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# National Assessment of Historical Shoreline Change: A Pilot Study of Historical Coastal Bluff Retreat in the Great Lakes, Erie, Pennsylvania

By Cheryl J. Hapke, Shamus Malone, and Meredith Kratzmann



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Cover: Actively failing bluff along Lake Erie, Pa., coastline. Photograph by Shamus Malone,  
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# National Assessment of Historical Shoreline Change: A Pilot Study of Historical Coastal Bluff Retreat in the Great Lakes, Erie, Pennsylvania

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## Abstract

Coastal bluff retreat is a chronic problem along many high-relief coastlines in the United States. As coastal populations continue to grow and community infrastructures are threatened by erosion, there is increased demand for accurate information regarding trends and rates of bluff retreat. There is also a need for a comprehensive analysis that is consistent from one coastal region to another. To address these national needs, the U.S. Geological Survey (USGS), as part of the National Assessment of Coastal Change Hazards Project, conducted a pilot study of bluff retreat along the Lake Erie, Pa., coastline to assess the feasibility of undertaking a larger, multi-state analysis in the Great Lakes region. This report provides an overview of the pilot-study location and bluff geomorphology, the data sources and methodology, results of the analysis, and a discussion of the feasibility of undertaking a similar analysis along eroding bluffs in other Great Lakes states.

This pilot study is part of an ongoing effort by the USGS to provide a comprehensive analysis of historical shoreline change and cliff and bluff retreat along open-ocean coastlines of the conterminous United States and parts of Hawaii, Alaska, and the Great Lakes. One purpose of the work is to develop standard, repeatable methods for mapping and analyzing coastal change so that systematic and consistent periodic updates of coastal erosion can be made nationally.

Bluff-retreat evaluations are conducted by comparing the location of a historical bluff edge digitized from aerial photographs with those of recent bluff edges interpreted from both aerial photographs and lidar topographic surveys. The historical bluff edge is from 1938, whereas the more recent bluff edges are from 1998 and 2006 lidar data. Long-term (68-year) rates of retreat are calculated using the available bluff-edge data. The rates of retreat presented in this report represent conditions from the 1930s to 1998/2006, and are not intended for predicting future bluff-edge positions or rates of retreat. The report presents bluff-retreat rates for 32 km of a 60-km stretch along the Lake Erie, Pa., coastline. Data are discontinuous due to gaps in source data and lack of continuous bluffs.

The average rate of coastal bluff retreat for the Lake Erie, Pa., bluffs was  $-0.3 \pm 0.1$  m/yr (retreat rates are presented as negative numbers in this report), based on rates averaged from 1,595 individual transects. Retreat rates generally were lowest where bedrock outcrops are exposed as the basal unit in the bluff. The highest rates are associated with anthropogenic activities, including jetties that trap littoral sediment, depleting a source of material for the natural replenishment of protective beaches downcoast, and extensive irrigation of farmlands on the tops of the bluffs, which can destabilize bluffs by enhancing ground-water outflow.

## Introduction

Although the rates are variable, most of the bluffs along the Lake Erie, Pa., coast are in an erosional state. Bluff retreat results in loss of land and damage to private and community properties. Because coastal environments are of critical importance to the tourist industry and residential development, the U.S. Geological Survey (USGS) is conducting a National Assessment of Coastal Change Hazards. One component of this effort, the National Assessment of Shoreline Change, documents changes in shoreline position as a proxy for coastal change (Morton and others, 2004; Morton and Miller, 2005; Hapke and others, 2006). The USGS has also completed an assessment of coastal cliff erosion in California (Hapke and Reid, 2007) as part of the National Assessment project. In the case of this analysis, the coastal change being assessed is the erosion at the upper edge of the coastal bluff, a commonly used indicator of coastal bluff retreat. The bluff top is used instead of the base for several reasons: (1) the base is sometimes obscured by shadowing in our data sources; (2) the bluff base is irregularly interpreted on the historical imagery; and (3) emplacement of seawalls and revetments, some of which may not be identifiable on the light detection and ranging (lidar) data, can result in apparent accretion of a bluff base.

A principal purpose of the USGS coastal change research is to develop repeatable methodologies for measuring change so that the database of change along the coast of the United States can be periodically and systematically updated in an internally consistent manner. The primary objective of this effort is to implement consistent and regionally applicable methods of assessing and monitoring coastal bluff retreat.

## Prior Assessments of Lake Erie Bluff Retreat

In 1974, the Coastal Resources Management Program (CRM) of the Pennsylvania Department of Environmental Protection (PA DEP) undertook an inventory of shore hazards, including coastal flooding and bluff recession. This study (Knuth and Crowe, 1975) was intended to determine the degree to which shoreline erosion and bluff retreat were occurring in Erie County. The study also justified the creation of structural setbacks. The Commonwealth of Pennsylvania passed the Bluff Recession and Setback Act in 1980. Included in the terms of the Act was a stipulation that required CRM to continue to monitor and update recession rates, with new recession studies to be undertaken periodically. Pennsylvania, in accordance with the requirements of the Bluff Recession and Setback Act, has monitored its recession rates at least once every 4 years since 1982. Initial bluff-monitoring control points were established in 1982, with additional control points added in 1985 and 2002. Bluff-recession measurements at 125 fixed control point monuments were made in 1982-83, 1986-87, 1989-90, 1994-95, 1998-99, 2002-03, and 2006-07.

