The Bluff Erosion Potential (BEP) Index

A Process-Geometric Model to Map Bluff Erosion Hazards on the PA Coast of Lake Erie: Bluff Retreat and Index Methodology – Revised December 2021

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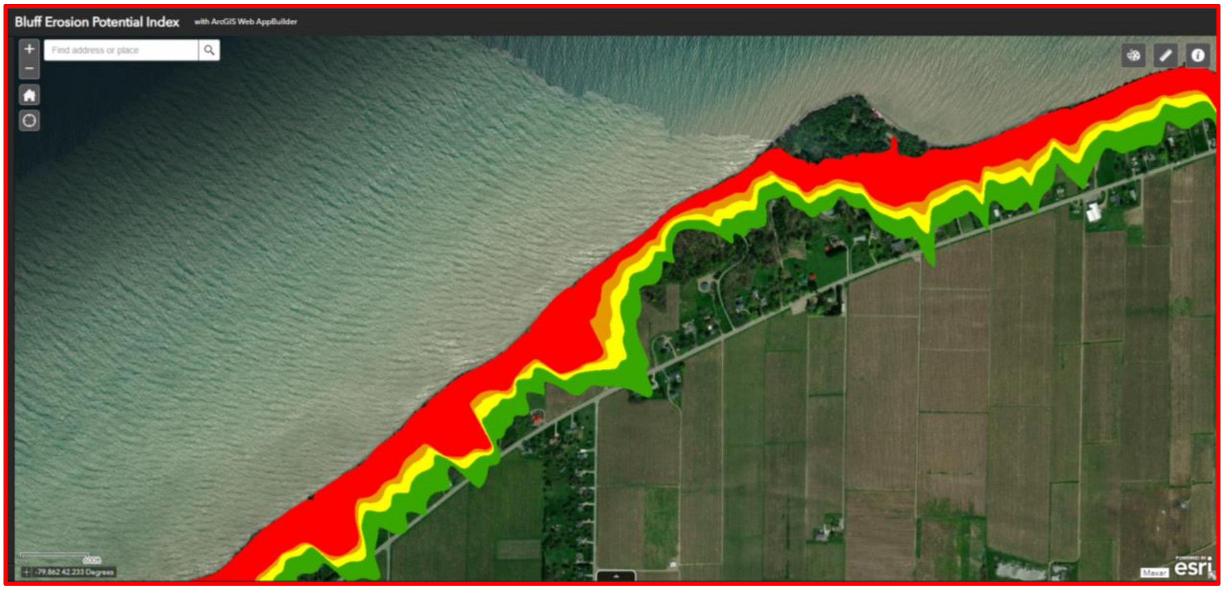

Swath-map and line-map versions of BEP Index bluff hazard zones on part of the eastern Erie County coast of Lake Erie. The landward edges of the VHEP (red), HEP (amber), MEP (yellow), and LEP (green) zones above are shown below by red, amber, yellow, and green boundary lines, respectively.

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

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Introduction

This report, *The Bluff Erosion Potential (BEP) Index: A Process-Geometric Model to Map Bluff Erosion Hazards on the PA Coast of Lake Erie*, describes the methodology and assumptions developed to define relative coastal erosion hazard zones on the Pennsylvania bluff coast of Lake Erie. Detailed background information on the coastal geology, hazards, and management of the bluff coast of Pennsylvania is available online at pawalter.psu.edu (*The Lake Erie Bluff Coast of Pennsylvania: A State of Knowledge Report on Coastal Change Patterns, Processes, and Management (Foyle, 2018)).*

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

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

The Geometry of Bluff Retreat

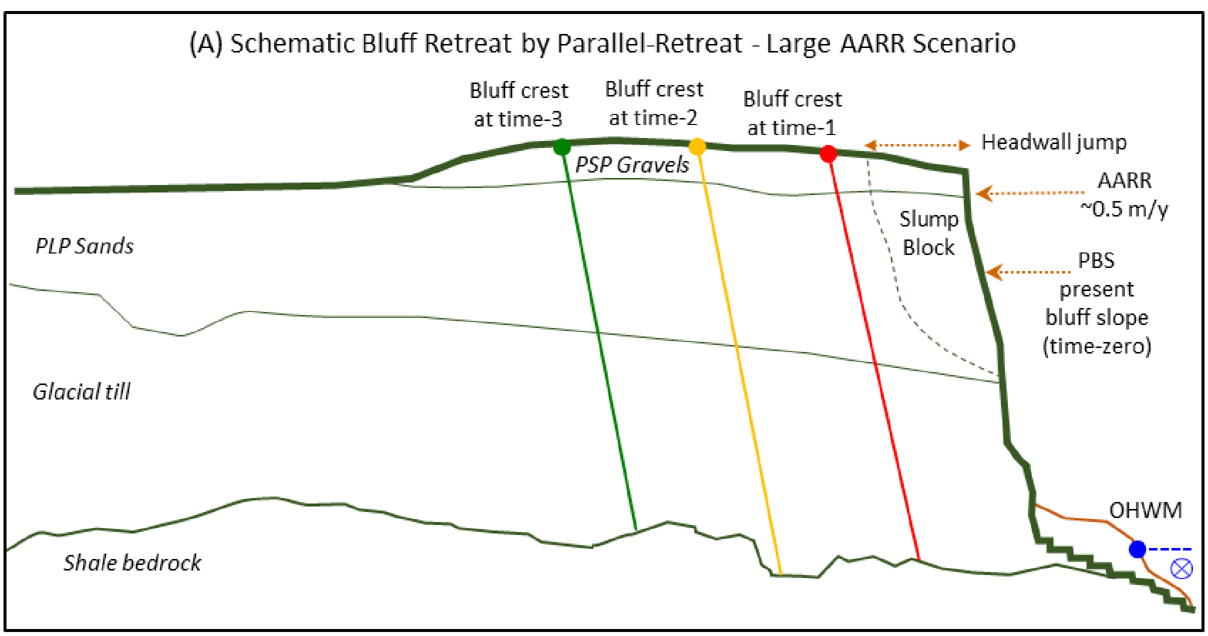
The Bluff Erosion Potential (BEP) Index in this report graphically illustrates the potential for future land losses due to erosion in the vicinity of bluffs along the Pennsylvania coast of Lake Erie. It provides a geometric estimate of the probable future locations of the bluff crest as the bluff face, 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. 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 and Lake City; Foyle, 2018), or at bluffs that do not have a well-developed bedrock toe (much of western Erie County), 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 (Figure 1).

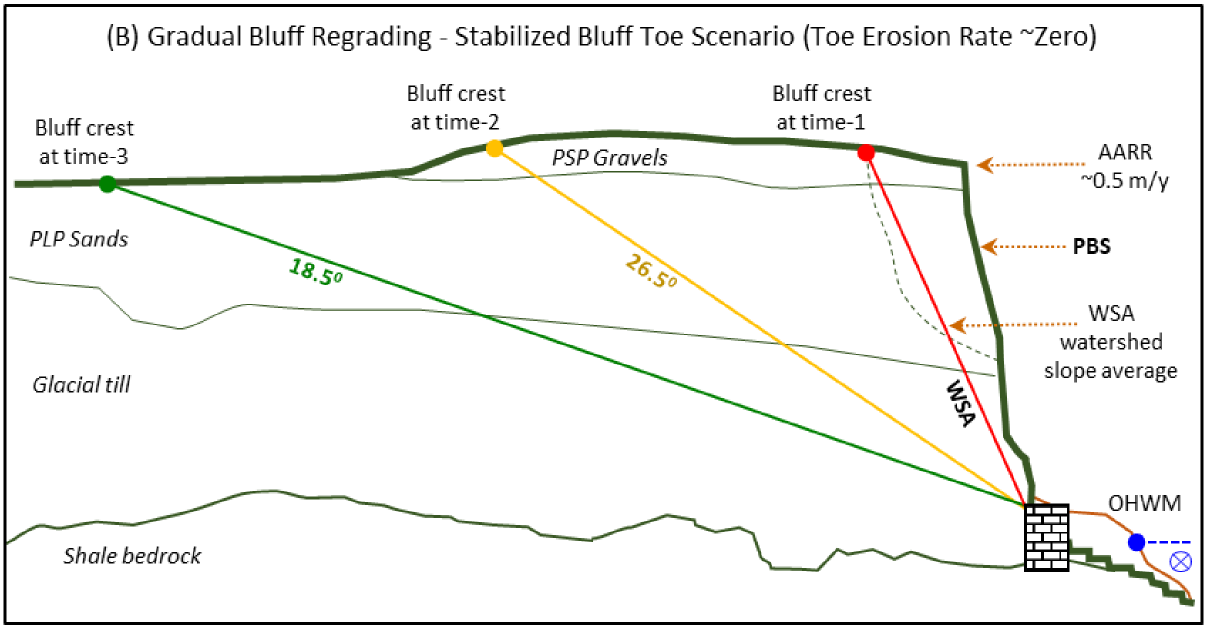
Figure 1: *A bluff-erosion mitigation project, at the Concordia University campus on Lake Michigan, Wisconsin. The bluff face has been regraded to an engineered-stable slope angle (SSA) of 25~30°, low-mass vegetation plantings added, and surface and groundwater management incorporated. Rip-rap protection has been placed at the bluff toe. In the background, naturally steeper bluffs (~55°) erode due to subaerial, subsurface, and hydrodynamic processes (Image: JSOnline.com).*

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 ~50, ~120, and ~200 years from now, that is, over one to two residential-building lifetimes. These timeframes are conservative estimates for several reasons. Firstly, 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. Secondly, the long-term AARRs derived from this project's lidar and aerial photo data over a 77-year time interval between 1938 and 2015 are being used to extrapolate change well into the future. The associated extrapolation uncertainty is mitigated to a large degree by the duration of the observation window used to obtain those long-term AARRs ($AARR_{77}$; 1938-2015) that uses historical crest-position data provided by the US Army Corps of Engineers (Cross et al., 2016) and recent 2015 lidar data. While uncertainty in the crest position on the older data set is on the order of 15 m (or, ~0.19 m/y annualized), it is comparatively small and similar to the annualized uncertainties in the newer data. Thirdly, because increasing volumes of material have to be removed for each incremental decrease in bluff slope, change rates associated with the regrading process may decrease over time, other factors being equal. Lastly, suitable data on slope-evolution rates in the Great Lakes Basin are not available which increases uncertainty in the timeframe estimate 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. Concurrently, steep slopes attempt to regrade naturally to more stable (gentler) slopes. The consequence of these processes is a bluff profile that retreats (relatively rapidly; Figure 2A) and concurrently regrades (relatively slowly; Figure 2B) over time to result in a progressively lower-sloped bluff face and a bluff crest located at a progressively more landward location (Figure 2C). The parallel bluff-face retreat and planar bluff slopes shown schematically in Figure 2 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; Figure 3). Bluffs with multi-layered stratigraphy, such as on the Pennsylvania 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).

