and 1980s.

Modern PRMs are mathematically and computationally demanding because of the complexity of the variables that govern bluff retreat over a range of timescales and distances, from short-term storm events controlling shear stress on the lakebed and wave height and run-up, to long-term climate-driven changes in precipitation and groundwater recharge. Castedo et al. (2012) note that quantifying the resistive forces acting on a bluff (which reduce its tendency to fail) is still challenging because they can be measured as cohesion, tensile strength, shear strength, or compressive strength, with the latter now considered the best measure (Wilcock et al., 1998; Budetta et al., 2000; Wolters and Muller, 2008; Trenhaile, 2009). Kamphuis (1987) and Trenhail (2009) note that the resistance of cohesive materials to erosion is governed by complex interactions between many factors including mineralogy, inter-granular forces, compressive strength, clay content, plasticity, compaction, and pore water pressure and chemistry. Modeling of cohesive bluffs has the potential to become exponentially more complicated when complex stratigraphy is added (Figure 7.2).

Figure 7.2: *Schematic diagram showing how variability in bedrock composition and aspect may influence processes and rates of subaqueous weathering and erosion in the nearshore. Profiles (a) and (b) tend to be dominated by wave quarrying that generates small slabs of debris that waves and littoral currents can use to physically enhance erosion. The quarrying process is caused by wave impact and fluid (air, water) pressure at discontinuities such as bedding planes and joints. Profile (c) tends to be dominated by weathering and abrasion (if a suitable sand supply is present) processes due to the relative lack of topographic irregularity (Image: modified from Trenhaile, 2009).*

In general, the majority of PRMs simplify the nearshore-bluff stratigraphy for computation purposes to consist entirely of the same materials, or to consist of a simple one- or two-layered system. On bluffs such as those on the Pennsylvania coast, stratigraphy is more complicated along any given profile and also along-coast between profiles. As many as five stratigraphic units can be present, namely: jointed and gently undulating shale bedrock; compact glacial till prone to stress-relief jointing; less compact glacial till prone to soil creep and gullying; lacustrine silts and sands prone to translational slides and rotational slumps; and beach-ridge sands and gravels prone to translational slides and rotational slumps. Even in the nearshore, the composition and aspect of bedrock will significantly influence the amount and type of weathering and erosion that occurs and this also complicates the modeling effort. Figure 7.2 (from Trenhaile, 2009) shows examples of bedrock architectures that are similar to those found on the Pennsylvania coast. Bedrock aspect on most of the coast is similar to that depicted in Figure 7.2a, while at localized zones where faulting and folding occur, the aspect may approach that shown in Figure 7.2b.

Figure 7.3 shows an example of a conceptual framework that defines a PRM for the North Sea coast at Holderness, UK, against which Castedo et al. (2012) tested a multi-parameter PRM. Significant driving (activation) mechanisms for this PRM such as sea-level change and tidal range (the hydrodynamic forces in the lower part of the diagram) would play only minor roles on the Pennsylvania coast. Conversely, subaerial driving forces (top part of the diagram) in this particular model show many similarities with the forces active on Pennsylvania coastal bluffs shown in Table 7.1. Spatial and temporal variations in bluff geotechnical properties resulting from complexity in (i) the depositional environments that built the bluff stratigraphy, and (ii) the volume and pore pressures of groundwater, are likely very important factors controlling bluff behavior on the Lake Erie coast (Foyle, 2014).

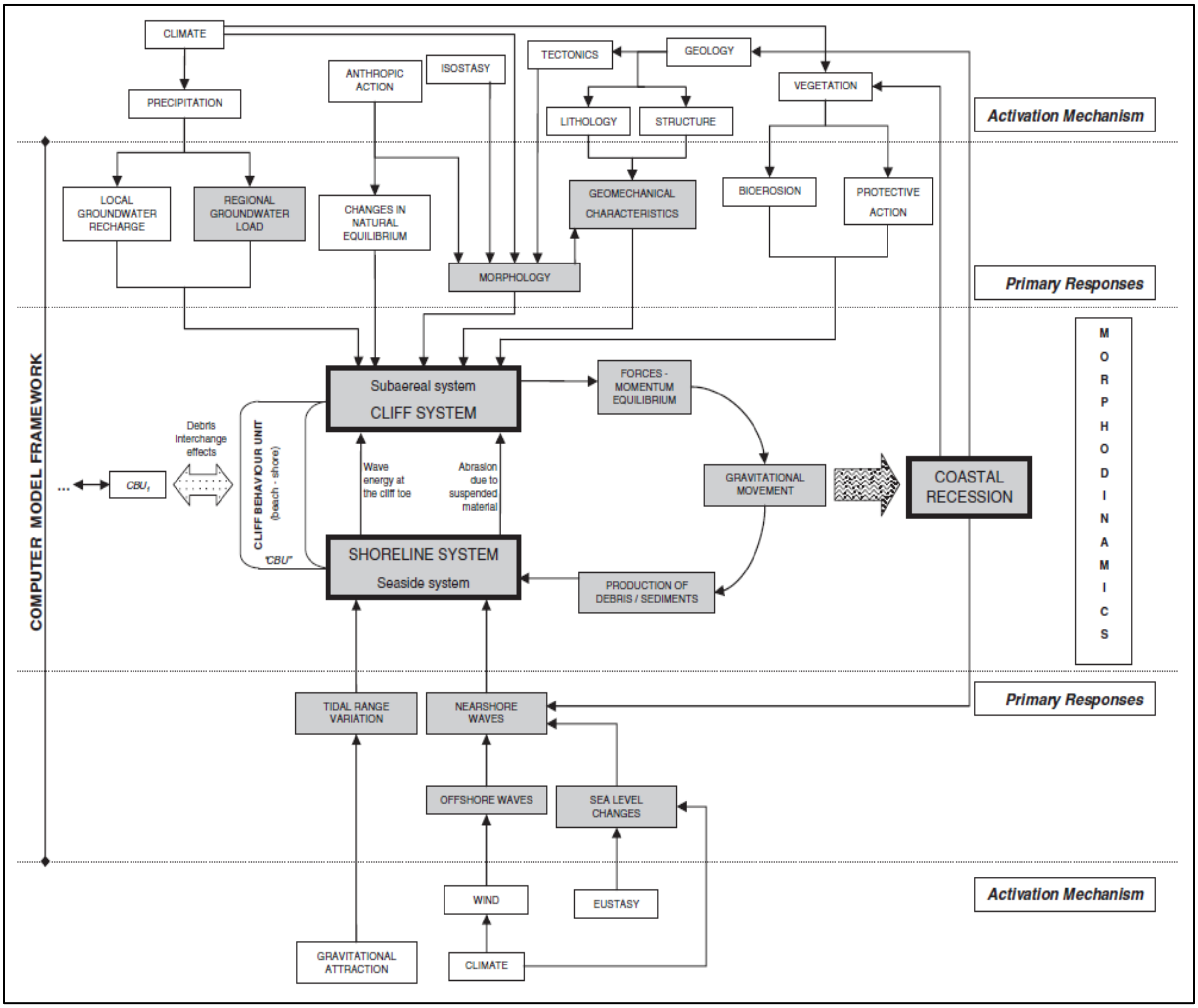


Figure 7.3: *Conceptual diagram of a Process-Response Model (PRM) showing activation (driving) mechanisms and primary responses for a bluff crest-to-nearshore (cliff+shoreline) profile on an oceanic coast. The most important factors (e.g., nearshore waves) acting on the system to induce measurable change for this ocean-coast model are highlighted with shading (Image: modified from Castedo et al., 2012).*

Recent bluff-change models for Great Lakes and similar coastlines have been published by Southgate and Nairn (1983), Nairn et al. (1986), Nairn and Southgate (1993), Baird (2003, 2004, 2008), Walkden and Hall (2005), Trenhaile (2009) and Castedo et al. (2012, 2013). These types of models represent the current state of the art in bluff retreat modeling using the process-response concept. Trenhaile (2009), for example, modeled the evolution of a non-cohesive nearshore (subaqueous) substrate over a 3000 yr simulation timeframe in which profile change was ascribed as the product of wave abrasion across the nearshore, and wave-impact stresses at the shoreline, beach and bluff toe. The model used specified inputs for factors such as tidal range; nearshore gradient; abrasional sediment abundance and grain size; critical shear stress for substrate erosion; substrate compressive strength; and various model coefficients that numerically describe shear stress, abrasion, and wave impact equations. Nearshore profile geometries built by this high-energy ocean-coast model were subsequently compared with real profiles from historical records.

The Trenhaile (2009) ocean-coast model replicated, to a reasonable degree, real profiles that were available for the northern coast of Lake Ontario which had a significantly different hydrodynamic regime than the ocean coast modeled. For example, tidal range was ~0.1 m in Lake Ontario, not 2 m as modeled; ocean swell was absent due to fetch limitations; and wave climate was much less energetic than on the North Sea coast modeled. This led Trenhaile (2009) to conclude that the coefficients widely used in the empirical and theoretical equations used in PRMs are not yet sufficiently-well field tested. He also concluded that it is difficult to meaningfully check model results against historical records of coastal profiles from model-similar areas because the latter are in short supply. So, while model results may reasonably or closely replicate the morphology of real coastal profiles against which they are being tested, they can do so even for settings for which the models were not designed and that can have very dissimilar hydrodynamic regimes. This tends to occur because the numerical values assigned to model coefficients in PRM equations cannot be easily calibrated to the real world, even though model assumptions are generally good.

To illustrate the challenges that still exist in modeling cohesive clay coasts, Trenhaile (2009) summarizes the state of the science by noting that:

> *"… it is questionable at present whether models can be used for engineering purposes to simulate the long-term development of a specific cohesive clay coast, or to predict the short-term response of a particular coast to human or natural forces. Conversely, models can be used to investigate the general nature of the relationships that exist between the many factors that influence the erosion and development of clay coasts … ." They can also be used "… to identify, or emphasize, those poorly understood aspects of clay coast morphodynamics that hinder our ability to forecast their development and probable response to a variety of natural and anthropogenic forcing factors."*

Recent modeling by Castedo et al. (2013) serves as a useful case study to illustrate the types of assumptions, data, methods, and outcomes associated with PRMs, in this case a two-dimensional (2-D) PRM with a focus on recession rates and failure frequencies for part of the Ontario coast of Lake Erie. The model was developed for cohesive coasts without a bedrock toe or bedrock nearshore, along a cross-sectional profile that extends from the nearshore to the bluff crest. The principal goal was to determine how slope failure is related to wave-induced erosion at the bluff toe. Because of the absence of bedrock, wave-induced erosion was inferred to be the principal factor driving bluff retreat, with lesser contributions by other subaerial factors. This means that such models (e.g., Trenhaile, 2009; Geomorphic Solutions, 2010; Castedo et al., 2013) are not directly applicable to large sectors of the Pennsylvania coast because bedrock is prevalent at the toe of the bluff along the eastern coastal reach and in the nearshore along both the western and eastern coastal reaches.

The Castedo et al. (2013) PRM incorporates variables such as profile shape, bluff recession rate, bluff height (as two end-members: 10 m, 25 m), seasonal and inter-annual lake level variability, beach morphodynamics, bluff geotechnical properties, types of slope failures (as two typical end-members), and typical seasonal wave climate for central Lake Erie (Table 7.2). Because historical data were scarce, the model results could not be calibrated against records of past change and so were compared for realism with general bluff-retreat rates for Lake Erie. For 100-year model runs with small beaches and typical seasonal and inter-annual variations in lake level, the average bluff-retreat rates ranged from 0.25 to 0.45 m/y, which is consistent with background rates in Lake Erie (and also with background rates over much of the globe). Compared to earlier works, the Castedo et al. (2013) PRM incorporates a relatively large number of processes and conditions believed to influence bluff behavior. These include hydrodynamic processes (e.g., wave-induced shear stress; absence of beach percolation; duration of seasonal beach-freeze; no bed armoring), beach dynamics (e.g., height, frequency and force of wave run-up), bluff geotechnical properties (e.g., compressive strength), and bluff failure mechanisms, scales and frequencies.

The model includes assumptions that can be very site-specific such as that bluff retreat does not occur until colluvial debris at the base of the bluff (supplied by a prior bluff failure event) is removed. The model also assumes that when bluff height increases, slopes can become less stable due to gravity (Edil and Vallejo, 1980) or more stable due to colluvial debris providing protection from wave run-up. Lastly, the model assumes that shielding of the nearshore platform from erosion by a veneer of coarse-grained sediment occurs and is important. The latter assumption, while often important on cohesive coastal zones, may be relatively insignificant where the sediment supplied from the bluff is dominated by cohesive clays and silts as on the Pennsylvania coast.

Wave data (NOAA, 2011) and lake levels (International Great Lakes Datum — IGLD, 1985, USACE website) used in the sample runs.

Winter (Jan–Feb–Mar) — lake level 173.99 m (IGLD 1985)							
H0 (m)	*No wave record due to ice conditions*						
T (s)							
% frequency							
Spring (Apr–May–Jun) — lake level 174.39 m (IGLD 1985)							
H0 (m)	0.5	1	2	3	4	5	6
T (s)	2	3.5	4.5	5.5	–	–	–
% Frequency	33.03	36.33	2.23	0.10	–	–	–
Summer (Jul–Aug–Sep) — lake level 174.29 m (IGLD 1985)							
H0 (m)	0.5	1	2	3	4	5	6
T (s)	2	3.5	4.5	6.5	–	–	–
% frequency	31.27	41.73	1.90	0.33	–	–	–
Fall (Oct–Nov–Dec) — lake level 173.99 m (IGLD 1985)							
H0 (m)	0.5	1	2	3	4	5	6
T (s)	2	3.8	4.5	5.5	6.5	7	7.5
% frequency	8.87	36.27	16.57	9.40	1.5	0.2	0.1

Frequencies are for the percentage of the season in which waves arise in Lake Erie.

Table 7.2: *Table 3 from Castedo et al. (2013) showing wave climate data for Lake Erie used in that paper's bluff-retreat modeling on the Ontario, Canada, coast. H0 is deep-water wave height and T is wave period. Such fundamental hydrodynamic datasets are required for shoreline/bluff process-response models and can be developed from existing NOAA buoy records (e.g., buoys 45132, 45142, 45167) available online at http://www.ndbc.noaa.gov/.*

Models such as these identify many interesting relationships in the dynamic bluff coastal zone that may be very specific to the site being modeled. In the Castedo et al. (2013) PRM, retreat rates were consistent with the known association between enhanced erosion during lowered lake levels leading to enhanced bluff retreat during subsequent high lake levels. Larger and steeper (and therefore coarser grained) beaches were negatively correlated with bluff retreat rates, primarily due to the run-up protection effect of those beaches. Beaches were positively correlated with the time between failure events (by stabilizing the bluff toe), and with the number of small-but-frequent failures (because colluvial debris reduces the likelihood of large failure events, which results in small failures becoming relatively more important). Some of these relationships may not be valid on the bedrock-associated Pennsylvania bluff coast. For example, Foyle (2014) examined relationships between average annual change and beach width and bluff elevation in eastern Erie

County. Bluff change rates were marginally more negative where beaches were wider (correlation coefficient r = 0.03), but this was probably because wider beaches (away from marinas and stream mouths) are a consequence of active bluff failure which builds large colluvial debris fans at the base of the bluffs. This suggests that hydrodynamic processes acting at the bluff toe are not as important as subaerial processes (including groundwater) as a cause of bluff recession on parts of the Pennsylvania coast, because it could not be shown that wider beaches were associated with less bluff retreat. Bluff retreat rate, however, was positively correlated with bluff height: higher bluffs (>210 m MSL) retreat faster than lower bluffs (<200 m MSL), with rates of 0.30 and 0.17 m/yr, respectively, but the correlation coefficient was also very low (r = 0.15).

Castedo et al. (2013) further found that retreat rates were greater in model runs with lower rather than higher bluffs and in runs where more rather than less colluvial debris was present. This odd relationship developed because of the protective effect of colluvial debris and the time required for waves to remove it: the effect was small, however, because of the dominance of easily transportable clay-sized particles in the colluvial deposits. Colluvial deposits, because they result from a failure event and get deposited chaotically at the base of the bluff, have compressive strengths that are ~10-15% lower than in their in-place condition (Castedo et al., 2012). Higher bluffs were seen to fail most commonly by rotational slumping, while lower bluffs were seen to fail by smaller-volume topples (debris falls): the net result was that retreat rates are higher for taller bluffs, and that taller bluffs are characterized by more infrequent but larger failures compared to lower bluffs. The influence of lake level and lake-level trend on bluff failure was complicated and dependent on feedbacks with other bluff characteristics (such as presence or absence of a beach, erodibility of the bluff material, etc.). Bluff retreat was also seen to be greater during periods of higher lake level because this allows wave energy to be better focused on a limited section of the bluff face. Runs that included seasonal variation in lake levels resulted in more frequent but smaller failures than runs that included longer-term inter-annual variations in lake level.