Long-term (25-year) average retreat rates as high as 1.0 m/yr at specific control-point locations and bluff recession up to 11.3 m between monitoring cycles have been documented as part of the monitoring program. Some control points are in stable bluff areas and show no measurable recession. Although the long-term average recession rate based on all the control points for the Lake Erie Coastal Zone is 0.23 m/yr, recession tends to be spatially variable and temporally episodic. Additionally, the control-point measurement sites were chosen independently of known erosion hazard areas; therefore, in some cases, very low retreat rates were measured as part of the study when rates in immediately adjacent areas were much higher. The location of a control point at which the long-term recession rate is 0.04 m/yr is

shown in figure 1. The control-point location does not accurately reflect the high rates of retreat and high hazard in the area. In contrast, a long-term recession rate of 1.0 m/yr was documented at an adjacent control point (fig. 2), located in what was found to be a rapidly receding stretch of coastline. Because the control points are randomly located with respect to coastal processes, recession hazard is adequately monitored at some locations but not at others.

The Pennsylvania monitoring effort has generated highly accurate bluff-retreat data and a robust temporal database. Because the field measurement effort is labor intensive, the resulting spatial density of control points (approximately 0.5 km apart) may not adequately capture the greatest erosion hazards.

In 1994, the U.S. Army Corps of Engineers (USACE) published a report describing available bluff retreat data and assessments that existed for all of the Great Lakes coastlines, including methods used and data accuracy. According to this report (Stewart, 1994), earlier assessments of bluff retreat were undertaken in the mid 1970s by using aerial photographs from 1938/39-1975 (Knuth and Crowe, 1975) and photogrammetric methods to determine a long-term rate of bluff retreat for a 36-year period. The 1994 USACE report was intended to present prior methods of determining bluff retreat, not to provide new data.

Although numerous analyses of bluff retreat have been conducted throughout the coastal United States including the Great Lakes, a critical need remains for (1) a nationwide compilation of reliable retreat data that includes a modern bluff-edge position and (2) a standardization of methods for compiling and comparing cliff positions and mathematically analyzing the trends.

## **Geology, Physiography, and Recession of the Coastal Bluffs along the Pennsylvania Portion of Lake Erie**

The coastal bluffs along Pennsylvania's Lake Erie shoreline in Erie County (fig. 3) are located in the Eastern Lake Section of the Central Lowland Province (Knuth and others, 1981; Pennsylvania Department of Conservation and Natural Resources, 2000) (fig. 4). The region is north and west of the Appalachian Plateau Province. The escarpment marking the division between the provinces is visible from most areas of the coastal zone (fig. 5). Surface drainage is from the lowland north to Lake Erie and is locally controlled by glacial deposits. The physiography and topography are a function of geologic structure, bedrock strata, and Pleistocene glaciation (Knuth and others, 1981).

A series of northwest-sloping, lake-parallel, low-relief ridges make up the Eastern Lake Section of the Central Lowland Province. The ridges are unconsolidated sands and gravels that were deposited during the most recent deglaciation of the area about 18,000 years ago. The ridge bordering Lake Erie at one time sloped gently into the lake. Erosion of the shoreline has resulted in a southeastward retreat of the lake-land interface and the formation of steep bluffs adjacent to the lake.

The coastal bluffs of the Great Lakes are underlain by bedrock that is exposed at the base in some areas (Sevan and Braun, 1997). Quaternary continental glaciation produced several ice-sheet advances into northwestern Pennsylvania (Knuth and others, 1981). During each advance, materials generally consisting of glacial till were transported from the northeast and deposited locally. The tills on the bluffs of Erie County are made up of fine-grained till that overlies the Devonian shales, which were partially eroded prior to the glacial deposition, producing an irregular surface and intermittent exposures along the shore (Knuth and others, 1981). Overlying the glacial tills and visible on exposed bluff stratigraphy are

lacustrine, strand, and alluvial deposits. Lacustrine deposits are the result of proglacial lakes depositing thinly interbedded clayey silt and silty clay. The strand deposits are also the result of proglacial lakes in the form of ancient shorelines of silty sand, sand, and sand and gravel. In many places the bluff stratigraphy is obscured by an accumulation of colluvium, which forms large debris fans on the lower bluff face that are commonly covered with pioneer vegetation (Knuth and others, 1981).

Bedrock exposures at the base of the bluffs in the coastal reach east of Presque Isle and locally west of Presque Isle (figs. 6 and 7) are of the Canadaway Formation, Middle Upper Devonian in age (Pennsylvania Department of Conservation and Natural Resources, 1990). The bedrock along the base of the bluff influences coastal processes in three ways. First, in areas of sand deficiency, precluding beach development, the bedrock exposures act as a natural seawall with respect to wave energy. The reflection of wave energy removes sediment from the nearshore and deposits it farther offshore (Knuth and others, 1981). As a result, sediment that might have been available is removed from the longshore transport system, exacerbating sediment deficits and precluding beach development. Second, exposures of bedrock in the zone of breaking waves promotes "plucking," which produces shingles from a few centimeters to 1 m in size. This eroding bedrock is an important source of siltstone gravels (Clemens, 1976). The capacity of the littoral transport system to move those shingles substantial distances is evidenced by the volume of shingles seen on Presque Isle Beaches, as much as several kilometers downdrift from the nearest bedrock exposures. The shingles tend to remain in the nearshore (fig. 7) as a result of the large grain size, providing material for beach building as they weather. Third, linear joints in the bedrock that are exposed to storm waves expand by hydraulic force to produce the incised or cusped morphology seen in the bluffs east of Presque Isle (fig. 8). On a larger scale, these incisions produce headland-cove morphology, and pocket beaches tend to form in the sheltered areas (Knuth and others, 1981). In most cases, the small pocket beaches are the only beaches along the reach from the City of Erie east to Six Mile Creek (fig. 3).

