Bluff Retreat Along the Pennsylvania Lake Erie Coast: A Guide to Bluff Retreat Science and Management

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Cover Photo

2009 Bluff Retreat Along the Eastern Pennsylvania Lake Erie Coast (Credit: David Skellie (retired), Pennsylvania Sea Grant

Executive Summary

The Pennsylvania Department of Environmental Protection's Coastal Resources Management Program currently provides technical assistance to Lake Erie coastal property owners through on-site assessments and data reviews, which rely on physical site assessments, aerial imagery reviews, web-based and geographic information system data reviews (i.e., soils, topography, and land use), and personal accounts from property owners and municipal officials. Recommendations for Lake Erie coastal property owners are provided for shoreline protection, surface and groundwater control, bluff stabilization, and vegetation best management practices. To enhance these existing services and information, the Pennsylvania Sea Grant College Program and The Pennsylvania State University at Erie, the Behrend College received Pennsylvania Growing Greener funding to develop a guide titled *Bluff Retreat Along the Pennsylvania Lake Erie Coast: A Guide to Bluff Retreat Science and Management*. The guide was developed as a resource for property owners, municipal officials, and natural resource managers living and working along the Pennsylvania Lake Erie coast, to offer an advanced understanding of coastal change processes, describe and evaluate factors driving bluff retreat, evaluate the status of bluff retreat along the Pennsylvania Lake Erie coast, and features a Bluff Erosion Potential (BEP) Index developed specifically for the Pennsylvania Lake Erie coast, and provides recommendations and priorities for bluff management.

The content of *Bluff Retreat Along the Pennsylvania Lake Erie Coast: A Guide to Bluff Retreat Science and Management* is organized as follows:

Chapter 1: Current Understanding of Coastal-Change Processes – provides an overview of the coastal processes affecting the Pennsylvania Lake Erie bluffs.

Chapter 2: Factors Driving Bluff Retreat - provides an overview of natural and anthropogenic factors driving bluff retreat, with a focus on stormwater and wastewater.

Chapter 3: Bluff Retreat along the Pennsylvania Lake Erie coast – provides an overview of the Pennsylvania Coastal Resources Management Program's control point monitoring program as well as the bluff retreat analysis conducted by Rafferty and Naber (2021) along the Pennsylvania Lake Erie coast using high resolution data and the Digital Shoreline Analysis System (DSAS).

Chapter 4: Bluff Erosion Potential Index – provides an overview of the Bluff Erosion Potential (BEP) Index developed for the Pennsylvania Lake Erie coast.

Chapter 5: Managing Bluff Retreat: Recommendations and Priorities - identifies data gaps, needs, and research questions related to bluff management, science, and engineering along Pennsylvania's Lake Erie coastline; and provides management and mitigation recommendations.

Chapter 6: References - provides a listing of the literature used in this report, as a coastal information resource that focuses on bluff-retreat science, engineering, and management.

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Chapter 1: Current Understanding of Coastal-Change Processes

The Pennsylvania Coastal Resources Management Program (PA CRM) identifies shoreline erosion and bluff retreat as the most significant problems associated with the Pennsylvania Lake Erie shoreline. Bluff retreat, as defined in Chapter 85 of the Pennsylvania Code, is the loss of material along the bluff face (***Figure 1.1***) caused by the direct or indirect action by one or a combination of groundwater seepage, water currents, wind generated water waves, or high-water levels. Areas along the bluff where the rate of progressive bluff retreat creates a substantial threat to the safety or stability of nearby existing or future structures or utility facilities are known as Bluff Recession Hazard Areas (BRHAs) (PA DEP, 2013). Nearly all the Pennsylvania Lake Erie shoreline is designated as a BRHA. 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 the Bluff Recession Setback Act (BRSA). Pennsylvania regulations state that to qualify as a bluff, a coastal landform must meet a minimum height (relief) criterion of five feet. The BRHA excludes bluff areas where the bluff toe is greater than 250-feet from the shoreline's Ordinary High-Water Mark (OHWM is 573.4-feet, IGLD, 1985) or from a more lakeward bluff crest (in a tiered bluff case).

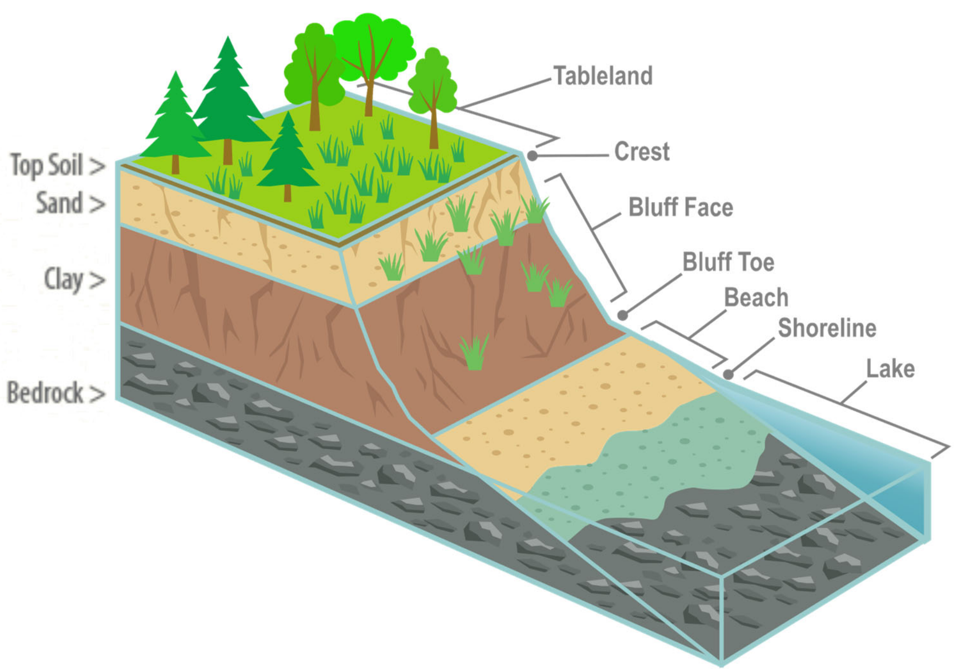


Figure 1.1. *Typical elements and geological layers of a bluff along the Pennsylvania Lake Erie Coast. The bedrock is shown at or just below lake level, which is typical for western Erie County, but it may extend up the bluff face as much as 23-feet in eastern Erie County. (modified from Cross et al., 2007)*

Pennsylvania possesses approximately 76.6 miles of Lake Erie bluff coast, stretching along nine coastal municipalities in Erie County, including Springfield Township, Girard Township, Lake City Borough, Fairview Township, Millcreek Township, the City of Erie, Lawrence Park Township, Harborcreek Township, and North East Township (***Figure 1.2***). The coast is characterized by unconsolidated bluffs and banks ranging in elevation from five to 180-feet above lake level (***Figure 1.3***). Depending on location, the unconsolidated bluff sediments may rest upon as much as 23-feet of Devonian bedrock that often forms a resistant bedrock toe (Foyle, 2018). 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.

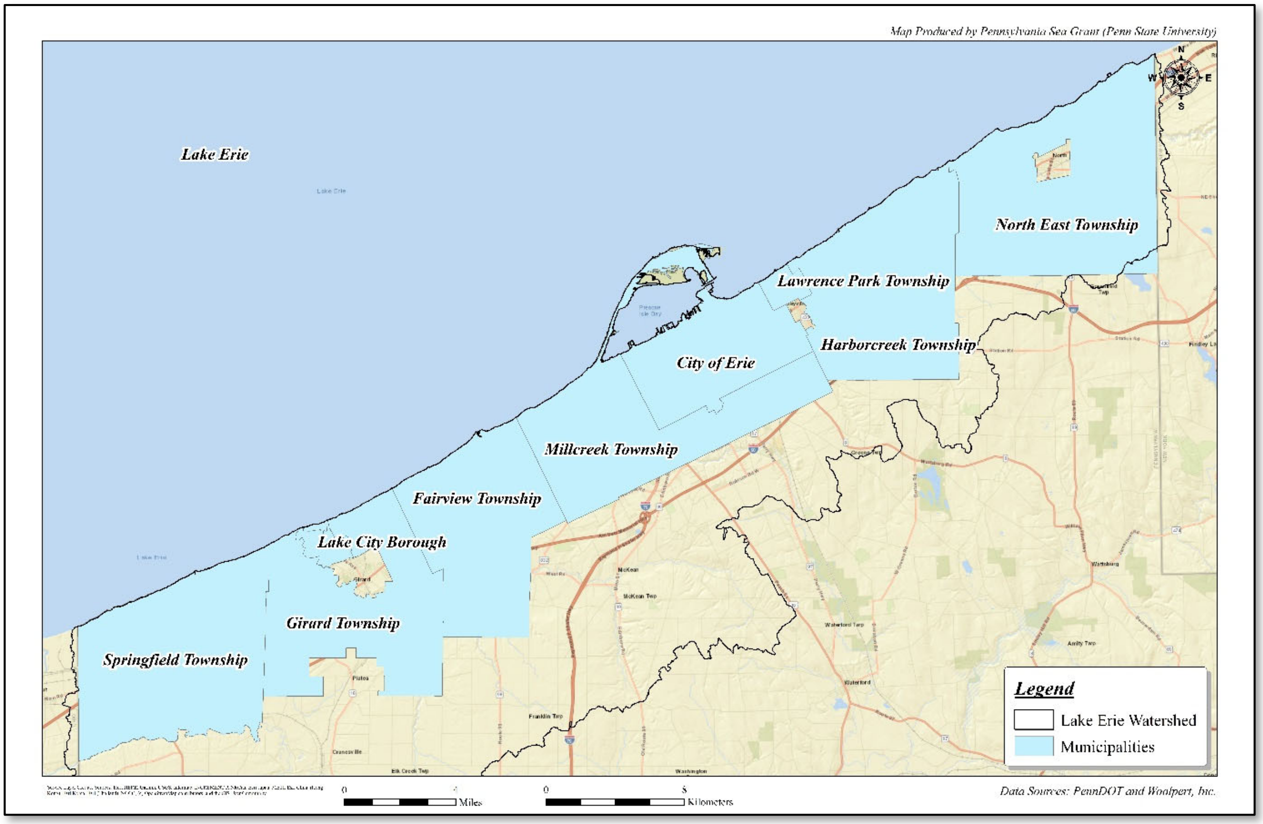


Figure 1.2. *Map of communities including Springfield Township, Girard Township, Lake City Borough, Fairview Township, Millcreek Township, City of Erie, Lawrence Park Township, Harborcreek Township, and North East Township along the Pennsylvania Lake Erie coast.*

Figure 1.3. *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. Images: from April 2015; available from PA CRM Program at http://www.dep.pa.gov).*

Physical losses associated with bluff retreat, including the loss of land at the top of the bluff face by mass wasting, threaten Pennsylvania's coastal economy. Economic losses associated with bluff retreat include loss of property, loss of tax base, loss of coastal agricultural land, loss of recreational opportunity, structural losses, and mitigation costs. While natural bluff processes are essential for the ecological health of Lake Erie, accelerated retreat associated with human activities pose a threat to the Lake Erie ecosystem (Foyle and Naber, 2012). The Erie County Department of Public Safety (ECDPS) 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.

The ECDPS (2012) analysis showed that 265 structures were at risk of significant damage or complete destruction from coastal erosion over the next century (***Figure 1.4***). The buildings were distributed among nine municipalities, with approximately 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 approximately $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 approximately $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 three miles of the Lake Erie coastline and would be susceptible to potential economic losses associated with bluff retreat. In 2007, viticulture contributed approximately $2.4 billion (directly and indirectly) to the state economy.

Figure 1.4. *Loss of property along the Pennsylvania Lake Erie coast due to bluff erosion. Photo on left was taken in 2007 and photo on right was taken in 2019. Note that part of the building became undermined, leading to removal of the building. (Credit: PA CRM)*

Bluff retreat is a normal and natural process common to bluff coasts worldwide. Coastal populations spend significant time and effort trying to combat the problem (Cross et al., 2007). And while a natural 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.

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

Hydrodynamic factors	Base-of-bluff factors	Bluff face and internal factors	Hinterland factors
Waver 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, and 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
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/meter of coast

The process of bluff retreat is notably distinct from beach erosion because the loss of sediment from a bluff is permanent while beaches may lose and regain sandy sediments over various time scales (hours to centuries). Sand lost from a beach to the littoral zone is likely to eventually return to the same beach or to downdrift beaches. 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 approximately 80% silt and clay, and 20% sand and gravel (Morang et al., 2011; Jones and Hanover, 2014; Foyle and Schuckman, 2021; Foyle et al., 2021). 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 deep-water 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 approximately one year for mud to settle through a 65-foot-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 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). ***Chapter 2*** provides an overview of natural and anthropogenic factors driving bluff retreat, with a focus on stormwater and wastewater.