In areas where the AARR is lower (e.g., due to toe stabilization, the presence of a wide beach, limited groundwater flux, or a long time having passed since a prior slump), the timeframes involved in bluff evolution to a more stable slope may 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 in the BEP Index will be 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 (BEP) zones may consequently be wider.





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 at the bluff toe denotes a coastal structure (seawall, revetment, etc.).

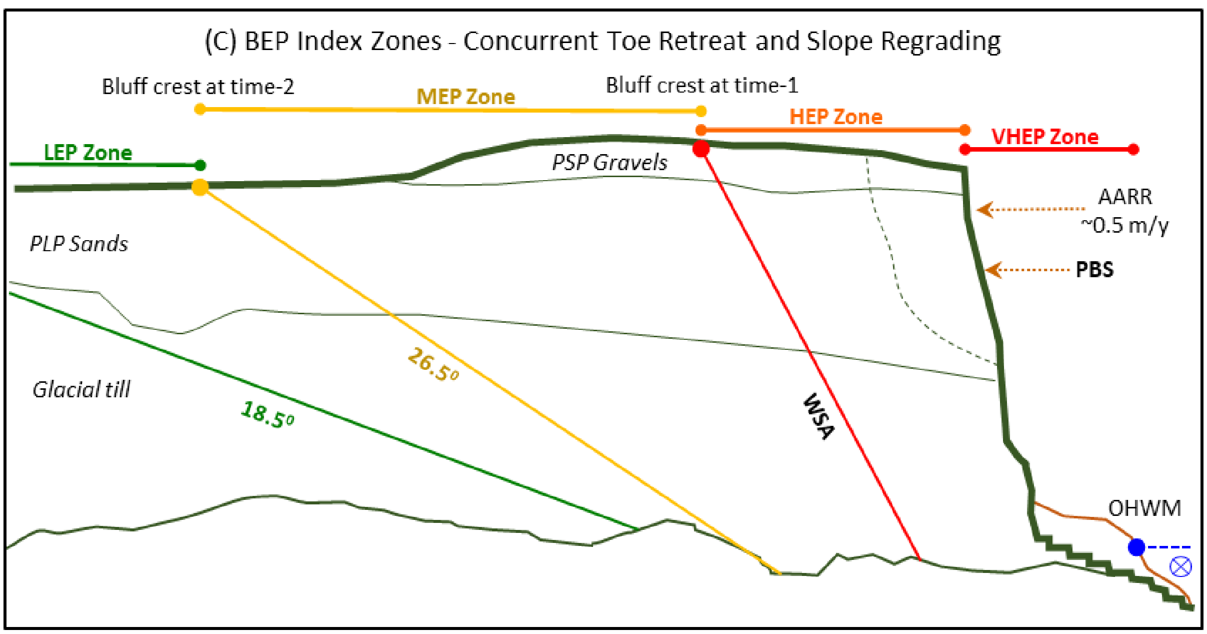


Figure 2: *Schematic cross-section showing retreat (A) and regrading (B) components of bluff evolution. These are used in the BEP Index to conservatively demarcate erosion-potential zones (C) along the bluff coastline. Erosion potential decreases progressively in the landward direction, moving from the active-hazard VHEP zone at the bluff face towards the LEP zone inland. Lake Erie is to the right. A simplified schematic stratigraphy is shown (from Foyle, 2018).*

Stable slopes are difficult to define, and have a time context, but can be (i) estimated using general geotechnical and slope-stability metrics (e.g., USACE, 2003), or (ii) 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; Luloff and Keillor, 2016). Defining construction setback lines is fundamentally a means of reducing erosion or flooding hazards that is practiced in many coastal states, from Florida to Oregon. 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 used in this report 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 the low erosion potential zone (LEP zone), for example, will not be subject to erosion until farther in the future than areas within the high erosion potential zone (HEP zone).

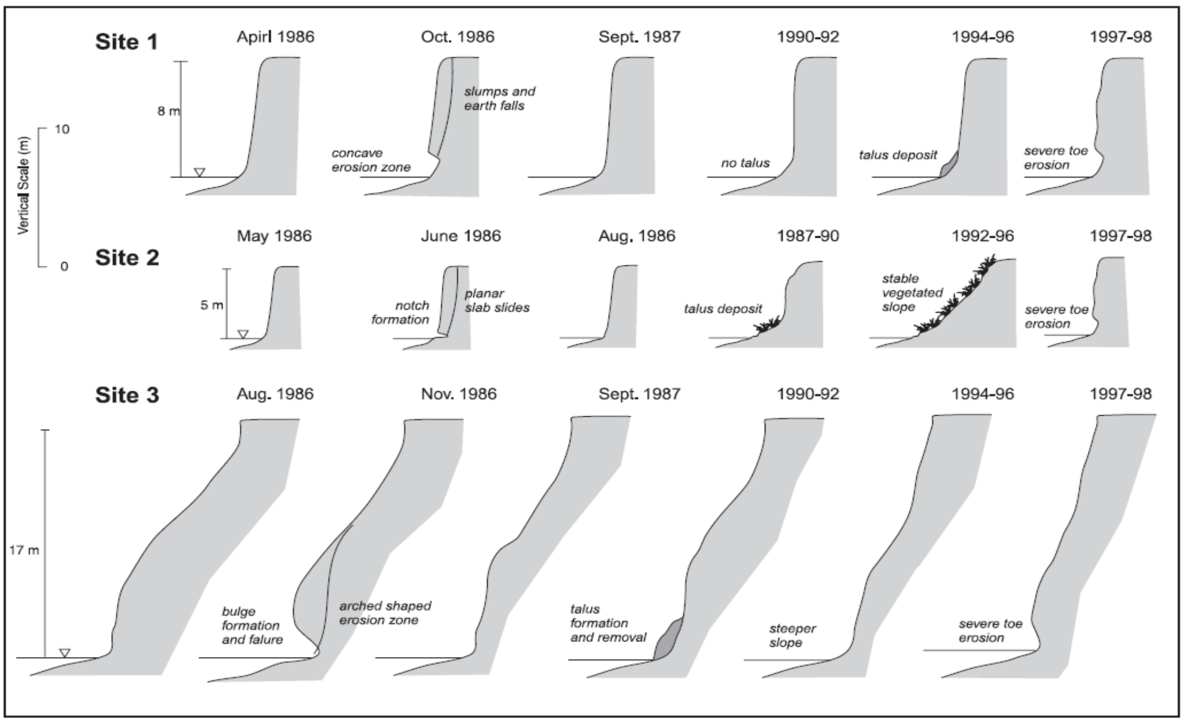


Figure 3: *Patterns of bluff-profile evolution over a decade documented by Amin (2001) in western Erie County. Note that the bluff rarely retreats in a purely planar mode because erosion and deposition at different elevations continually change local slopes (Image: Amin, 2001).*

The average annual retreat rate (AARR) for a bluff, the present bluff slope (PBS), and a stable-slope angle for the bluff materials (SSA), are three of several important parameters affecting bluff-crest migration (see related information at a Wisconsin coastal atlas at https://wicoastalatlas.net). 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 for years to decades into the future will 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. Such quasi-stable bluffs occur on Maryland's Chesapeake Bay coast where formerly active bluffs have been isolated from wave energy for up to several centuries and have achieved a stable angle of repose of ~35^0 (Chapter 2 in Foyle (2018)). Similar quasi-stability can be seen along the Erie County coast on the southwest side of Presque Isle Bay. Here, wave power is reduced due to wave-fetch reduction provided by the nearby Presque Isle strandplain. While wave attack may be significantly reduced, however, groundwater continues to play a role in bluff instability (Urban Engineers, Inc., 2004), as does stormwater runoff over the urban landscape and through subsurface drainage systems. Along the bay's southeast side, urban development on reclaimed lowland isolates the mainland bluffs from the bay waters. Here, the AARR term no longer has a component driven by hydrodynamic processes and crest retreat rates over decades approach zero.

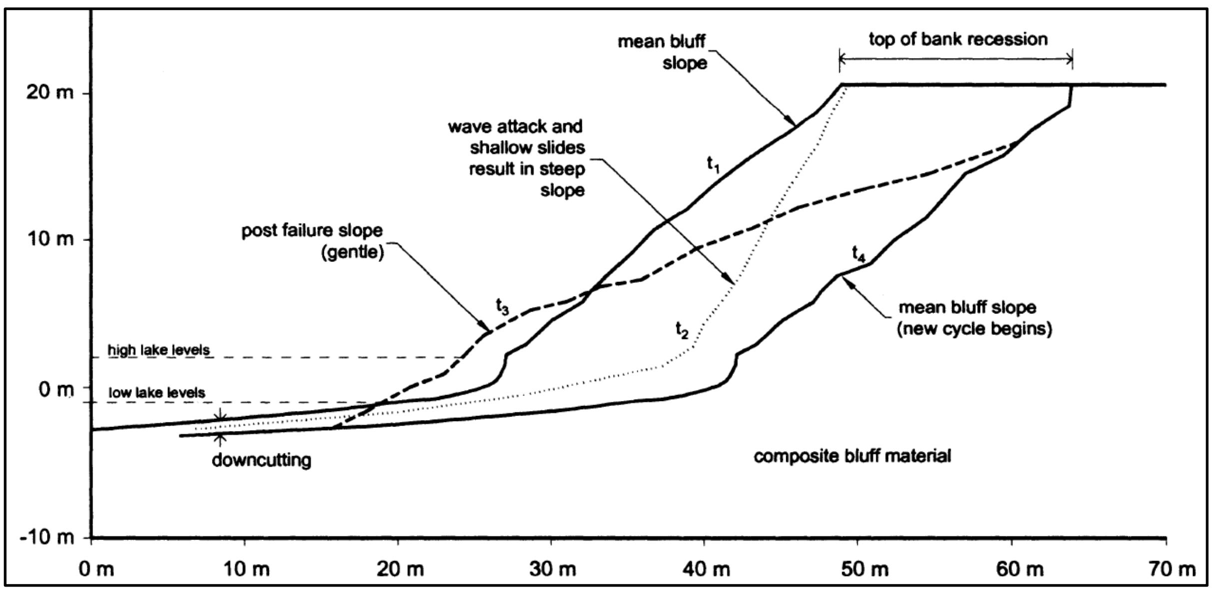


Figure 4: *A common bluff failure cycle on Great Lakes bluffs, particularly where stratigraphy is non-uniform. A repeating failure cycle can result in extended periods of bluff-crest stability (low AARRs; time-1 to time-2) alternating with shorter periods of significant crest retreat (high AARRs; time-2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

The concept of a stable slope angle (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) 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).