Pennsylvania's bluffs range in height from 1.5 to 60 m. Without wave contact at the base, bluffs are inherently stable, with only minimal loss of soil due to gravity-induced bluff creep, usually visible only at the bluff crest. Heavy ground-water flows exiting the bluff face between the lakeward tilted glacial till (clay) layer and permeable lacustrine sands and gravels supply adequate moisture to support trees and a dense mat of vegetative cover. The bluff consists mostly of a clay-rich glacial till and because the roots of the forested vegetation mat are unable to penetrate the clay substrate, the mat simply lies on the bluff face as a mat of roots and organic mass. There is a delicate balance between the root mat and the ground water, which exits the upper bluff face above the glacial till. The ground water moves down through the mat, nurturing vegetative growth. Within a healthy stabilized bluff, the ground water is completely absorbed into the root mat and the system is balanced (fig. 9a). When lake levels are high or during large storms, waves can reach the base of the bluff, causing extensive erosion of the unconsolidated soils and unprotected vegetation mat (fig. 9b). When the vegetation mat is removed from the base of the bluff, the upper areas of the bluff face become unstable, causing the upper vegetation mat to break apart, slip, and collapse in sections to the base of the bluff (fig. 9c). Wave erosion will continue to remove collapsed vegetation-mat sections until all debris is eroded from the base of the bluff. Steep bluff slopes denuded of vegetation are further susceptible to other erosion processes (ground-water flow, surface-water flow, wind, and rain) (fig. 9d) and will continue to recede landward until an angle of repose is established (fig. 9e).

The most common type of bluff retreat along Lake Erie is in the form of soil slides. There are two common types of slides—rotational and translational. A rotational slide fails

along a concavely curved rupture (see fig. 2). The resulting slump surface is spoon-shaped and is rotational about an axis that is parallel to the slope (Varnes, 1978). The classic slump is common in homogeneous materials. Rotational slumps tend to occur in clayey soils and not in sands.

In translational slides, the mass of soil progresses down and out along a more or less planar surface and shows no rotational or backward tilting characteristics of a slump (Varnes, 1978). Translational slides (fig. 10) tend to move as one mass, and the separation line is somewhat linear in appearance.

Along Lake Erie, most bluff instability starts with wave contact at the base. Ground water flow is common and is a secondary erosional process in creating bluff instability and in advanced stages of bluff recession. CRM has determined through field experience, observation, and project trial and error that, in most cases, ground-water flow is not a catalyst of bluff recession but is simply an ambient hydraulic feature that becomes visible when vegetation is removed from the bluff profile. Erosion driven by both ground water (elevated pore pressure) and surface-water overflow is necessary to bring the steep bluff profile back to the angle of repose. Groundwater is also necessary on reposed bluff profiles to promote rapid revegetation of bluff slopes.

## Methodology

The methods used in this analysis closely follow those of Hapke and Reid (2007), who developed a methodology for estimating regional-scale coastal bluff retreat for California. As in Hapke and Reid (2007), the modern bluff edge used in this analysis is interpreted from lidar data. Lidar from 1998 and 2006 were available for most of the Lake Erie, Pa., coastline. Additionally, a historical bluff edge (1938) was digitized from existing orthophotographs.

In order to interpret a bluff edge from the lidar data, digital elevation models with a 1-m-cell size were created from lidar data using standard geographic information system (GIS) methods. A hillshade rendering for each grid was generated and used to digitize the interpreted bluff edge using the visual break in slope. A hillshade, or shaded relief map, uses slope and aspect data to determine a hypothetical shaded surface that visually enhances surface features. Hillshades are useful for enhancing the visualization of a surface, and the resulting three-dimensional rendering was used to interpret and digitize the bluff edge using the visual break in slope. This visual rendering approach has advantages over slope or second-derivative (gradient) methods of edge enhancement in that objects such as buildings or vegetation that are near the bluff edge are easier to identify and omit from the data set (Hapke and Reid, 2007). The bluff top along the Lake Erie, Pa., coastline is heavily vegetated with relatively tall trees that obscure the bluff edge in many places. Therefore, the slope and gradient methods are not regionally applicable.

Along most of the Lake Erie, Pa., coast, the bluff is a flat-topped, elevated terrace with a distinct lakeward edge (see figs. 1, 2, and 5). In some areas, however, there is no well-defined break in slope, or the break is obscured by dense vegetation. In these situations, the interpretation of the bluff edge from the lidar data reverted to the same feature that was surveyed on the historical maps, as determined by superimposing the two data sets. Aerial photographs and the orthophotographs were frequently utilized when digitizing the bluff edges from the hillshades to resolve ambiguities in the identification of the bluff edge.

Gaps in the bluff-retreat analysis occur primarily in areas where streams dissect the continuous bluff line or in lowland areas (such as Presque Isle). This pilot study presents bluff-retreat rates for 60 km of the Pennsylvania coast. Gaps result when the bluff edge is

ambiguous or absent. In addition, single transects were eliminated in areas where there are long, narrow headlands or deep, narrow gullies, because these features represent singularities not representative of overall bluff change.