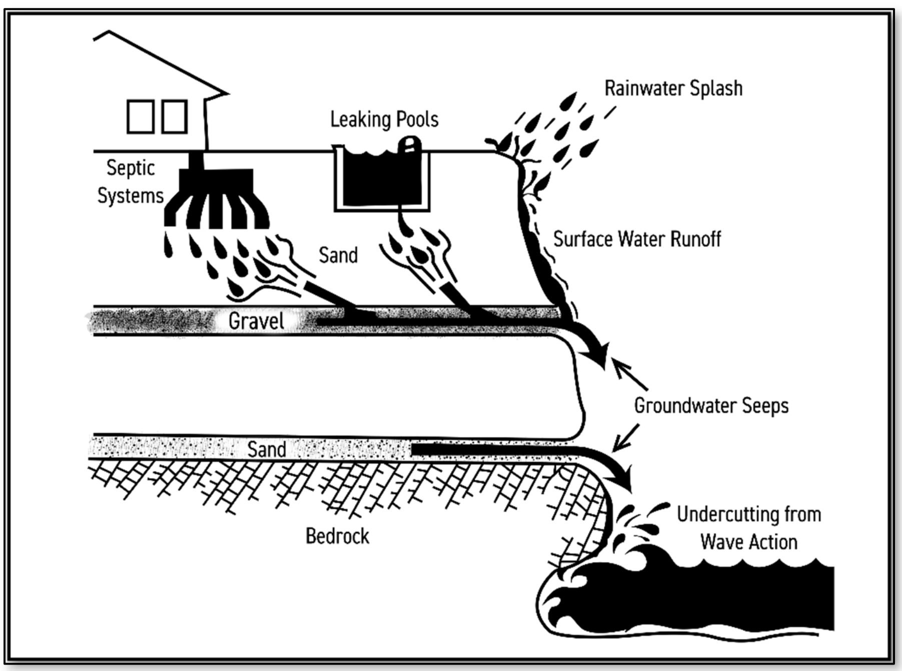


Figure 1.5. *Schematic illustration of several natural processes and anthropogenic factors that contribute to bluff instability on the Pennsylvania coast (modified from PA DEP, 2002).*

Chapter 2: Factors Contributing to Bluff Retreat

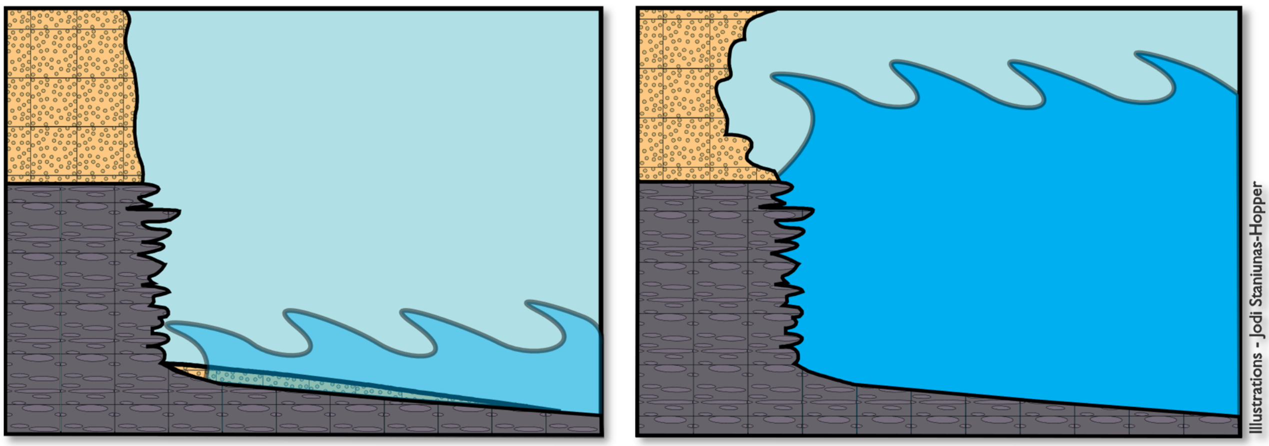
Bluff retreat occurs as bluff slope angles decrease to reach a stable slope angle. Bluff failure mechanisms and erosion processes occur at different frequencies and varying magnitudes of retreat (Swenson et al., 2006). Most of the bluffs along the Pennsylvania Lake Erie coast are too steep to survive over time without loss (Cross et al., 2007). The processes that result in the erosion of the bluff face are natural and have been occurring since the formation of Lake Erie, and particularly over the past 3,500 years of long-term lake-level rise (Pengelly et al., 1997; Herdendorf, 2013). These processes are essential to the overall ecological health of Lake Erie (PA DEP, 2013). Eroded materials from the bluff face nourish near-shore environments with sediments, nutrients, and organic matter. Fine grained sediments eroded from the bluff replace beach sediments that are lost to deeper water, while larger cobbles and boulders that find their way into the lake from the bluffs provide physical habitat for a multitude of aquatic organisms.

Even though bluff erosion and retreat result from natural processes, human activities in or near BRHAs have the potential to accelerate bluff retreat. Vegetation covering the bluff face and crest stabilizes the bluff soils with reinforcing root networks. Bluff slopes are continuously supplied with groundwater flows from the water table within the adjacent tableland. A single large tree can withdraw up to 200 gallons of water from the soil each day through evapotranspiration, helping to prevent saturation-induced bluff failure (PA DEP, 2013). Removal of the vegetation by landowners can accelerate bluff retreat by eliminating these mitigating effects. The conversion of inland forests to agriculture uses has resulted in greater quantities of groundwater flowing toward Lake Erie. Residential and industrial development increases impervious surface cover, reducing the amount of soil available for water absorption. Increased groundwater flow creates greater hydrostatic pressures on the bluff face as well as greater soil moisture content along the bluff crest and face. Both effects can increase shoreline erosion and bluff retreat rates along the Lake Erie coast.

Beaches protect the bluffs from erosion by absorbing wave energy before it reaches the toe of the bluff. Fluctuating lake levels can significantly impact the amount of waver energy affecting bluffs. Landowners seeking to protect lakefront beaches often construct groins to retain sediments along their frontage. Improperly designed or constructed groins can disrupt the littoral sediment transport system, redirecting sediment laden currents offshore and starving downdrift beaches of sand replenishment. Groins designed to prevent erosion in one area often have the effect of accelerating erosion in nearby areas. However, properly constructed shoreline protection structures can slow erosion rates while limiting disruption to littoral sediment transport systems. Below six factors driving bluff retreat are reviewed.

Wave Action

Wave action at the bluff toe removes eroded material that would otherwise act to stabilize the bluff (Swenson et al. 2006). This is especially true when storm surge and wave setup elevate water levels to the point where waves break at the bluff toe (Buonaiuto and Bokuniewicz, n.d.) (***Figure 2.1***). A familiar part of the beach may be a changed and unrecognizable area after a major storm (Cross et al., 2007). In addition, periods of higher lake levels can result in the bluff toe being exposed to increased wave action. Without wave action, sediments falling down the bluff could build up at the toe, creating a more gradually sloping bluff face that is more stable and less subject to retreat (Cross et al., 2007). Variability in both wave action at the bluff toe and the processes acting on the bluff face affect retreat rates. In contrast, waves can also deposit new material at the toe of the bluff. If more sand is being deposited than removed, a wide beach may develop. A wider beach decreases the frequency of wave contact at the toe of the bluff. The power of the waves will be exerted on the sloping beach sand instead of the bluff toe, and erosion



rates may decrease.

When lake levels are low, waves may expend energy against the resistant shale bedrock layer, and erosion occurs slowly (left). When lake levels are high, waves are more likely to impact softer, Quaternary age, sediment layers above the bedrock, and bluff face and crest erosion rates increase (right). (modified from Cross et al., 2007).

Lake Levels

Lake Erie water levels fluctuate constantly and determine the elevation range over which wave energy is expended on the bluff face. Daily changes (short-term), seasonal cycles, and long-term changes in the level of the lake all occur. The water level at any moment is the result of complex interactions between climate, wind, precipitation, bathymetry, and the levels of the upper lakes. Lake Erie water levels are primarily determined by the supply of water provided to the system. The total supply of water to Lake Erie includes precipitation over the lake, runoff from the surrounding basin and inflow from an upstream lake, minus evaporation from the surface of the lake.

Short-term water level fluctuations are primarily wind driven. These short-term fluctuations, usually last from a couple of hours to several days, can be very dramatic and are the result of storms or ice jams. Storm surge or wind setup occurs when high winds from one side of the lake pushes water levels up at one end of the lake and make the level drop by a corresponding amount at the opposite end. When the wind subsides abruptly the water level will often oscillate back and forth as a seiche until it stabilizes again. The Pennsylvania Lake Erie coast is not as susceptible to storm surges and seiches, due to its SW-NE orientation and prevailing westerly winds, when compared to areas near either end of the basin. Seasonal fluctuations range on average from 12 to 18-inches from winter lows to summer highs (***Figure 2.2***). The Great Lakes are generally at their lowest levels in the winter months. In the fall and early winter, when the air above the lakes is cold and dry and the lakes are relatively warm, evaporation is greatest. As the snow melts in the spring, runoff to the lakes increases. Evaporation from the lakes is least in the spring and early summer when the air above the lakes is warm and moist and the lakes are cold. At times, condensation on the lake surface replaces evaporation. With more water entering the lakes than leaving, the water level rises.

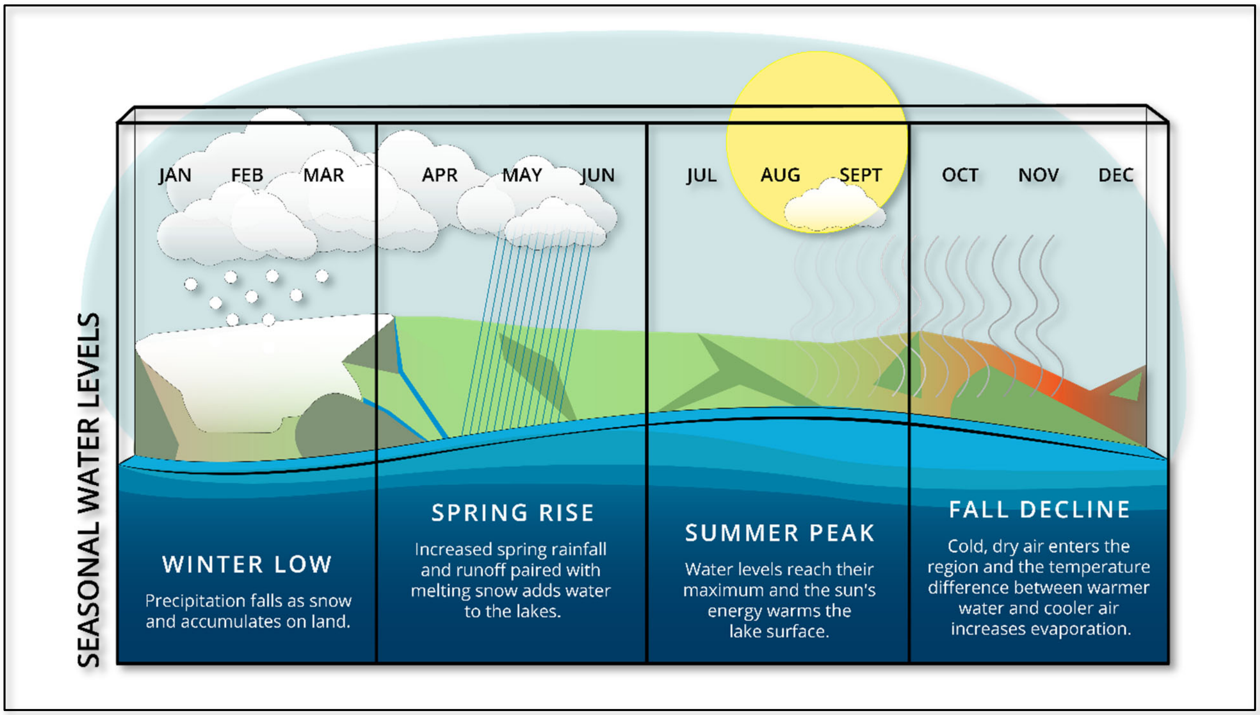


Figure 2.2. *Seasonal fluctuations of water levels from winter lows to summer highs. (Credit: NOAA).*

Long-term fluctuations occur over periods of consecutive years and have varied dramatically since water levels have been recorded for the Great Lakes (1918-present). Continuous wet and cold years will cause water levels to rise. Conversely, consecutive warm and dry years will cause water levels to decline. Over the last decade, the Great Lakes have seen dramatic changes in water level - from an extended period of low water ending in 2013 to a dramatic rise in water levels resulting in the current record highs. Since April 2015, Lake Erie water levels have remained above the 1918-2020 long-term average (571.42 feet).

The amount of wave energy that reaches the bluff toe has a significant impact on the long-term bluff retreat rate (Krueger et al., 2020). During periods of low lake level, wide beaches at the base of the bluff protect the bluff toe from waves and storm surge. During high lake levels, waves inundate and erode the beach, reducing the run-up length, thereby exposing the bluff to higher wave energy because less wave energy is dissipated on the beach (Krueger et al., 2020). The inundation of beaches as lake level rises allows large waves to erode bluffs more effectively but also allows small waves to retain enough energy to cause erosion.