Bayesian Models

Bayesian (statistical) modeling of coastal change is a continually developing field in coastal science and appears to have great potential in providing statistical and probabilistic solutions to multi-variate coastal change behaviors. The goal in developing more precise coastal-change models is that conditions and relationships between process variables continue to be more accurately identified and defined. First developed in the late 18th century, Bayesian methods became more widely applied beginning in the late 20th century when better computing and computational methods were developed (www.bayesian.org) that would allow quicker calculation of joint-probability distributions and other outputs. Bayesian methods have since been extensively used to find probabilistic solutions to problems in areas as diverse as astrophysics, weather forecasting, landscape evolution, and criminal justice. The method (Bayes, 1763; Barnard, 1958) has been used in a wide range of geoscience applications, including:

- analysis of coastal susceptibility to sea-level rise (Gutierrez et al., 2011)
- landslide analysis in non-coastal settings (Lee et al., 2002; Pistocchi et al., 2002; see review in Hapke and Plant, 2010)
- groundwater flow and soil quality analysis (Back, 2007; Uddameri, 2007; Li and Jafarpour, 2010)
- subsurface geophysical modeling (Buland and Omre, 2003; Gonzalez et al., 2016)
- structural geology (De la Varga and Wellmann, 2016)
- indoor radon mapping (Apte et al., 1999).

Bayesian modeling is being utilized by the US Geological Survey (e.g., Hapke and Plant, 2010; Gutierrez et al., 2011) as a tool to better predict coastal change given an *a priori* knowledge of existing physical conditions, principal processes, past change, and expected environmental change over time (Figures 7.4 and 7.5). The online dictionary Wikipedia describes a Bayesian model as:

> *"… a probabilistic graphical model that represents a set of random variables and their conditional dependencies via a directed acyclic graph (DAG). Formally, Bayesian networks are DAGs whose nodes represent random variables in the Bayesian sense: they may be observable quantities, latent variables, unknown parameters or hypotheses. Edges represent conditional dependencies; nodes that are not connected (no path from one of the variables to the other in the network) represent variables that are conditionally independent of each other. Each node is associated with a probability function that takes, as input, a particular set of values for the node's parent variables, and gives (as output) the probability (or probability distribution, if applicable) of the variable represented by the node." (https://en.wikipedia.org/wiki/Bayesian_network)*

The Bayesian statistical approach is ideal for datasets derived from long-term observations of phenomena such as long-term shoreline change (Gutierrez et al., 2011). Providing information about coastal change using the Bayesian probability approach also has the benefit of improving science communication in support of decision-making, in addressing management questions, and in budget planning.

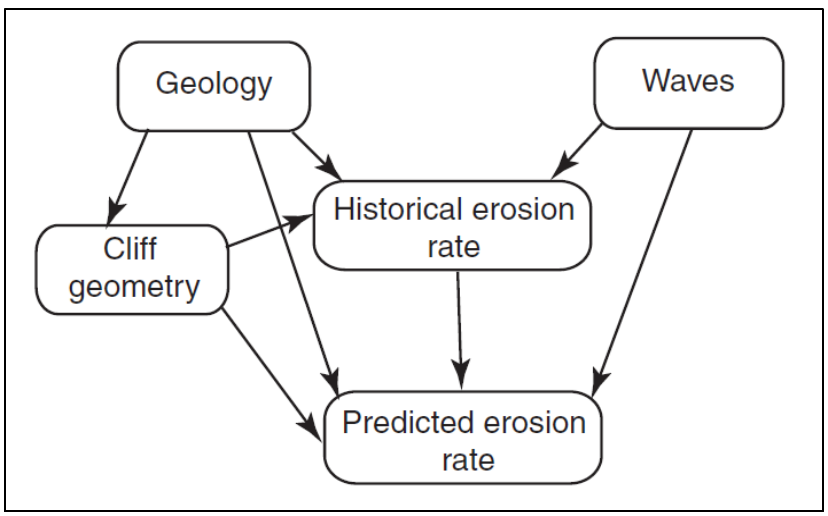


Figure 7.4: *Conceptual diagram of a Bayesian model applicable to coastal bluff retreat on the California coast where marine processes are inferred to be the principal agent of bluff change. Waves, geology, and cliff geometry influence the historical erosion rate, while all four variables influence the predicted erosion rate. Not shown are feedbacks that likely exist between, for example, cliff geometry and geology with waves: i.e., the height, wavelength, and energy density of waves impinging on the coast are influenced by shore-platform development in a nearshore where bedrock is present (Image: modified from Hapke and Plant, 2010).*

Modeling coastal bluff retreat over time is amenable to Bayesian methods because each bluff failure event is dependent on, and not independent of, prior failure events (Lee et al., 2001; Hapke and Plant, 2010). Bayesian modeling can factor-in the prior history of a site to address this complication, and can also incorporate (by iterative updating) changes occurring due to feedbacks between the principal controlling processes, and between the responses of the bluff to those processes. Unlike coastal erosion in beach environments, bluffs are more challenging to model, and thus suited to Bayesian modeling. Typically, a bluff that becomes unstable due to wave attack at the toe will eventually fail into a new, more stable, equilibrium geometry. The bluff will then remain relatively stable for some period of time despite continued wave attack. Bluff failure is thus most often episodic, though there may also be a continuous record of slow, minor, slope failure via soil creep or solifluction. Episodicity is often fostered by processes such as toe-armoring (e.g., temporary accumulation of colluvial debris) reducing wave attack at the bluff toe; seasonal increases in beach width and elevation; and seasonal ice-shelf development.

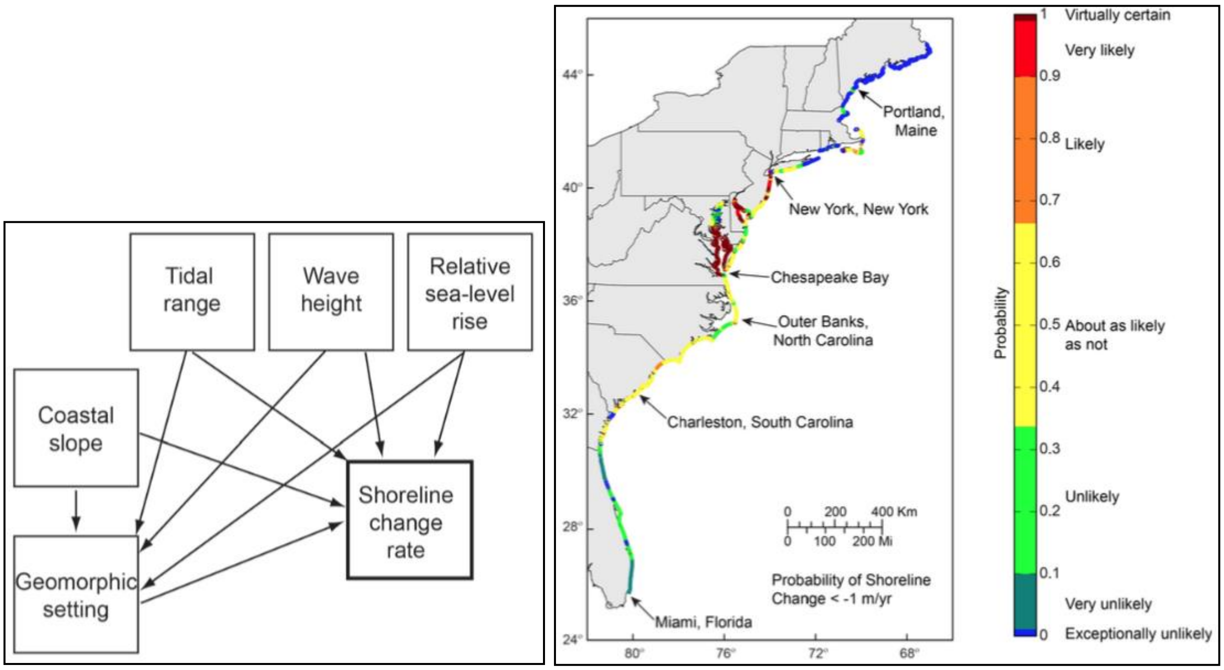


Figure 7.5: *Conceptual diagram (left) of a Bayesian model developed by the US Geological Survey to predict long-term shoreline change in response to sea-level rise. The rate of relative sea-level rise, mean wave height, and tidal range were assumed to be driving forces; the coastal slope and geomorphic setting were assumed to be geological boundary conditions; and the shoreline-change rate was used as a vulnerability indicator for hazard-mapping purposes. Map (right) of the U.S. Atlantic coast showing output from the Bayesian model in graphical form: the probability of shoreline erosion of less than 1 m/yr (Images: modified from Gutierrez et al., 2011).*

Hapke and Plant (2010) provide a very useful case study in the application of the Bayesian approach to predicting bluff retreat on a bluff coast in the United States (Figure 7.6). They modeled short-term bluff retreat on the southern California coast over 3-year and 7-year time periods at two specific sites (52 and 60 km in length, respectively) using 100 m transect spacings in the GIS-hosted model. They concluded that Bayesian methods are an effective tool in the prediction of bluff-crest positions and in the identification of future erosional hotspots, particularly over the short timeframes of their study and on a coast where hydrodynamic forcing dominates. Their model correctly forecast known bluff retreat rates at 70-90% of transects over the 3- and 7-year periods. These impressive results are comparable to similar success rates reported by Dahal et al. (2008) in their Bayesian modeling of non-coastal landslide hazards in the Himalayas (~88% of forecasts correct).

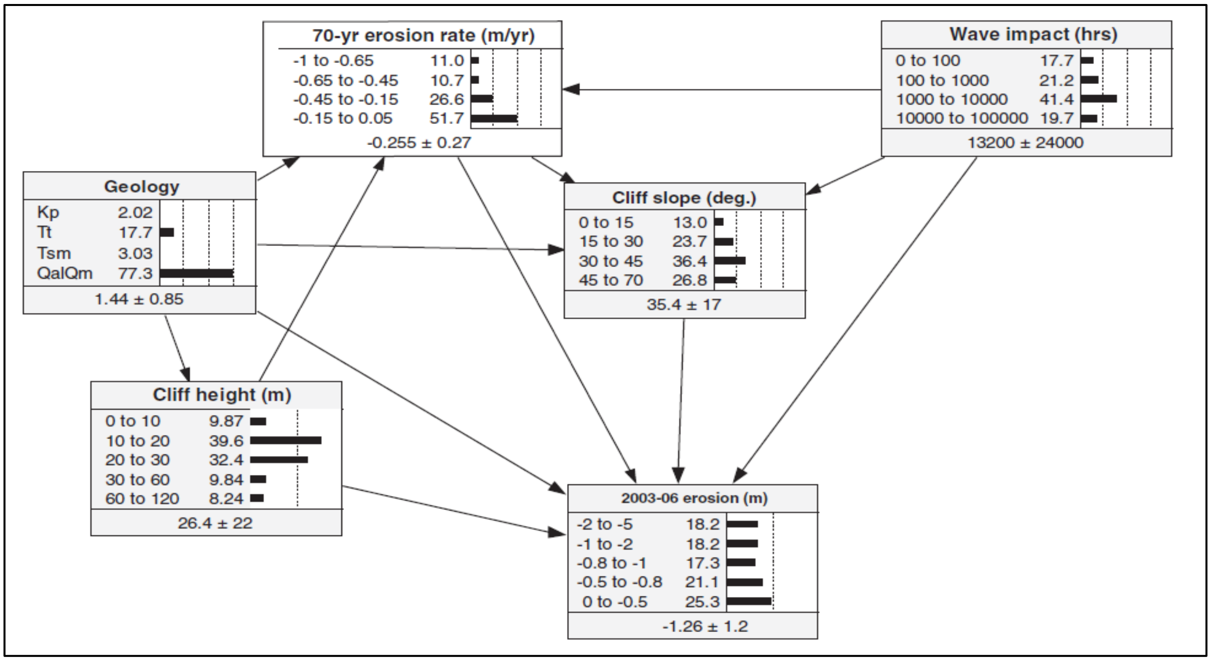


Figure 7.6: *Detailed schematic of a Bayesian model used to predict bluff retreat over a three-year interval on the San Diego coast of California. A set of five variables was used to describe existing conditions (geology, cliff height, cliff slope), prior behavior (long-term bluff-crest retreat rate), and inferred principal forcing agent (wave impact hours). Numerical data are sorted into appropriate bins, each with an associated probability of occurrence (Image: modified from Hapke and Plant, 2010).*

Figure 7.6 summarizes the conceptual model used by Hapke and Plant (2010) wherein Pacific coastal bluffs were sufficiently-well characterized using just five perceived-most-important variables. These variables were geology, cliff height, and cliff slope that described existing (prior) conditions of the sites; and historical bluff-crest retreat rate that described the response (prior behavior) of the bluffs, given those conditions, to wave impact hours (selected as the principal forcing variable. The model incorporates user-defined assumptions on processes and responses. For example, cliff height is inferred to be controlled only by the geology variable and contributes to the bluff erosion rate, whereas cliff slope is inferred to be controlled by three variables and also contributes to the erosion rate, but to a different degree (Figure 7.6). Key to achieving successful predictions in the Bayesian approach is identifying the starting conditions, what processes are important and unimportant, what responses are important and unimportant, and how these processes and responses interact and feedback with each other within a numerical probabilistic framework. In the California model above, the prediction-success rate of 70-90% was achieved by running the short-term model from a start-point in the past for a duration of either 3 or 7 years (different for the two sites) to a finish point. A discrete value (e.g., bluff geology in numerical form), or a distribution of values (e.g., wave impact hours), was known for each of the variables at the start and end times. Thus, 1998 or 2003 conditions (different for the two sites) were used to predict bluff location in 2005 or 2006 by using information from prior work on bluff stratigraphy and topography (initial conditions), wave climate (forcing agent), and long-term bluff-retreat rate (prior behavior). The predicted 2005 or 2006 bluff-crest locations were then compared with the actual bluff-crest positions known from LiDAR data and the prediction success-rate determined as a means of model validation.

Considering possible application of a Bayesian approach to the Pennsylvania coast, there are variables that can easily be derived, and there are variables that would require new field work. For simplicity, assuming that the California variables are also important on Lake Erie, the variables bluff height, bluff slope and historical erosion rate can easily be derived from modern and recent LiDAR, and from historical aerial photographs (but with a short- to intermediate-term bias because of data-quality issues). Bluff geology is currently not well known, but can be obtained from field mapping at a select number of representative coastal sites. Wave impact hours, currently not known, can be derived from an existing NOAA NDBC buoy-provided history of deep-water wave characteristics in Lake Erie (http://www.ndbc.noaa.gov/). To be useful, these data need to be mathematically transformed into shallow-water wave characteristics at the coastline. The waves variable may be the most challenging variable to quantify because the nearest NDBC buoy is quite far from the Pennsylvania coast, but fortuitously wave climate may not be as significant a variable in eastern Erie County in particular (due to the presence of bedrock at the bluff toe).

Variables not utilized in the California model, such as groundwater pore pressures and groundwater fluxes, likely play large roles in the stability of Pennsylvania bluffs (a spatial and seasonal effect). Obtaining these data would require a field-sampling scheme at a number of hydrogeologically representative sites within 0.5 to 1 km of the bluff edge. It is also likely that freeze-season duration and monthly precipitation data would be needed from climatological records. These variables likely contribute to temporal variability in bluff retreat rates, as well as spatial variability once a percentage of the precipitation recharges the surficial groundwater aquifers above bedrock. For coastal management in Pennsylvania, an additional benefit of Bayesian modeling when conducted within a GIS framework, as is now becoming the norm, is that probability distribution maps can be generated to better convey coastal hazard information to coastal managers, municipalities, and the general public (Hapke and Plant, 2010; Gutierrez et al., 2011; Figure 7.5).