Rates of bluff retreat were generated in a GIS with the Digital Shoreline Analysis System (DSAS), an ArcGIS© extension (Thieler and others, 2005). This tool contains three main components that define a baseline, generate transects perpendicular to the baseline that intersect the bluff edges at a user-defined separation along the coast, and calculate rates of change based on measurement locations established by the transects. A baseline was constructed lakeward of, and roughly parallel to, the general trend of the bluff edge. Using DSAS, transects were spaced at 20-m intervals.

In this study bluff-retreat rates were averaged over a 68-year time period for the western portion of the area and over a 60-year time period for the eastern portion (fig. 3). Averaged rates of coastal change are frequently used in coastal-zone management and can provide information on the spatial distribution of regional bluff-retreat trends, but they provide little information on specific hazard zones because of the highly variable nature (both spatially and temporally) of coastal bluff-retreat process and response. The dominant influences on the temporal variation of coastal bluff retreat are related to weather variations (storm intensity and frequency), climate variations, and fluctuations in lake-water levels. Spatial variations in bluff retreat are related to the physical characteristics of the bluff-forming material (lithology and geologic structure) and anthropogenic impacts such as irrigation and the emplacement of protective structures. Because bluff retreat and rates of bluff retreat vary substantially in space and time, the averaged data presented in this report are not a good predictor of future annual change.

Following the methodology used by Hapke and others (2006) and Hapke and Reid (2007), the total cliff-edge position error ( $E_p$ ) is calculated by adding in quadrature the orthorectification error ( $E_r$ ), digitizing error ( $E_d$ ), and lidar bluff-edge position uncertainty ( $E_l$ ):

$$E_p = \sqrt{E_r^2 + E_d^2 + E_l^2} \quad (\text{Equation 1})$$

The orthorectification error represents the estimated maximum root mean square (RMS) error for orthophotographs at a scale of 1:12,000 in this study. The digitizing error reflects the maximum error specified in past studies (Anders and Byrnes, 1991; Crowell and others, 1991; Moore, 2000; Hapke, 2004) and is applied to the historical bluff edge only. Lidar cliff position error is the maximum error associated with the lidar positioning and GPS errors (Stockdon and others, 2002) for the modern date.

A separate  $E_p$  is calculated for each time period and data source ( $E_{p1}$  and  $E_{p2}$ ). These values were combined and annualized to provide an error estimation for the bluff-retreat rate at each transect. The annualized error ( $E_a$ ) is expressed by:

$$E_a = \frac{\sqrt{E_{p1}^2 + E_{p2}^2}}{\text{time}} \quad (\text{Equation 2})$$

## Bluff-Retreat Rates

The coastline of Lake Erie is divided politically into seven townships and the City of Erie (fig. 3), which extend from Springfield Township in the west to North East Township on the east, next to the Pennsylvania-New York border. For the pilot study, bluff-retreat rates were assessed separately for two sections of coast, defined by the availability of 2006 versus 1998 lidar data. Wherever possible, the most recent data were used. However, no lidar data are available for 2006 for most of Harborcreek Township (8 of 11 km) and all of North East Township. This portion of the coastline is referred to in the discussion as the “eastern section,” and the rates presented are 60-year assessments, from 1938 to 1998. The end-point rate was used because there were only two dates of bluff edges available. The bluff-retreat rates for the western section, composed of the remaining five townships (Springfield, Girard, Fairview, Millcreek, and Lawrence Park) and 3 km of Harborcreek Township, are assessed over a 68-year time period, from 1938 to 2006. No bluff retreat data are presented for the City of Erie, as it is a heavily developed and engineered coastline with few measurable bluffs.

For the eastern section of the Lake Erie, Pa., coastline, the average bluff-erosion rate was  $-0.2 \pm 0.1$  m/yr, which is equal to an average retreat of 12 m over the 60-year time period of the analysis (table 1). The eastern section is 22 km in length but because there are many data gaps, retreat rates were calculated along only 4.7 km. The rates of bluff retreat are highest in the central portion of the section, where the maximum rate of  $-1.0 \pm 0.1$  m/yr was measured (fig. 11). The highest rates are found along a stretch of coast in the western 6 km of North East Township. The actively eroding bluffs (fig. 2) are in areas where the land use on the top of the bluff is predominantly agricultural, suggesting that irrigation may, in part, be responsible for the higher rates. The active bluffs, slump deposits, and headscarps are readily visible on Google Earth satellite imagery (<http://earth.google.com/>).

The western section is a total of 40 km in length along which 68-year bluff-retreat rates were generated for 27 km of coast. There is a large data gap extending from Presque Isle in Millcreek Township to the eastern boundary of the City of Erie (fig. 3). The average rate of bluff retreat in the western section is  $-0.3 \pm 0.1$  m/yr (table 1), and rates are consistently higher west of Presque Isle (fig. 12). The highest rate in the western section,  $-1.0 \pm 0.1$  m/yr, is in western Girard Township just east of several groins. Additionally, a large portion of the Springfield Township bluffs has high rates of retreat (0.6–0.8 m/yr). Predominant littoral transport rates along the Lake Erie, Pa., coast are east to west. The higher rates of erosion in these areas are likely related to the impoundment of littoral sediment behind the nearby upcoast Conneaut Harbor jetties and, more locally, groin fields. The trapping of these sediments essentially eliminates the source of protective beach material for the downcoast bluffs. The trend of lower erosion rates with distance from the harbor jetties is additional support for the influence of the jetties on the coastal system.