Groundwater

Groundwater is water filling the voids, pores, fractures and holes in the soil and rock below the ground surface (ODNR, 2010). Groundwater includes all of the water that seeps into the ground from rain, snow melt, and human-made sources such as irrigation systems, septic systems, downspouts and leaking sewer or water pipes. Water tends to be drawn downward through the soil by gravity until it meets a layer of the sediment that is impervious. It then flows along that interface (Cross et al., 2007). In the Lake Erie watershed, the upper layer is usually a sandy permeable layer, through which water flows freely. Beneath that is a clay layer that water does not easily penetrate; therefore, water flows along the top of this layer, usually out to the bluff face (***Figure 2.3***). This is a simplified picture because the clay layer has many irregular areas of a sandier sediment within it, and since these sandy areas may carry water, the course of the water flow is not easily predictable. Whatever path it takes, groundwater emerges on the face of the bluff, sometimes as a seep and sometimes as a gushing rivulet or rill. At that point, the running water washes the sediments down the bluff face, eventually undercutting the weak, sandy layer above. Over time, that sandy layer will also collapse down the bluff.

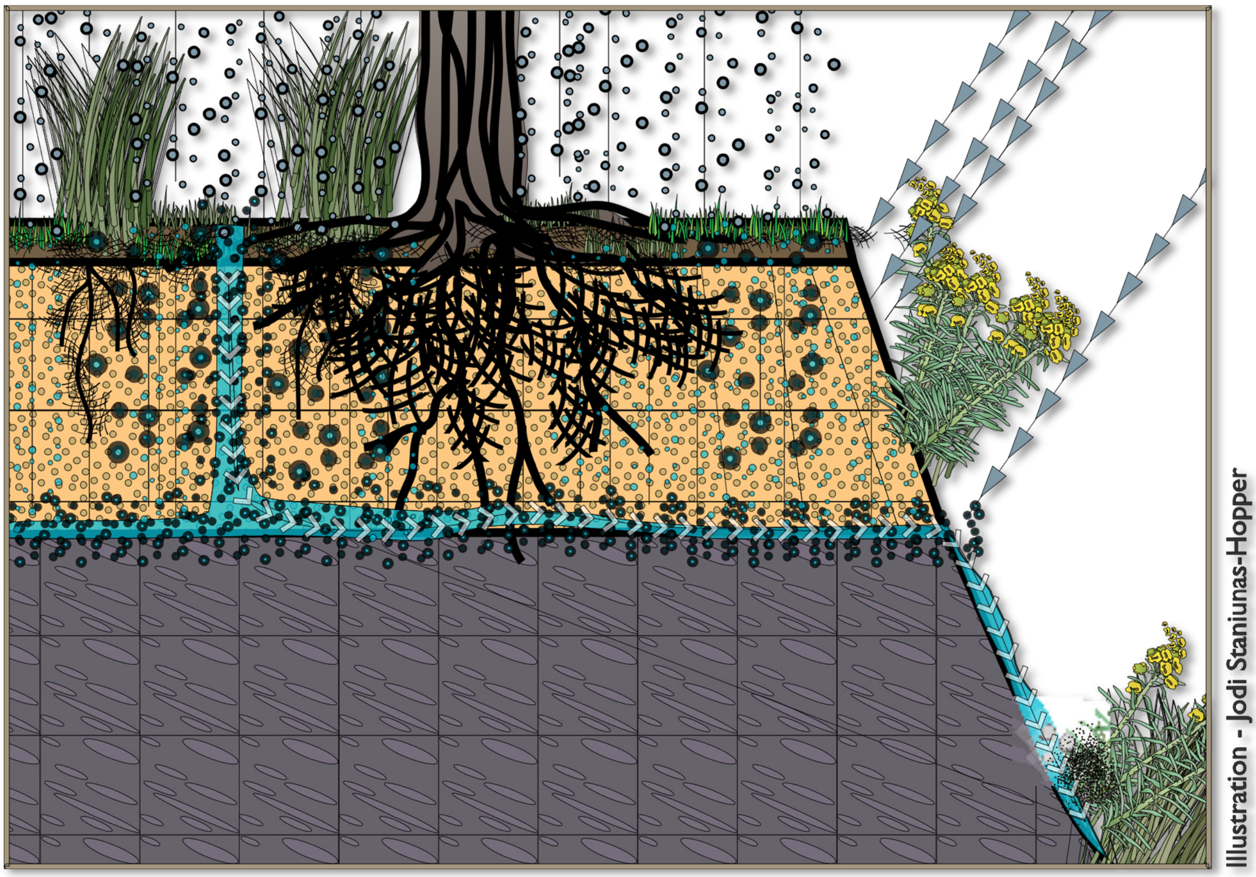


Figure 2.3. *Groundwater, filtering down through the sandy layer, pools on the upper surface of this impermeable layer. It then runs along the layer in a downhill direction, usually toward the bluff where it emerges as a spring or seep. (modified from Cross et al., 2007).*

The extent to which groundwater contributes to bluff retreat is a complicated and site-specific determination. Groundwater flow is a natural occurrence and can be a beneficial source of moisture for the vegetation on the bluff face. Too much groundwater, however, can be an important cause of bluff retreat. ODNR (2010) identifies four causes of groundwater-related bluff erosion.

1) When the water reaches the water table or the less permeable layer, it moves horizontally through the soil or rock toward the bluff face. The water will seep out of the bluff face, eroding the bluff material as it exits.

2) The flow of groundwater can act as a lubricant, reducing the friction between the soil particles or layers of soils. The resulting slippery condition can cause sliding or slumping of a portion of the bluff.
3) As flowing groundwater moistens normally dry clay soils, the soil is weakened. For example, a block of dry clay is harder than wet clay, which is often slippery and easy to mold in one's hand. The wetted soil may not be able to withstand the weight of the overlying soil and slumping may occur.
4) As soils absorb ground water, they become heavier. Increased weight of a soil due to ground water can exceed the weight that the soil can support. This can lead to slumping of the bluff (***Figure 2.4***).

Signs of groundwater erosion include seeps or flowing water emerging from the bluff face; vegetation common to wet soil growing on the bluff face; sudden loss of land after periods of long or heavy rains; flows of mud down the bluff face; ridges of soil on the bluff face or near the bluff edge from previous slumping; trees with curved trunks and upper portions of trunks leaning upslope; and leaning or moved posts, poles, fencing, and other small structures (ODNR, 2010).

Figure 2.4. *Slumping along the Lake Erie bluff in Lake Erie Community Park in Lake City Borough, Pennsylvania (Credit: J. Michael Campbell, Ph.D., Mercyhurst University).*

Surface Water

Surface water is any water that is on land including ponds, lakes, rivers, and standing water after rainfall (ODNR, 2010). Sources of surface water on a landscape include rain, snow melt and stormwater. Surface water runoff occurs any time the ground does not absorb all the precipitation, which then runs over the surface. Flows are an erosive force, causing sediment to be dislodged and carried to the base of the bluff. Over time, flows across an unprotected bluff may produce deep gullies (***Figure 2.5***). Even during gentle summer rains, poorly vegetated bluff sediments may be washed downward into the lake by surface runoff. Runoff from roof tops, paved areas, downspouts, and saturated lawns can also flow down over the crest of the bluff from the tableland. The greater the percentage of paved or impervious areas on the tableland near the bluff, the greater the potential for stormwater runoff and problems.

During short, heavy rainfall events where there is little time for infiltration, water may pond on top of the bluff near the bluff edge, adding extra weight to the land (ODNR, 2010). If this water remains for a long time, the bluff may not be able to withstand the added weight and slumping near the bluff edge may occur. Alternatively, this water may infiltrate the bluff materials and cause the water table to rise, leading to bluff instability due to increased pore-water pressures (Foyle et al., 2021). Light rainfall events that last a long time can allow for more water to infiltrate the ground and may result in groundwater erosion. Over a long period of time, infiltration from prolonged and numerous rain events can increase the weight of the bluff, lubricate the soil layers and/or reduce the strength of soils, resulting in slumping of the bluff materials (ODNR, 2010).

The best way to limit the impact of stormwater on bluffs is to maintain natural drainage to the extent possible by avoiding constructing stormwater detention ponds near bluffs; directing downspouts away from the bluff to the front of lots; and avoiding pipes that direct stormwater down the face of bluffs as they are prone to failure due to the instability of the bluffs.

Figure 2.5. *Gullies along the Pennsylvania Lake Erie bluff face formed due to surface water flow over the bluff crest (Credit: Anthony M. Foyle, Ph.D., Penn State Behrend).*

Freeze/Thaw Cycles

Bluff erosion often follows a seasonal cycle, with higher erosion rates recorded during the early winter and spring months (ODNR, 2010). In late fall to early winter, storms are generally more severe leading to higher volumes of surface and ground water. The excess water alone can be a serious issue; however, Pennsylvania's cold winters can lead to freezing of water on and within the bluff.

Surface water that freezes on the bluff face traps ground water beneath, resulting in a greater volume of water captured in the upper portions of the bluff (***Figure 2.6***). This trapped water within the bluff adds weight, which can increase the chance of erosion. If water within the bluff also freezes, the added weight and stress increases the likelihood of erosion. Erosion can also be caused by water freezing within cracks or openings within bluffs. During winter, ground water seeping from a bluff face can freeze and expand. The freezing of the ground water weakens the bluff face and increases the likelihood of bluff erosion during spring thaws.

Figure 2.6. Surface water that freezes along the Pennsylvania Lake Erie bluff face does not allow ground water to escape from the bluff, leading to increased pore-water pressures and subsequent bluff failure during spring thaws. *(Credit: Shelby Clark, PA CRM).*

When spring arrives, snow melt, thawing ice within and on the bluff, and rainstorms all contribute to continued erosion. The amount of ground and surface water erosion that occurs in the spring depends in part on the winter weather. For example, lack of precipitation during the winter may result in lower spring ground water levels. However, if ground water is frozen within the bluff throughout the duration of winter months, slumping will often occur during the spring thaw.

Wastewater

Features of coastal development, including siting of septic systems, are likely to increase the instability of coastal bluffs (Lulloff and Keillor, 2015). On-lot septic systems that discharge wastewater to groundwater add to the risk of bluff slumping or failure ***(Figure 2.7***). Homes built near, or setback from, coastal bluffs are not safe locations for on-site septic systems as the added weight increases the loads and stresses on nearby slopes. Additionally, the liquids that infiltrate into underlying soils reduce the friction between soil particles, making the soil less stable, can migrate to adjacent slopes, and seep from the bluff face onto the beach and into the lake (Lulloff and Keillor, 2015). This partially treated sewage not only reduces the stability of slopes which contributes to slope failure, but it also contains fecal matter that constitutes a health hazard to beach users and adds pollutants to the lake.

Wastewater management practices near bluffs should include limitations on discharge to groundwater within the unstable area portion of the bluff top. On-site waste disposal systems, including mound systems, should be placed landward of the coastal buildings they serve so that the effluent from these systems does not contribute to bluff landslides (Lulloff and Keillor, 2015).

Figure 2.7. *Septic system lost during a bluff retreat event along the Lake Michigan coast. Image on left was taken January 1, 2006 and image on right was taken March 20, 2006 following the slumping event (Credit: Barry Sullivan, Ozaukee County; https://greatlakesresilience.org/case-studies/land-use-zoning/minimizing-bluff-top-development-risk).*

Chapter 3: Bluff Retreat along the Pennsylvania Lake Erie Coast

The Pennsylvania Coastal Resources Management Program (PA CRM) and municipalities along the Lake Erie shoreline currently rely on periodic physical monitoring of approximately 130 established control-point sites in the field to determine the position of the coastal bluff crest and any changes in crest position over time due to erosion (Foyle, 2018). 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 PA CRM. 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. While a valuable resource, and an excellent ground-check on more recent digital methods of mapping coastal change, the control-point methodology is a labor-intensive, weather-dependent method of bluff-crest mapping. It does not provide sufficient spatial resolution on bluff recession due to a typical transect spacing of 500-meters (1,640 feet) that is not closely scaled to the dimensions of stable-bluff and bluff-failure zones (10 - 100 meters; 33 – 328 feet). This will increasingly limit its utility as a means of providing the quality of coastal-erosion data that are necessary for any future revisions to, and active management of BRHA.

Geospatial analysis of historical and present bluff geometry using state-of-the-art remotely sensed data (lidar; orthoimagery) and ground-truthing within a Geographic Information System (GIS) framework can provide the scientific basis for sustainable coastal development recommendations for Pennsylvania municipalities and individual properties along Lake Erie. Rafferty and Naber (2021) explored whether bluff crest change over time could be calculated using remote sensing techniques and the Digital Shoreline Analysis System (DSAS), an ArcGIS extension available from the United States Geological Survey (USGS). Bluff crest rates of change were calculated by comparing bluff-crest lines delineated from lidar collected in 2007, 2012, and 2015. Orthoimagery collected in 2012 and 2015 were also used in the bluff crest delineation. Change analysis using DSAS has been adopted nationally to quantify the occurrence and severity of coastal erosion and upland loss in regions as geographically and geologically diverse as California, Georgia, Hawaii, Pennsylvania, Washington, and Wisconsin (Foyle, 2018).

PA CRM Control Point Monitoring

The Bluff Recession Setback Act (BRSA) of 1980 allows regulation in the vicinity of the coastal bluff top through the establishment of Bluff Recession Hazard Areas (BRHAs). The aim is to balance the ecological benefits of natural bluff retreat with the risks posed by development. The intent is 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.

To manage the retreating bluffs along Pennsylvania's Lake Erie coast, the PA CRM and the nine 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 1975. From each of these control points, distances to the bluff edge are measured approximately every four-years along a specified compass bearing unique to each site. The control points are now spaced at 500-meter (1,640 feet) 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.