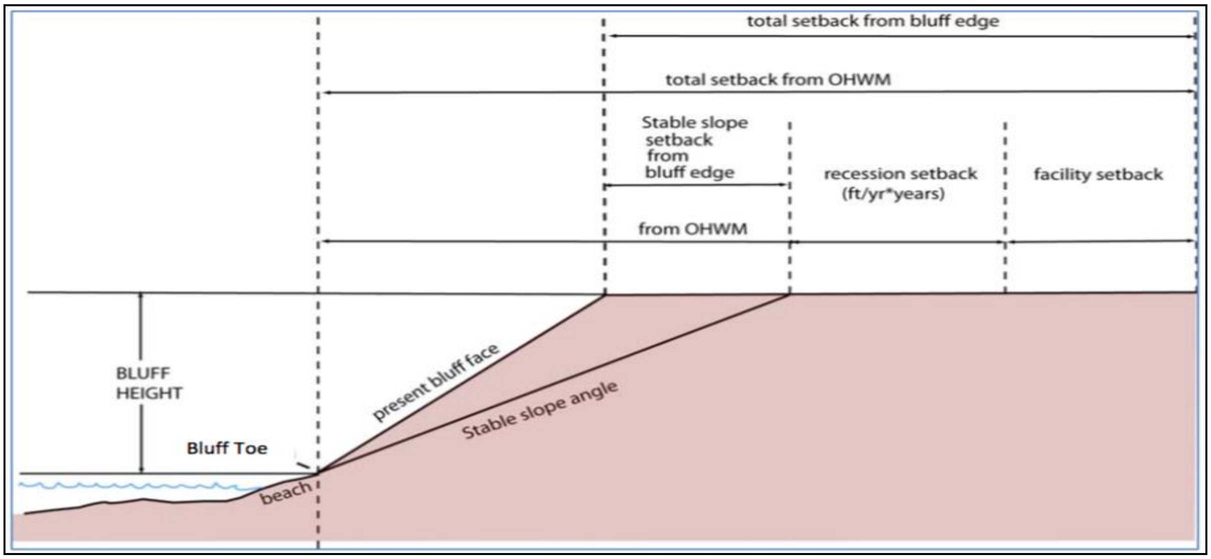


***Figure 5**: Schematic diagram showing how the stable slope angle (SSA) concept is used to determine construction setback lines for coastal bluffs. In conjunction with an average annual retreat rate (AARR), a construction or planning timeframe (T), and a facility setback, the total setback from the bluff edge is determined (Image: modified from Managing Coastal Hazard Risks on Wisconsin's Dynamic Great Lakes Shoreline, by Luloff and Keillor, 2016; see also Chapter 8 in Foyle (2018)).*

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 (Luloff and Keillor, 2016). 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^{o} (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^{o} (till bluffs on Lake Michigan), to as high as 35^{o} (marine bluffs on the Chesapeake Bay, Maryland). Stable slopes of 60^{o} may be reasonable for bedrock cliffs in Wisconsin, while 80^{o} is common for bedrock ledges at the bluff toe in Pennsylvania (Foyle and Naber, 2011). SSAs are thus strongly linked to geotechnical characteristics. End-member values of 18-20^{o} and 30-33^{o} are commonly involved in the management of unconsolidated soils and bluff sediments. Time is also a factor: 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 18.5^0 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; OHWM) 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 (Chapter 8 in 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 18.5^0). In municipalities in California and Washington, IBC guidelines have been adapted such that the minimum criterion for building near slopes that exceed 18.5^0 is that a building foundation be located no closer to the crest than a distance equal to at least the smaller of (i) 12 m or (ii) one third of the total slope height (z) above the toe. In cases where the slope is steeper than 45^0, the suggested construction setback (12 m or z/3) is measured from where an imaginary 45^0 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.

The BEP Index Concept

The BEP Index is a simple process-geometric model of coastal bluff-erosion potential for the Pennsylvania coast of Lake Erie. It relies fundamentally on components of the (AARRxT)+ method of setback delineation discussed in 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 to a regrading of the bluff face toward a more stable slope angle (SSA). For setback delineations, an optional facility setback is often included that leaves space for a building to be relocated (Figure 5). Figure 6 shows coastal-construction guidance provided by FEMA that incorporates the retreat and regrading components. The 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 SSA is also a critical component of the BEP Index described herein. Figures 5 and 6 show that even on coasts where wave-induced erosion at the bluff toe is arrested (e.g., by seawalls, wide beaches, revetments, or nearshore breakwaters), crest retreat can continue due to the slow process of slope regrading so that the bluff face may become incrementally more stable over time.

Figure 6 schematically shows how FEMA guidance on coastal construction setbacks is related to terms in the BEP Index. On naturally retreating bluffs, FEMA considers that the future bluff-crest position is largely a function of erosion at the toe and face. On coasts where the toe or shoreline has been stabilized, FEMA recognizes that a bluff crest may still retreat, but at a slower rate that will lead to an SSA over some extended time period. 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 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 bluff slope (PBS; reflects potential stability or instability) and watershed slope average (WSA);

shale toe presence/absence and height (affects bluff resistance to wave erosion); bluff crest AARR (reflects the integrated response of the bluff system to multiple driving and resistive forces); present bluff-crest location (the reference point for estimating future bluff-crest locations); two reference end-member SSAs (an 18.5^0 slope based on planning practices on the Great Lakes; a 26.5^0 slope based on generalized bluff geotechnical properties); and an assumed horizontal-planar tableland landward of the bluff (for geometric simplicity). These observable and derivable bluff characteristics are inferred to be the product of a large number of interacting, spatially and temporally variable, environmental conditions and processes (Table 7.1 in Foyle (2018)) that are otherwise difficult to measure economically or in a statistically meaningful way. These include three-dimensional variations in internal stratigraphy and groundwater pore pressures; variations in wave climate, precipitation, and seasonal air temperatures; etc. (Table 1).

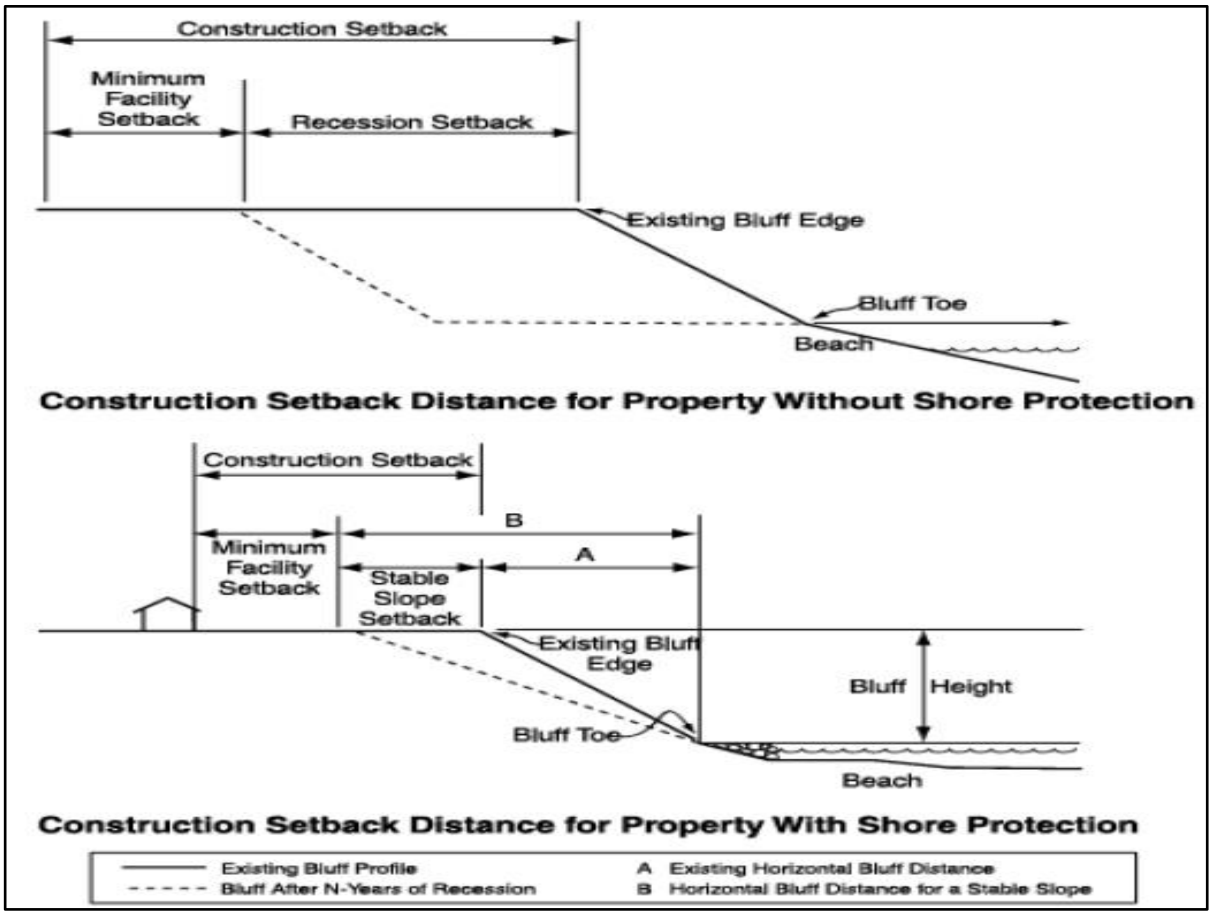


Figure 6: *Schematic diagram from FEMA showing bluff evolution over time, showing the erosional retreat and slope-regrading components of bluff change. The upper image shows rapid bluff erosion where it is consequently difficult for slow regrading to be seen. The lower image shows a dominance of slope regrading on a toe-stabilized bluff. FEMA considers both components in providing guidance for delineating construction setbacks from the bluff edge (Image: modified from FEMA Residential Coastal Construction Training Guide at http://www.fema.gsov/residential-coastal-construction).*

The BEP geometric model is not intended to provide property-scale resolution of erosion hazards (even though on-screen magnification in a GIS may allow such apparent resolution). Rather, the BEP Index broadly identifies potentially risky bluff-top swaths of land at the multi-property to subwatershed scale. This limitation in spatial resolution is largely dictated by the sampling scale associated with the DSAS 20 m transect spacing used in the coastal-change analysis. 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.