## Conclusion

One goal of this pilot study was to explore the feasibility of conducting a regional bluff-retreat assessment for the Great Lakes coastal zone. Each state uses a different approach to address erosion hazard, and there is little regional consistency in what data are available and how bluff-retreat rates are measured and presented.

The relatively recently available (2006, 2007) lidar data set collected by the USACE provides a regional, modern source for future coastal hazard assessments. However,

historical data (aerial photography or maps) are not consistently available, although they are likely to exist and to be of sufficient quality for use in a long-term bluff-retreat assessment. Additionally, because available historical bluff edges are not easily accessible in digital format, as part of any long-term bluff retreat assessment the bluff edge would need to be generated from original data sources.

A regionally consistent assessment of coastal-bluff hazards in the Great Lakes area would require significant resources, but the resulting database would be valuable as a management tool for coastal-zone managers of the Great Lakes states.

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**Table 1.** Summary of the length, number of transects and rates of bluff retreat, Erie, Pennsylvania.  
[m, meters; m/yr, meters per year]

Coastal section	Number of transects	Average retreat rate (m/yr)	Total retreat (m)
Western	1,359	$-0.3 \pm 0.2$	20.4
Eastern	709	$-0.2 \pm 0.2$	12.0



**Figure 1. (A)** This low-angle oblique aerial photograph shows an area of high recession along Lake Erie, Pennsylvania, bluffs that is not documented in a State Coastal Resources Management Program monitoring study as a result of the original location of the control point from which distance to the bluff edge is measured. **(B)** This low-altitude vertical aerial photograph of the same area shows the location of the control point (blue dot) and the azimuth (blue arrow) along which the transects are measured. Photographs from Pennsylvania Coastal Resource Management Program.



**Figure 2. (A)** This low-angle oblique aerial photograph shows a location along the coast of Lake Erie, Pa., where high bluff recession was accurately documented in a Pennsylvania Coastal Resources Management Program monitoring study because the location of the control points along which bluff retreat is measured captured the large landslide. **(B)** This low-altitude vertical aerial photograph of the same area showing the location of the control point (blue dot) and the azimuth (blue arrow) along which the transects are measured. This is also the area of the highest measured retreat rate (1.0 m/yr) assessed in this pilot study. Photographs from Pennsylvania Coastal Resource Management Program.