From 1975-2019, at varying time intervals, PA CRM monitored bluff recession at 129 control points along the Pennsylvania Lake Erie coast. The mean rate of bluff change along the Pennsylvania Lake Erie coast during these varying time intervals was 0.51 feet/year (***Table 3.1; Figure 3.1***). Springfield Township had the highest mean rate of bluff change at 0.89 feet/year. Millcreek Township had the lowest mean rate of bluff change at 0.22 feet/year. 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 (66 feet) of localized land loss occurring over a short time period (several-weeks).

Table 3.1. *Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (1975 to 2019) by municipality determined through the PA CRM control point monitoring program (Rafferty and Naber, 2021).*

Municipality	Number of Transects	Mean Rate of Change (ft/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	25	0.89	0.63	(0.65, 1.14)
Girard Township	17	0.71	0.43	(0.50, 0.91)
Lake City Borough	-	-	-	-
Fairview Township	16	0.44	0.36	(0.26, 0.61)
Millcreek Township	15	0.22	0.32	(0.06, 0.39)
City of Erie	3	0.42	0.32	(0.05, 0.79)
Lawrence Park Township	4	0.35	0.14	(0.21, 0.48)
Harborcreek Township	22	0.35	0.39	(0.19, 0.51)
North East Township	27	0.41	0.48	(0.23, 0.59)
All	129	0.51	0.51	(0.42, 0.60)

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 meter (1,640 feet) spacing is also not closely scaled to the sizes of urban property parcels (25 – 100 meters; 82 – 328 feet) on the Pennsylvania coast. Nor is it scaled to the dimensions of stable-bluff zones, common types of active slumps (5 – 100 meters wide; 16-328 feet), and inactive historical slumps (pre-

1880 era; 250 – 3,000 meters wide; 820 – 9,843 feet). 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. Continuation of the method in Pennsylvania, however, is advantageous because it permits regular interactions between PA CRM 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).

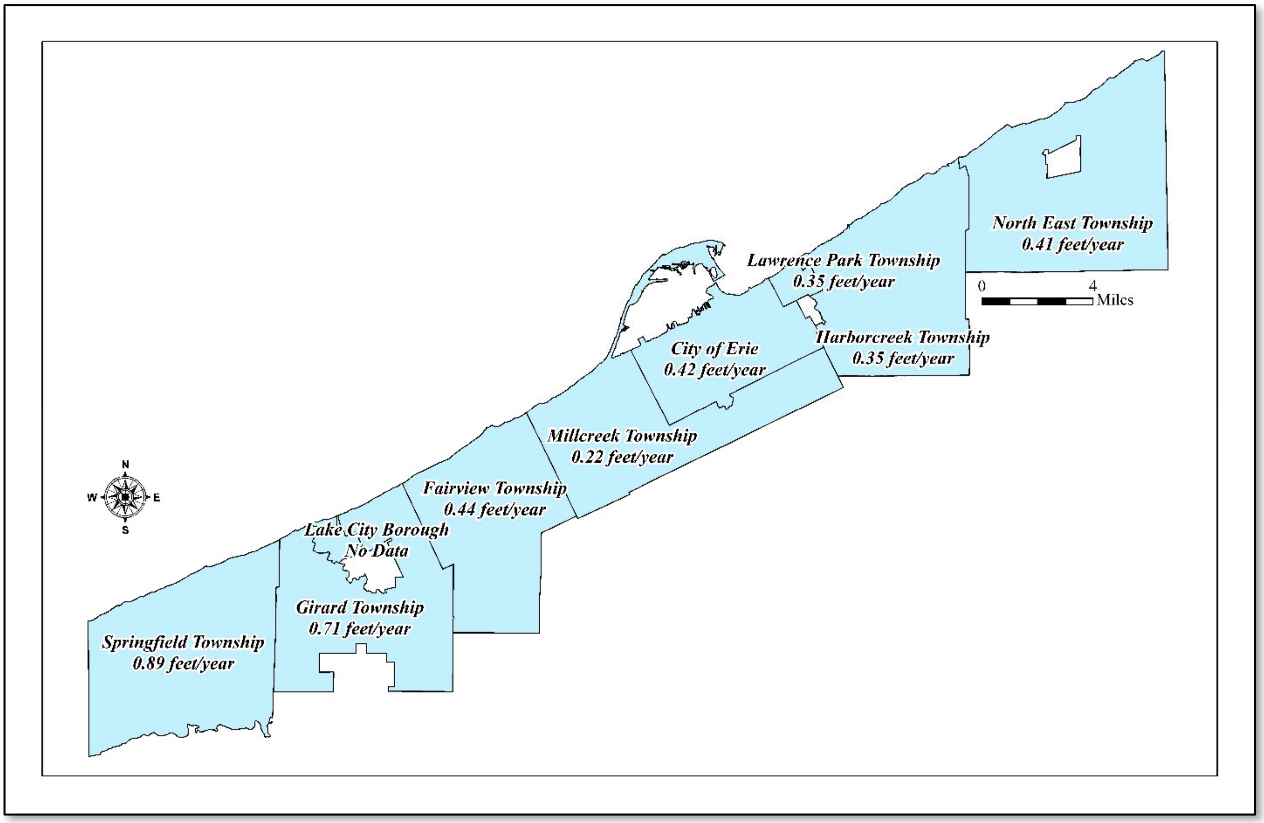


Figure 3.1. *Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (1975 to 2019) by municipality calculated by PA CRM through the control point monitoring program.*

Assessing Bluff Retreat using the Digital Shoreline Analysis System (DSAS)

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, is 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.

Rafferty and Naber (2021) assessed bluff crest change along the Pennsylvania Lake Erie coast over time using remote sensing techniques and Digital Shoreline Analysis System (DSAS). Woolpert, Inc. delineated Pennsylvania Lake Ere bluff crestlines for 2007, 2012, and 2015 using a multi-step feature extraction method, including: ground filtering, digital terrain model (DTM) preparation, hillshading, slope calculation, feature extraction, and quality control and quality assurance (QC/QA) and manual edits. GPS Real Time Kinematic waypoints were used to ground truth the crestlines at different points, which were captured on various public lands that intersected or were located on or near the crestlines. DSAS was used to calculate the rate of bluff crest change from 2007 to 2015 (short-term) and 2012 to 2015 (very-short-term) (see Rafferty and Naber, 2021 for detailed methodology). DSAS v5.0 is a freely available ESRI® ArcGIS desktop add-in developed by USGS to calculate rate-of-change statistics from multiple crestline positions (Himmelstoss et al., 2018). DSAS allows for an automated method for establishing measurement locations and performing change calculations.

The rate of bluff-crest change was assessed at 2,232 transects along the Pennsylvania Lake Erie coast between 2007 and 2015 and was 0.71 feet/year (***Table 3.2; Figure 3.2***). Northeast Township had the highest mean rate of bluff change fat 0.87 feet/year. Lake City Borough had the lowest mean rate of bluff change at 0.50 feet/year. The rate of bluff-crest change was also assessed at 1,753 transects between 2012 and 2015. The mean rate of bluff change was 1.01 feet/year (***Table 3.3; Figure 3.3***). Northeast Township had the highest mean rate of bluff change at 1.50 feet/year. Lake City Borough had the lowest mean rate of bluff change at 0.50 feet/year. The mean rate of bluff-crest change from 2012 to 2015 was higher than the mean rate of change from 2007 to 2015 and from PA CRM observations between 1975 and 2019 (***Table 3.4***).

Table 3.2. *Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2007 to 2015) by municipality (Rafferty and Naber, 2021)*

Municipality	Number of Transects	Mean Rate of Change (ft/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	427	0.55	0.37	(0.51, 0.58)
Girard Township	231	0.71	0.46	(0.65, 0.77)
Lake City Borough	6	0.50	0.36	(0.20, 0.78)
Fairview Township	267	0.70	0.66	(0.62, 0.78)
Millcreek Township	170	0.54	0.55	(0.46, 0.63)
City of Erie	235	0.75	0.58	(0.68, 0.82)
Lawrence Park Township	59	0.69	0.63	(0.53, 0.85)
Harborcreek Township	446	0.75	0.62	(0.70, 0.81)
North East Township	391	0.87	0.91	(0.78, 0.96)
All Municipalities	2,232	0.70	0.64	(0.68, 0.73)

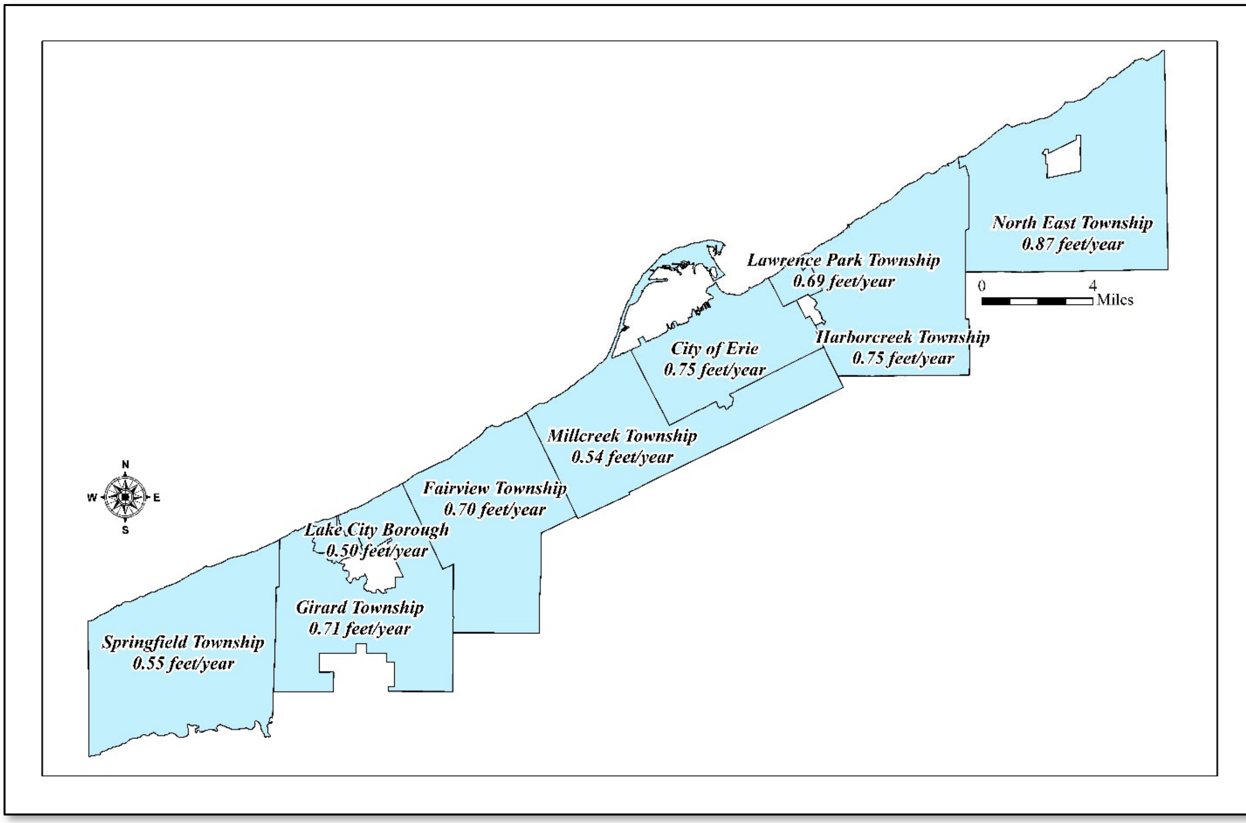


Figure 3.2. *Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2007 to 2015) by municipality (Rafferty and Naber, 2021).*

Table 3.3. *Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2012 to 2015) by municipality (Rafferty and Naber, 2021).*

Municipality	Number of Transects	Mean Rate of Change (ft/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	354	0.77	0.72	(0.70, 0.85)
Girard Township	140	0.86	0.79	(0.73, 0.99)
Lake City Borough	6	0.50	0.18	(0.36, 0.65)
Fairview Township	200	0.79	0.90	(0.66, 0.91)
Millcreek Township	148	0.71	0.68	(0.60, 0.82)
City of Erie	194	0.94	0.86	(0.82, 1.06)
Lawrence Park Township	44	1.39	1.59	(0.93, 1.86)
Harborcreek Township	345	1.13	1.01	(1.03, 1.24)
North East Township	322	1.48	1.35	(1.33, 1.62)
All Municipalities	1,753	1.01	1.02	(0.96, 1.06)