Chapter 8: Current Practices and Trends in Bluff Setback Determination in North America

Overview

In northwest Pennsylvania, approximately 90% of the bluff coast of Lake Erie is formally designated a Bluff Recession Hazard Area (BRHA; PA DEP 2013) wherein the county's eight municipalities and the City of Erie impose limitations on potentially risky bluff-adjacent development. The few non-BRHA sectors occur primarily at stream mouths where broad valley re-entrants ensure that the bluff crest is located far from the shoreline and the risk of bluff-toe erosion by lake hydrodynamic forces is perceived to be minimal. Within the Erie County BRHA, which includes the active bluff face that is considered a no-build area, new construction and significant renovations to existing structures are subject to minimum setback requirements that are predicated on a Minimum Bluff Setback Distance criterion (MBSD; PA DEP 2013). This MBSD criterion is defined as the product of the expected lifetime of a planned structure (T = 50 years for residential; 75 years for commercial; 100 years for industrial), and the average annual retreat rate of the bluff crest (AARR) which is based on almost four decades of coastal monitoring. Currently, the state MBSD ranges from 8 to 60 m, depending on the average annual bluff-crest retreat rate in the municipality and on the proposed structure. In certain municipalities, the state MBSD is replaced with a significantly more stringent setback requirement that is effectively derived using a longer structure lifetime in the MBSD equation above. The economic risks associated with development too close to a bluff edge in Pennsylvania are significant. For example, the municipalities of North East and Harborcreek contain just over $18 million worth of land and existing buildings within the 100-year BRHA. This land and structures may be expected to experience significant damage or complete destruction over the next century (ECDPS, 2012).

Hapke et al. (2009) provide a concise summary of the history of development of the Bluff Recession and Setback Act (1980) that established construction setback standards on the Pennsylvania coast of Lake Erie. The PA DEP Coastal Resources Management Program (CRMP) inventoried coastal hazards in the mid-1970s, and compared historical bluff positions (from 1938 aerial photos) with positions at the time (Knuth and Crowe, 1975) to identify the characteristics of shoreline erosion and bluff retreat in Erie County. On the basis of project findings, the Commonwealth of Pennsylvania passed the Bluff Recession and Setback Act in 1980 and identified BRHAs within which setback requirements were established. The BRHAs were designated for the eight coastal municipalities in 1980 and for the City of Erie in 2009. The BRHA comprises the bluff face and adjacent tableland (upland) that extends inland to the industrial setback distance which ranges from 8 to 60 m (25 to 200 ft) on the Lake Erie coast (PA DEP, 2013; Chapter 4). Municipalities having BRHAs within their jurisdictions are required to enact specific minimum setback ordinances governing construction and development activities within the BRHAs. In 2011, Act 72 amended the BRHA definition to exclude areas where the bluff toe is located more than 76 m (250 ft) from the ordinary high water mark (OHWM) of 174.7 m (573.4 ft) MSL.

Pennsylvania has been monitoring bluff retreat rates approximately every 4 years since 1982 when an initial set of bluff-monitoring control points were established at ~1 km intervals along the coast. Additional control points were added in 1985/1986 and 2002 so that 130 control points spaced at ~0.5 km intervals now form the basis of the growing state database on bluff retreat. Average retreat rates as high as 1 m/yr at specific control-points, bluff retreat of as much as 11.3 m between monitoring years, and significant variability in rates between control points, have been documented as part of the monitoring program. For additional details on bluff retreat, crest identification, monitoring, management, and regulations along the Lake Erie coast, the PA DEP CRMP provides the

Municipal Reference Document: Guidance for the Implementation of the Chapter 85 Bluff Recession and Setback Regulations (2013). This document is available for public review and download at: http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-94560/394-2000-001.pdf

Nationally, and particularly since the development of the Coastal Zone Management Act (CZMA) in 1972, the siting of residential and commercial buildings and larger infrastructural elements on bluff coasts has been subject to growing scrutiny due to increasing concern over flood, erosion, and landslide hazards in the coastal zone. This trend is also seen, for example, in the incorporation of coastal hazard planning in the hazard mitigation plans of coastal counties on both ocean and Great Lakes coasts (e.g., Erie County, PA, Hazard Mitigation Plan; ECDPS, 2012). The impacts of coastal hazards are increasing nationally in the United States due to population growth in coastal areas and due to the migration of population and development to municipalities in scenic coastal areas as diverse as Erie County, PA, Chatham County, GA, and Kitsap County, WA.

Developing and implementing setback regulations, policies and guidelines is a complex process both legally and scientifically in the United States. This is because of implications regarding the *Takings Clause* (5th Amendment of the Constitution) on the legal side of the issue and, on the science/engineering side, the necessity of predicting the locations of safe development sites on bluff-adjacent property parcels at specific times in the future. Newer trends in defining setbacks with greater science and engineering rigor may have the unintended consequence of limiting construction on coastal lots to the inland parts of the property parcel far from the owner's intended scenic coastal-overlook location. For example, setbacks using methodologies being developed by municipalities in Wisconsin and California (Chapter 2) may mean setbacks of over 200 feet from the ordinary high water mark (OHWM) which can limit structure locations and footprints in small lots.

Scientific methods used to estimate with minimal error the position of a stable or retreating coastal bluff (face or crest) at selected times in the future are in their relative infancy despite decades of endeavor on the subject. Estimating future bluff-crest locations today relies primarily on deterministic methods rather than probabilistic methods because the problem is challenging mathematically and in terms of the geotechnical knowledge required on the ground. A probabilistic approach to resolving this problem is a new trend in coastal hazard prediction today and, over time, should evolve to a degree of usefulness that matches or exceeds probabilistic approaches used elsewhere in the geosciences. Nationally, probabilistic methods are currently used in coastal, earthquake, and flood hazard assessment at the federal level (e.g., sandy-coast erosion hazard and seismic hazard characterizations by the US Geological Survey; and riverine and coastal flood hazard characterizations by the Federal Emergency Management Agency; see Chapter 7).

Coastal states participating in the NOAA Coastal Zone Management Program follow various and increasingly similar methods to map bluff crests and determine setback distances. Setback requirements in ocean and Great Lakes states are typically required and enforced by municipalities in areas where bluffs retreat at rates at or in excess of 0.3 m/yr (1 ft/yr). These coastal sectors are typically referred to using a number of similar phrases: erosion hazard areas, coastal erosion areas, bluff recession hazard areas, and high risk erosion areas (Chapter 2). The methods employed to define bluff setback distances have become more rigorous over time and have become more consistent with each other. States that are most proactive in bluff retreat issues now have online viewers available. Government agencies, property developers, and owners can view geodata (e.g., hydrology, historical shorelines and crest lines, retreat rates, setback lines) at the near-property-parcel level of detail within an interactive GIS framework (e.g., safe setback lines or stability lines for Bayfield County, WI; http://maps.bayfieldcounty.org/BayfieldFlexViewer/). Less proactive states typically make static imagery available upon request to property owners and are still transitioning to online GIS-hosted interfaces. To predict how much a coastal bluff crest is likely to recede over some future time frame, a coastal scientist or engineer now uses patterns and trends in past behavior of the bluff crest to estimate (mathematically or by modeling) its future location at a specific time in the future (Chapter 7). Once the estimated future position is established, ideally within a GIS framework, a setback from the present location of the bluff crest can be decided upon that will govern the safe placement of any proposed structure.

In the United States today, there are effectively three general means by which a setback line is established on a bluff coast. While there are slight variations between states concerning the number of components included in the governing equations, or the method of calculation, there is a high degree of general consistency on Atlantic, Pacific, and Great Lakes coasts. The three general methods used are:

- the basic **"AARRxT"** method, which uses a future estimated bluff position as the setback line for a building being considered for construction today
- the "**(AARRxT)+"** method (see Luloff and Keillor, 2016), which uses a similar approach but moves the setback line further landward by typically incorporating a stable slope setback (SSS) factor and/or a relocation or safety buffer (SB)
- the rare "**Stringline**" method, which uses an overly simplistic geometric approach for setback delineation on infill properties (i.e., undeveloped properties on an otherwise well-developed urban bluff coast)

Of the three approaches, the "(AARRxT)+" method, in various forms, is currently the most rigorous deterministic method and, for now, is a standard to emulate and/or surpass for those states or municipalities not already using it (such as those still using the "AARRxT" method). The most common variations in the use of the "(AARRxT)+" method discussed below concern the value chosen for "SB" that varies by state, the incorporation of a setback multiplier for tall bluffs steeper than 11.25 degrees (by Michigan), and factoring in seismicity (by California).

Bluff Retreat Rates, Future Bluff Positions, and Setback Delineation

The Basic AARRxT Method

Nationally, the most fundamental and simple method of calculating a retreat setback distance is to calculate the product of a long-term average annual bluff retreat rate (AARR) and the expected lifetime or planning horizon (T) for a planned structure near the bluff (Recession Setback, Figure 8.1). Pennsylvania and New York, for example, use this method. Pennsylvania allows coastal municipalities to impose more rigorous setback standards if considered necessary or prudent by a municipality. Pennsylvania utilizes three structure-lifetime categories for the T term, namely 50 years for residential buildings, 75 years for commercial buildings, and 100 years for infrastructural elements (such as pumping stations and utility facilities). Other states, such as New York, Minnesota, Wisconsin and California, use 40 to 50 year structure lifetimes, but the trend nationally, particularly where bluff retreat proceeds at significant rates (> 0.3 m/yr) is to move towards longer structure lifetimes such as a 100-year benchmark. This trend is being driven by (i) improvements in construction codes nationally over the past several decades, particularly in coastal zones (e.g., the Florida Building Code); and (ii) by the transition in quality and monetary value of ocean- and lake-front residential structures since World War II from small summer cabins to large year-round first and second homes.

Identifying the AARR in the method above relies on the use of historical data with varying degrees of positional error (Moore, 2000), duration of coverage over time, and frequency of data collection. Longer datasets with shorter sampling frequencies allow the statistically best erosion-rate averages to be extracted from the historical data. For greatest statistical quality, at least 50 years of annually collected data is ideal, as demonstrated by Johnsson (2003). The further the dataset departs from this ideal, the greater the errors become due to aliasing and other factors (Zuzek et al., 2003). The ideal requirement for long data-coverage duration and short data-collection intervals is an obvious and ongoing limitation in determining accurate retreat rates and consequently bluff setbacks. Some states, such as those distant from early-colonized east coast areas, have more problematic datasets than others, due to less availability of older historical data (e.g., NOS T-sheets and early aerial photography) and infrequent data collection. This problem should be resolved as data collection continues in the future and sampling frequencies become shorter as technology allows more rapid and economic data collection (e.g., McDonald et al., 2010).

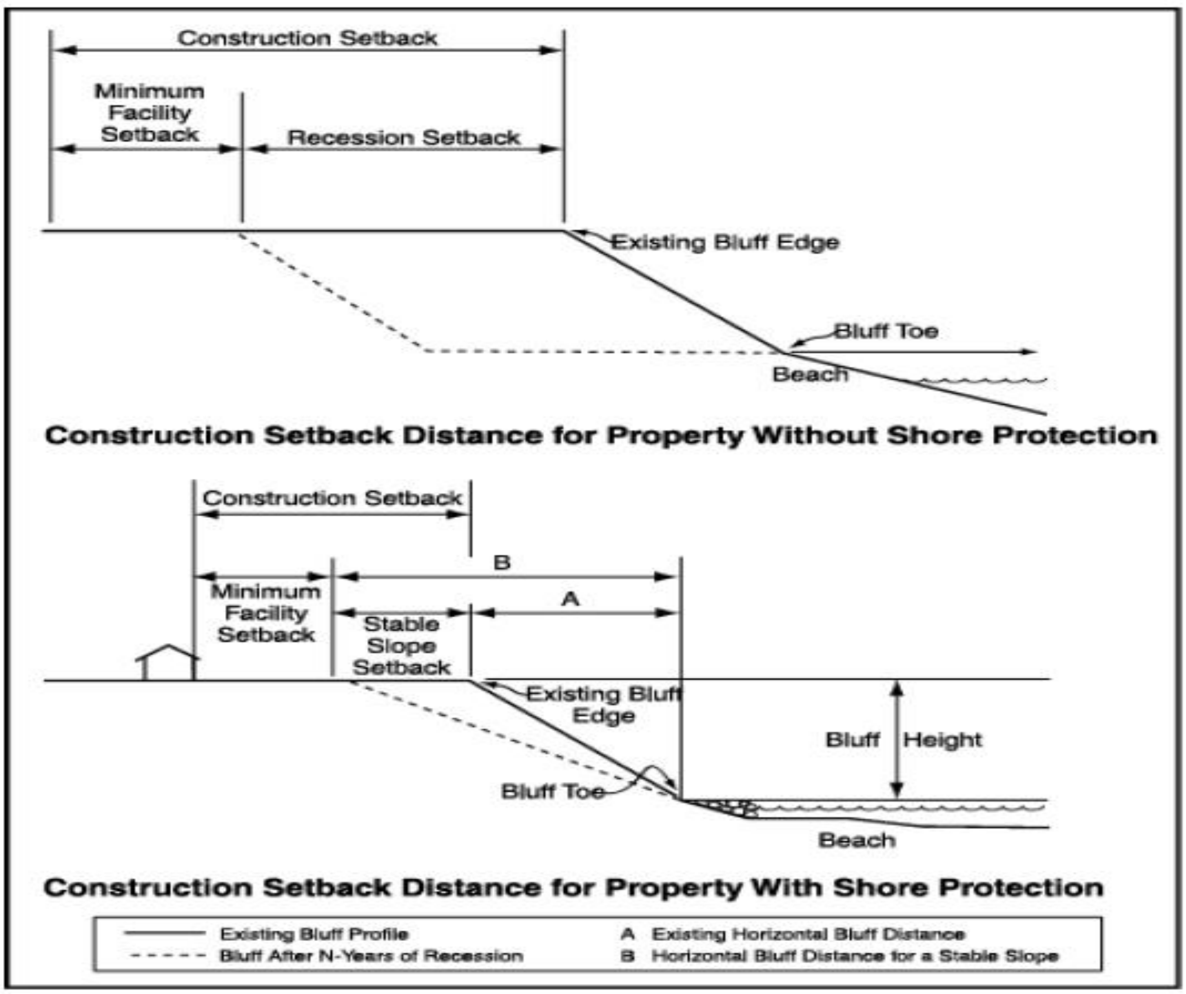


***Figure 8.1**: Schematic diagram showing elements and reference features used to map construction setback lines landward of a bluff crest. The upper image approximates the "AARRxT" method (but adds an SB term) while the lower image approximates a simplified "(AARRxT)+" method from which the AARRxT term is excluded. The Stable Slope Setback and the Minimum Facility Setback terms are synonymous with the SSS and SB terms in the text (Image: modified from FEMA Residential Coastal Construction Training Guide at http://www.fema.gsov/residential-coastal-construction).*

The more pressing problem is that this deterministic "AARRxT" method uses historical bluff-crest positions to predict future locations of the bluff crest at specific times in the future. It assumes that rates and magnitudes of processes driving change in the past will not change in the future, and it assumes that bluff change is linear for mathematical expediency. This is analogous to the problem of using historical stock market trends to predict future changes in the stock market. While often producing feasible results, both endeavors utilize assumptions that may not be valid over time and location and are consequently subject to potential errors. However, this is the current state of the science of predicting where a coastal bluff crest will be located in the future.

The most prevalent AARR reference feature used in the United States is the bluff crest or bluff edge (see Chapter 1). This is typically picked using one or more of the following methods:

- visually in the field by topographic survey
- from variable-scale historical aerial photographs
- from photogrammetry using aerial photo stereo pairs
- from orthorectified large-scale aerial photos
- from visual analysis of LiDAR DEM contour-spacing changes
- from first derivative (slope) or second derivative (rate of change of slope) maps derived from LiDAR DEMs using an *a-priori* threshold value to identify the crest on bluffs that have curved transitions to the upland plateau.

Currently, the degree of uncertainty in the location of any historical crest position can be included in a GIS database to develop statistically more useful AARRs. Typically, AARRs are calculated using appropriate mathematical routines such as the end-point rate (when there are two data years), and the regression-analysis rate (when there are multiple data years). Determining the actual development setback is then, at its simplest, a process of plotting the setback distance in the landward direction away from the bluff edge by taking the product of the AARR and the expected lifetime (T) of the proposed structure (or, in some cases, a number of years related to a specified planning horizon). In certain municipalities in California, a safety factor multiplier (values range from 1.0 to 4.0; Johnsson, 2003) or an *a priori* buffer (effectively an SB term; ~3 m) is used to allow for uncertainties in the two terms in the "AARRxT" method. The multiplier allows for uncertainty in future bluff retreat rates due to expected increases in sea-level change rates, and in the legal uncertainty in defining the T term in the equation. Because increases in sea level and lake level are known to increase rates of bluff retreat (Chapter 5), Great Lakes states such as Pennsylvania would benefit from knowing future lake-level trends for the most probable global climate change scenarios. The California Coastal Commission is considering adding a slope-stability component (an SSS term) to their methodology so that the California setback calculation method becomes even more conservative as it evolves towards the "(AARRxT)+" method described below.