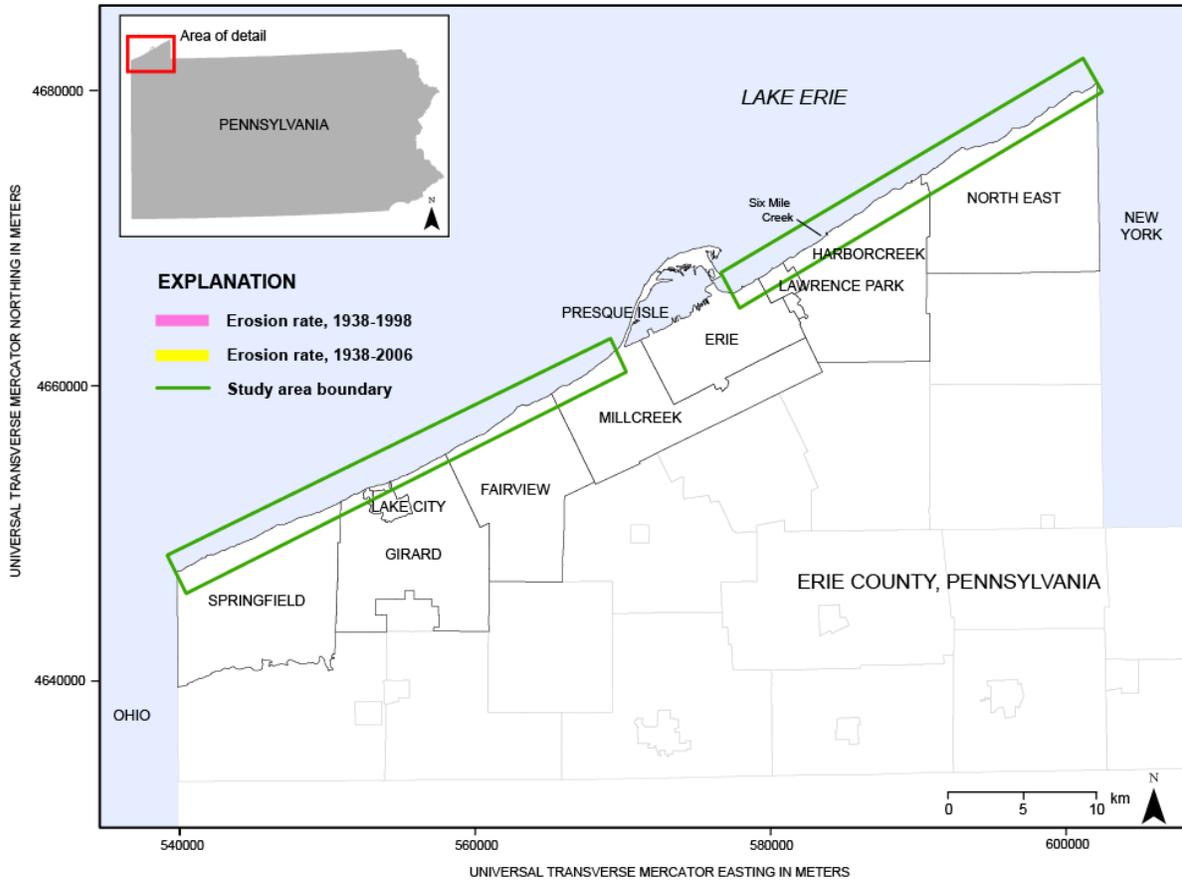
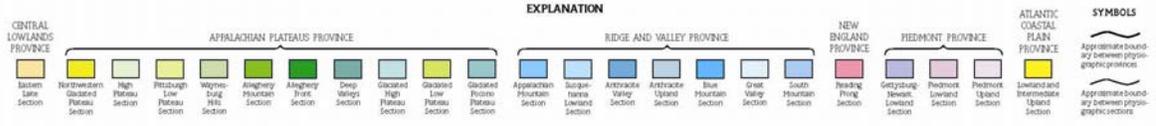
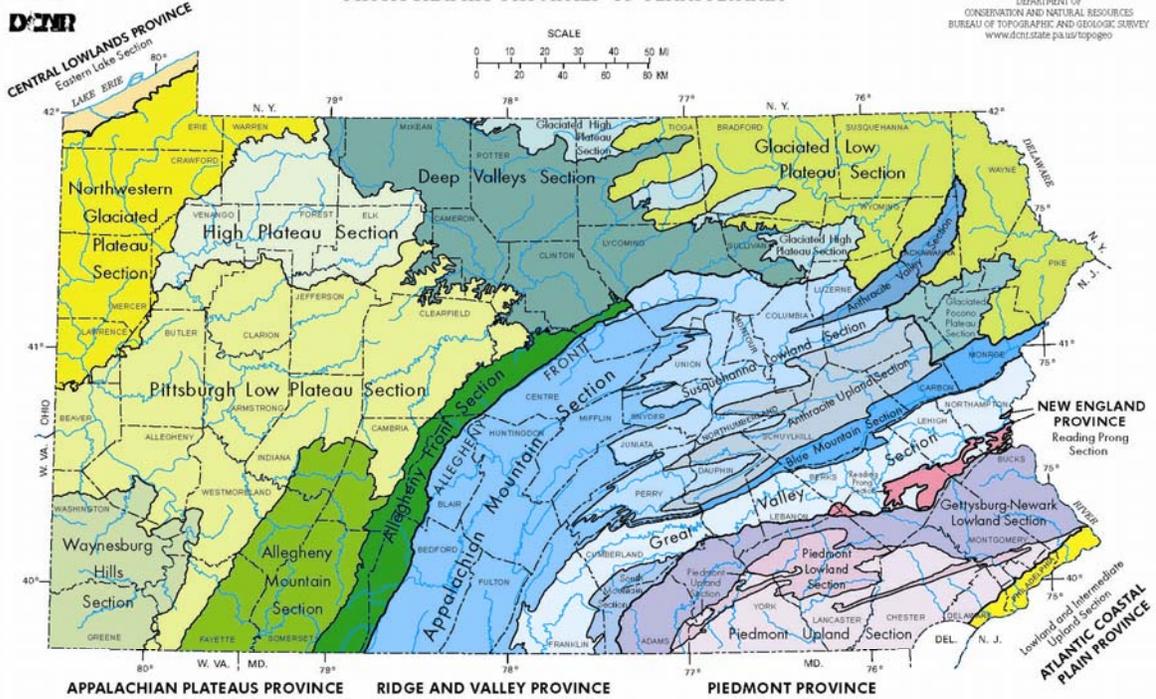


Figure 3. Location map of the Lake Erie, Pa., Coastal Zone including the study areas along which recession rates were calculated.

PHYSIOGRAPHIC PROVINCES OF PENNSYLVANIA

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Compiled by W. D. Sevan, Fourth Edition, 2000.

Figure 4. Map showing physiographic provinces of Pennsylvania. The bluffs of Lake Erie are in the upper northwestern corner of the state, in the Central Lowlands Province. (From Sevan, 2000)



**Figure 5.** Oblique aerial photograph looking south from Lake Erie, Pa. The division between the Central Lowland Province and the Appalachian Plateau Provinces is demarcated by the dark tree line near the top of the photo (indicated by white line). Photograph from Pennsylvania Coastal Resource Management Program.