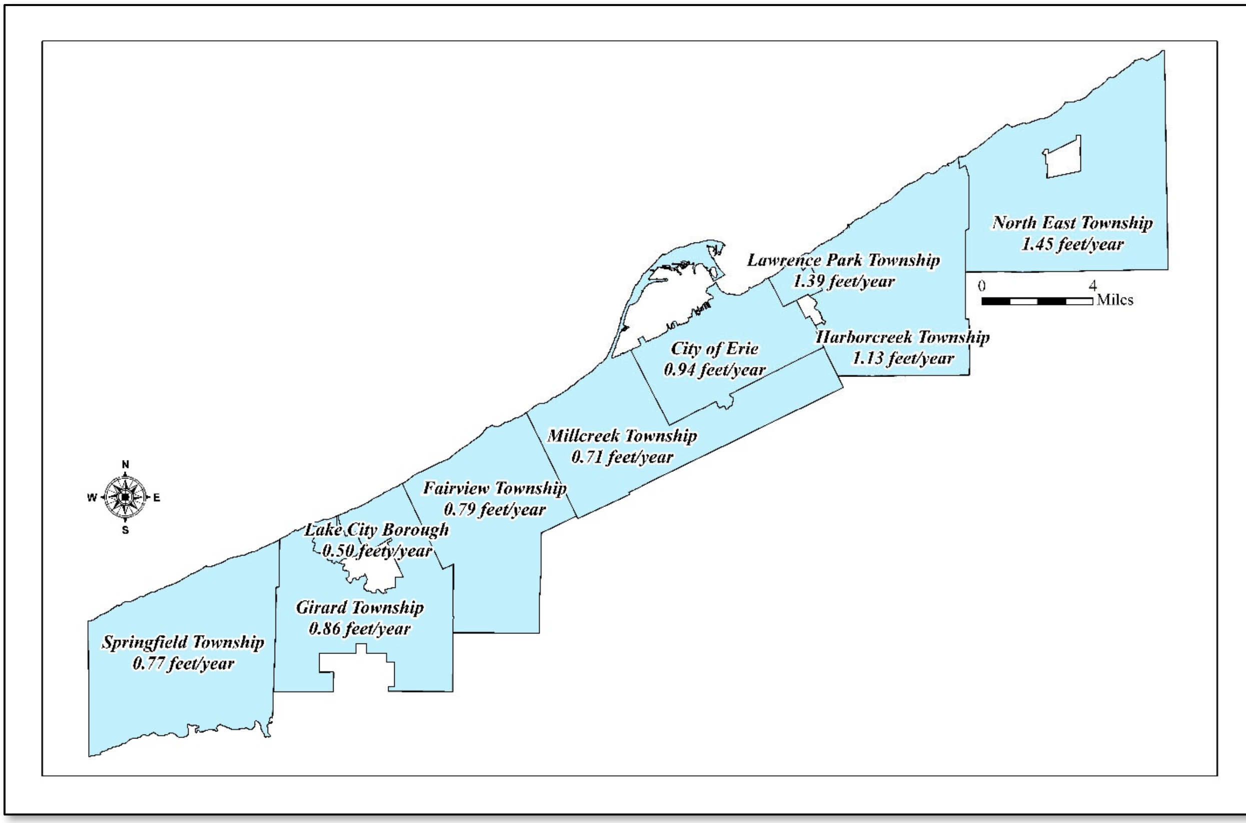


Figure 3.3. *Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2012 to 2015) by municipality.*

Table 3.4. *Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2007-2015; 2012-2015; and 1975-2019) by municipality (Rafferty and Naber, 2021).*

Municipality	Mean Rate of Change (ft/yr) (1975-2019)	Mean Rate of Change (ft/yr) (2007-2015)	Mean Rate of Change (ft/yr) (2012-2015)
Springfield Township	0.89	0.55	0.77
Girard Township	0.71	0.71	0.86
Lake City Borough	-	0.50	0.50
Fairview Township	0.44	0.70	0.79
Millcreek Township	0.22	0.54	0.71
City of Erie	0.42	0.75	0.94
Lawrence Park Township	0.35	0.69	1.39
Harborcreek Township	0.35	0.75	1.13
North East Township	0.41	0.87	1.48
All Municipalities	0.51	0.71	1.01

The eight-year timeframe (2007-15), with more transects, likely gives a better picture of bluff movement over time along the Pennsylvania Lake Erie coast than the three-year timeframe (2012-15) with fewer transects. While a valuable resource, and an excellent ground-check on more recent digital methods of mapping coastal change, the PA CRM control-point methodology is a labor-intensive, weather-dependent method of bluff-crest mapping, and it does not provide sufficient spatial resolution on bluff retreat due to a typical transect spacing of 500 meters (1,640 feet) that is not closely scaled to the dimensions of stable-bluff and bluff-failure zones. Rafferty and Naber (2021) sought to evaluate the feasibility of using remote sensing techniques and DSAS to assess the bluff retreat over time at a tighter spatial resolution (20 meters; 66 feet). Using remote sensing data techniques and DSAS provided a viable method for assessing bluff movement over time and will improve over time with improved lidar resolution and longer time scales to assess. The strength of PA CRM data is the longer time scales in which bluff movement is assessed. The lack of spatial scale (129 control points versus 2,232 transects) of PA CRM data, however, may result in over/underestimating the true bluff retreat rate along the Pennsylvania Lake Erie coast.

Chapter 4: A Bluff Erosion Potential (BEP) Index for the Pennsylvania Lake Erie Coast

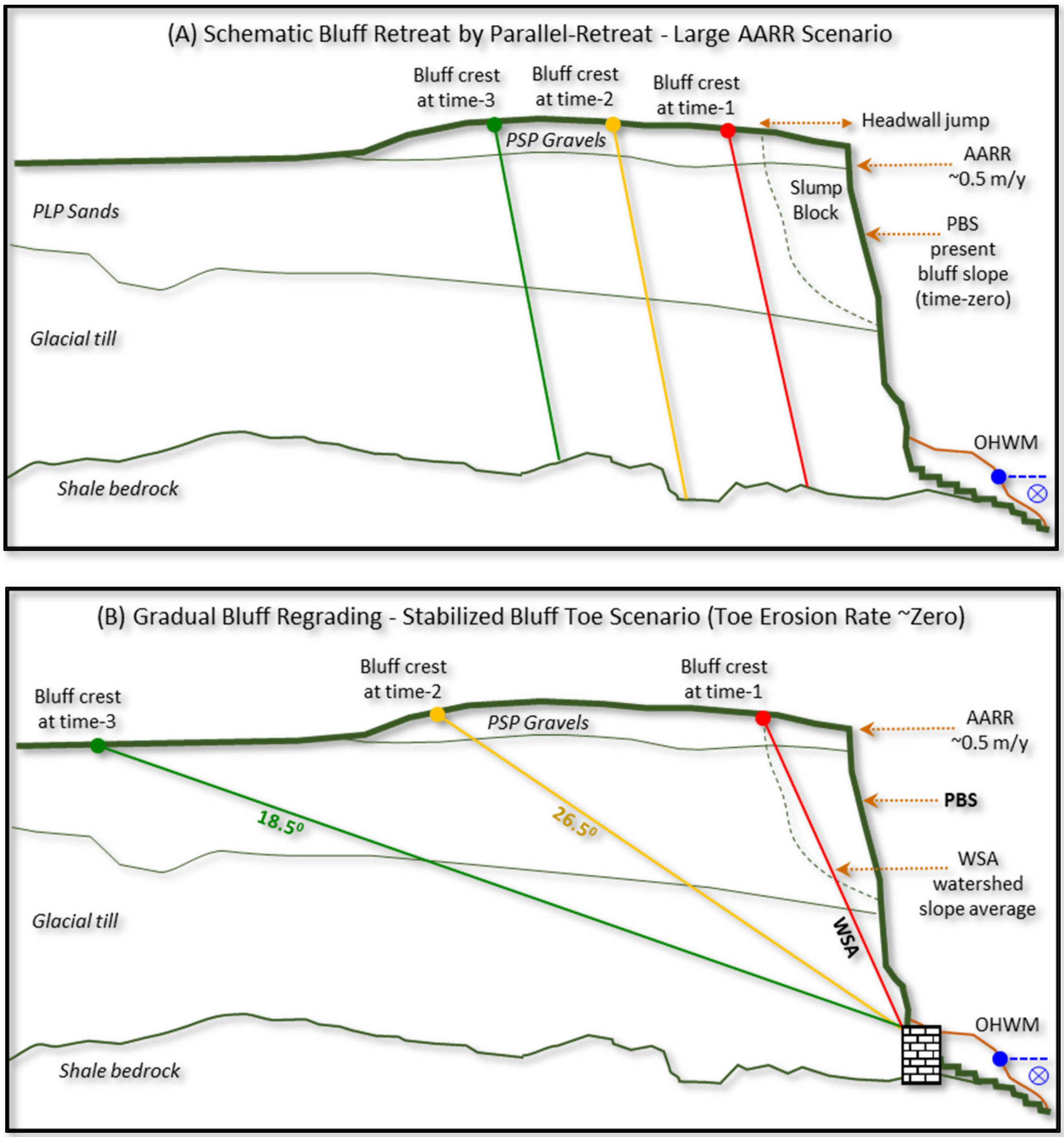
The Bluff Erosion Potential (BEP) Index graphically illustrates the potential for future land losses due to erosion in the vicinity of bluffs along the Pennsylvania coast of Lake Erie. The BEP Index provides a geometric estimate of the probable future locations of the bluff crest as the bluff face, toe, and crest retreat landward over extended time periods that approximate the lifetimes of residential and commercial structures. The estimated future position of the bluff crest is a useful proxy for estimating the relative erosion risk of tableland areas located adjacent to the bluff crest during future decades. Foyle (2019) details the methodologies used to create The BEP Index. ***Chapter 4*** provides a general overview of bluff erosion potential and the BEP Index.

Geometry of Bluff Retreat

Certain areas, specifically those nearer the present bluff crest, will have a higher erosion potential (and therefore a higher risk of property losses) than those located farther landward. Similarly, the erosion potential of areas adjacent to high bluffs (e.g., paleo-strandplain sectors of the Erie County coast near North East Township and Lake City Borough, Pennsylvania; Foyle, 2018), or at bluffs that do not have a well-developed bedrock toe (much of western Erie County, Pennsylvania), will be greater than for low bluffs or for bluffs that have a high bedrock toe. The basic premise that a spatial link exists between erosion potential (or risk of property loss) and bluff proximity is fundamental to erosion hazard management on bluff coasts globally.

Bluff retreat in the landward direction is driven by a combination of wave (hydrodynamic), subsurface (groundwater), and surface weathering/erosion (subaerial) processes that vary in relative importance along the coast (spatially) and over years and decades (temporally). The BEP Index provides an estimate of where the bluff crest may conservatively be located over one to two residential-building lifetimes. These timeframes are conservative estimates for several reasons. For example, average annual retreat rates (AARRs) for bluffs, and the slow process of grade adjustment (toward an equilibrium or stable slope), vary over time and with location due to variations in bluff properties in three dimensions, and to variations in the severity of erosion processes that also vary spatially and temporally. However, the inclusion of long-term AARRs ($AARR_{77}$; 1938-2015) that use historical crest-position data (provided by the US Army Corps of Engineers; Cross et al., 2016) and high-resolution 2015 lidar data mitigate some of the temporal uncertainty. While uncertainty in the crest position on the older data set is on the order of 50-feet (0.65 feet/year annualized), it is comparatively small and similar to the annualized uncertainties in the newer data. Furthermore, because increasing volumes of material have to be removed from the landscape for each incremental decrease in bluff slope and landward jumps of the bluff crest (due to slumping), change rates associated with the regrading process likely decrease over time, other factors being equal. Lastly, suitable data on slope-evolution rates in the Great Lakes Basin are not available, which adds further uncertainty in the timeframe estimates used in the BEP Index.

The timeframes over which bluffs evolve and influence the erosion potential of the adjacent tableland reflect the time required for the bluff face to translate landward due to hydrodynamic, subsurface, and subaerial erosion processes. Subsurface and subaerial processes are particularly important where the bluff toe is hindered from moving landward due to coastal structures that protect it from hydrodynamic forces. The premise of the BEP Index is that steep bluff slopes erode more quickly than gentle slopes and attempt to regrade naturally to a more stable condition. The consequence of these processes is a bluff profile that retreats (relatively rapidly; ***Figure 4.1A***) and concurrently regrades (relatively slowly; ***Figure 4.1B***) over time to result in a progressively lower-sloped bluff face and a bluff crest located at a progressively more landward location (***Figure 4.1C***). The parallel bluff-face retreat and planar bluff slopes shown schematically in ***Figure 4.1*** are mathematical simplifications: parallel bluff-face retreat is a rare phenomenon, being most likely to occur on homogeneous bluffs over longer timeframes (e.g., Amin, 2001; Zuzek et al., 2003). Bluffs with multi-layered stratigraphy, such as on the Pennsylvania Lake Erie coast, are more likely to retreat through a "repetitive failure cycle" (Zuzek et al., 2003) where periods of relative bluff-crest stability and instability alternate (***Figure 4.2***).