	FACTOR		RELATIVE IMPORTANCE				EXPLANATION
			CRITICAL	HIGH	MOD	LOW	Premise: Long-term AARRs indirectly reflect these (often ill-defined) geotechnical and process-controlling variables
	AAR Rate	Bluff crest AARR 2012-2015 (7 yr AARR)				x	Not ideal, because only small changes may occur over 7 yrs in specific areas; mapping uncertainty is larger
		Bluff crest AARR 1938-2015 (77 yr AARR)	o	x			Ideal. Longer-term data yield better statistics, capture environmental factors, and match policy, economics timeframes
SYSTEM OUPUTS:							
	Angle	Bluff slope in excess of watershed average (all-transect average)	o	x			Highlights areas of extra-steep slopes (more likely to fail than less-steep slopes)
VISIBLE		Bluff slope in excess of mgmt-favored 18.5 degrees and 26.5 degrees			x		Most straightforward; has a basis in construction codes (IBC) and regulations (Ontario; Wi)
BLUFF		Near-crest or near-toe steep-swath location			x		Suggests future stability or instability: e.g., steep slopes at the toe or crest may increase failure likelihood
CONSEQUENCES		2012-2015 bluff-face change: erosional and depositional swaths				x	Suggests future stability or instability: e.g., large-difference swaths may cause stability or instability (cause dependent)
	Gwater	Relative groundwater flux through the bluff face	o	x			Large fluxes cause bluff instability (lubrication, mass, reduced shear strength)
		Proximity to incised streams and (groundwater) re-entrants			x		Sloping water tables near the bluff may deflect groundwater away from the bluff face
		Till - Lacustrine contact topography = lateral groundwater directivity			x		Bumpy topography influences groundwater flow along top of till and may induce ravine formation and crest retreat
	Waves	Wave energy delivered/year to bluff	o	x			Unavailable for this project; an important factor in non-shale-toe bluffs in west Erie County where beach volume varies
		Presence/absence/height of a shale toe	o	x			Important in western Erie County, where it's often absent; can allow hydrodynamic driving forces to be relatively large
SYSTEM INPUTS:		Beach width (bluff toe to shoreline)		x			Larger-volume beaches reduce hydrodynamic forces at the bluff toe and lower face
		Bathymetric shielding or focusing of wave energy by shoals				x	Large nearshore sand/till shoals may shield part of the coast in western Erie County
PROCESSES		Presque Isle and marina wave shielding		x			Smaller waves reach the bluff - less toe erosion occurs as a result
DRIVING							
&	Gravity	Bluff crest elevation	o	x			Taller bluffs are associated with larger slumps & greater headwall jumps
EFFECTING		Material shear, compressive, and tensile strengths	o	x			Very scarce information for the PA coast - unavailable this project
CHANGE		Buildings/large tree mass			x		Add mass to the bluff top and lead to greater instability
	Runoff	Bluff plateau landward/lakeward slope			x		Affects runoff over, and groundwater flux at, the bluff face
		Bluff face and plateau remediation efforts			x		When effectively designed, these pull surface water and groundwater away from bluff face
	Climate	Number of freeze days			x		Non-variant along coast; can change over decades (climate); can seasonally reduce groundwater flux at the bluff face
		Snowfall/ice mass			x		Somewhat variable along the coast; may randomly overload short sectors of bluff

Table 1: *Geo-environmental factors (system inputs) contributing to bluff retreat along the Pennsylvania coast of Lake Erie. The relative importance of each factor in bluff retreat is also shown. Interactions among these factors lead to visible bluff geometries (system outputs) that are utilized in the Bluff Erosion Potential (BEP) Index.*

The BEP Index for the Pennsylvania coast 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 particular 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 (Chapter 2 in Foyle (2018)).

The DOGAMI model incorporates general geometric considerations, geologic information, and retreat-rate data to map hazard swaths of differing magnitude in the landward and along-coast directions (Figure 7). It directly or indirectly incorporates elements such as: bluff slope, estimated stable slope angle, incremental coastal retreat due to sea-level rise, bluff crest AARR from intermediate-term (55 yr) historical data, a time factor (the useful life of a structure; 60-100 years), the size of typical slump-headwall jumps during slide events (empirically related to bluff height), and a safety factor (multiplier) to compensate for uncertainty. The DOGAMI model is less geometric in its approach than the BEP Index because the Oregon coast has a larger (but still general) database of available geological information. The latter includes landslide locations, sizes, and geometries; landslide hazard maps; a long record of coastal change; detailed coastal stratigraphic data; landslide analyses; wave climate characterization; and seismic-event histories.

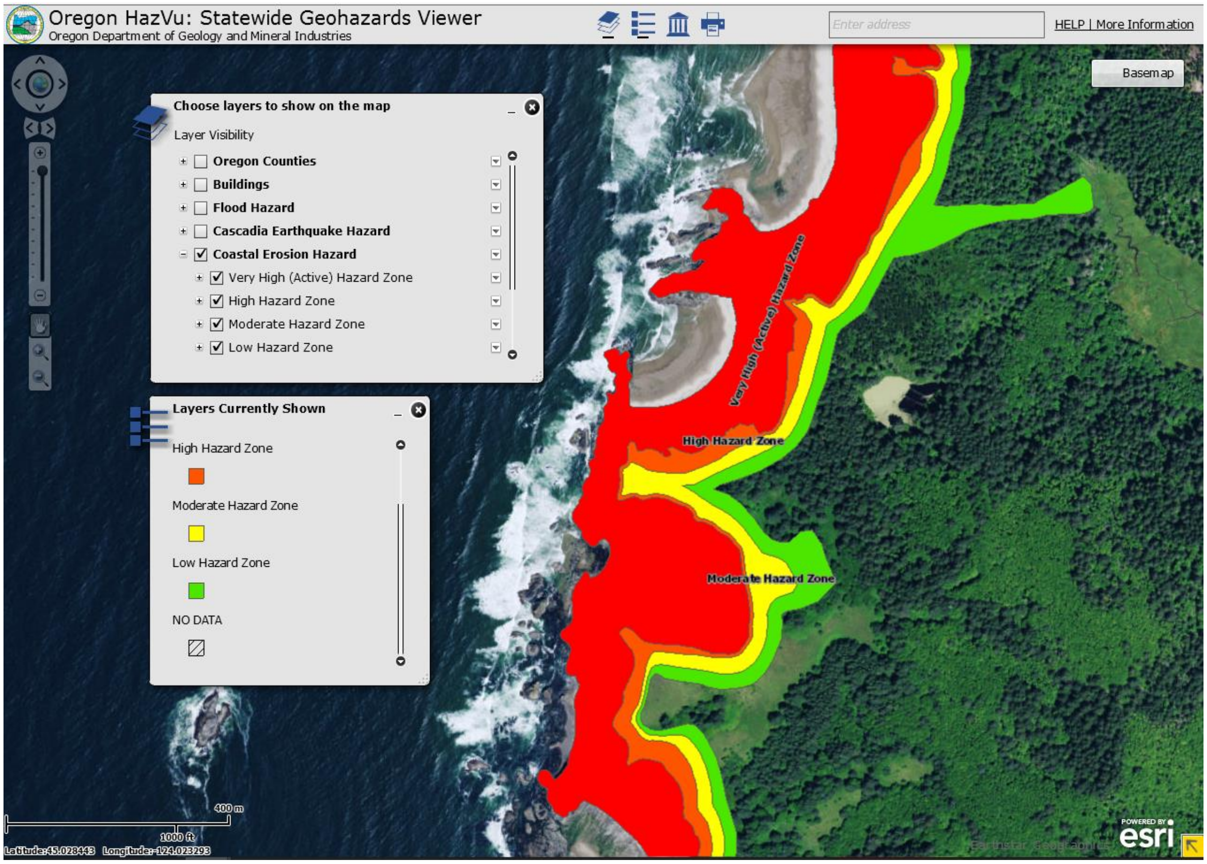


Figure 7: *Screenshot view of the DOGAMI model's coastal erosion hazard zones along a high-relief part of the Oregon coast. Erosion hazards decrease in the landward direction, and there is significant variability in the width of hazard zones in the along-coast direction. The maximum coastal-hazard zone width on this part of the Oregon coast is ~300 m (~1000 ft) (Image: from Oregon DOGAMI HazVu Statewide Geohazards Viewer, available at http://www.gis.dogami.oregon.gov/hazvu/).*

The BEP Index developed for the Pennsylvania coast identifies four erosion-potential swaths that are oriented approximately parallel to and track the present bluff crest. In order of decreasing erosion potential and increasing distance inland, these swaths 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 (Figure 2). The variable-width swaths cover the region between the bluff toe and a line located as much as 272 m landward of the bluff toe, beyond which the erosion potential is insignificant at building-lifetime timescales. The lakeward and landward edges of each swath are defined by coordinates calculated at each of almost 2850 DSAS transects (excludes non-bluff and no-data areas) spaced at ~20 m intervals along the entire bluff coast.