The Improved (AARRxT)+ Method

A significant improvement to the "AARRxT" method to determine a bluff setback line is to treat the coastal bluff as a constantly changing landform in dynamic equilibrium with the numerous subaerial, subsurface, and hydrodynamic (lake) processes that shape it (see Chapter 4). This general approach to setback delineation is being considered for use (or is already in use in some form) in states such as California, Michigan, Minnesota, New York, Oregon, and Wisconsin (Ohm, 2008; Kastrosky et al., 2011; Luloff and Keillor, 2016). The method locates a more conservative setback line landward of one calculated using the "AARRxT" method (Figure 8.1).

The AARRxT term is retained in this method as the means to estimate how far the bluff crest may retreat in the future based solely on its historical behavior. It will obviously approach a value of zero on long-term stable bluffs that are no longer subject to erosive hydrodynamic, subaerial, and subsurface processes. Such stable vegetated bluffs locally occur on Maryland's Chesapeake Bay coast where strandplain progradation has isolated formerly active bluffs from wave energy for up to several centuries (Chapter 2). A similar case of natural bluff stabilization occurs on the southwest side of Presque Isle Bay. Here, wave power is significantly reduced due to wave-fetch reduction and shelter provided by the Presque Isle strandplain. Along the bay's southeast side, urban development on infilled land now isolates the mainland bluffs from the bay waters.

The "(AARRxT)+" method adds an SSS term (Figure 8.1) which is a stable slope setback, also referred to as a slope-stability setback line or a factor-of-safety line. It is predicated on the concept of a long-term stable slope angle (SSA) for slopes that is dependent on geotechnical properties and environmental conditions. The SSS recognizes that topographic slopes in general exist in a dynamic state and will weather and erode over long time periods to develop a stable slope angle (SSA) that will result in landward movement of the crest line. The anthropogenic-relevant timescales involved are not well understood: for coastal bluffs, the timescale is likely on the order of many decades to centuries depending on geotechnical properties and climate. This fundamental dynamic factor is recognized by the International Building Code (IBC) in its guidelines for siting buildings near the toe and crest of sloped terrain, and by numerous municipal interpretations of those guidelines (e.g., Liberty Lake Planning & Building Services, WA; City of Los Angeles Department of Building & Safety, CA; https://codes.iccsafe.org/public/document/IBC2018).

The horizontal SSS term and its related angular SSA term can be derived in at least four ways, using site-specific scale to regional-scale data. The most geotechnically rigorous method is to use site-specific slope stability analysis modeling (USACE, 2003) which uses site-collected data to generate a horizontal distance landward of the bluff crest beyond which the risk of a future slump failure is minimal. By convention, this "safety line" occurs when a modeled Factor of Safety term exceeds a value of 1.1 (for the pseudo-static case in earthquake-prone areas such as the Pacific coast) to 1.5 (for the static case where there is no seismic risk). The SSA term can alternatively be derived by in-field slope measurements of nearby stable bluff areas such as has been conducted in Wisconsin, where stable slopes range from 18.4 to 21.8 degrees (Ohm, 2008). Depending on climate and bluff geotechnical properties, bluff slopes inferred as stable may range from 11.25 degrees for till bluffs in Michigan, to as high as 35 degrees for Chesapeake Bay marine-sediment bluffs in Maryland. It may range from 60 degrees for bedrock cliffs in Wisconsin (Chapter 2), to about 70 degrees for Cretaceous chalk cliffs at the Falaises d'Etretat in Normandy, France (Figure 8.2). In Canada, a universal SSA of 18.5 degrees is used for planning purposes by the province of Ontario for bluffs on its Great Lakes coastline: a plane is projected upward from the base of the bluff (or OHWM) to intersect the bluff top landward of the existing bluff crest. This defines a reference line from which the AARRxT and SB distances are referenced. A similar approach is used in Wisconsin (Figure 8.3).

Thirdly, the SSS term may be derived by adopting IBC guidelines for building near moderate- to steep-gradient static slopes (>18.5 degrees or 33%; no toe erosion). In hilly inland municipalities such as Ventura, CA, and Spokane and Clark Counties, WA, the IBC guidelines have been adapted so that a building foundation should be located no closer to a slope crest than a distance equal to at least the smaller of (i) 40 feet or (ii) one third of the total slope height above the toe. In cases where the slope is steeper than an *a priori* 45 degrees (100 %), the suggested setback (40 ft or slope height/3) is measured from where an imaginary 45-degree plane, projected upward from the toe of the slope, intersects the terrain behind the slope crest. This slope consideration by the IBC recognizes that steep slopes, even in areas where erosion by hydrodynamic processes is not a factor, evolve over time into less-steep slopes. The IBC stable slope criterion is thus a good starting point when considering alternative ways to reduce the impacts of slumps on bluff-top buildings and infrastructure because it at minimum recommends a stable-angle setback. For bluffs on the Pennsylvania coast, the IBC approach alone may be less stringent than would be advised for areas where wave action increases bluff instability and leads separately to bluff retreat (e.g., in western Erie County; see IBC Chapter 18 at https://codes.iccsafe.org/public/document/IBC2018/chapter-18-soils-and-foundations).

Figure 8.2: *Slowly-eroding, vertical, banded chalk and chert cliffs near Etretat (Normandy), France.*

Lastly, the SSS term may be derived by assigning it a horizontal distance value landward of the bluff crest based on the maximum landward headwall retreat observed from the historical record of slumps in the area. In parts of eastern Erie County, for example, where very large rotational slumps are locally common, this approach could yield an SSS value of as much as ~60 feet. Regardless of how the SSS term is derived, geometric considerations mean that taller bluffs will necessarily have larger SSS values, for any given stable slope angle, than lower bluffs (Figure 8.3). On tall bluffs, therefore, an “unbuildable land” issue becomes important for property owners, but it can be addressed. In Wisconsin, for example, the stable slope (SSS) component of setback at a site can be reduced if a property owner adopts mitigation methods to increase slope stability (e.g., by removing groundwater from the substrate, by regrading the slope, by plantings, etc.; see Chapter 6).

In cases where either a rock cliff (Figure 8.2), or a bedrock toe at the base of an otherwise unconsolidated bluff, has a significant wave-cut notch present, Bayfield County, WI, recommends adding the maximum horizontal depth of the notch to the SSS distance. Where a wave-cut notch is present at the base of the bluff in San Diego, CA, the bluff crest is not simply picked where the bluff slope intersects the tableland, as is done in Pennsylvania in most cases. Instead, a line is drawn vertically upward through the bluff from the landward limit of the wave-cut notch. If that line plots landward of the break-in-slope derived crest line, it is then used as the bluff crest for setback-measurement purposes. Fortuitously, persistent wave-cut notches are not well developed on the Erie County, PA, coast due to the comparatively mild wave climate and lower bedrock and glacial-till strengths.

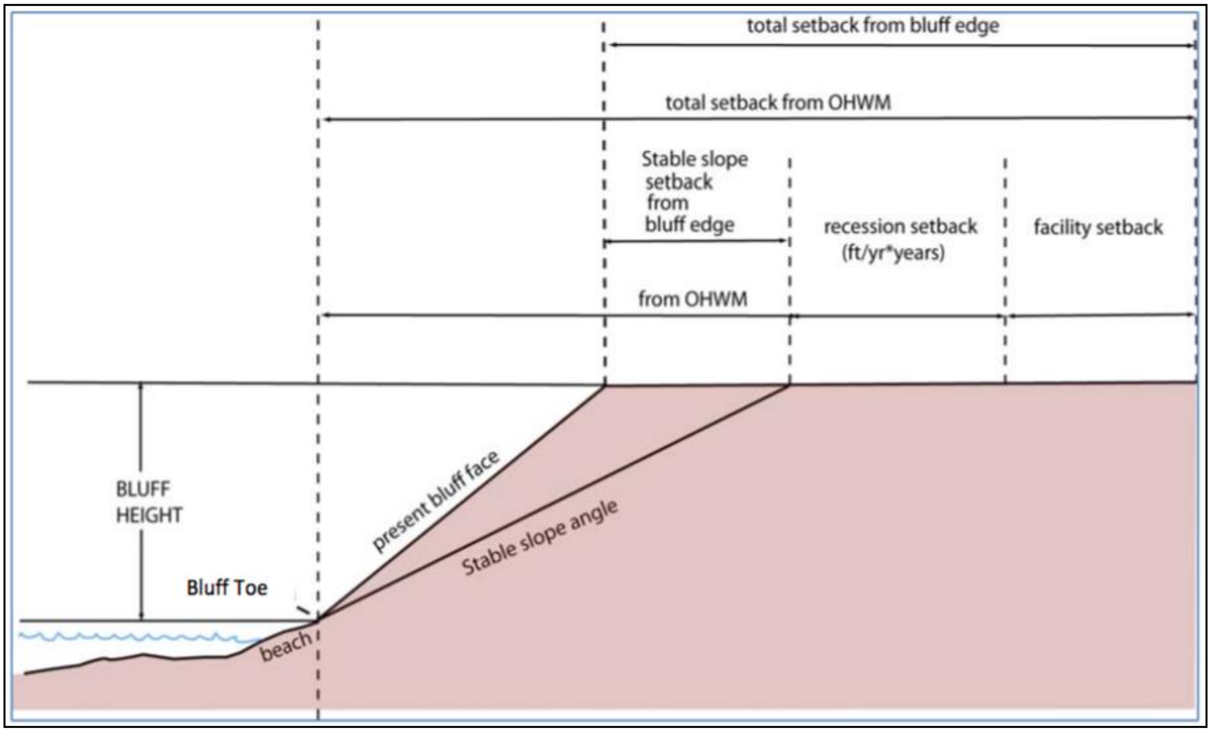


Figure 8.3: *Schematic diagram showing elements and reference features used to determine construction setback lines for Wisconsin coastal bluffs. The image shows the components of the "(AARRxT)+" method described in the text: the Stable Slope Setback (SSS); the Recession Setback (AARRxT); and the Minimum Facility Setback (SB) (Image: modified from Managing Coastal Hazard Risks on Wisconsin's Dynamic Great Lakes Shoreline, by Luloff and Keillor, 2016).*

The SB term is a default minimum facility setback distance, safety buffer, or building relocation buffer (Figure 8.3) used in several states. It is used to increase the setback of a proposed building from the future bluff edge determined using the AARRxT and SSS terms in the equation. The rationale is that a setback based on the design life of a building, the average annual retreat rate, and the stable slope angle, will theoretically result in the building sitting exactly at the future-bluff edge once the design life is reached. This would prevent any last-minute mitigation actions or restrict attempts to move the structure because access would not be possible on the lake or ocean side of the building. The SB term addresses this issue by adding an additional buffer, typically of 3 to 10 m (10 to 30 ft).

The Stringline Method

Along certain bluff coasts in the United States, such as Santa Cruz, CA, a "Stringline" setback is used. This is a very simplistic and not widely used method of setting the setback line for a property parcel. While limited in use to an undeveloped property parcel on an otherwise well-developed urban bluff coast (i.e., for infill development), the approach is problematic because it allows new construction to be sited as far bluffward as a straight line that joins the bluffward corners of buildings in the property parcels on either side. Given that properties on either side of the parcel in question were likely built years to decades earlier, the new structure becomes effectively exempt from the older setback requirements as well as any newer, usually more stringent, science-driven setback requirements. The infill structure gets "short-changed" on the years of buffering that the adjacent properties have enjoyed because they are now in the later stages of their setback years. There is no consideration given to bluff retreat rates for the area, the expected life of the structure, nor any information that may be known about slope stability. Property siting permits relying on the "Stringline" method in California will in the future be expected to navigate the increased coastal-hazard risk associated with the method. This could be accomplished by waiving the California Coastal Commission of liability associated with permit issuance (Chapter 2); requiring the owner to accept all responsibility for the high-hazard development; or requiring the owner to waive access to disaster-relief funds and subsidized economic assistance in the event of property damage (www.coastal.ca.gov/recap/chap3.html).

Review of Setback Delineation Methods and the Case for the (AARRxT)+ Method

Of the three approaches reviewed above, the "(AARRxT)+" method, and its variants, are the most rigorous methods currently used to identify safer, more conservative, bluff setbacks (Figure 8.3). The "(AARRxT)+" is a methodology to emulate until better science-supported probability-based methods are developed and adopted. It is superior to the "AARRxT" method because it fundamentally recognizes that slopes are by nature unstable and tend to reduce grade (and therefore exhibit crest retreat) over time via weathering and erosion. This grade reduction due to natural subaerial and subsurface processes takes place even in the absence of hydrodynamic processes affecting the foot of the slope. In the presence of wave attack at the foot of a coastal bluff, the time required to achieve a stable slope is extended because toe erosion maintains slope steepness. The grade reduction and crest-retreat concepts are fundamental factors incorporated in the IBC recommendations for construction setbacks on static slopes where wave-induced erosion of the lower slope is absent.

While the "(AARRxT)+" method is being increasingly considered for adoption (Johnsson, 2003; Ohm, 2008; Kastrosky et al., 2011), regional nuances in the calculation and inclusion or exclusion of its component terms are common. Specific examples of variations on the method follow, from which it is clear that there is, in general, much commonality in usage among states and provinces. The province of Ontario, Canada, for example uses the method only when the record of historical bluff positions used to calculate the AARR is at least 35 years in length. In areas where there is no or poor data, a default Erosion Allowance of 30 m (~100 ft) is used to determine the setback, either by itself or in conjunction with an 18.5 degree (~1:3 slope) SSA term if that can be estimated (OMNR, 2001). An SB term (Figure 8.3) is not used. Ontario's planning horizon for its Great Lakes bluffs located between eastern Lake Ontario and northwestern Lake Superior uses a T value of 100 years. Along with a similar T value used by the municipality of Point Arena, CA on the Pacific Ocean, these are among the most conservative planning horizon terms used in North America.

Five coastal counties in Wisconsin (Racine, Ozaukee, Sheboygan, Manitowoc, and Douglas counties) have adopted an "(AARRxT)+" method similar to the one described here (Figure 8.3) , and the Wisconsin Coastal Management Program has developed a model ordinance for construction setback distances (Luloff and Keillor, 2016). Web-based building-setback and stable-slope angle calculators are available for parts of the Lake Michigan and Lake Superior coasts of Wisconsin. These are designed to promote wise, but voluntary, bluff-top development with a significant reduction in hazards (https://www.geography.wisc.edu/coastal/viz3d/). By inputting data on the expected structure lifetime (T; e.g., from county or state regulations); bluff height, present slope angle, and estimated stable slope angle (SSA); and the historical AARR; the building setback calculator estimates a safe property setback that includes a building relocation (SB) buffer. While the online calculator provides a more scientific approach to setback determination compared to an older 23 m (75 ft) minimum statewide setback requirement (part of the Wisconsin Shoreland Protection Act), the latter can still be used if it indicates a larger setback than the newer setback calculator. Ordinarily, the 23 m minimum statewide setback applies to unincorporated coastal areas and is measured landward from the Ordinary High Water Mark (OHWM; Keillor and White, 2003; Luloff and Keillor, 2016). This older standard can result in interesting setbacks for progressively taller bluffs: for a 22-degree sloped bluff taller than 9 m (30 ft), the 23 m setback line would intersect the topography at or lakeward of the bluff crest (Ohm, 2008; Kastrosky et al., 2011). Wisconsin uses a structure life (T) of 50 years, while in areas of bedrock cliffs a default AARR estimate of 0.03 m/yr (0.1 ft/yr) is used because data on bedrock retreat is scarce. The SSS component of setback at a site can be reduced by a property owner if the slope is stabilized (e.g., by removing water or by adding plantings, etc.).