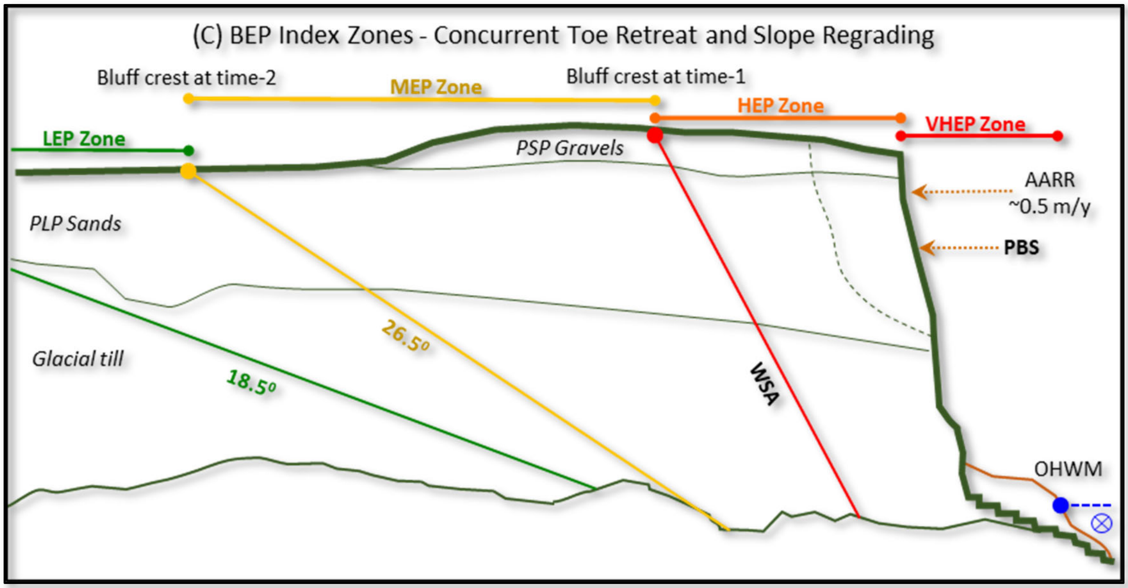


Figure 4.1. *Schematic cross-section showing erosional retreat (A) and regrading (B) components of bluff evolution. These are used in the BEP Index to conservatively demarcate erosion-potential zones (C) along the bluff coastline. Erosion potential decreases progressively in the landward direction, moving from the active-hazard VHEP zone at the bluff face towards the LEP zone inland. Lake Erie is to the right and a simplified schematic stratigraphy (from Foyle, 2018) is shown. AARR = average annual retreat rate; OHWM = ordinary high-water mark; PBS = present bluff slope; PSP = paleo-strandplain; PLP = paleo-lacustrine plain; WSA = watershed slope average; VHEP = very high erosion potential, HEP = high erosion potential, MEP = moderate erosion potential, LEP = low erosion potential; brick pattern denotes a coastal structure (seawall, revetment, etc.).*

In areas where the AARR is lower (e.g., due to toe stabilization, the presence of a wide beach, limited groundwater flux, or a short time having passed since a prior slump), the timeframes involved in bluff evolution to a more stable slope will increase. This is because slope regrading will be the primary cause of crest retreat over time. Regrading is a comparatively slow process, potentially orders of magnitude slower than retreat due to wave-driven erosion. This means that erosion-potential zones on the BEP Index maps are generally narrower for low-AARR areas compared to locations where the AARR is large. In the latter locations, the role of slope regrading may be relatively small, bluffs may be steeper, and erosion-potential zones may consequently be wider.

Stable slopes are difficult to define, and have a time context, but can be estimated using general geotechnical and slope-stability metrics (e.g., USACE, 2003), or defined *a-priori* through a planning approach where stable slopes are specified to facilitate locating construction setback lines. Such a stable slope criterion, the stable slope angle (SSA; Foyle, 2018), is being used or considered for use in construction setback delineation in the states of California, Michigan, Minnesota, New York, Oregon, and Wisconsin (Johnsson, 2003; Ohm, 2008; Kastrosky et al., 2011; Lulloff and Keillor, 2015). Defining construction setback lines is fundamentally a means of reducing erosion or flooding hazards that is practiced in many coastal states. It has the effect on bluff coasts of incentivizing new development to move farther from the bluff crest toward distal tableland areas where the erosion potential (erosion hazard) is greatly reduced. The BEP Index goes a step further in that it incorporates a temporal component where several, coast-parallel, erosion-potential zones (swaths) are defined rather than a single construction setback line. Areas lying within low erosion potential zones (LEP zones), for example, will not be subject to erosion until farther in the future than areas within very-high erosion potential zones (VHEP zones).

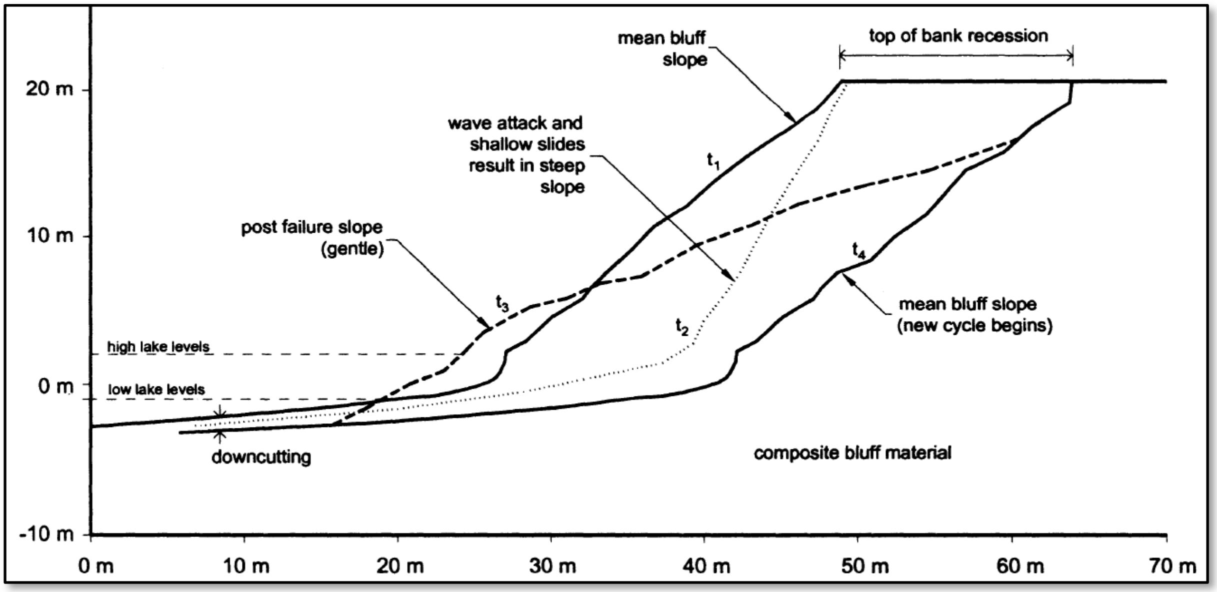


Figure 4.2. *A common bluff failure cycle on Great Lakes bluffs. A repeating failure cycle can result in extended periods of bluff-crest stability (low AARRs; time-1 to time-2) alternating with shorter periods of significant crest retreat (high AARRs; time-2 to time-3). The post-slump gentle slope at time-3 will ultimately steepen to the mean slope (time-4) due to renewed toe erosion and subsequently fail (modified from Zuzek et al., 2003).*

The average annual retreat rate (AARR) for a bluff, the present bluff slope (PBS), and a stable-slope angle (SSA), are three of several important parameters affecting bluff-crest migration (see a Wisconsin bluff retreat calculator at https://geography.wisc.edu/coastal/viz3d/). The AARR, when multiplied by a time term (T) related to either the expected lifetime of a structure or a planning timeframe, is a common means of estimating how far a bluff crest may retreat over a pertinent future time-period based solely on its historical behavior (a deterministic approach; Foyle, 2018). However, Moore et al. (2000) note that even the most precise data on historical coastal erosion rates only yield average erosion rates for the specific time-period studied. Extrapolating those past averages decades into the future can introduce uncertainty because controlling variables may change. Estimated future crest positions can therefore have potentially significant uncertainties. The AARR term may approach a value of zero on long-term stable, low gradient, or bedrock-toed bluffs that are no longer subject to erosive hydrodynamic, subaerial, and subsurface processes.

The concept of an SSA recognizes that topographic slopes exist in a dynamic state. Where toe erosion is not a factor, slopes may slowly weather and erode over long time periods to approach a stable slope (i.e., achieve grade) that is in dynamic equilibrium with driving (e.g., gravity) and resistive (e.g., shear strength, friction) forces. This will cause landward movement (at decreasing rates over time) of the crest even as the location of the toe remains constant. One reason for the rate decline is that each incremental decrease in slope requires that a progressively larger volume of bluff material be moved downslope. The timeframes involved in this slope-grading process are geographically variable and not yet well understood for slopes generally, nor for the Pennsylvania coast specifically. For coastal bluffs in temperate climates, the relevant timeframe over which significant change occurs is likely on the order of multiple decades to centuries depending on geotechnical properties and climate. This fundamental aspect of slope evolution is recognized by the International Building Code (IBC) in its guidelines for siting buildings near slopes, and by state and municipal interpretations of those guidelines in the United States (https://law.resource.org/pub/us/code/ibr/icc.ibc.2009.html).

Estimating an SSA value can be accomplished in several ways, from using site-specific, slope stability modeling (USACE, 2003); to using general geotechnical and regional-scale bluff behavior data (Allan and Priest, 2001; Priest and Allan, 2004); to using planning-based criteria (Lulloff and Keillor, 2015). The most geotechnically rigorous method is to use site-specific slope stability analysis (USACE, 2003), which uses site-collected data and various assumptions to model a location landward of the bluff crest beyond which the risk of a future slump failure is minimal. The SSA term can alternatively be derived by in-field slope measurements of nearby ("peer") stable bluff areas such as has been conducted in parts of Wisconsin where typical stable slope angles range from 18.4-21.8 degrees (Ohm, 2008). Depending on climate and bluff properties (e.g., groundwater content, stratigraphic complexity, cohesion, shear strength, grain size, cementation extent, compaction, etc.), bluff slopes inferred as stable can have a significant geographic range in values: from 11.25 degrees (till bluffs on Lake Michigan), to as high as 35-degrees (marine bluffs on the Chesapeake Bay, Maryland). Stable slopes of 60 degrees may be reasonable for bedrock cliffs in Wisconsin, while 80 degrees is common for bedrock ledges at the bluff toe in Pennsylvania (Foyle and Naber, 2012). SSAs are thus strongly linked to geotechnical characteristics. End-member values of 18-20 degrees and 30-33 degrees are commonly involved in the management of unconsolidated soils and bluff sediments. Time is also a factor as low slopes have a greater probability of being stable over longer time periods than steep slopes.

On the Ontario, Canada, coasts of Lakes Erie and Ontario, a planning based SSA of 18.5-degrees is used for coastal management purposes (OMNR, 2001): a plane is simply projected upward from the base of the bluff (or Ordinary High-Water Mark) to intersect the bluff top landward of the existing bluff crest. This defines a reference line (a stable slope setback line) on the landscape from which a specific construction setback distance is then measured. A similar approach is used in Wisconsin (Foyle, 2018). A planning based SSA term may alternatively be adapted, for example, from IBC guidelines for building near moderate- to steep-gradient static slopes (by IBC definition, those steeper than 18.5-degrees). In California and Washington municipalities, IBC guidelines have been adapted such that the minimum criterion for building near slopes that exceed 18.5-degrees is that a building foundation be located no closer to the crest than a distance equal to at least the smaller of (i) 40-feet or (ii) one third of the total slope height (z) above the toe. In cases where the slope is steeper than 45-degrees, the suggested construction setback (40-feet or z/3) is measured from where an imaginary 45-degree plane, projected upward from the toe of the slope, intersects the terrain behind the crest. These slope considerations by the IBC recognize that natural slopes, even in the absence of hydrodynamic processes, are prone to evolve over human timeframes into less-steep slopes.

Bluff Erosion Potential (BEP) Index Concept

The BEP Index is a simple process-geometric model of coastal bluff-erosion potential on the Pennsylvania coast of Lake Erie. It relies fundamentally on components of the (AARRxT)+ method of setback delineation (Foyle, 2018). In the (AARRxT)+ method, the position of the bluff crest at some future point in time (T) is related to the average annual retreat rate (AARR) and regrading of the bluff face toward a more stable slope angle (SSA). SSA is a critical variable in the method compared to "prior generation" setback determinations that tended to rely solely on the AARRxT term to determine where a setback line should be established. The BEP Index considers that bluff retreat due to hydrodynamic, subsurface, and subaerial processes occurs simultaneously with the process of slope regrading. However, the processes occur at significantly different rates, with change due to toe and slope erosion potentially being several orders of magnitude greater than that due to slope regrading.

The BEP Index is based on easily measured land surface characteristics and on general inferences about slope stability for unconsolidated bluffs typical of the Pennsylvania coast. The land surface characteristics used are those that can be mapped and extracted from lidar-based Digital Elevation Models (DEMs) and aerial imagery covering the bluff region, for example by using transect-generating geo-sampling software such as DSAS (Thieler at al., 2009). The BEP Index incorporates the following information: present (2015) bluff slope (PBS; reflects potential instability) and watershed slope average (WSA); shale toe presence/absence and height (reflects bluff resistance to wave erosion); AARR (1938 to 2015) of the bluff crest; present (2015) bluff-crest location (the reference point for estimating future bluff-crest locations); two reference end-member SSAs (18.5-degree slope based on planning practices on the Great Lakes; 33-degree slope based on generalized bluff geotechnical properties); and an assumed horizontal-planar tableland landward of the bluff (for geometric simplicity).

The BEP Index is not intended to provide property scale resolution of erosion hazards (even though on-screen magnification in a GIS allows such apparent resolution). Rather, the BEP Index broadly identifies potentially risky bluff-top swaths of land at the multi-property to sub-watershed scale. This limitation in spatial resolution is largely dictated by the sampling scale associated with the DSAS 20 meter transect spacing used in the coastal change analysis (Rafferty and Naber, 2021). Therefore, a site-specific slope-stability analysis, or a site geotechnical survey, by a licensed engineer would be recommended for an individual property being considered for mitigation of existing problems or the addition of new construction.