Map-Derived BEP Components

The widths of the BEP zones in map view vary along the coast, being controlled by the geotechnical properties of the bluff (e.g., shear strength, cohesion) and the failure-driving forces (e.g., gravity, wave attack, pore-water pressure, etc.) that are collectively reflected in the bluff retreat rate (Table 1). The width of each BEP zone in map view is determined using five parameters obtained from lidar-derived DEMs and aerial imagery using DSAS transect-generating software (Thieler at al. 2009). Data are obtained at DSAS transects using a 20 m along-coast spacing.

1 The present bluff slope (PBS), a value determined for each transect, in degrees (^{0}). 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. ~32^0 for the Walnut Creek watershed; ~43^0 for the Sevenmile Creek watershed), a geotechnical 26.5^0 stable-slope angle (SSA), and a planning-based 18.5^0 SSA, in degrees (^{0}).
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 simply in Figure 8 and in greater detail on an interactive web map at: https://e8arcport.ad.psu.edu/portal/apps/webappviewer/index.html?id=66f65224ed874d71b63cc0aafd5ab64f

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 on the basis of 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 (Figure 8). The 2015 toe elevation ranged from 0 - 6 m above Spring 2015 mean lake level. 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 will be widest where bluffs are tall, the AARR value is large, and the present bluff-face slope is relatively low.

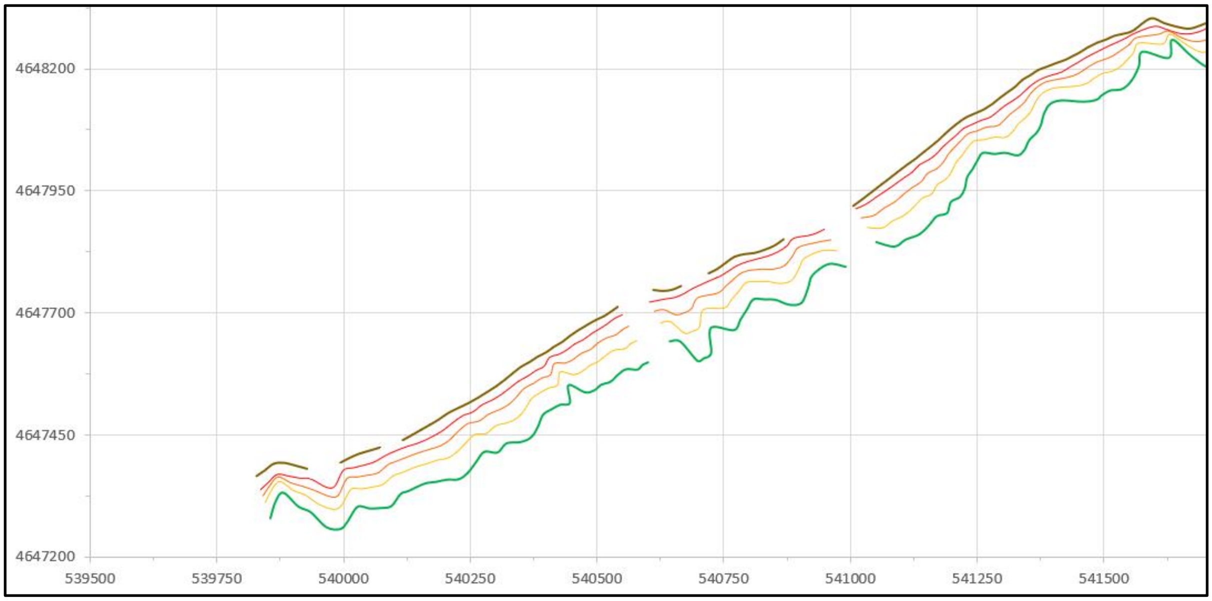


Figure 8: *Basic line-map view of the bluff vicinity extending eastward from the Ohio state line showing the BEP Index concept for the Pennsylvania bluff coast (250 m x 250 m UTM grid). Note similarities with the Oregon DOGAMI model shown in Figure 7. Lake Erie is on the top half of the image. Erosion 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 above, respectively. The two gaps denote "no data" zones where ravines cut across the bluff face. Combined, the BEP zones are ~100 m in total width along this highly erosional stretch of Erie County coast. On the BEP Index interactive web map, the BEP zones and 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 (see Assumptions & Limitations #19); 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 ~20 m per event and that 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., 0.2 m/yr), by sudden and catastrophic slumping on the bluff face (e.g., 20 m/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. In general, it 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 yrs), plus a horizontal distance related to the angular difference between the PBS and WSA slopes (Figures 2 and 8). For the entire coast, the landward limit of the HEP zone extends an average of ~12 m inland of the 2015 bluff crest and can locally extend as much as 72 m 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 26.5^0 SSA (see Assumptions & Limitations #18), 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 ~20 m 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 26.5^0 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 26.5^0 SSA. Numerically, the inland limit of the MEP zone at any given transect is equal to (AARR x 120 yrs) plus a horizontal distance related to the angular difference between the PBS and 26.5^0 SSA slopes (Figures 2 and 8). For the entire coast, the landward limit of the MEP zone extends an average of ~28 m inland of the 2015 bluff crest and can locally extend as much as 144 m 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 18.5^0 SSA (see Assumptions & Limitations #17), 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 yrs) plus a horizontal distance related to the angular difference between the PBS and 18.5^0 SSA slopes (Figures 2 and 8). For the entire coast, the landward limit of the LEP zone extends an average ~60 m inland of the 2015 bluff crest and can locally extend as much as 272 m landward.

Assumptions and Limitations of the BEP Index

The following section reviews the assumptions, geometric aspects, and possible limitations of the BEP Index model:

1. Because of uncertainty in climate predictions, the BEP Index assumes that 20th Century climate trends in the Great Lakes Basin will remain relatively unchanged through 2200. Consequently, the index does not attempt to incorporate the effects of changing precipitation (timing, form, and volume), storminess, and temperatures on bluff resilience. For example, the model does not include the bluff-stabilizing effects of drier climate periods nor the bluff destabilizing effects of wetter climate periods.

2. Because of uncertainty in predicting lake levels over multiple decades, the BEP Index assumes that 20th Century lake-level trends will continue relatively unchanged through 2200. Lake levels will continue to rise and fall over multi-year to multi-decade cycles, fluctuating about the long-term mean. The index consequently does not attempt to factor in the bluff-stabilizing effects of a lake-level fall nor the destabilizing effects of a lake-level rise.

3. The BEP Index assumes that the abundance and functionality of erosion-mitigating coastal engineering structures (recently comprising ~24% of the Pennsylvania coast; Stewart, 2001) will remain relatively unchanged over the next century. This may be accomplished through repairs to existing structures, long-term resilience of existing structures, ongoing replacements of failing structures by new construction and, overall, by no significant net addition or loss of structures (or structure functionality) to the coast.

4. The seven-year 2008-2015 bluff retreat data used in the bluff-change analysis part of this project are less than ideal for defining BEP Index hazard zones over the long term. Because of this, the BEP Index uses long-term 1838-2015 ($AARR_{77}$) rates of bluff retreat that use historical crest-position data (provided by the US Army Corps of Engineers; Cross et al., 2016) and 2015 lidar data acquired for this project. While positional uncertainty in the crest position for the 1938 data set mapped from T-sheets is on the order of +/-15 m, when annualized it is comparatively small and similar to the annualized uncertainties in the newer data (0.19 m/y annualized). The long-term 77-yr retreat rates are used at each of the almost 2850 DSAS transects where possible. Where data transects occur on short bluff stretches that lack a mapped 1838 crest, the BEP Index relies on a retreat-rate estimate for those transects based on the average long-term retreat rate for the specific coastal watershed within those transects are located. The long-term $AARR_{77}$ rate also averages out changes in the "engineering status" of the modern shoreline across its longer timeframe. While maximum sizes of bluff slumps are estimated to be ~20 m for the Pennsylvania coast from the few active and recent-historical slumps that are visible, the observational (empirical) time-series remains too short to derive statistically meaningful event frequencies and size characteristics.

5. Other medium- to long-term bluff-crest position data exist for the Pennsylvania coast but were not used in this project. Specifically, bluff crest locations for the entire southern Lake Erie coast were compiled by Cross et al. (2016) for 1878/1879 (from historical charts) and 1978 (from aerial photography) in a geospatial database. Retreat rates for that study were calculated using a DSAS transect spacing of 50 m, compared to this study's 20 m transect spacing.

6. Results from erosion hazard mapping in Oregon show that uncertainty in estimating bluff retreat is highest for bluffs with the potential for large, but infrequent, block failures. In some of

these areas, the DOGAMI methodology generated small bluff retreat predictions for their high hazard zone because large slumps were not well captured in their 55 yr dataset. Limitations due to this phenomenon were reduced by (1) adding a safety factor to bluff retreat (by doubling the AARRs), and (2) providing an additional component of retreat independent of the erosion rate by factoring in the difference between the present bluff slope and the stable angle of repose for bluff talus (~33^0). By similarly utilizing stable slope angles, the Pennsylvania BEP Index includes the latter factor, and excludes the former (more subjective) safety factor that seems arbitrary.

7. The erosional unconformity at the top of the shale bedrock toe in Erie County is assumed to be geometrically almost horizontal beneath the bluff and adjacent inland areas. While the subjacent shale and sandstone strata do dip gently southward at less than 5^0, this is unlikely to be the case for the capping unconformity at all locations. Significant topography can be seen on the unconformity at creek channels in both the along-coast and inland directions. This topography is due to Holocene downcutting (at an average rate of ~0.25 cm/yr) by streams responding to a drop in Lake Erie base level over the past ~10,000 years. Some bedrock topography may also exist due to bedrock scour by former Pleistocene ice sheets and basal tills that once covered NW Pennsylvania. Evidence of this can be seen just east of Twelvemile Creek where over-compacted glacial till in the bluff just above lake level contains large angular clasts of shale ripped from bedrock immediately beneath (Figure 9). However, the scarcity of detailed bedrock mapping in Erie County (c.f., Richards et al. 1987) precludes alternative realistic assumptions on the geometry of the bedrock surface beneath coastal watersheds in the vicinity of the bluffs. The geometry is important because an increase in bedrock elevation in the inland direction will lead to lowered rates of bluff toe retreat due to wave impact, and thus to lowered rates of bluff crest retreat (if groundwater complications are ignored). The opposite is also true. This geometric consideration can lead to rates of bluff retreat varying temporally as the bluff retreats landward over an irregular bedrock surface at a given location. Retreat rates will vary spatially because different sectors of bluff along the coast intersect different bedrock geometries as they retreat landward. Hence, the BEP Index timeframes are approximations rather than certainties.