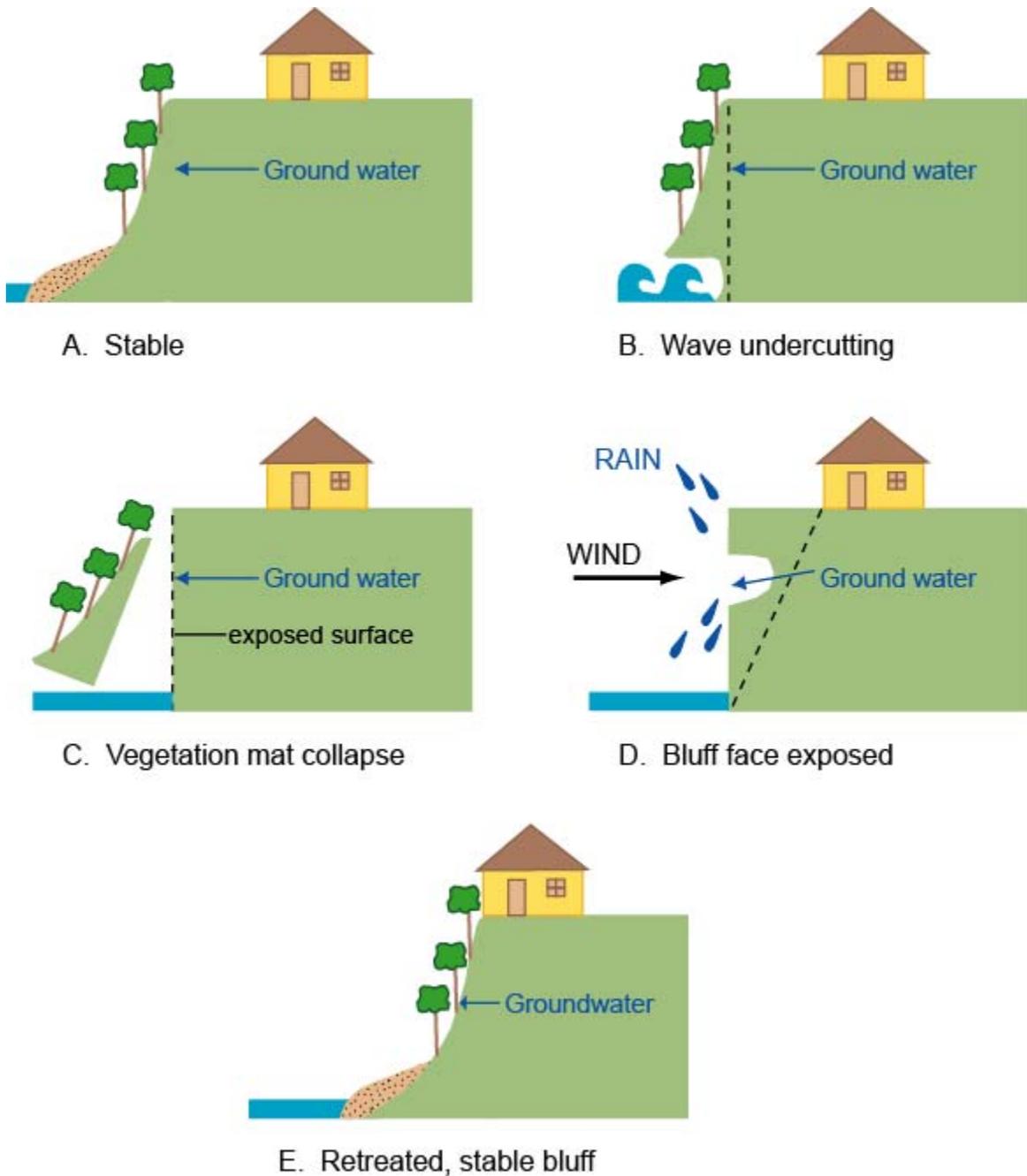
**Figure 6.** Oblique aerial photograph of bluffs in Harborcreek Township, Pa. (see fig. 3 for location). The base of the bluff in this location is exposed Devonian sandstone and shale, which is overlain by unconsolidated glacial deposits (contact indicated by yellow line). Bluff recession rates tend to be lower where the basal exposures are bedrock. Photograph from Pennsylvania Coastal Resource Management Program.



**Figure 7.** Photograph showing bedrock exposure in base of bluff and shingle beach near Presque Isle, Pa. Photograph from Pennsylvania Coastal Resource Management Program.



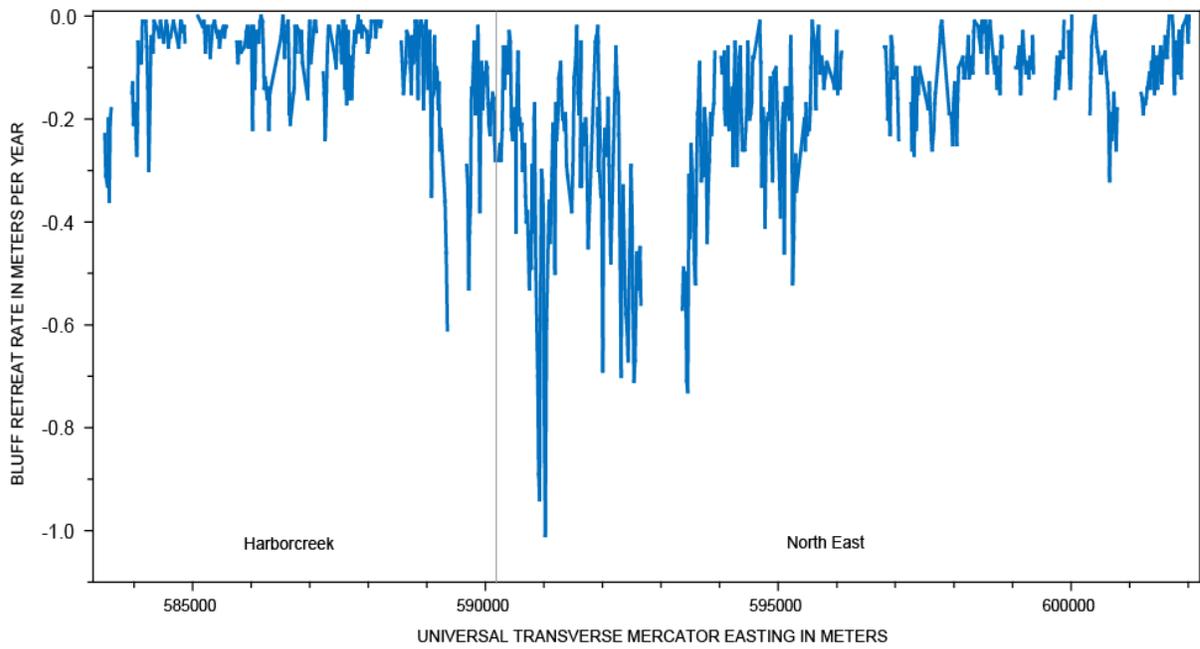
**Figure 8.** Aerial photograph showing headland-cove morphology formed in portions of the Lake Erie, Pa., bluffs in areas where jointed bedrock makes up the bluff face. The morphology can also be seen in the submerged portion of the bluff, where the jointing in the bedrock is also visible. Photograph from Pennsylvania Coastal Resource Management Program.