One downside to the Wisconsin "(AARRxT)+" approach is that it can yield very large setback requirements under certain conditions that may limit the feasibility of widespread adoption. Applying the method to the Pennsylvania coast using a bluff height of 55 m (180 ft), an AARR of 0.4 m/yr (1.25 ft/yr), a T value of 100 years, an existing bluff slope of 48 degrees, an SSA of 20 degrees, and a 7.5 m (25 ft) SB term, yields a setback line located 147 m landward of the existing bluff crest. This is a significant distance that may approach or exceed the lot depth in certain locations and would be viewed unfavorably by property owners. For further comparison with Pennsylvania, the setback is significantly lower for a more typical Pennsylvania bluff with a height of 24 m (80 ft), an AARR of 0.3 m/yr (1 ft/yr), and a T of 75 years where the resulting setback is reduced to 75 m (248 ft) landward of the bluff crest. While a smaller setback, this value is approximately 25% greater than the 61 m (200 ft) setback required by Girard Township for residential, commercial, and industrial properties. Girard Township has the most stringent municipal guidelines for setbacks in Erie County, while the City of Erie has the least stringent, at 7.5 m (25 ft). Notably, PA DEP data show that the AARR for bluffs in Girard Township and Presque Isle Bay average 0.27 m/yr and 0.14 m/yr, respectively.

An additional downside to the large setbacks indicated by the "(AARRxT)+" method is that residential buildings may need be located such a large distance back from the bluff edge that the lake view becomes restricted and a takings issue may arise. For example, for a typical 80 ft bluff on the Erie County coast, as reviewed above, a home occupant's line of sight to the lake would intersect the lake surface ~ 1 km (~3200 ft) offshore. This means the home owner does not see the beach, the shoreline, the surf zone and nearshore waters from the ground floor of the building. The magnitude of the lost "water view" increases rapidly with bluff height and concomitant increase in setback distance.

Minnesota does not use an SSS term in their version of the method and uses a set value of 7.5 m (25 ft) for the SB term to allow for possible structure relocation. In areas where historical bluff-change data is absent or of poor quality, the state recommends a default setback value of 38 m (125 ft). Michigan modifies the "(AARRxT)+" method by adding a "high bluff" multiplier (in the range of 1.0 to 2.0) to the AARRxT component in incremental steps (in ~3-degree or 5% slope increments) for bluffs that are steeper than 11.25 degrees (20%). The T term also varies: it may have a value of 30 or 60 years, depending on whether the proposed structure is small and moveable or large and immoveable. The SB term has a set value of 5 m (15 ft) to allow for major storms.

Municipalities in California (such as Point Arena and Fort Bragg) require a minimum setback distance of 7.5 m (25 ft) if the methods above yield small setbacks (see Chapter 2). They also require that the time-span of data coverage for determining the AARR value be as long as possible and no less than 50 years in order that meaningful AARR values are derived. It is not clear what happens if the 50-year requirement is not met (Point Arena Municipal Code (2016): http://qcode.us/codes/pointarena/view.php?frames=on). Municipalities and Local Coastal Programs (LCPs) in California may also include an allowance for possible increases in bluff-retreat rates due to sea-level rise within the SB term. If a bluff crest area already possesses a factor of safety against landslide of greater than 1.5 (i.e., typically a low-slope or erosion-resistant bluff), the "(AARRxT)+" method can be replaced by the "AARRxT" method using a T equal to 100 years. The latter "AARRxT" method is typically supplemented with an SB term of 3 m (10 ft) to preclude foundation-exposure at the bluff edge once the 100 year economic lifetime of the structure has passed. An increasing number of coastal municipalities and LCPs in California are also mandating that permitted structures on the bluff top do not require, during construction or at any time during the 100-year planning horizon, any form of shore protection.

In Oregon, where a variation of the "(AARRxT)+" method is used, municipalities such as the coastal city of Brookings impose more stringent construction-setback requirements on properties where average slopes exceed 8.5 degrees (15%) or where the property is located along an ocean bluff coast with unconsolidated (often glacial till) sediments. In the state of Washington, bluffs are also dominantly of glacial origin. The city of Seattle utilizes web-based map products showing steep-slope areas (22 degrees; 40%) and potential slide areas to assist the public in coastal bluff-hazard and landslide-hazard identification (Figure 8.4).

Ohio's Coastal Erosion Area methodology (see Chapter 2) relies on a variation of the deterministic "AARRxT" method (https://gis.ohiodnr.gov/MapViewer/?config=cea). Ortho-rectified aerial photography collected over a 10-30 yr time period (e.g., 1973-1990 era; 1990-2004 era) is used to determine the AARR along the bluff using a 33 m (100 ft) monitoring-transect spacing. The AARR is then multiplied by T=30 yrs to define a swath of coast (the Coastal Erosion Area; zero to several hundred feet wide) that extends inland from the younger reference feature (e.g., the 2004 bluff crest) and extends lakeward to the OHWM line. The CEA maps out the area of coast at risk of being lost over a future 30-yr time period: the landward CEA line is effectively an estimate of where the bluff crest will be in 30 years (Figure 8.5). Unlike other states, however, new construction or significant renovations are allowed within the CEA but the permit application must demonstrate that adequate shore protection is in place to protect the new structure for at least the CEA's 30-yr timeframe. Photographic (or other digital) data are collected no more frequently than once every 10 years in order to regularly update the CEAs. Depending on erosion trends, and because the CEA is defined using an AARR, a specific coastal site (e.g., a property parcel or part of a property parcel) may occur within or outside of a CEA during successive CEA updates which occur approximately every decade (Figure 8.5; McDonald et al., 2010).

Pennsylvania and a small number of other states continue to use the "AARRxT" method. The AARR used in Pennsylvania is the average rate of bluff retreat within a given municipality as measured and calculated by PA DEP. As mentioned above, individual municipalities often impose more stringent setback requirements through municipal ordinances if considered prudent. For example, Girard Township enforces a minimum setback for a residential property of 61 m (200 feet), over three times larger than the state requirement for the township. Table 8.1 shows the current state and municipality setback guidelines on the Lake Erie bluff coast within the BRHAs established by the Bluff Recession and Setback Act (1980). Higher municipal setbacks shown in Table 8.1 are located in western Erie County, reflective of the greater bluff-retreat rates experienced in these areas where a tall bedrock toe is absent. The City of Erie has a lower minimum bluff setback distance (7.5 m; 25 ft) than any of the other municipalities. This is at least partly because bluffs along the south shore of Presque Isle Bay have a bedrock toe, are exposed to only a limited wave fetch (less than 4 miles), are well vegetated, and locally have a long history of coastal engineering (sea walls, marinas, shore-zone infill, etc.). PA DEP data indicate that the bay bluffs are significantly more stable than most other bluffs along Pennsylvania's Lake Erie coast.

Figure 8.4: *Part of the City of Seattle Landslide Prone Areas map showing coastal and inland steep-slope hazard areas. An interactive map version is available at http://seattlecitygis.maps.arcgis.com/apps/webappviewer/index.html?id=f822b2c6498c4163b0cf908e2241e9c2.*

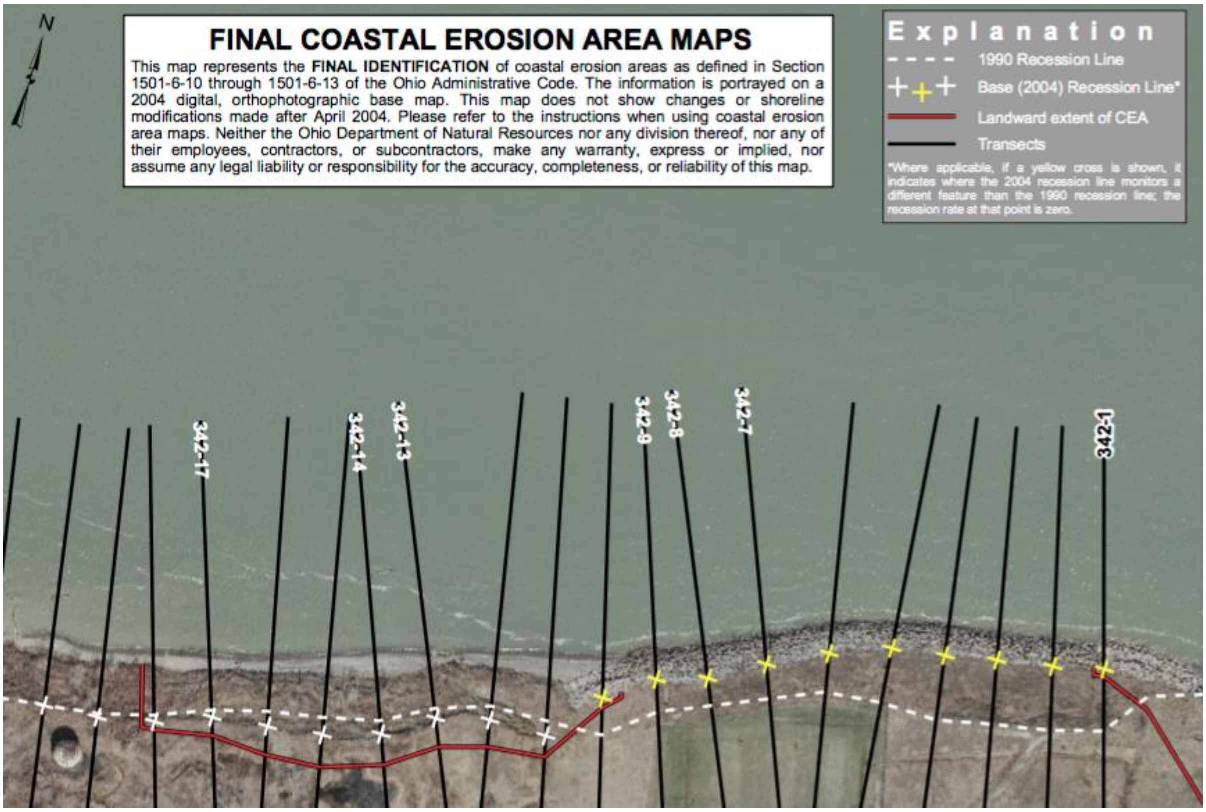


Figure 8.5: *Screenshot of an Ohio Coastal Erosion Area (CEA) map from Painesville on the Lake, OH. Two CEAs (red lines) flank an erosion-mitigation project (riprap at Transects 342-1 to 342-10). Transects have a 33 m spacing. Where the CEA is narrower than the method's Calculated Accuracy Limit, the CEA is not established. (e.g., Transects 342-18 to 342-20). Similarly, where a bluff was stabilized between mapping events (Transects 342-1 to 342-10), a new Base Recession Line is mapped and a CEA is not established (Image: modified from https://gis.ohiodnr.gov/MapViewer/?config=cea and http://apps.ohiodnr.gov/Website/Geosurvey/2010_CEA_pdf/CEA_MAPBOOK_LAKE_342.pdf).*

MINIMUM BLUFF SETBACK DISTANCES ERIE COUNTY, PA						
Municipality	Residential Setback		Commercial Setback		Industrial Setback	
	State Minimum	Municipal	State Minimum	Municipal	State Minimum	Municipal
Springfield Twp	100'	100'	150'	150'	200'	200'
Girard Twp	60'	200'	90'	200'	120'	200'
Lake City Boro	60'	150'	90'	150'	120'	150'
Fairview Twp	50'	100'	75'	100'	100'	100'
Millcreek Twp	50'	50'	75'	75'	100'	100'
City of Erie	25'	25'	25'	25'	25'	25'
Lawrence Park Twp	50'	75'	75'	75'	100'	100'
Harborcreek Twp	50'	50'	75'	75'	100'	100'
North East Twp	50'	50'	75'	75'	100'	100'

Table 8.1: *Current minimum bluff setback distances (MBSDs) for BRHAs along the Lake Erie coast (Image: modified from PA DEP Municipal Reference Document: Guidance for the Implementation of the Chapter 85 Bluff Recession and Setback Regulations (PA DEP, 2013)).*

Chapter 9: Data Gaps, Data Needs, and Research Questions for the Lake Erie Bluff Coast of Pennsylvania

Overview

This chapter consists of a listing of forty-eight data gaps, needs, and research questions relating to bluff management, science, and engineering on the Pennsylvania coast. While listed in no particular order, the emphasis is on science needs with the intent that addressing these needs over time can lead to better coastal management in areas such as:

- defining better science- and engineering-based construction setbacks
- identifying preferred engineering, bioengineering, and biotechnical solutions to slope instability and erosion
- developing better process-response and probabilistic models of future bluff-crest positions rather than relying on retrospective trend methods
- continually improving the quantity and quality of coastal-science information that is available to the general public and coastal stakeholders

Data Gaps, Data Needs, and Research Questions

1. Coastal mapping to identify nearshore joint and fault patterns: These structural features are known to influence groundwater flow in overlying unconsolidated bluff strata, which can lead to changes in bluff stability due to changes in groundwater pore pressures. Patterns can be mapped using the DEP oblique aerial photo database and digital ortho-rectified aerial photos collected as part of this and other projects.

2. Nearshore sediment isopach maps: This is critical for sediment-budget models in coastal hazard assessment, and for lake-bed habitat assessments. States such as Ohio, Oregon and Washington have mapped littoral cells and developed coastal sediment budgets to identify erosion-prone stretches of bluff coast. The Ohio DNR LESEMP map viewer contains coarse-resolution sediment maps that extend into Pennsylvania waters that could provide a framework for future mapping efforts.

3. High-resolution nearshore bathymetric maps: States such as California have high-resolution side-scan bathymetry coverage of nearshore areas. The Ohio DNR LESEMP map viewer provides moderate- to high-resolution bathymetric coverage that also extends into Pennsylvania waters. Currently, Pennsylvania bathymetry is mapped by NOAA at a relatively low resolution very infrequently, and surf zone coverage doesn't yet exist. These data are an important input for wave modeling that allows better quantification of the hydrodynamic forces that drive bluff-toe erosion in particular. Collection of these data may tie in with a proposed NOAA National Marine Sanctuary site identification/assessment need.

4. High resolution bluff-adjacent tableland elevation and slope maps: This will permit better quantification of surface runoff over the landscape and bluff face. Such information, derivable from recent LiDAR data, is important for future bluff-retreat modeling, for example, using Bayesian methods.

5. Detailed GIS-based mapping and categorization of shoreline structures (orientations, dimensions, lifespans, crest elevations, conditions, etc.): This type of information was collected on a coarse scale by the Lower Great Lakes Erosion Study on the Lake Erie perimeter (Stewart, 1999) and more recently at an improved scale by the US Army Corps of Engineers (Cross et al., 2016). More-detailed, GIS-based structure data would be very important for any future bluff-retreat modeling due to the impacts of structures on coastal sediment supply and bluff-toe stability.

6. Multi-property to watershed-scale to municipality-scale bluff geotechnical data for the coast: Such information, currently lacking, is critical to future bluff-retreat modeling using, for example, Bayesian methods in order to improve bluff-retreat prediction capabilities.

7. Representative multi-property to watershed-scale to municipality-scale bluff-face stratigraphic sections: Bluff retreat is influenced by stratigraphy, and stratigraphically similar coastal segments may behave in similar ways. Compiling this type of data will reduce an input-data limitation for future probabilistic models and provide more site-relevant information to coastal engineering firms.

8. Subdivision of the Erie County shoreline into stratigraphically and geotechnically similar segments: This will permit more accurate probabilistic bluff stability modeling because models will be able to incorporate reasonable stratigraphic and geotechnical assumptions at multi-property to watershed scales.

9. Beach-resource (width, depth, and volume) mapping for the coast: This is important for western Erie County in particular, where a tall protective bedrock toe is absent and where the beach volume can thus have an important influence on bluff retreat. Any future modeling of bluff retreat will need these data to incorporate the role of wave attack at the bluff toe.

10. Onshore near-bluff subsurface bedrock topography: Mapping the elevation of Devonian bedrock, bedding dips, and topography within the bluffs will allow more accurate bluff retreat-rate predictions. This is because retreating bluffs will continue to intersect an irregular bedrock surface that will change the relative geotechnical resistance of the bluff to erosion over time.

11. Bluff-face slope maps: Presently not available, bluff-face slope maps can easily be developed in a GIS from LiDAR data collected as part of this project. Bluff geometry is an important input in developing better construction setback criteria. Derivative products such as bluff-slope deviation maps (from average or stable slopes) would facilitate development of a bluff erosion hazard index such as this project's Bluff Erosion Potential (BEP) Index.

12. Bluff-face slope-derivative maps: If Pennsylvania were to develop an improved construction setback methodology, such as the "(AARRxT)+" method or similar, it needs data on stable-slope angles and actual slope angles by property or watershed, for vegetated, non-vegetated, bedrock-toed, and non-bedrock toed settings. This data can be developed in a GIS from existing LiDAR data.

13. Appropriate structural lifespans: Pennsylvania should consider using a 75-100 yr structural lifespan for residential properties when determining construction setbacks. This means increasing the current state-minimum value used in eight of the Erie County municipalities, and exceeding the municipal requirements in five of the municipalities. Coastal states nationally are

recognizing the need for longer structure lifespans in setback calculations, because coastal development is no longer "summer camp" centric and modern coastal construction standards favor longer-lived primary and secondary residences.