8. Because of the more frequent presence of a thicker bedrock toe along more miles of bluffs, the eastern Erie County (EEC) AARRs are more strongly controlled by subaerial and groundwater processes, and less by hydrodynamic (wave) processes, than are the western Erie County (WEC) AARRs.

9. While bedrock retreat rates due to wave attack are not known for Erie County, bedrock areas are inferred to have a long-term AARR of 0.03 to 0.06 m/yr (values used by Wisconsin and Oregon, respectively, for similar materials). These low bedrock retreat rates at the toe of the bluff along specific stretches of the Lake Erie coast are interpreted to be integrated into likely slower long-term retreat rates observed at the bluff crest.

10. WEC non-bedrock and low-bedrock bluff sectors are inferred to have an AARR controlled more strongly by wave attack than by surface runoff and groundwater flux compared to sectors with a bedrock toe. Amin and Davidson-Arnott (1995) found that seasonal bluff erosion (April-December) on the lowermost 1.75 m of the bluff at a study site in WEC eroded at a maximum average rate of ~1.2 m/yr during a high lake-level (174.95 m) period. Of the 1.75 m of lower bluff monitored, wave-induced erosion and failure was greatest on the lowermost 1 m, with maximum rates occurring at ~0.5 m above the toe.

11. The BEP Index assumes that the $AARR_{77}$ (1938-2015) erosion rates utilizing historical data from Cross et al. (2016) and recent lidar data collected for this project will persist without significant change for the next one to two centuries. This is a significant assumption, considering that future lake-level and climate trends are unknown. However, the fact that AARR data are co-considered with stable-slope criteria in the BEP Index reduces the relative importance of errors associated with uncertainty in future AARRs.

Figure 9: *A 7 m tall section of glacial till and overlying lacustrine beds resting on bedrock (partly hidden by a 0.2 m thick prism of beach cobbles) east of Twelvemile Creek in eastern Erie County. The basal (darker) till horizon contains numerous large angular clasts of shale, ripped from underlying bedrock. The latter can cause significant topography to develop at the till-bedrock contact throughout the county.*

12. Bluff faces on the Pennsylvania coast and on most coasts exhibit complex variability in slope (micro- and meso-topography), with the slope angle varying with position on the bluff face. This complexity is governed by the interplay between bluff geotechnical properties, failure-event characteristics, and erosion/weathering processes. Because this variability in slope angle at different elevations cannot be realistically predicted, the BEP Index assumes slope planarity for present and future bluff faces. Average planar reference slopes (18.5^0, 26.5^0, WSA, and PBS) are used by the BEP Index for simplicity and repeatability. This means that bluff geotechnical properties are averaged over the entire bluff profile. The slope derived from lidar ground strikes on the bluff face is similar to simply dividing the bluff relief (Δz) by the horizontal

distance (x) between the toe and the crest along a given DSAS transect. While mathematically expedient, this assumption is a simplification.

13. Reference bluff slopes (WSA; geotechnical 33°; planning-based 18.5°) used in BEP zone delineation are similarly treated as planar surfaces due to the unknown 3-D geometry of the bluff interior (Figure 2). Normally, differences in the geotechnical properties and geometries of bluff strata would dictate differing slope angles for the face of each major stratigraphic unit. Internal 3-D geometry is known to be complex but geologic maps showing this detail are not available. For example, there can be 5 m of top-till elevation change over a short 25 m distance in the along-coast direction.

14. The plateau surface (tableland) landward of the bluff edge is assumed to be at the same approximate elevation as the present bluff crest. This is a simplification that solves the problem of determining where on a map an internal planar sloping surface (one of three reference SSA slopes), extended upward from the toe of the bluff at a specific angle, will intersect an undulating (non-planar) landscape. Because of this approximation, the HEP, MEP, and LEP zones will in reality be somewhat narrower than mapped (i.e., have a less conservative width) for landward-dipping tablelands and for bluffs backed by coast-parallel ravines. BEP zones will be somewhat wider than mapped (i.e., have a more conservative width) for lakeward-dipping tablelands. Because near-bluff landscape slopes within the BEP zones generally tend to be low (< 5°, away from ravines), the error induced by this assumption is expected to be relatively small.

15. The bluff toe is assumed to translate horizontally in a landward direction. Implicit in this assumption is that lake level will not vary significantly over a two-century timescale. Toe translation therefore does not have a vertical component due to possible lake transgression or regression. A vertical-upward translation of the bluff toe in response to a rise in lake level would cause the BEP zones to be narrower because bluff height would effectively decrease and the stable-slope planes would travel a shorter distance from toe to tableland. Conversely, a fall in lake level (regression) may not necessarily result in an increase in bluff elevation because the bluff becomes stranded in place and the toe does not translate lakeward: there would be no associated widening of the BEP zones.

16. For the purposes of the BEP Index, a natural bluff face on the Pennsylvania coast will attempt to approach an equilibrium grade over time (Figure 2). In the absence of toe erosion, which maintains steeper slopes and causes slope instability, a progressively more stable slope means that crest retreat rates will progressively decline and eventually become insignificant. Conversely, a continuance of toe erosion (the most common scenario) may significantly extend the length of time required for a slope to reach a quasi-stable state (e.g., 18.5° SSA slope) where the rate of crest retreat becomes insignificant. This is because any decrease in slope will be counteracted by continued bluff-toe retreat (Figure 4). In the latter case, continuous and high rates of toe erosion may prevent the bluff face ever achieving a stable slope angle, and long-term average crest retreat may then occur at rates similar to toe-retreat for decades to centuries. The process is complex.

    The slope re-grading process is driven primarily by subaerial weathering and erosion, due to groundwater flux and surface runoff. Conceptually, a typical bluff face is conservatively assumed to approach a WSA slope over ~50 - 100 yrs (~1 building lifetime); an angle-of-repose slope of ~26.5° over ~100 - 150 yrs; and a planning-based stable slope of ~18.5° over ~200 yrs (~2 building lifetimes). The timeframes involved in slope evolution are necessarily gross estimates with a large degree of uncertainty because data on the process timescales in Pennsylvania are not available. However, the time inferences are reasonable considering the results of bluff-slope evolution studies on the Chesapeake Bay, Maryland (Foyle, 2018). The BEP Index slope-regrading timeframes used here are also similar to those used in the Oregon (DOGAMI) coastal hazards analysis by Allan and Priest (2001) and Priest et al. (2004) (Figure 7). Concerning slope-regrading rates, Priest and Allan (2004) reported that subaerial erosion rates for Quaternary marine terrace slopes on the Pacific coast (with a ~33^0 stable angle of repose) are ~2.5 cm/yr (via sheet wash, soil creep, etc.) when wave-induced toe erosion is not occurring. In Pennsylvania, erosion rates at the bluff toe may locally approach zero if the bluff is partially protected from wave attack by engineering structures, offshore landforms such as Presque Isle, long-term accumulation of slump (colluvial) debris, deposition of wide and thick beach deposits in front of the bluff, or presence of developed lowlands at the base of the bluff (e.g., downtown Erie). However, the bluff may not attain quasi-stable low slopes if there is continued toe erosion and landward translation of the bluff, which tend to keep the profile steep. This effect will be more pronounced in westernmost Erie County (WEC) where toe erosion is in general more rapid historically because unconsolidated till is often present at, or just above, lake level. Conversely, a significant groundwater flux may enhance the slope-regrading process because aquifer horizons are in general located in the top half of the bluff. This is likely to be important along the tallest bluffs (e.g., near North East and Lake City) and where large forested wetlands occur on the tablelands between the bluff and PA Route 20.

17. The 18.5^0 (1:3) slope criterion in the BEP Index is a common and conservative planning-based SSA that is used here to define the landward edge of the LEP zone. A natural landscape slope at this angle is generally considered stable over the long term under most environmental conditions. It is an angle commonly used for regulatory purposes in determining construction setback lines on unconsolidated coastal bluffs where it is based on geotechnical analysis, inference, or slope measurements in the field. It is used on all of Ontario's Great Lakes bluff shorelines to set a line to which AARR-related setbacks are then added (Foyle, 2018). This low slope is also recommended in Wisconsin as the SSA to define a tableland intercept to which an AARR-related setback may then be added (Luloff and Keillor, 2016; Figure 5). This Wisconsin SSA is based on mapping on Lakes Superior and Michigan, where non-eroding stable slopes generally average between 18.4^0 and 21.8^0, respectively (Ohm, 2008; Foyle, 2018). Ordinance language used by Racine, WI, states that all permanent structures on Lake Michigan bluffs should be set back a distance needed to allow a stable slope, plus the distance of the expected shoreline recession over a sixty-year period, plus a minimum facility setback distance from the expected location of the future bluff crest (Figure 5).

    The concept of a stable slope angle in coastal planning, on which the 18.5^0 slope is predicated, varies with local geology and by state. In Wisconsin, for example, stable slopes range from 14^0 for red clay till, to 26^0 for sandy till, to 30^0 for sand and gravel, to 60^0 for bedrock. For context, Pennsylvania's Lake Erie bluffs generally consist of clay and sandy tills overlying shale bedrock, and are capped by sandy paleo-lacustrine and gravelly paleo-strandplain deposits (Figure 2). The till section typically dominates in thickness and hence the 18.5^0 SSA is an appropriate planning-based SSA to use in Pennsylvania. An 18.5^0 (1:3) slope is also used as a reference slope by the International Building Code (Foyle, 2018), and by states and municipalities who adopt their recommendations, as the threshold for determining how large building setbacks should be for static (no toe erosion) sloped terrains. The City of Seattle, WA, uses a similar 21.8^0 bluff-slope angle on slopes taller than 3 m to identify a no-build "Environmentally Critical Area" on the slope, an associated 15 m landward buffer, and an additional 4.5 m building setback (Foyle, 2018). The state of Washington coastal atlas considers, very conservatively, that unconsolidated bluffs are only stable when their slopes are less than 8.5^0. If groundwater flux is low or the bluff material is competent (e.g., bedrock), the stable slope angle may be larger. The state of Maine notes that slide-prone bluffs tend to be tall (>6 m); steep; clay rich; eroding at the toe (at Mean High Water Level, MHWL); and groundwater rich. Vegetation-poor slopes steeper than 20^0 are considered highly unstable. Slopes with moderate vegetation and slopes of 10-20^0 are considered unstable, while vegetated slopes flatter than 10^0 are considered stable, a criterion similar to that used in Washington.