The BEP Index adapts a map-based coastal hazard index methodology developed for similar bluff geographies on the Pacific coast of Oregon. The Oregon Department of Geology and Mineral Industries (DOGAMI) model of beach and bluff erosion hazards was developed for several of Oregon's coastal counties (Gless et al. 1998; Allan and Priest, 2001; Priest and Allan, 2004) and is currently the most comprehensive GIS-based model of bluff erosion hazards nationally. The Oregon approach is significantly more informative than hazard-awareness mapping conducted by other states. Maine, for example, uses a simple map color-scheme approach to indicate the presence, absence, and relative degree of hazard for stretches of bluff coast based on prior bluff behavior and does not include hazard variability in the landward (onshore) direction. Michigan uses a very similar approach but adds numerical data to the maps to increase their technical utility (Foyle, 2018).

The BEP Index identifies four erosion-potential zones that are oriented approximately parallel to and track the present bluff crest. In order of decreasing erosion potential and increasing distance inland, these zones are the Very High Erosion Potential (VHEP) zone; the High Erosion Potential (HEP) zone; the Moderate Erosion Potential (MEP) zone; and the Low Erosion Potential (LEP) zone. The variable-width zones cover the region between the bluff toe and a line located as much as 890 feet (272 meters) landward of the toe, beyond which the erosion potential is expected to be insignificant at building-lifetime timescales. The lakeward and landward edges of each zone are defined by coordinates calculated at each of approximately 2,900 transects spaced at 66-foot (20-meter) intervals along the entire bluff coast.

Bluff Erosion Potential (BEP) Index Components

The widths of the BEP Index zones vary along the coast, being controlled by the geotechnical properties of the bluff (e.g., shear strength, stratigraphy) and the failure-driving forces (e.g., gravity, wave attack, pore-water pressure, etc.) that influence the bluff retreat rate. The width of each BEP Index zone is estimated using five observable geometric parameters (***Figure 4.3***). These are obtained from lidar-derived DEMs and aerial imagery using DSAS transect-generating geo-sampling software at each transect, using a 66-foot (20-meter) along-coast spacing.

1. The present bluff slope (PBS), a value determined for each transect, in degrees (^{O}). Where the PBS is absent at a transect, the watershed average slope (WSA) is used as an approximation.
2. The elevation of the (2015) present bluff crest in meters above lake level (m).
3. The average annual retreat rate between 1938 and 2015 ($AARR_{77}$), in meters per year (m/yr).
4. The watershed slope average based on all transects with data in each watershed (WSA; e.g. ~32^{O} for the Walnut Creek watershed; ~43^{O} for the Sevenmile Creek watershed), a geotechnical 26.5^{O} stable-slope angle (SSA), and a planning-based 18.5^{O} SSA, in degrees (^{O}).
5. The elevation or absence of shale bedrock or developed lowlands at the bluff toe, in meters (m).

The four BEP Index zones, in order of decreasing erosion potential and increasing distance in the landward direction, are shown for a short stretch of coast in simple line-map view in ***Figure 4.4*** and are described as follows.

The Very High Erosion Potential (VHEP) Zone: The VHEP zone is the active hazard zone and is the least uncertain of the BEP zones. It is defined based on identifiable morphologic features that may be seen in the field, on aerial photos, and on lidar-derived DEM profiles and maps. Overall, it is the present zone of active bluff instability, although parts of the bluff face may be intermittently stable for years to decades. General instability leads to identifiable patches of erosion, transport, and deposition that vary in dimension and location on the bluff over time. There is generally a high degree of micro- and meso-topography that results from infrequent (e.g., rotational slumps) through near-continuous (e.g., soil creep) bluff-failure processes that affect small areas (square meters) through large areas (thousands of square meters). Morphologic features include stress-release fractures at slump headwalls; small till bursts in over-compacted till; slump chutes and colluvial debris fans associated with rotational slumps; benches and terraces associated with translational slides; ridge, runnel and gully topography due to surface runoff; sapping zones and springs due to groundwater flow; seasonal popcorn texture and desiccation features on exposed till faces; crenulated soil surfaces due to soil creep; scarcity of mature vegetation; etc. The VHEP swath extends from the toe of the bluff to the present bluff crest and encompasses recent and active slumps, the present bluff face, and accumulated colluvial debris that may temporarily reside at the toe of the bluff. The 2015 toe elevation ranged from 0 – 19 feet (0 - 6 meters) above Spring 2015 mean lake level (571.5 feet; 174.2 meters). Weathering and erosion on the bluff face generally maintain steep-vegetated through bare-soil slopes. These are easily distinguishable on DEMs and aerial photos from generally flatter tableland terrain that is located landward of the bluff crest, and from beach deposits that are located lakeward of the bluff toe. The VHEP zone experiences a variety of mass movements (soil creep through block falls) or has done so historically, and it can consequently be expected to continue changing due to mass-wasting processes. Instability is evident in the form of topographic, soil, hydrologic, and vegetation characteristics. Any construction within the VHEP zone is inherently risky and this landscape region is already subject to oversight by the Bluff Recession and Setback Act (PA DEP, 2013). The VHEP swath is widest where bluffs are tall, the AARR value is large, and the present bluff-face slope is relatively low.

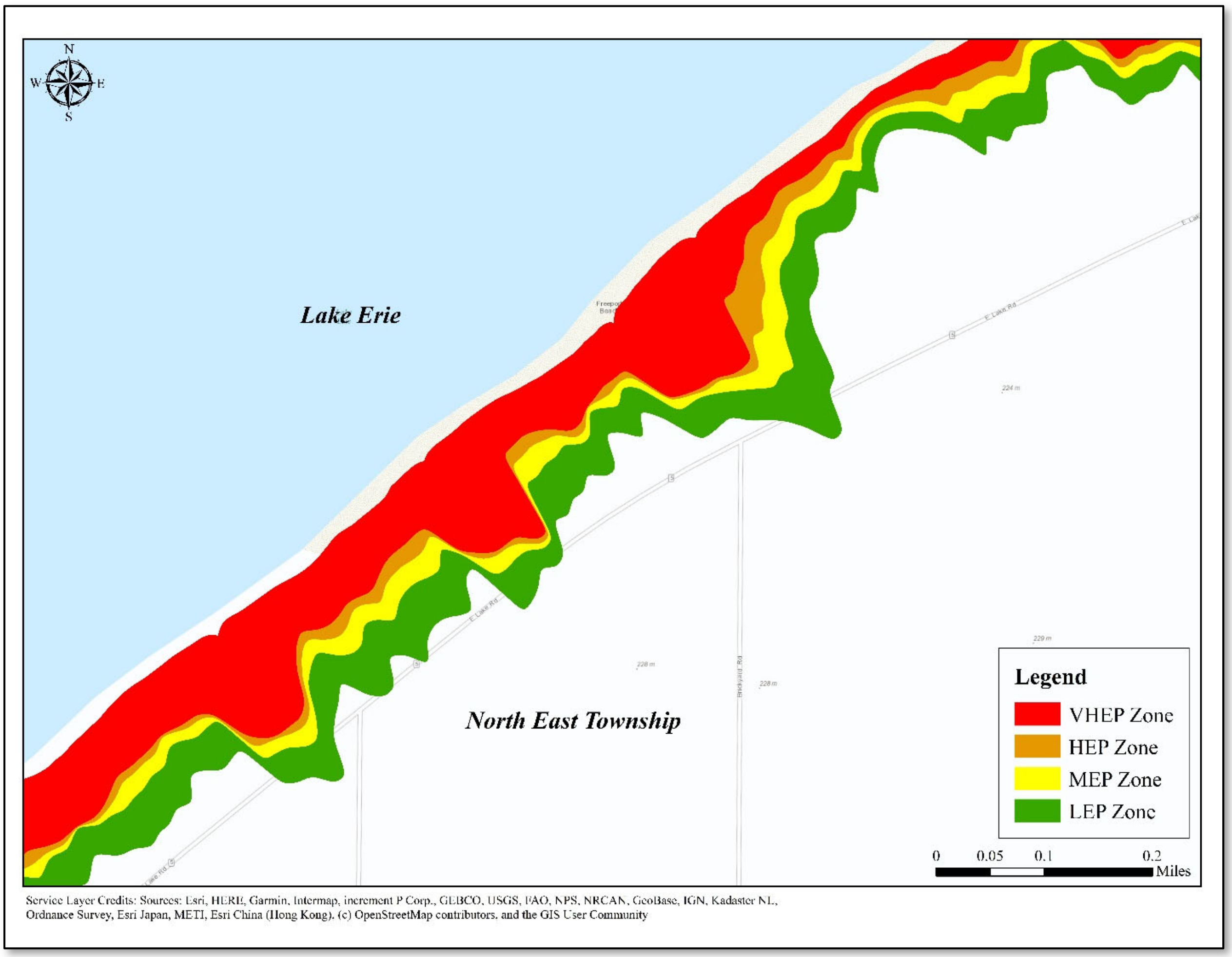


Figure 4.3. *Bluff Erosion Potential (BEP) Index hazard zones on part of the eastern Erie County, Pennsylvania coast of Lake Erie. View the BEP Index at: https://e8arcport.ad.psu.edu/portal/apps/webappviewer/index.html?id=66f65224ed874d71b63cc0aafd5ab64f).*

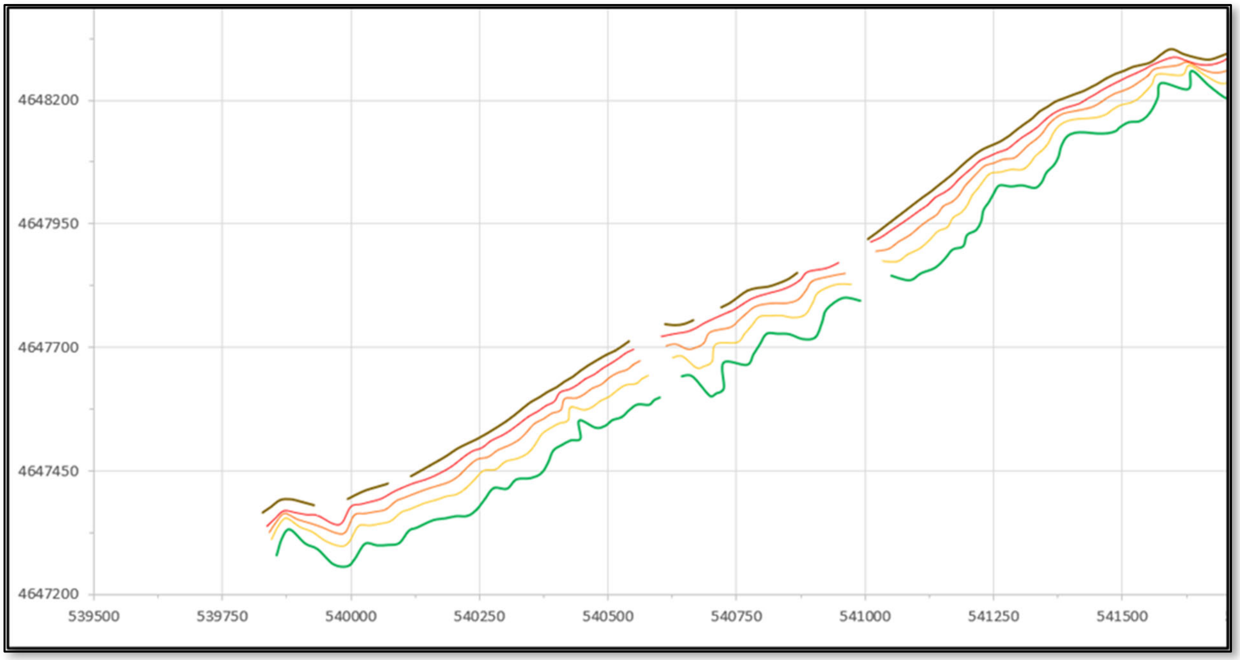


Figure 4.4. *Basic line-map view of the bluff vicinity near the Ohio state line showing the BEP Index concept for the Pennsylvania bluff coast (250 m x 250 m UTM grid). Lake Erie is on the top half of the image. Erosion potential decreases progressively in the landward direction, moving from the VHEP Zone on the bluff face (between the 2015 bluff toe, in brown, and the 2015 bluff crest, in red) towards the LEP Zone whose landward limit is defined by the green line. The landward limits of the HEP and MEP Zones are indicated by the amber and yellow lines, respectively. The two gaps denote "no data" zones where ravines cut across the bluff face. Combined, the BEP zones are ~330 ft (~100 m) in total width along this highly erosional stretch of Erie County coast. On the BEP Index interactive web map, the BEP zone boundaries are smoothed, as simulated here, using a PAEK (Polynomial Approximation with Exponential Kernel) methodology.*

The High Erosion Potential (HEP) Zone: The HEP zone abuts the landward edge of the VHEP zone and extends from the present bluff crest inland a distance that is dictated by the five geometric criteria listed above. There may or may not be morphologic evidence of instability in this zone: features such as overhangs, soil fractures, and subsidence may occur close to the bluff edge. The landward edge of the HEP swath is determined by a combination of where the watershed slope average (WSA) plane intersects the tableland and where the AARR integrated over 50 years will move the crest: it marks the probable location of the bluff crest in ~50 - 100 years. The bluff crest will migrate to this location due to bluff retreat associated with ongoing toe, face, and crest erosion; incremental natural regrading of the bluff face towards a more stable slope (WSA) identified for each watershed; and the possible occurrence of large but statistically infrequent slump events. On the Pennsylvania coast, both the average size and recurrence interval of headwall jumps during slumps are unknown due to spatial and temporal scarcity of monitoring data. What is known is that the largest slumps can cause a headwall jump (a landward jump of the bluff crest during a failure event) of as much as ~65 feet (~20 meters) per event and a slump event can last from seconds to weeks. There is thus a high probability that the HEP zone will exhibit active erosion in the next ~50-100 years, whether that is driven by slow, relatively continuous, retreat of the crest and toe (e.g., 0.7 feet/year or 0.2 meters/year), by sudden and catastrophic slumping on the bluff face (e.g., 65 feet/month or 20 meters/month), or by a combination of the two mechanisms. The probability of active erosion within the HEP zone will decrease in the landward direction, towards the boundary with the MEP swath. Construction within the HEP zone is risky and the HEP swath generally lies lakeward of residential setback lines already established by Erie County municipalities (Foyle, 2018). In general, the HEP swath is widest where some combination of the following occurs: tall bluffs, large AARR value, and steep present bluff-face slope (PBS) relative to the WSA. The HEP will be narrowest along sections of coast where bluffs are low and the AARR value is small. Numerically, the landward limit of the HEP zone at any given transect is equal to (AARR x 50 years), plus a horizontal distance related to the angular difference between the PBS and WSA slopes. For the entire coast, the landward limit of the HEP zone extends an average of ~40 feet (~12 meters) inland of the 2015 bluff crest and can locally extend as much as ~236 feet (~72 meters) landward.