14. Bedrock toe retreat rate: This is currently not known for the Pennsylvania coast, and is pertinent to bluff retreat modeling in eastern Erie County in particular. States such as Wisconsin assume a rate of ~0.03 m/yr (~0.1 ft/yr) as input for construction setback calculators. Similarly, the erodibility of glacial tills and lacustrine sands are not known for the Pennsylvania coast at more than a few sites. Estimates for all three rates would permit better bluff-retreat modeling.

15. Bluff-crest overhangs: It is not known how many miles of the Pennsylvania bluff crest overhangs the lower bluff face, nor by how much. This is pertinent to current field-based measurement, and to possible future LiDAR-based measurement, of bluff retreat and to any future revisions to setback requirements.

16. Slope stability analysis: These types of data are practically non-existent for the Pennsylvania coast, except at two sites. US Army Corps of Engineers-style geotechnical slope-stability analyses would be recommended for calculating future coastal slope-stability angles.

17. Climate change impacts: Similar to states such as Washington, Maryland, and New York, Pennsylvania has a need to understand climate-change induced impacts on existing and future coastal engineering-structure lifetimes; lake levels; rainfall seasonality, quantities, rates, and states; and bluff vegetation patterns because these variables directly influence bluff stability.

18. Seismic hazards: West-coast states incorporate a seismic-hazard component into estimations of bluff stability through Factor-of-Safety line determinations. Obtaining USGS-generated assessments of future seismic hazard for NW Pennsylvania (50-100 yr timeframe) would be beneficial because seismic shaking induces bluff instability.

19. Basin-wide consistency: Can conformity be achieved in bluff hazard mapping methodologies and mitigation strategies across the entire Great Lakes Basin? Can Best Management Practices (BMPs) be developed as part of this process if undertaken within the framework of the NOAA Coastal Zone Management Program?

20. The Pennsylvania coastal construction setback methodology: Will it be sufficient in the future, given that it is retrospective and uses assumptions that may be unrealistic? While the methodology is simple and straightforward, is there another state or methodology that Pennsylvania can emulate? For example, the California Coastal Commission (CCC) recommends a "Setback = (AARRxT) + Maximum Historical Slump Cutback + Safety Buffer" method while parts of Wisconsin promote a similar "Safe Setback Line = Stable Slope Setback + Recession Setback + Facility Setback (+ Rock-Toe Undercut Distance, if present)" method.

21. Using mathematical methods, such as Bayesian methods, to better predict the location of the 50-yr and 100-yr bluff crest in Erie County: This may be difficult given the along coast variability in degree of bedrock and shore-structure protection, groundwater flux, and bluff composition. The method could be initiated at the coastal reach (or pilot study) scale and then fine-tuned over time as data coverage improves.

22. Sediment supply and nearshore water quality: What are the sediment volumes supplied by historical rotational slumps and translational slides versus the background sediment volumes associated with more insidious subaerial grain-by-grain erosion?

23. Large rotational slumps: What are the historical frequencies and dimensions of large rotational slumps county-wide? Limited work on the Ontario coast of Lake Erie suggests that large slumps have a periodicity of 10-20 years. Rotational slumps can remove large amounts of upland quickly and it is thus important to be able to estimate typical sizes of these events for planning purposes.

24. Slip plane daylighting: Do the slip planes for large rotational slumps always daylight at the glacial till/lacustrine sand geologic contact? This has implications for choosing engineering, bioengineering, and biotechnical mitigation measures.

25. Rotational slump mapping: Periodic mapping of slump scars (e.g., on a 5-yr cycle) would allow coastal sectors with this mechanism to be assigned a risk ranking depending on whether slumps are active, potentially active, or prehistoric. LiDAR and ortho-rectified aerial photography, and possibly 1938-era aerial photography, would be useful data sources for this.

26. Updating setbacks: Along highstand coastal sections, should an average or a maximum cutback associated with rotational slump events be added as an additional safety factor to setback calculations? This should be considered if, for example, the "(AARRxT)+" method (or similar) were to be adopted in delineating setbacks in the future.

27. Watershed geometries and dimensions: Is there a statistical relationship between coastal watersheds and bluff instability or retreat rates that might be useful for planning purposes? Watershed characteristics vary along-coast and likely influence groundwater recharge. Subsequent groundwater flux and pore pressures at the bluff face contribute to bluff retreat.

28. Lake-level management: Is reducing lake level a viable solution for interstate coastal and bluff erosion problems on Lake Erie? This option has been considered for the Upper St. Lawrence River – Lake Ontario basin, and would affect four states and one province on the perimeter of Lake Erie. Alternatively, is maintaining a stable lake level feasible? Recent work suggests that lake-level cyclicity at certain frequencies may lead to more lakebed erosion and bluff retreat than would occur if lake levels were stable.

29. Lake Erie levels: What are the best predictions concerning Lake Erie levels over the next 50, 100, and 200 years? A 2011 review by NOAA suggests lake levels will fall by as much as 1.8 ft by 2080. A fall in lake level will enhance bluff stability in bedrock-free areas, but associated climate changes may enhance bluff instability due to changing precipitation and runoff patterns.

30. Long-term bluff stability: How long does it take a coastal bluff to achieve the stable slope angle used in setback calculations by other states? Does it take longer than a typical structure lifetime and therefore lead to too-conservative a setback?

31. Bluff behavior: How variable are rates of toe erosion, rotational slumping, translational slumping, and soil creep on the Pennsylvania coast? How might that affect possible future development of a better setback methodology?

32. Probabilities: There is a need to move bluff hazard mitigation and hazard planning towards probabilistic methods and map products. This has already been done for seismic hazard (USGS), flood hazard (FEMA), landslide hazard (industry), and sandy-coast erosion hazard (USGS) problems.

33. Bluff re-entrants: Risk of slope failure and crest retreat exists not only along the lakefront but also extends inland at coastal ravines and stream mouths. Should the near-coast reaches of these steep ravines and valleys, which often have significant value in terms of ecosystem services, be regulated in a similar manner to the lakefront bluff edge? Monitoring data for these features is scarce.

34. Changing bluff-retreat trends in certain municipalities: Are east Erie and Lawrence Park bluff retreat rates declining over time, or increasing less quickly, due to wave shielding by the eastward-growing terminus of the Presque Isle peninsula?

35. Sediment flux to the littoral zone: What is the sediment flux to the littoral zone due to bluff retreat in areas outside of a limited number of transects studied by DEP over three decades ago? This type of information would be useful for an up-to-date coast-wide sediment budget, and would also be pertinent to Presque Isle erosion issues. Good information could be developed from comparisons of bluff-face changes using recent-era LiDAR data.

36. Bluff toe abrasion: Does the present sediment supply to the littoral zone from the bluffs enhance bluff and lake-bed erosion (by supplying abrasives), or enhance deposition and stability (by supplying sand and gravel for protective beach development)? Is there a critical value for the abrade/no-abrade condition on Pennsylvania's bluff coasts?

37. Physical processes: How fast is face-weathering (leading to popcorn texture) of glacial till on the exposed bluff face? How fast is the process of pressure-relief joint development on exposed till? The latter process is an important mechanism influencing bluff retreat because it allows the formation of large slump blocks on the lower bluff.

38. Hydrodynamics: What is the optimal storm frequency for maximizing removal of weathered-bluff and slump-fan material from the toe of the bluff? How long do beneficial colluvial fans typically survive along Pennsylvania bluffs?

39. Geotechnical properties: What is the stable-slope angle for Pennsylvania bluffs with and without bedrock? How much does it vary along the coast? Should it be mapped by municipality or at a finer scale (watershed or multi-property scale) to facilitate coastal planning?

40. Bluff geometry: Do Pennsylvania bluffs follow a toe-crest-toe-crest alternating erosion process or is it dominantly a process of continuous crest retreat with slope reduction?

41. Groundwater flux and climate change: Is the present Erie County coastal groundwater regime evolving with climate change, at what rates, and with what time lags? How will this influence bluff retreat in areas where groundwater flux is driving erosion? GLWQA (2016) recommended that research be advanced on local-scale assessment of interactions between groundwater and surface water as it relates to Great Lakes water quality and discharge. This is a good second reason to promote coastal groundwater research beyond just the bluff-erosion issue.

42. The California solution: In California, the CCC allows bluff-top development to occur (i) if their setback equation is satisfied and (ii) if siting is such that the structure will not be at risk over its design life and will not require shoreline-protection structures now or at any time in the future. Could or should Erie County adopt a similar structures policy?

43. Retreat rate monitoring: There is no one accepted standard among coastal states regarding the retreat-rate sampling parameters of frequency, duration, and spatial separation. How many years of data should form the basis for determining the AARR? How often should bluff-edge data be collected via fieldwork or LiDAR interpretation? What is the ideal sample spacing for field control-point transects or GIS-based virtual transects? How should more accurate recent data be weighted relative to older data that rely on less precise measurements to obtain meaningful retreat-rate statistics. Pennsylvania DEP acknowledges that because bluff recession is often episodic in nature, the longer control points are monitored, the more accurate the calculated retreat-rate averages become.

44. Feeder bluffs: Approximately 24% of the Pennsylvania coast is currently protected by coastal engineering structures. Much of the remainder is owned or managed by private, commercial, and industrial individuals and organizations. Should Pennsylvania adopt a "feeder bluff" conservation mechanism similar to that of Puget Sound in Washington state (Chapter 2)? Feeder bluffs are sectors of coast that are preserved in a natural state without any erosion-mitigation efforts being attempted. The goal is to preserve a sediment supply to the littoral system that could otherwise be significantly reduced through erosion-mitigation efforts that often have adverse site and downdrift impacts. Tall (sandier) bluffs along the Warren strandplain sectors near North East and Lake City, and municipal/state lakefront parks, would be coastal areas worth consideration.

45. Vegetated Holocene bowls: Did the large moribund (now relatively stable) apparent rotational-slump features in eastern Erie County form during a different climatic regime or because of a regional seismic event? Are they an indicator of the increased sizes of bluff failures that may occur during environmental or climatic conditions that are dissimilar to today? If so, what were those conditions or triggering events and are they likely to be replicated in the future?

46. Geologic type sections: Can a logistically-manageable number of hydrodynamically, subaerially, and geotechnically distinct bluff sites be identified on the Pennsylvania coast to facilitate further study of the driving mechanisms of bluff retreat for future modeling purposes? Prior research suggests that the Pennsylvania bluff coast probably has at least 10-15, individually unique, coastal segments.

47. LiDAR resolution limitations: LiDAR ground-strike densities and patterns in steep-terrain coastal surveys exert a hidden influence on the sizes of topographic features that can be resolved on and near the bluff-face. Haneberg et al. (2009) note that features smaller than the ground-strike spacing, or less than an order of magnitude larger than the ground-strike spacing, are difficult to map. This is an issue for older (1990s era) LiDAR data in particular because it places a limitation on identifying the frequencies and sizes of, for example, small failure events on the bluff face.

48. Wave climate: Wave climate plays a significant role in bluff retreat on the Great Lakes coast. Installation of a network of wave gauges along the Pennsylvania coast, if undertaken, would permit compilation of real-time wave-climate data over time and provide data that is currently unavailable for areas distant from Presque Isle. Such an effort would allow better

understanding of wave characteristics along the Pennsylvania coast (e.g., for coastal engineering design), and provide critical data for input to coastal-change models (both Process-Response and Bayesian models). In the interim, very useful coastal wave-hindcast data are now available for Pennsylvania (and Lake Erie-wide) nearshore areas at a series of closely spaced synthetic wave-gauge sites (Figure 9.1). This dataset uses historical meteorological records to model past wave conditions, and currently covers the years 1979-2014. Maintained by the US Army Corps of Engineers Wave Information Studies program, it represents a large leap forward from the prior wave climate record that was based on a limited number of wave gauges spread across Lake Erie (http://wis.usace.army.mil/wis_project_overview.html).

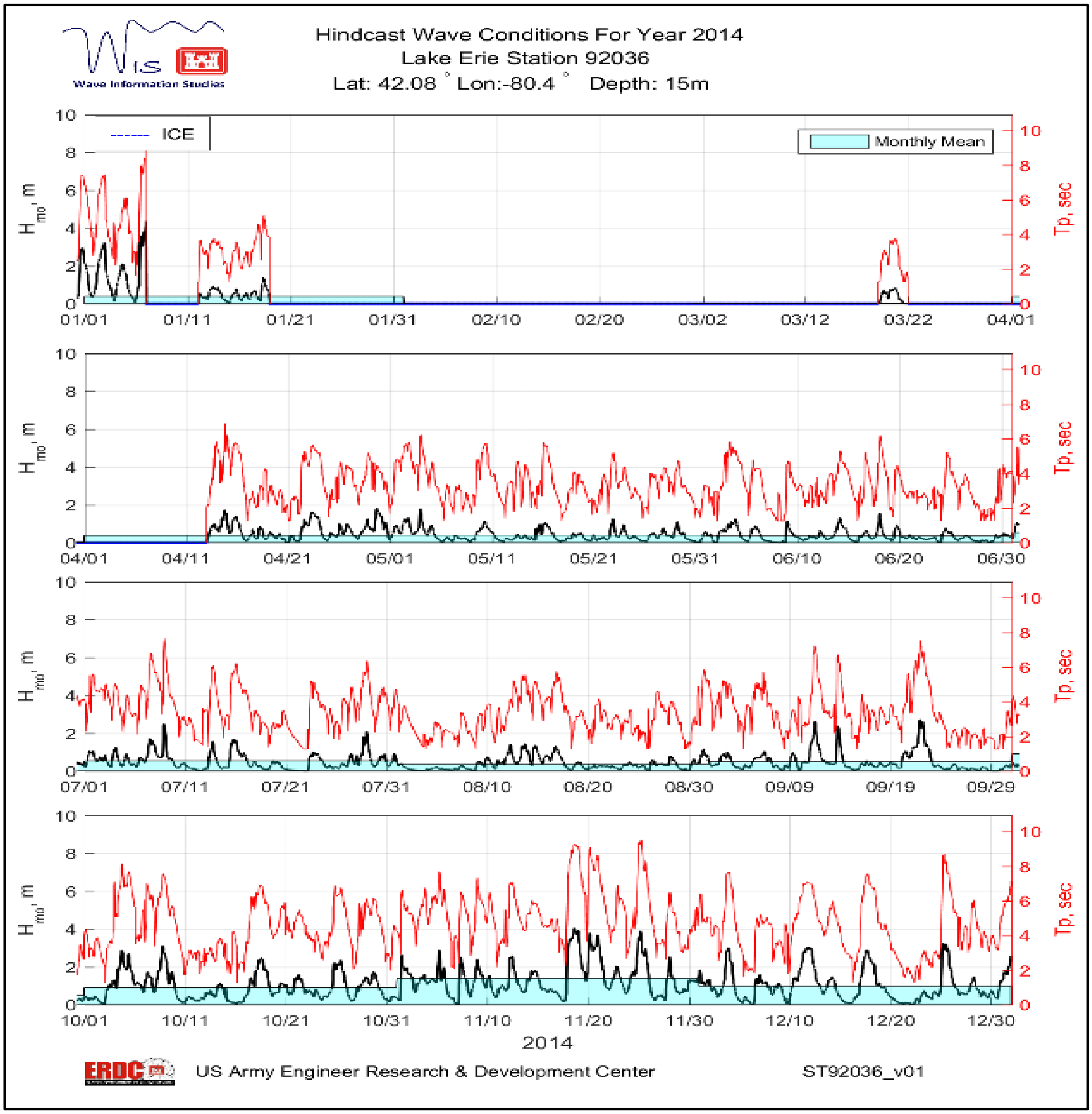


***Figure 9.1**: Screenshot example of wave hindcast data plot (for 2014) compiled for the Pennsylvania nearshore by the US Army Corps of Engineers WIS program. Station 92036 is from western Erie County. Similar data are available at http://wis.usace.army.mil/hindcasts.html?dmn=lake_erie.*

Chapter 10: Conclusions and Technical/Management Recommendations for Bluff-Retreat Issues on the Lake Erie Bluff Coast of Pennsylvania

Conclusions

In the *Recommendations* section below, this concluding chapter summarizes eight bluff-management related recommendations pertinent to the Pennsylvania coast of Lake Erie. The recommendations are based on review of the literature on coastal erosion and bluff-retreat issues in the Great Lakes Basin, on ocean coasts nationally, and to a lesser extent internationally. The recommendations below are derived from *Chapter 9: Data Gaps, Data Needs, and Research Questions for the Lake Erie Bluff Coast of Pennsylvania*. They are intended to highlight areas where an increased level of knowledge on the management, science, and engineering of Pennsylvania's bluff coast may lead to improved coastal resiliency, help form a stronger basis for future coastal management and decision-making, and increase stakeholder awareness.