Nationally, FEMA uses the stable slope setback concept in guidance materials for coastal construction but does not specify an angle: supporting graphics (Figure 6) suggest the angle may be close to the 18.5^0 slope angle described here (http://www.fema.gsov/residential-coastal-construction). Figure 10 shows a model Ohio DNR coastal-engineering design for mitigating erosion along Lake Erie bluffs. The recommended stable-engineered slope of 26.5^0 is similar to the geotechnical-based 26.5^0 slope described in the next section. In summary, for a bluff face on the Pennsylvania coast today, it is inferred that environmental processes will cause the bluff to evolve towards a ~18.5^0 slope by natural weathering, erosion due to runoff and groundwater flux, and rotational or translational slides and soil creep, over a timescale of one to two centuries. However, as reviewed above, toe erosion may prevent or slow progress towards a stable-slope equilibrium. In such cases, the bluff may maintain a steeper, eroding, profile over time (Figure 11).

18. The 26.5^0 (1:2) slope criterion in the BEP Index is a geotechnical SSA that is used to define the landward edge of the MEP swath. It is an intermediate-slope angle that lies between the 18.5^0 planning-based slope described above and the watershed slope average (WSA) measured from 2015 lidar data and averaging just under 33 ^{0} (1:1.5) for all coastal watersheds in Erie County. Properties or planned properties lying lakeward of the 26.5^0 slope intercept with the tableland may therefore be expected to be at greater risk from bluff retreat than properties progressively further inland (between the 26.5^0 and 18.5^0 slope intercepts) because the bluff crest will reach the former location sooner. The 26.5^0 slope criterion in the BEP Index is supported by Chesapeake Bay data on bluff-slope stability and evolution (Foyle, 2018). It also approximates a common stable angle of repose value for unconsolidated dry geologic materials (silts, sands and gravels) and is used in the definition of hazard zone boundaries in the Oregon DOGAMI model (Allan and Priest, 2001; Priest et al. 2004).

A similar 30^0 slope is used for coastal planning on the California bluff coast (Johnsson, 2003). In the case of overly steep or overhanging Pacific bluffs, the construction setback reference feature is no longer the bluff crest, but is a line on the tableland where a 30^0 plane projected upward and landward from the bluff toe intersects the landscape. On the Oregon coast, a comparable 26.5^0 (1:2) slope is used specifically for unconsolidated-sediment bluffs to define a more conservative landward edge for the DOGAMI low-risk hazard zone that is otherwise calculated using a 33^0 (1:1.5) slope angle (Priest et al. 2004). A similar 30^0 slope is also commonly used as an engineered landscape slope throughout the United States (Figure 10). Figure 12 shows an engineered 30^0 slope constructed where natural bluffs intersect the marina access road descending across the bluff face at Shades Beach Park in eastern Erie County. Figure 13 shows a natural bluff face with a somewhat similar (~37^0) slope that has been isolated from toe erosion for decades. In Pennsylvania, for a typical Lake Erie bluff face today, it is estimated that the bluff will approach this 26.5^0 slope by natural weathering, erosion due to runoff and groundwater flux, and rotational or translational slides and soil creep, over a timescale of ~100 – 150 yrs, provided toe erosion does not prevent equilibrium being reached.

19. The watershed slope average (WSA) criterion in the BEP Index is used to define the landward edge of the HEP zone. It is an average slope value determined for each of ~60 coastal watersheds by averaging the slopes obtained from all of the DSAS transects with slope data within a watershed. It averages 32.5^0 (1:1.5) for all coastal watersheds in Erie County. For the Lake Erie coast, it is inferred that a present bluff face slope (PBS) that is steeper than the WSA will regrade to this more-stable slope over a timescale of ~50-100 years (Figure 2). It will achieve this by natural weathering, erosion due to runoff and groundwater flux, soil creep, and through the possible occurrence of infrequent rotational or translational slides. If the bluff at any particular DSAS transect has a PBS equal to or less than the WSA, the bluff is inferred to retreat solely at the AARR over the following ~70 years as it evolves towards a 26.5^0 MEP slope.

    The WSA is a useful reference in the BEP Index when considered within the context of the "repetitive failure cycle" of Zuzek et al. (2003). In that model, stratigraphically complex bluffs frequently retreat through a "repetitive failure cycle" in which extended periods of relative bluff-crest stability (gentle slopes) alternate with short periods of instability (steep slopes) and pass through an "average-slope" bluff state (Figure 4). This failure cycle can result in extended periods of low AARRs as bluffs slowly steepen by toe erosion (time-1 to time-2) alternating with shorter periods of high AARRs as bluffs fail and enter a less-steep phase (time-2 to time-3) before subsequently entering a new steepening phase (time-3 to time-4). Given that steep slopes are more likely to fail than gentle slopes, bluff-face slope relative to a local average (e.g., a watershed slope average; WSA) may provide a qualitative indication of whether the bluff is likely to fail soon (steep slope areas), or whether it is likely to be stable for an extended period (gentle slope areas; Figure 4) because it has failed in the recent past.

    The WSA can be used in conjunction with the present bluff slope to generate PBS-WSA slope-difference maps. This permits a quick visual assessment of where, in a watershed or on a particular sector of bluff face, slopes are steeper (and therefore more likely to fail) or flatter (and therefore less likely to fail) than average. It is also a useful topographic concept for use in bluff management because certain vegetation species may be more appropriate for planting on steeper-than-average slopes compared to lower-than-average slopes. Steeper slopes, for example, will likely be more mobile (prone to soil creep) than gentle slopes.

20. The present bluff slope (PBS) used in the BEP Index ranges in slope from 15^0 to 72^0 by transect, with an average value almost equal to the WSA. PBS values may exceed the WSA at transects where toe erosion is unimpeded by the presence of engineering structures, a resistant bedrock toe, or a large-volume beach. Values may be lower than the WSA where toe protection exists because steeper slopes are not being forced by toe retreat, while subaerial weathering and erosion continue to cause regrading. It may also be lower than the WSA where groundwater flux causes enhanced crest retreat. The PBS slope at any given DSAS transect is the product of a complex interaction between failure-causing forces and bluff geotechnical properties that resist bluff failure. It is an average bluff-face slope measured from the 2015 lidar dataset at each DSAS transect and, in the BEP Index, is used to help delineate the boundary between the VHEP and HEP zones is therefore the average slope between the toe and crest of the bluff at a DSAS transect. For ease of calculation, this average slope treats the bluff face as a planar sloping surface when it is, in fact, primarily non-planar (Figure 14). The top portion of actively eroding bluffs often has a vertical to concave-outward face (due to slumping). The lower portion often tends to have either a convex-outward face due to accumulation of colluvium, or a near-vertical face due to bedrock presence (Figure 14) or toe erosion by waves that is accompanied by rapid removal of colluvium (Figure 3).

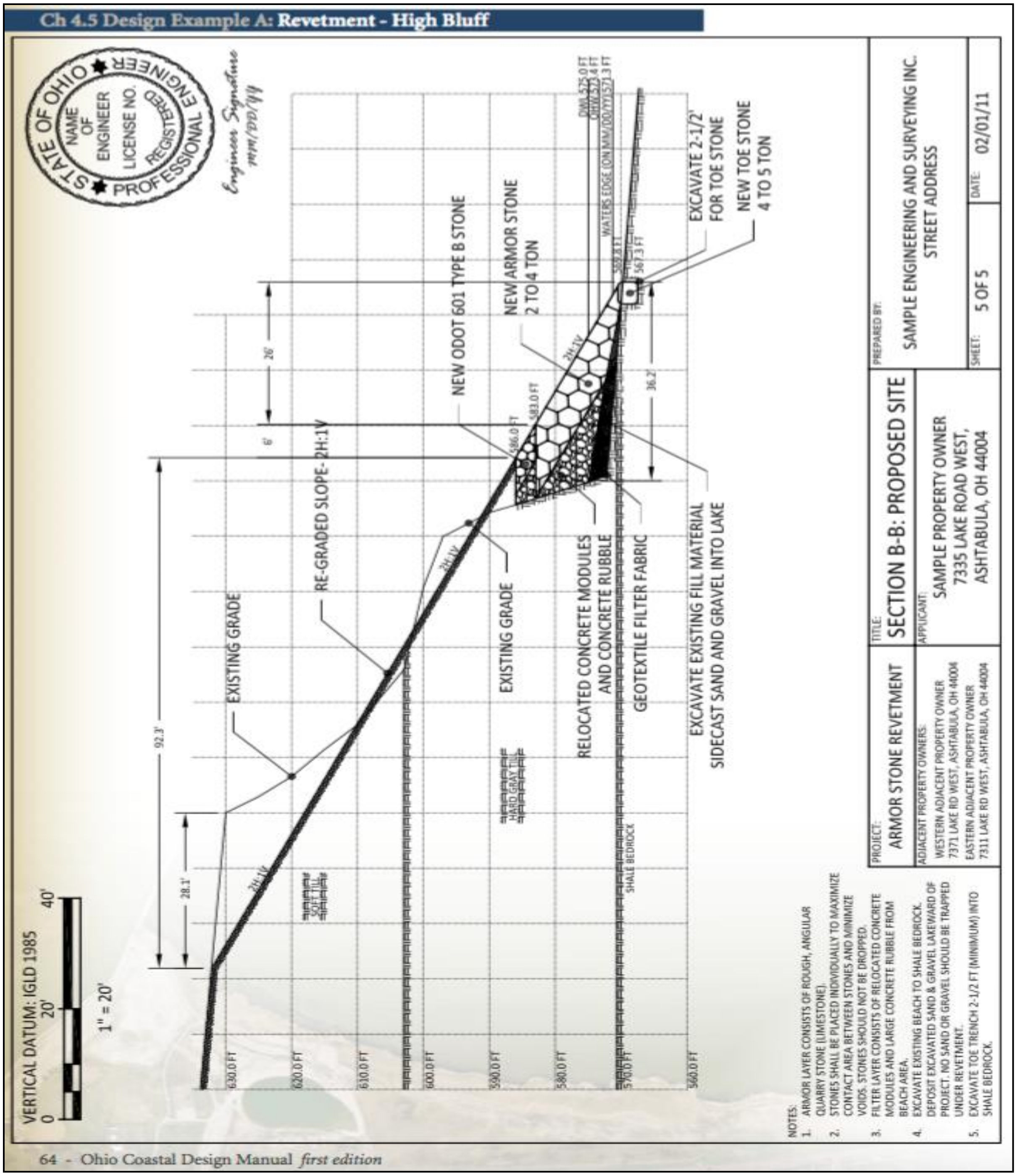


***Figure 10:** Model erosion-hazard mitigation design for a high (composite material) bluff on the Ohio coast showing a recommended engineered-stable slope of 26.5⁰. Such model plans (this one from Ohio DNR) provide guidance to coastal engineers (Image: modified from the Ohio Coastal Design Manual at http://coastal.ohiodnr.gov/portals/coastal/pdfs/designmanual/Ch4_5A.pdf).*