The Moderate Erosion Potential (MEP) Zone: The MEP zone extends from the landward edge of the HEP zone inland a distance that is also dictated by the five geometric criteria listed above. The landward edge of the MEP swath conservatively defines the likely location of the bluff crest in ~100 - 150 years. The bluff crest will migrate to this location due to bluff retreat associated with ongoing toe, face, and crest erosion, continued natural regrading of the bluff face toward a 26.5 degree SSA, and the statistically more likely occurrence of large and infrequent slump events that can cause a landward jump of the bluff crest of as much as ~65 feet (~20 meters) per event. There is a moderate probability of erosion over the next ~100 - 150 years, with that probability declining in the landward direction across the MEP zone. The MEP zone may be the narrowest of the BEP swaths because its width is influenced by the angular difference between the 26.5-degree SSA and the WSA at each transect. In general, the MEP zone is widest where some combination of the following occurs: tall bluffs, large AARR value, and steep WSA relative to the 26.5-degree SSA. Numerically, the inland limit of the MEP zone at any given transect is equal to (AARR x 120 years) plus a horizontal distance related to the angular difference between the PBS and 26.5-degree SSA slopes. For the entire coast, the landward limit of the MEP zone extends an average of ~92 feet (~28 meters) inland of the 2015 bluff crest and can locally extend as much as ~470 feet (144 meters) landward.

The Low Erosion Potential (LEP) Zone: The LEP zone extends from the landward edge of the MEP zone inland to a point that is again dictated by the five geometric criteria listed above. The landward edge of the LEP swath conservatively defines a likely location of the bluff crest ~200 years from now. Potentially, it may take longer for the bluff crest to reach the landward edge of the LEP because i) landscape weathering/erosion rates that are difficult to quantify may decline as the bluff-face slope declines, ii) erosion by groundwater flux through the bluff face may decline as the bluff face slope declines and the areal outcrop of aquifer horizons on the bluff face increases, and (iii) each incremental decrease in slope angle yields a progressively larger volume of bluff material that will require more time to be removed. The bluff crest will migrate to this location due to continued bluff retreat, continued natural regrading of the bluff face toward an 18.5-degree SSA, and the larger statistical likelihood of occurrence of slump events over this longer timeframe. Overall, there is a low probability of erosion over the next ~150 - 200 years within this swath. This is particularly true in the more landward parts. In general, the LEP zone is widest where bluffs are tall and the AARR value is large. Numerically, the inland limit of the LEP zone at any given transect is equal to (AARR x 200 years) plus a horizontal distance related to the angular difference between the PBS and 18.5-degree SSA slopes. For the entire coast, the landward limit of the LEP zone extends an average ~197 feet (~60 meters) inland of the 2015 bluff crest and can locally extend as much as ~890 feet (~272 meters) landward.

Chapter 5: Managing Bluff Retreat: Recommendations and Priorities

As populations continue to move closer to the coastal regions of the Great Lakes for economic and lifestyle reasons, bluff management and erosion mitigation will continue to grow as important focuses of coastal management programs over time. The goal of management and 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; and
- lakebed downcutting in the surf zone and nearshore.

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 Vermont Northwest Regional Planning Commission produced *The Shoreline Stabilization Handbook for Lake Champlain and Other Inland Lakes* that reviews the most used solutions to bluff instability on Lake Champlain and other inland lakes (VT NRPC, 2004). While the handbook was developed for Lake Champlain, the approaches discussed 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; LHCCC, 2013; Keillor and White, 2003; Lulloff and Keillor, 2015). Generally, bluff management and 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; and
- removing or restricting mass-loading at or near the bluff crest.

Chapter 5 provides recommendations for managing and mitigating bluff retreat, with a focus on BMPs for property owners and natural resource managers. Foyle (2018) provides an extensive, detailed review of specific mitigation approaches, including hard stabilization (otherwise referred to as engineering solutions) and soft stabilization (otherwise referred to as bioengineering and biotechnical solutions) approaches. In addition, ***Chapter 5*** identifies several data gaps, needs, and research questions relating to bluff management, science, and engineering on the Pennsylvania coast. The emphasis is on science needs with the intent that addressing them 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; and
- continually improving the quantity and quality of coastal-science information that is available to the public and coastal stakeholders.

Recommendations for Managing Bluff Retreat

This section summarizes 10 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 (Foyle, 2018; Luloff and Keillor, 2015). The recommendations 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.

1. Continue to improve coastal-hazard information access for stakeholders and the 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 (https://pawalter.psu.edu/) would 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), and GIS-based interactive mapping tools are the most effective means of allowing data access and visualization (e.g. https://e8arcport.ad.psu.edu/portal/apps/webappviewer/index.html?id=61bf7c5dcaba421fa26b56b2dd2c48cc).

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 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 Foyle, 2018); 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.

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 Northwestern Pennsylvania. 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 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-National Flood Insurance Program (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 Great Lakes Environmental Research Lab (GLERL) and NOAA Center for Operational Oceanographic Products and Services (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 Office for Coastal Management for geospatial and mapping data; and/or

- 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; Foyle, 2018) 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; Foyle, 2018). 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 could be increased from the current 50-year 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 Lake Erie 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) 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 Northwestern 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 a 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 (Foyle, 2018). 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, 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 (Foyle, 2018). Other areas are characterized by continuous soil creeps and sliding vegetation mats. Stepped benches extending tens to hundreds of feet 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.

9. *Stormwater management and on-site waste disposal designs developed as part of coastal construction site design should direct stormwater and effluent away from the bluff and should not discharge to the groundwater within the unstable portion of the bluff top.*

Features of coastal development, including siting of septic systems and stormwater control measures, are likely to increase the instability of coastal bluffs (Lulloff and Keillor, 2015). Changes to surface water drainage patterns in coastal areas can destabilize bluffs. Stormwater and wastewater discharges to groundwater increase risk of bluff slumping or failure. Stormwater and wastewater management practices near bluffs should include limitations on discharge to groundwater within the unstable area portion of the bluff top.

Managing stormwater on private property should minimize alteration to normal surface water drainage patterns (Lulloff and Keillor, 2015). Guidance materials should be developed and distributed to coastal landowners highlighting proper stormwater management principles for bluff top development. Stormwater should be directed away from the bluff, and existing stormwater drainage patterns to nearby ravines and gullies should be maintained where possible. Development should be discouraged from encroaching upon these gullies and ravines so that these features can continue to effectively convey stormwater to the coast. Stormwater management practices near bluffs should also include limitations on discharge to groundwater within the unstable area portion of the bluff top. Directing stormwater away from bluffs helps maintain the stability of coastal slopes both on the property to be developed and that of others. Stormwater retention basins constructed inland from coastal slopes contribute to infiltration and increased groundwater discharge at the slopes. Low Impact Development (LID) is an approach to stormwater management that promotes stormwater infiltration within individual lots in a subdivision. LID practices such as rain barrels can be effectively utilized if properly modified for bluff tops. Enlarged storage capacity rain barrels (e.g. multi-barrel systems) with slow release can avoid negative impacts to slope stability following large storms. However, other LID practices such as rain gardens and porous pavement can increase groundwater flow toward the bluff face, making bluffs less stable. It is important that these systems be constructed as far from the bluff as possible.

On-site waste disposal systems, including mound systems, should be placed landward of the coastal buildings they serve so that the effluent from these systems does not contribute to bluff landslides (Lulloff and Keillor, 2015). Coastal community setback ordinances should exclude the placement of on-site waste disposal systems in the setback area. Homeowners prefer that mounds systems not be visible from the street and therefore opt to construct the systems in the back yard. The backyards of homes that are setback from coastal bluffs, however, are not safe locations for on-site waste disposal systems. The added weight of these systems increases the loads and stresses on nearby slopes. The liquids that infiltrate into underlying soils reduce the friction between soil particles, migrate to adjacent slopes and seep from the bluff face onto the beach and into the lake (Lulloff and Keillor, 2015). This partially treated sewage not only reduces the strength of slopes contributing to slope failure but contains fecal matter that constitutes a health hazard to beach users and adds pollutants to the lake.

10. Non-structural shore protection measures should be encouraged.

The traditional response to coastal erosion has been to attempt to intervene in the natural process by building protective structures to divert wave action, stop erosion at one point, and build up the beach at another (Lulloff and Keillor, 2015). These actions to protect a shoreline, however, can have unintended adverse impacts on other locations and over the long term. The permitting of new shore protection structures can be a contentious process as adjacent property owners and other interested parties claim harm to properties. The effectiveness and survival of shore protection structures are threatened by severe storm waves riding ashore on storm surges, by bluff/bank collapse, by freeze-thaw fracturing of armor stone, and by lakebed erosion. Most shore protection structures interfere with the natural erosion process that contributes material to beaches. Some portions of typical shore protection structures intrude upon the public lakebed or are constructed below the Ordinary High-Water Mark. As a result, they often limit public lateral movement along the coast and reduce the amount of sand containing sediments that builds beaches. Downdraft shoreline can have reduced sand cover in the near shore area, therefore, increasing the potential for lakebed erosion. Lakebed erosion, an unseen coastal hazard, can undermine shore protection structures, leading to a shortened structure life and the prospect of catastrophic collapse, triggering massive slope failure in some places and the loss of facilities on bluff top land.

Shore protection structures should be considered only as a last resort and then only to protect existing buildings, not undeveloped lots. Non-structural shore protection measures such as bluff top stormwater and wastewater management, maintaining and enhancing vegetation on coastal slopes and beach nourishment should be used to protect existing at-risk structures. If non-structural options are not feasible, shore protection structure designs should include a site investigation of slope stability and lakeshore erosion, a no adverse impacts (NAI) analysis for all new shore protection structure applications, a plan for ensuring adequate quality control of materials used in the designed structure, and adequate monitoring and maintenance plans.

In the Great Lakes, the littoral transport system carries sand and other sediments along the coast by waves and currents. Shore protection structures interfere with natural erosion and littoral drift that contribute sand to protective beaches and can deprive the littoral transport system of sediments that replenish areas that are down current (Lulloff and Keillor, 2015). When this occurs, down current areas of the structures lose land because there are no sediments left to restore those removed by the longshore drift. In addition, installation of shore protection structures results in the loss of natural habitat for fish and other aquatic organisms.

Data Gaps, Needs, and Research Questions

This section consists of a listing of data gaps, needs, and research questions relating to bluff management, science, and engineering on the Pennsylvania coast (Foyle, 2018). 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; and
- continually improving the quantity and quality of coastal-science information that is available to the public and coastal stakeholders.

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 PA 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 (https://gis.ohiodnr.gov/MapViewer/?config=lesemp).

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. 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 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 the Bluff Erosion Potential (BEP) Index (*see Chapter 4*).

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-year 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. 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 approximately 0.1-feet/year 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-year 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 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-year 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-year 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-feet 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. *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 PA 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.

35. *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?

36. *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.

37. *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?

38. *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?

39. *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?

40. *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.

41. *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?

42. *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 retreat is often episodic in nature, the longer control points are monitored, the more accurate the calculated retreat-rate averages become.

43. *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 (Foyle, 2018)? 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 strand plain sectors near North East Township and Lake City Borough, Pennsylvania, and municipal/state lakefront parks, would be coastal areas worth consideration.

44. *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?

45. *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.

46. *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 because it places a limitation on identifying the frequencies and sizes of, for example, small failure events on the bluff face.

47. *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. 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).

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