Fundamentally, the challenge in dealing with bluff erosion issues on the agricultural and urban coast of NW Pennsylvania is to continue to effectively manage the *natural coastal erosion - coastal population growth* nexus that is an underlying cause of problems in many coastal regions. The challenge is greater on bluff coasts because bluff erosion is irreversible and the potential for sudden and catastrophic failure events is higher than for low-relief beach and wetland coasts elsewhere in the state. Any measures taken to reduce or stop erosion on bluffs impact natural resources and human populations to varying degrees depending on the measures used. The challenge is to achieve a flexible balance between conserving the natural environment and meeting the needs of coastal populations. The importance of this challenge is reflected in the ongoing emphasis on Resilient Coastal Communities by the NOAA Office for Coastal Management and by The Nature Conservancy (see details at https://coast.noaa.gov/digitalcoast/tools/coastalresilience.html).

The level of understanding and quantification of bluff behavior, and the roles played by internal geotechnical properties, external driving forces, and initial conditions, continues to evolve. Many basic issues are resolved, but fundamental challenges remain due to the complexity of bluff systems. Estimating future bluff crest positions in Pennsylvania, as in some other states, continues to be reliant on deterministic methods that use past behavior as a predictor of future behavior, and assumes that historical environmental conditions and retreat rates will be replicated in the future. Recent coupled subaerial-submarine process-response models (Chapter 7) are a step in the right direction but, to date, are limited in number and variety. Model runs have been primarily used in cohesive bluff crest-to-nearshore settings that do not directly apply to over half of the Pennsylvania coast. Much still needs to be resolved on the relative roles of wave shear stresses and abrasion (hydrodynamic forces); and on the material geotechnical properties and groundwater pore pressures within the layered, relatively complex, bluffs seen in Pennsylvania. Probabilistic methods, such as used in seismic and flood hazard mapping, are a potential new approach to the science of predicting bluff retreat: probability-based hazard maps are already being developed by the USGS for sandy ocean coasts (Chapter 7). This mapping approach, if adopted for bluff coasts, will be a very effective means of communicating meaningful, statistics-based, bluff-change information to coastal planners and stakeholders such as property developers and owners.

A fundamental difficulty remains in bluff science and engineering: quantifying natural three-dimensional complexity in bluff stratigraphy, geotechnical properties, and responses to the internal and external stressors that drive bluff failure. This challenge needs to be resolved incrementally so that continually improving predictive models can do a better job across different geologies and timeframes. This difficulty is not unique to bluff retreat on cohesive coasts: natural system complexity is also a challenge across the geosciences such as in groundwater, seismic-hazard, volcanic-hazard, and climate modeling. However, the science of understanding bluff behavior stands to gain from advances in each of these other science areas. While the physics involved in geotechnical analyses is well understood and can be used effectively in simpler controlled conditions at the small scale, a challenge lies in applying methods to more complex and large systems at various spatial and temporal scales over which forcing agents can be very variable. An allied problem is that it is expensive to adequately map 3-D geotechnical properties in bluffs and this can lead to the restriction of analytical studies to small, site-specific areas. This may be agreeable for a specific property owner who may have the funds to support that level of geotechnical analysis. But it poses a problem for engineers, geologists, and regulators when a limited data density on their coast limits the accuracy of any bluff-stability and construction-setback calculations that may have to rely on regional averages.

Bluff-behavior models also remain subject to uncertainty because for models to be run in realistic timeframes, assumptions and simplifications have to be made to circumvent some of the complexity in time and space of geological and geotechnical properties. Often, coefficients are picked and used in numerical models that help a model produce agreeable or correct solutions for a specific set of conditions: however, the model may not work as well for a different set of conditions.

Recommendations

1 Continue to improve coastal-hazard information access for stakeholders and the general public.

Existing and historical information on coastal stratigraphy, geotechnical properties, and the magnitude of bluff-failure hazards in Erie County, beyond a qualitative level, is scarce and not sufficiently centralized and cross-referenced. This limits data accessibility needed for effective coastal planning, hazard mitigation, and increasing coastal resiliency. It also limits the availability of information that may be important to buyers, sellers, and realtors involved in coastal property transactions. As far as is practical, all publications, technical reports, maps, and data pertinent to coastal bluff hazards in Pennsylvania and the Great Lakes Basin should be inventoried, catalogued, and made accessible online directly (as actual documents, maps, and data) or indirectly (as references or links to offsite documents, maps, and data). The *Pennsylvania Great Lakes Water and Land Technical Resources Center* (WALTER) web portal, a later component of this project (see Chapter 1), will serve as an ideal coastal information resource and repository and is a major step in this direction. Digital geodata and interrogable content should be maintained and updated on a regular (e.g., annual) basis to keep managers and stakeholders aware of important developments and trends in coastal monitoring and hazard assessment on the Great Lakes coasts including Pennsylvania. The "coastal atlas" approach used by several states (e.g., Washington; Chapter 2), and GIS-based interactive mapping tools such as that shown in Figure 10.1, are the most effective means of allowing data access and visualization.

2 Provide more proactive technical information for planners and contractors.

This will help meet planning, development, and conservation needs among city and municipal planning agencies, coastal contractors, and regulatory agencies. States such as Ohio and Wisconsin in particular (Chapter 2) provide stakeholders and construction contractors navigating the permit-design-build process with web-based information and calculators. Data provided ranges from site-specific bluff, nearshore geologic, and construction setback information and imagery; to site-adaptable model coastal-engineering plans for mitigating bluff-retreat problems (see Ohio Coastal Design Manual and LESEMP in Chapter 2; Chapter 6); to information on bioengineering and biotechnical mitigation methods. The Pennsylvania coastal zone would benefit if a range of coastal cross-sections and map products (e.g., GIS-based at the watershed or municipality scale) were available that showed a comprehensive selection of technical bluff information. Such information could include: relative slope stability, existing slope angles, estimated stable-slope angles, dominant failure-mechanisms, bluff-face topography, historical landslide locations, historical and present bluff-crest positions, bluff-crest retreat rates, bluff stratigraphy, coastal-engineering structures, geotechnical properties, erosion hotspots, nearshore materials, significant wave heights, and wave energy density at the shoreline, etc. The WALTER web portal is an ideal interface to provide these types of data.

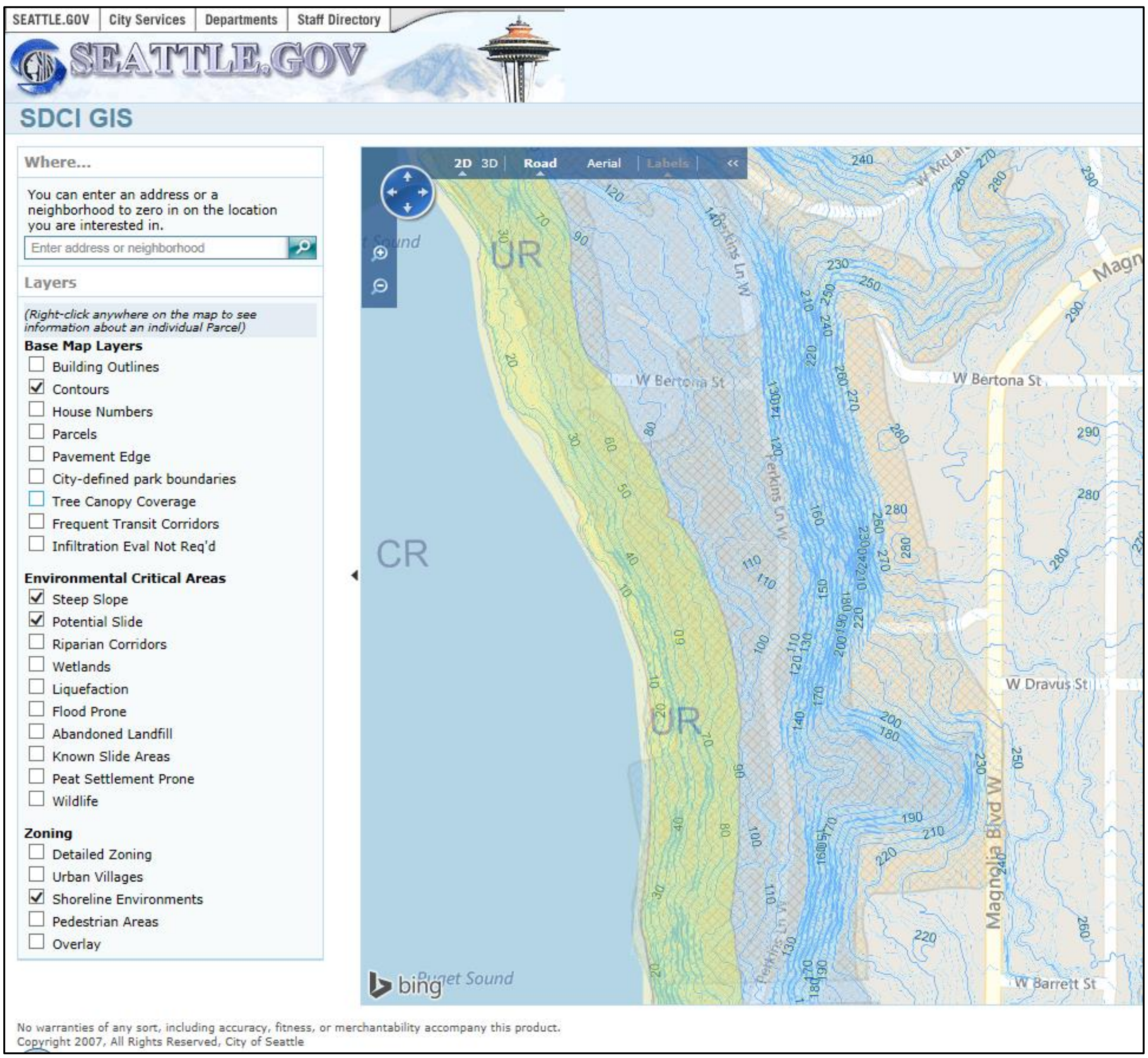


Figure 10.1: *Making hazards science visible to the public. Screenshot of part of the City of Seattle GIS hazards mapping tool that shows steep-slope and potential slide areas, topographic contours, and coastal zone layers. The tool is available at http://web6.seattle.gov/DPD/Maps/dpdgis.aspx.*

3 Acquire a higher spatial density and broader coverage of bluff stratigraphic, hydrodynamic, and geotechnical data to facilitate future coastal modeling.

For more effective long-term bluff-retreat mitigation planning and bluff-adjacent development planning, a significant quantity of new geotechnical, hydrodynamic, and stratigraphic data needs to be collected at an appropriate sampling scale in NW Pennsylvania (Chapter 3). Existing information is sparse and derived from very few sites in the central and western coastal reaches. This limitation exists despite the amount of federal, state, non-profit agency, municipality, and private sector (coastal engineering) activity on the coast and in coastal watersheds.

4 Expand coordination efforts as a means to efficiently acquire and share data.

Increasing coordination among research organizations; municipal, state, federal, and provincial agencies; and contractors working on Lake Erie is beneficial because it facilitates access to ongoing and future data collection and analysis that can be pertinent to bluff issues on the Pennsylvania coast. This effort could include coordination with:

- the US Army Corps of Engineers (e.g., the recent Lower Great Lakes Erosion Study, and future outgrowths; nearshore subaqueous LiDAR data)
- the FEMA-NFIP Great Lakes Coastal Flood Study (compiling information on shoreline materials, beach widths, and coastal landform types; www.greatlakescoast.org)
- the Great Lakes Commission's coastal monitoring program
- private-sector engineering consultants involved with large federal projects on the Great Lakes
- NOAA GLERL and NOAA CO-OPS, conducting research on lake levels and hydrodynamics
- PA DEP, compiling lake-bottom imagery
- local municipalities, for geotechnical information obtainable through coastal construction permit applications
- PA DEP, PASDA and NOAA-CSC for geospatial and mapping data
- adjacent states, for collaborations in digital coastal data acquisition

5 Consider transitioning to better science-based methodologies for determining setback distances from the bluff crest.

Current methods used in defining construction setbacks along the bluff coast are functional and meet current needs, but are not state-of-the-art and should be improved as coastal population pressures increase. The existing methodology relies on a retrospective deterministic approach (the "AARRxT" method; Chapter 8) to estimate future bluff-crest locations that in turn helps guide where construction setback lines are set. This methodology has already been replaced, or is being considered for replacement, with improved methodologies in other states (e.g., variations on the "(AARRxT)+" method; Chapters 2 and 8). These methodologies still rely on historical rates of bluff retreat (the AARR term), but add allowances for a stable slope angle (SSA term) and a relocation buffer (SB term). Considering recent improvements in coastal construction standards, and bluff-hazard management trends in other states, the expected lifespan (T) of coastal residential buildings in particular could be increased from the current 50-yr standard in Pennsylvania: this would foster definition of more conservative construction setbacks. In the long term, the most promising science-based approach to estimating future bluff-crest positions and determining coastal construction setbacks will most likely involve probabilistic, multi-variate modeling, and Bayesian methods. However, for this modeling to be as accurate as possible, a large amount of model-input data must first be collected for the Pennsylvania coast.

6 Acquire detailed bluff stratigraphic and geotechnical information at the individual- to multi-property property scale, if possible, through the construction permitting process.

An increasing number of municipalities (in California, in particular; Chapters 2 and 6) are recommending or requiring a site geotechnical investigation by a licensed civil engineer or engineering geologist when determining construction setbacks on a bluff property as part of a construction permit application. Municipalities in NW Pennsylvania could begin to adopt a similar requirement over a timeframe of years to decades. Over long time periods, this parcel-by-parcel approach to acquiring standardized data on bluff geotechnical properties will lead to better bluff management. It is also a feasible way to initiate infilling of the geotechnical-data gap for the bluff coast in each municipality. The process is necessarily slow because it is dependent on the frequency of construction-permit applications. However, it has the significant benefit that the costs of such data acquisition for improved coastal management are borne by the property developer and not by the existing municipality-wide tax base.

7 Acquire detailed bluff stratigraphic and geotechnical information at representative sites in each of 10-15, geomorphically similar, coastal segments.

If Recommendation 6 concerning bluff characterization at the property-parcel scale is not yet feasible, obtaining that information at the multi-property to watershed (or coastal segment) scale may be more practical. Either scale of data acquisition should be an ultimate goal for effective management of bluff-erosion hazards, although both approaches are costly and necessarily long-term. The watershed-scale approach to coastal data acquisition is similar to the approach used by Ohio's LESEMP (Chapter 2). The watershed approach circumvents the logistical and possible legal complications in obtaining geotechnical information at the individual private-property scale. Identifying coastal segments where bluff geotechnical properties, stratigraphy, and processes are similar, and then obtaining data representative of those coastal sections, would be a major step forward from the present, low data-density, state of bluff characterization. It is a useful intermediate-term step that would allow improved coastal management as detail at the near-property-parcel scale is progressively acquired over time.

8 Consider modifying construction setbacks along the coast to reflect different bluff failure mechanisms, and associated magnitudes of bluff crest retreat, on different coastal segments.

Based on a preliminary review of the PA DEP database of oblique coastal aerial photography (see Chapter 6), bluff failure mechanisms and magnitudes of bluff retreat may correlate strongly with specific coastal segments. Translational slumps appear to be more common along the western coastal reach while rotational slumps appear more common along the eastern coastal reach (Chapters 3 and 6). Other areas are characterized by continuous soil creeps and sliding vegetation mats. Stepped benches extending tens to hundreds of meters along-coast with headwall heights of meters are common dimensions for translational slumps. These failures, unlike rotational slumps, have the benefit of adding transverse topography to the bluff profile which reduces the opportunity for subsequent erosion by surface runoff. For property owners, this type of failure in western Erie County is more likely to result in less landward retreat of the bluff crest during a failure event, but also to result in a greater along-coast impact. This contrasts with the rotational slump response of greater headwall retreat but lesser along-coast extent. This latter mechanism appears more prevalent in tall bluffs along the eastern coastal reach where bedrock is present and where groundwater focusing at seeps and springs higher in the profile is probably more prevalent. Much of the variability in bluff-failure mechanisms could feasibly be captured at the watershed-scale via GIS-based mapping using recent and ongoing aerial photography and LiDAR data collections.