Figure 11: *Active erosion on relatively low-elevation (~12 m) bluffs in westernmost Erie County. Wave-induced toe erosion of the dominantly glacial till section, slumping due to groundwater flux, and the lack of a well-developed beach prism, result in a steep, non-equilibrium, rapidly retreating bluff face that does not attain a stable slope. Near-vertical jointing, common in the over-compacted glacial tills on this part of the Pennsylvania coast, causes the scale-like appearance of the bluffs (Image: from April 2015; available from Pennsylvania DEP Coastal Resources Management Program at http://www.dep.pa.gov).*

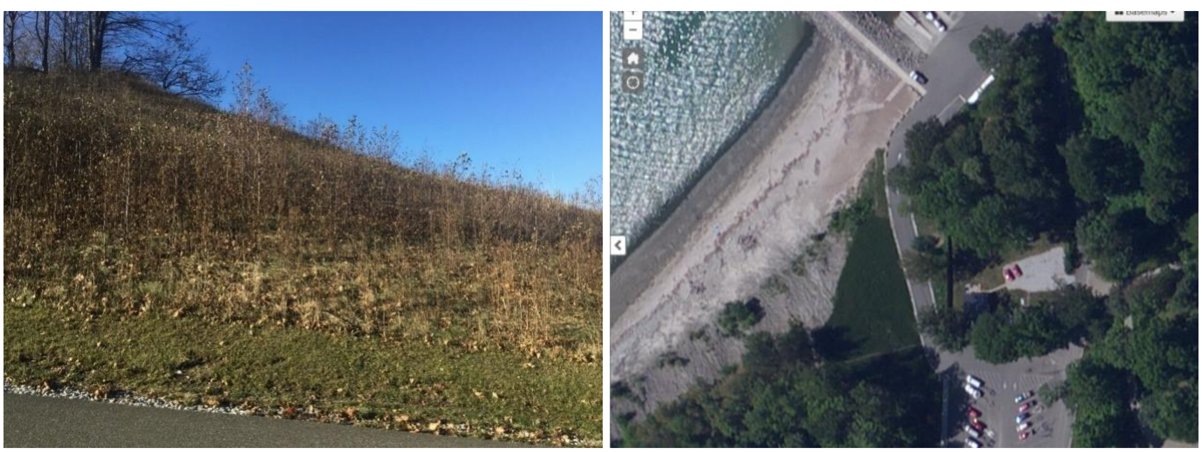


Figure 12: *Ground view of an engineered 30^0 slope constructed at Shades Beach Park in eastern Erie County (left), and aerial view of the same site (right). The slope marks the transition between naturally eroding bluffs to the west, and a marina-access road that descends across the bluff face to the lake. The ground view, looking west, shows mature trees developed at the top of the natural bluff in the background, and low-mass shrubs and grasses planted on the engineered slope in the foreground. The aerial view highlights the grassy engineered slope facing the roadway, and the steeper and poorly-vegetated eroding bluff face that faces the lake (Right image: google.com/maps).*

21. The landward edge of each BEP zone is an undulating line that represents an estimate of where the bluff crest will be located at future points in time. The estimate assumes continuity over time and space of ongoing environmental processes, the transect-derived AARRs, bluff geotechnical properties, and bluff elevation and internal stratigraphy. On the BEP Index interactive web map, the BEP zone boundaries are smoothed somewhat using a PAEK (Polynomial Approximation with Exponential Kernel) methodology.

22. The BEP Index geometric model does not provide property-scale resolution (even though on-screen magnification in a GIS may allow such apparent resolution). The goal of the Index is to identify bluff-top areas with differing degrees of erosion hazard. For individual properties, a site-specific slope-stability analysis, or a site geotechnical survey, by a licensed engineer would be recommended prior to remediation of existing problems or commencement of new construction.

23. In general, the erosion potential of the bluff-top plateau decreases with increasing distance landward of the bluff edge, and with increasing distance landward within an individual HEP, MEP, or LEP zone. BEP zone (swath) widths vary systematically along the coast, with only gradual changes to be expected between adjacent groups of properties. BEP zone widths may vary significantly between municipalities due to environmental differences between watersheds.

Figure 13: *A $\sim 37^{0}$ quasi-stable slope along the south side of Shades Beach Marina, eastern Erie County. The bluff toe has been isolated from wave attack for decades due to the presence of a wide beach fillet just updrift of Eightmile Creek and subsequent construction of a marina. View, looking east from the marina access road, shows mature vegetation on the bluff face, and a low-gradient engineered slope with planted grasses in the foreground.*

24. Active or recently active rotational slumps on the Pennsylvania coast have a maximum headwall jump of ~20 m and most commonly bottom out at the glacial till/lacustrine sand contact where debris chutes commonly begin. Translational slides generally bottom out at the same stratigraphic contact. Due to inter-grain cohesion and over-compaction, till may be more resistant to slumping than paleo-lacustrine silts/sands and paleo-strandplain sands/gravels under certain environmental conditions. Glacial till surfaces are often dominated by soil creep, thin mudslides, sheet wash, rill and gully incision by runoff, and small till bursts.

Figure 14: *Steep bluffs just east of Eightmile Creek in eastern Erie County. Bluff faces are typically non-planar because physical properties of the different stratigraphic layers differ. The basal bedrock cliff, where present, slopes at 45-90^o, commonly 55-65^o. The vegetation-free eroding glacial till section resting on bedrock typically has slopes of 40-50^o, while the talus partly covering the upper glacial till section typically has slopes of 40-60^o. Lacustrine sands and a thin soil profile at the top of this bluff commonly have 90^o slopes, occasionally reaching over 100^o when root masses bind the bluff material and allow overhangs to occur.*

25. Allan and Priest (2001) found that the maximum slump block width (headwall jump) for Oregon bluffs up to 45 m in height can be approximated as <u>bluff height/1.25</u>. For example, a slump on a 30 m tall bluff could result in a headwall jump as large as 24 m. A similar relationship may be valid for the Pennsylvania coast, given the broad similarities in bluff sedimentology in both areas. The infrequent headwall jump process, while rapid and potentially catastrophic locally, contributes to slope regrading over time.

26. A well-engineered toe structure or offshore breakwater may reduce or arrest toe erosion and significantly reduce the AARR value at a DSAS transect over the lifetime of the structure. This is

a fundamental premise in coastal engineering (Figure 1, Figure 10) but the slope landward of the toe will continue to weather and erode towards a more stable slope configuration that will cause crest retreat despite toe stability.

27. A non-eroding sector of bluff with a stable slope may be reactivated and begin renewed crest retreat if toe erosion is initiated due to toe-structure failure or changes in environmental conditions (lake level rise; wave climate, meteorology, etc.).

28. Shale-toe bluffs will generally, but not necessarily, exhibit lower crest-retreat rates. An exception occurs when groundwater flux and/or runoff are important contributors to bluff retreat at a site (Figure 15). In general, lower toe-retreat rates may allow the HEP, MEP, and LEP zone boundaries to be located at more lakeward positions after a specified time interval than would otherwise be the case. Because of this, it is likely that bluffs in eastern Erie County will have narrower BEP Zones than bluffs of similar height in western Erie County because their AARRs will be lower due to the presence of a tall bedrock toe.

29. Historical aerial photography suggests that most beach deposits on the Erie County bluff coast are ephemeral and mobile. They respond to changes in bluff sediment supply, upstream littoral sediment supply, and creek sediment supply; lake level; sediment-trapping engineering structures; and wave climate. While the lifetime of a natural beach in a particular coastal watershed is not well constrained, beach presence or absence will influence bluff retreat because a beach affects how much wave energy reaches and erodes the bluff. Longer-term AARRs (multiple decades) are more likely to incorporate (or average out) this phenomenon while short-term rates are not. This is important because this is another reason why long-term coastal change data can be more valuable than short-term data.

Figure 15: *Bluff and old seawall with a well-developed, 3.5 m tall, steep bedrock toe just west of Twelvemile Creek in eastern Erie County (left). A steep ravine exits the bluff just left of the pine tree on the bluff face. Despite the resistant bedrock toe, non-hydrodynamic forces cause slope failure and crest retreat at this site. In the DEM map view (right), the steep ravine erodes due to focused groundwater flux (a subsurface process) through strandplain gravels. The bluff crest occurs at the sharp slope change (shown by a transition to darker color shades due to the tight contour spacing), while the lake surface is the dark-grey zone towards the top-right on the map.*

30. Groundwater flux (m^3 of water/m^2 of bluff face/day; or m/d) through the bluff face will in general decrease over time as a bluff face regrades to a lower slope angle. This is because the cross-sectional area of an aquifer horizon at the bluff face increases with decreasing bluff-face slope, other factors being equal. The destabilizing effects of the groundwater flux will similarly decrease. This phenomenon may allow the bluff retreat rate to decrease over time in areas where groundwater flux is important because pore water velocity through the bluff material will progressively decline.

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