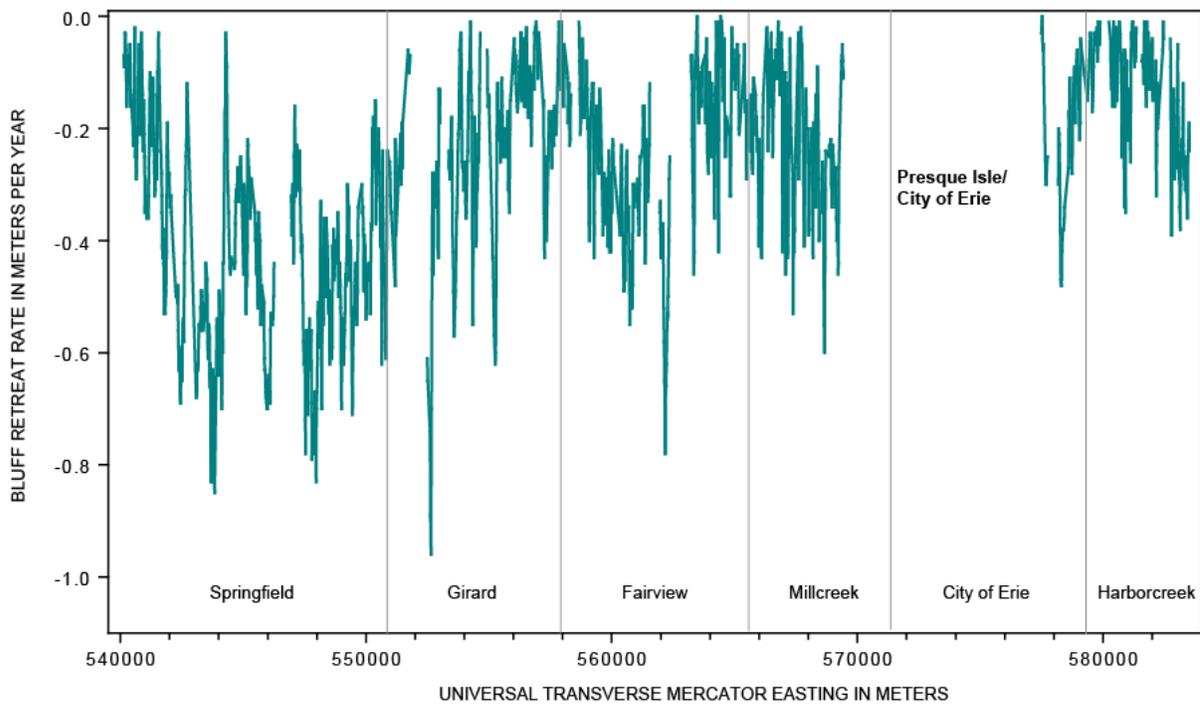
**Figure 9.** Schematic diagrams showing stages of bluff retreat unique to the Lake Erie, Pa., bluffs. **(A)** Bluff is in a stable condition; steep slopes are fully vegetated and vegetation is nourished by ample ground-water flows; residential structure is a safe distance from the bluff crest. **(B)** Wave contact at the base of the bluff undercuts the bluff face and creates instability for the now-unattached vegetation mat higher on the bluff face. **(C)** The bluff face, stripped of a protective vegetative mat, is increasingly susceptible to further erosion. **(D)** The unprotected and over-steepened bluff face is susceptible to the erosion processes of wind, rain, and ground-water flow. **(E)** The bluff slope retreats to an angle of repose, vegetation returns, and the bluff face is stabilized. However, bluff recession now has encroached close to the residential structure.



**Figure 10.** Photograph showing area of classic translational slope failure along coast of Lake Erie, Pa., where a relatively linear mass of bluff material separates and slides downslope. This type of slope failure is most common in bluffs composed of sand and silt. Photographs from Pennsylvania Coastal Resource Management Program.



**Figure 11.** Bluff-retreat rates in the Eastern study section of the Lake Erie, Pa., coast, 1938-98. The average rate of recession in this section was  $0.2 \pm 0.1$  m/yr. The highest rate,  $1.0 \pm 0.1$  m/yr, was measured in the central portion of the section in a predominantly agricultural area.



**Figure 12.** Bluff-retreat rates in the Western study section of the Lake Erie, Pa., coast, 1938-2006. The average rate of recession in this section was  $0.3 \pm 0.1$  m/yr. The highest rate,  $1.0 \pm 0.1$  m/yr, was measured in the central portion of the section in a predominantly agricultural area.