Chapter 11: Glossary of Bluff-Related Terms and Definitions for the Great Lakes and Pennsylvania Coasts

Terms and Definitions

The terms and definitions in the following glossary are extracted, verbatim or with minimal modification, from several state and other sources. These include Pennsylvania DEP, Ohio Coastal Management, Lake Champlain Sea Grant Publication LCSG-04-03 (2004), and Cross et al. (2007). For additional definitions of coast-related terms, an extensive 95-page *Glossary of Coastal Terminology (Morang and Szuwalski, 2003)* is available online from the US Army Corps of Engineers at http://luk.staff.ugm.ac.id/USACE/EM_1110-2-1100_App_A.pdf.

This Glossary provides the reader with the meanings of specific bluff- and management-related terms used in this report, in the field of coastal-management generally, and in the field of coastal geology and engineering. These terms are commonly used within all US state coastal management programs although the precise (and related legal) definitions may vary between programs.

Angle of Repose The maximum angle or slope at which a material, such as soil or loose rock, remains stable and does not collapse (regulatory definition; PA DEP, 2013).

Armor The outer layer of material, usually heavy stone, of a control structure exposed to direct wave action.

Bank A relatively steep topographic feature on a coast consisting of unconsolidated materials that, in Pennsylvania, is no higher than 5 ft above lake level.

Beach The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or the line of permanent vegetation.

Beach Nourishment A “soft” erosion-control measure that involves the placement of sand within the shore and nearshore zones to build-up beach thickness and width from shore to lake. Also, a form of “soft stabilization.”

Bedrock A general term for the rock, usually solid, that underlies soil or other unconsolidated, surface material.

Bioengineering The use of live plants and plant material to reinforce soil, serve as water drains, act as erosion-prevention barriers, and promote water drainage in wet soils.

Biotechnical The use of both live plant material and inert structures to stabilize and reinforce slopes.

Bluff A high bank (greater than 1.5 m in elevation in Pennsylvania) or bold headland with a broad precipitous face overlooking a lake (regulatory definition; PA DEP, 2013).

Bluff Crest The top edge or crest of the bluff; the part of the bluff where the tableland begins to slope downward toward the lake and bluff face.

Bluff Face The sloping surface of a high bank or bluff that extends from the bluff toe to the bluff crest.

Bluff Toe The base of a bluff where it meets the backshore part of a beach, or the shoreline or lake bed if a beach is absent.

Bluff Recession A phrase that is synonymous with the phrase "bluff retreat" in this report. It is the loss of material along the bluff face caused by the direct or indirect action of one or a combination of groundwater seepage, water currents, wind generated water waves or high water levels (regulatory definition; PA DEP, 2013).

Bluff Recession Hazard Area (BRHA) An area or zone where the rate of progressive bluff recession creates a substantial threat to the safety or stability of nearby existing or future structures or utility facilities. The term does not include any area where the horizontal distance, measured perpendicular to the shoreline, between the shoreline and the bluff toe is in excess of 250 feet. Such areas will not be subject to Environmental Quality Board regulations or municipal bluff setback ordinances (regulatory definition; PA DEP, 2013).

Bluff Setback Ordinance and Regulations Building codes, zoning ordinances, subdivision regulations, health regulations, special purpose ordinances and other applications of the police power, which provide standards for the location of structures and facilities in bluff recession hazard areas (regulatory definition; PA DEP, 2013).

Bluff Toe The base of a bluff (regulatory definition; PA DEP, 2013).

BMP or BMPs Best Management Practices. These are currently recommended practices for managing an environmental problem, area or resource.

Breakwaters Concrete, block, or rock structures that reduce the energy of approaching waves, creating a calm environment landward of the structure. Breakwaters are often attached to and parallel to the shore, but may also be built lakeward of the shoreline in the surf zone or nearshore.

Breakwaters, Detached Shore-parallel structures built in shallow near-shore environments, also referred to as offshore breakwaters or segmented breakwaters. Located just offshore, these structures reduce erosion and protect beaches by reducing wave action.

Bulkheads Vertical structures built to stop the land from sliding into the lake and to provide deep water access to adjacent shores. Commonly found at marinas or mooring facilities, they may also be found in urban areas and may be the base of a promenade along the lake.

Channeling A method of intercepting water, such as from downspouts and driveways, before it infiltrates the ground, and piping it to a desired location. Along the bluff, water is usually piped directly to lake level.

Cliff A high, very steep to perpendicular or over-hanging face of rock rising above a shoreline or adjacent water body.

Colluvium: A general name for loose, unconsolidated sediments that have been deposited at the base of hillslopes by either rainwash, sheetwash, slow continuous downslope creep, or a variable combination of these processes (Wikipedia, 2016).

Development In Pennsylvania, within the context of coastal zone management, the term is defined as (regulatory definition; PA DEP, 2013):

- the improvement of one lot or two or more contiguous lots, tracts, or parcels of land for any purpose including, but not limited to one of the following: (a) a group of two or more buildings or (b) the division or allocation of land or space between or among two or more existing or prospective occupants by means of or for the purpose of streets, common areas, leaseholds, condominiums, building groups or other features; or
- a subdivision of land

Dewatering The interception and removal of groundwater within the substrate using vertical pumped wells and/or sub-horizontal collection pipes.

Diamict A volume of sediment that is often of glacial origin, in which there are grains of various sizes mixed together (poorly sorted).

Downdrift The direction of predominant movement of coastal materials by currents.
Bank: The rising ground bordering the sea, river, or lake.

Drainage (soil) The rapidity and extent of the removal of water from the soil by surface runoff and by down-draw flow through the soil.

Drainage Systems A series of pipes and/or gravel-filled trenches installed on or within a bluff or bank that function to remove excess water.

Dune Construction Protects the area landward of the dune while enhancing the beach lakeward of the dune. Dunes function to protect the upland by limiting the number and force of waves reaching inland, while also providing protection from storms and strong winds.

Erosion The wearing away of rock or soil and the resulting movement of particles by wind, water, ice, or gravity.

Evapotranspiration Water lost in vapor form, both from the leaves of plants via transpiration and by evaporation from the surfaces of the vegetation and the ground.

Flow A mass movement involving rapid flowage of wet soil, rock, and displaced vegetation as a viscous mass down a slope or a channel; including mudflow, debris flow, and earth flow.

Geomorphology The study of the characteristics, origin, and development of landforms.

Glacial Till Poorly sorted and generally unstratified sediments, deposited directly by and underneath a glacier.

Groins (Groynes), and Groin Fields Shore-perpendicular structures that are connected to land and extend into the lake. They interrupt or slow the movement of sediment along the shore.

Groundwater Water that has been absorbed into the soil or underlying sediment in a recharge area and moves through the ground below the surface and water table.

Groundwater Seep A location where groundwater emerges on the face of the bluff or other bank, or any place on a landscape where groundwater seeps to the surface.

Gully Large intermittent drainage channel developed from the erosion forces of drainages occurring from surface water runoff.

Hard Stabilization The installation of any physical structure on or along the bluff (or elsewhere) to prevent erosion. Such structures are most commonly built with steel, concrete, rock, or wood.

Impermeable A material such as soil, sediment, or rock having a texture that does not permit fluids to move through it freely due to a lack of connected interstitial pores.

Impervious A surface characteristic that prevents water from entering the soil. Concrete driveways are commonly impervious.

Improvement A physical modification of an existing structure in Pennsylvania, regardless of cost, that requires the issuance of any permit by the municipality in which the structure is located (regulatory definition; PA DEP, 2013).

Infiltration The movement of water or solutions into or through a soil, sediment, or rock through pores, cracks or fractures; the flow of rainwater into soil material.

Jetties Navigational structures used to stabilize river mouths and tidal inlets. Jetties are shore-connected features built parallel to the navigation channel, which is usually perpendicular to the shore.

Joint A crack formed in rock sediment by movements normal to the cracks and without shear movements of the material on either side of the crack. Jointing may also be induced in glacial sediments by dehydration, lowering of the water table, or removal of overburden.

Lake In Pennsylvania, a body of fresh water covering at least 9,000 square miles (regulatory definition; PA DEP, 2013).

Littoral Current A natural current in which sand and sediment particles are moved along the coast within the surf zone. The current is typically induced by wave refraction and water-level set-up at the shoreline. Along the Pennsylvania Lake Erie shoreline, littoral currents move northeastward.

Littoral Drift The sediments that are moved along the shore by a littoral current.

Market Value The value of a structure determined by a certified appraisal or by determining the assessed value of a structure and applying the assessment ratio of the county in which the structure is located (regulatory definition; PA DEP, 2013).

Mass Movement The movement of soil, sediment, or rock down a slope as a slide, a flow, a fall, or a soil creep in which gravity is the principal driving force.

Minimum Bluff Setback Distance (MBSD) The shortest horizontal distance from a point on the bluff line to a point on a structure (regulatory definition; PA DEP, 2013).

Moderate Slope Often considered to be a slope of 45 degrees (1:1) or less, but may vary nationally. Typically, for steeper slopes, an imaginary 45-degree plane that extends from the bluff toe to the bluff crest defines a linear feature (baseline) landward of the bluff crest that is used by the International Building Code to reference construction setback distances from a slope crest.

Moveable Structure A home, cabin, shed, garage, or other construction in Pennsylvania that can be readily moved via standard structure relocation practices from a lot that has adequate width and grade to allow for its removal from the BRHA. The access road to the nearest paved road should be of adequate grade, width, and composition to allow moving of the structure. The cost of relocation should not be greater than 25% of the replacement cost of the structure (regulatory definition; PA DEP, 2013).

Municipality A county, city, borough, town or township or any other governmental unit when acting as an agent thereof or any combination thereof acting jointly (regulatory definition; PA DEP, 2013).

Ordinary High Water Mark (OHWM) A commonly-used reference line for legal purposes in the coastal zone nationally. On the Wisconsin bluff coast, for example, the OHWM is the point on the bank or shore up to which the presence and action of water is so continuous as to leave a distinct mark either by erosion, destruction of terrestrial vegetation, or other easily recognized characteristic. In Wisconsin's unincorporated coastal areas, the state standard setback for coastal construction is 75 ft from the OHWM. In Pennsylvania, the OHWM commonly lies at the toe of the bluff unless a large beach is present.

Parcel A piece of ground that existed as an independent tax lot on the records of the county prior to its inclusion in designated bluff recession hazard areas of a municipality (regulatory definition; PA DEP, 2013).

Percent Slope The direct ratio (multiplied by 100) between the vertical and the horizontal distance for a given slope; e.g., a 3-foot rise in a 10-foot horizontal distance is a 30 % slope.

Permeable A characteristic of geologic and other materials that allows water to move through it easily. Sandy soils are usually very permeable. Glacial tills and shale bedrock are relatively impermeable.

Pivot Point The point along a bluff line in Pennsylvania where the erosional forces effecting bluff stability change from lake-induced erosion to riverine or watercourse-induced erosion (regulatory definition; PA DEP, 2013).

Plat A map, drawing or print accurately drawn to scale showing the proposed or existing location of all structures (regulatory definition; PA DEP, 2013).

Raindrop Splash A process that causes soil erosion when raindrops hit directly on exposed soil. In heavy storms a significant amount of soil can be splashed up in the air. This occurs on both level and steep banks but has more severe results on steeper slopes.

Ravine A deep narrow cleft in the earth's surface, usually formed by a stream, surface runoff, or a groundwater seep.

Regrading or Terracing A relatively low cost means of stabilizing the bluff/bank by moving bluff material so that the slope is more stable due to the reduction of gravity's forces. It can involve the creation of terraces along the bluff face, often with switch-backs so that the terraces can act as pathways to the lake.

Revetments Onshore structures built to protect the toe of a bluff/bank from erosion caused by wave action. Structures are constructed at a stable angle and create a covering of erosion resistant material from the shoreline or toe of the bluff up to a point where wave action typically does not reach.

Rill A tiny drainage channel cut in a slope by the flow of water. A rill can develop into a gully with continuing erosion.

Rotational Slump A slide characterized by a rotational movement of a generally independent mass of rock or earth along a curved slip surface.

Runoff That part of the precipitation that appears in uncontrolled surface streams, drains, or sewers. It is stream flow unaffected by artificial diversion, imports, storage, or other works in or on the stream channels.

Sand Bypassing The intentional (or natural) relocation of sand from an updrift area of accretion to areas downdrift. Typically, intentional bypassing is performed at navigation channels and harbors where jetties and breakwaters capture a significant amount of littoral sand.

Saturated A condition in which the pores or joints of a material such as soil or sediment are filled with water; by definition, the zone of saturation lies beneath the water table.

Seawalls Onshore, shore-parallel structures built to reduce wave-induced toe erosion, with a secondary function of limiting flooding of the land behind the structure by reducing wave overtopping. These structures can have a vertical, stepped, or curved face, and typically have a horizontal surface (or cap) at the crest.

Setback The legally required minimum distance that a building must be from a property line or, on bluff-front property, from the crest of a bluff where coastal construction is regulated.

Sheet Erosion Storm water flow that occurs in sheets and removes thin layers of soil or sediment from sloping land. Sheet erosion tends to be less severe than raindrop splash. The extent of erosion resulting from sheet flow is dependent on factors such as the amount of precipitation, the water content and infiltration capacity of the soil or sediment, the depth and velocity of runoff, and the geometry of the slope.

Shoreline The ordinary high water mark of Lake Erie of 573.4 feet as defined in accordance with the International Great Lakes Datum 1985 (IGLD 1985) as recognized by the United States Army Corps of Engineers (regulatory definition; PA DEP, 2013).

Soil The loose surface material capable of supporting plant growth, and having properties resulting from the integrated effect of climate and living matter on the decomposition of bedrock and surficial surface deposits.

Soil Creep The gradual and steady downhill movement of soil and loose debris on a slope as a thin layer.

Slide A general term for a mass movement resulting from failure of soil or rock along a rotational or planar surface.

Slope The inclination of the land surface from the horizontal. Percentage slope is the vertical distance divided by the horizontal distance and multiplied by 100.

Stable Slope Angle Typically, a stable slope for unconsolidated geologic materials such as found in bluffs, cliffs and sand dunes above which long-term slope instability increases significantly. As applied to coastal bluffs, the slope of a "stable bluff" varies by setting and region. Examples of the upper limit for a stable slope range from 11.25 degrees (20%, MI), to 14 degrees (25%; WI), to 15 degrees (27%; WA), to 18.5 degrees (33%; ON), to 35 degrees (70%; MD). The 33% slope criterion is recognized by the International Building Code as the upper limit of stability for most slopes in the absence of toe erosion. When toe erosion is absent, steep natural slopes can be expected to take timescales of decades to centuries to reach a stable slope angle if environmental conditions remain constant.

Stratigraphy The study of the geometry and composition of layers (strata) of sediments and rocks that have been sequentially deposited over time.

Structure A man-made object in Pennsylvania having an ascertainable stationary location on or in land whether or not affixed to the land; structures are classified into three categories - residential, commercial, and light and heavy industrial (regulatory definition; PA DEP, 2013).

- Residential structures are defined as a place providing habitation for an individual or group of individuals.
- Commercial structures are defined as a place where commodities are exchanged, bought or sold.
- Light and heavy industrial structures are defined as a place where materials are refined, produced or fabricated and stored prior to shipment to commercial establishments. Hospitals, nursing homes, schools and other public service facilities are considered light and heavy industrial structures.

Structure Lifespan The useful life of the structure considering both economic and physical factors (regulatory definition; PA DEP, 2013).

Surface Runoff Water from rain or other sources that flows over the surface of the ground and does not soak into the ground.

Transect An imaginary line, perpendicular to the bluff, established during a survey for the purposes of locating the bluff line and measuring the MBSD (regulatory definition; PA DEP, 2013).

Unconsolidated Sediment or other materials where particles are loose and uncemented.

Upland or Tableland A general term for elevated land that lies landward of the bluff crest and above the zone of direct wave impact.

Vegetation Planting vegetation works well when paired with other measures. For instance, vegetation on a newly re-graded bluff will aid with the retention of soil, remove excess water from within the bluff, and reduce surface water and wind erosion. Vegetation is also a key element to building and retaining a dune along sandy beaches.

Watercourse A channel or conveyance of surface water having a defined bed and banks whether natural or artificial, with either perennial or intermittent water flow (regulatory definition; PA DEP, 2013).

Watershed All of the land area that is drained by one waterway and all of its tributaries.

Chapter 12: Extended Bibliography (for publication dates through December 31, 2016)

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