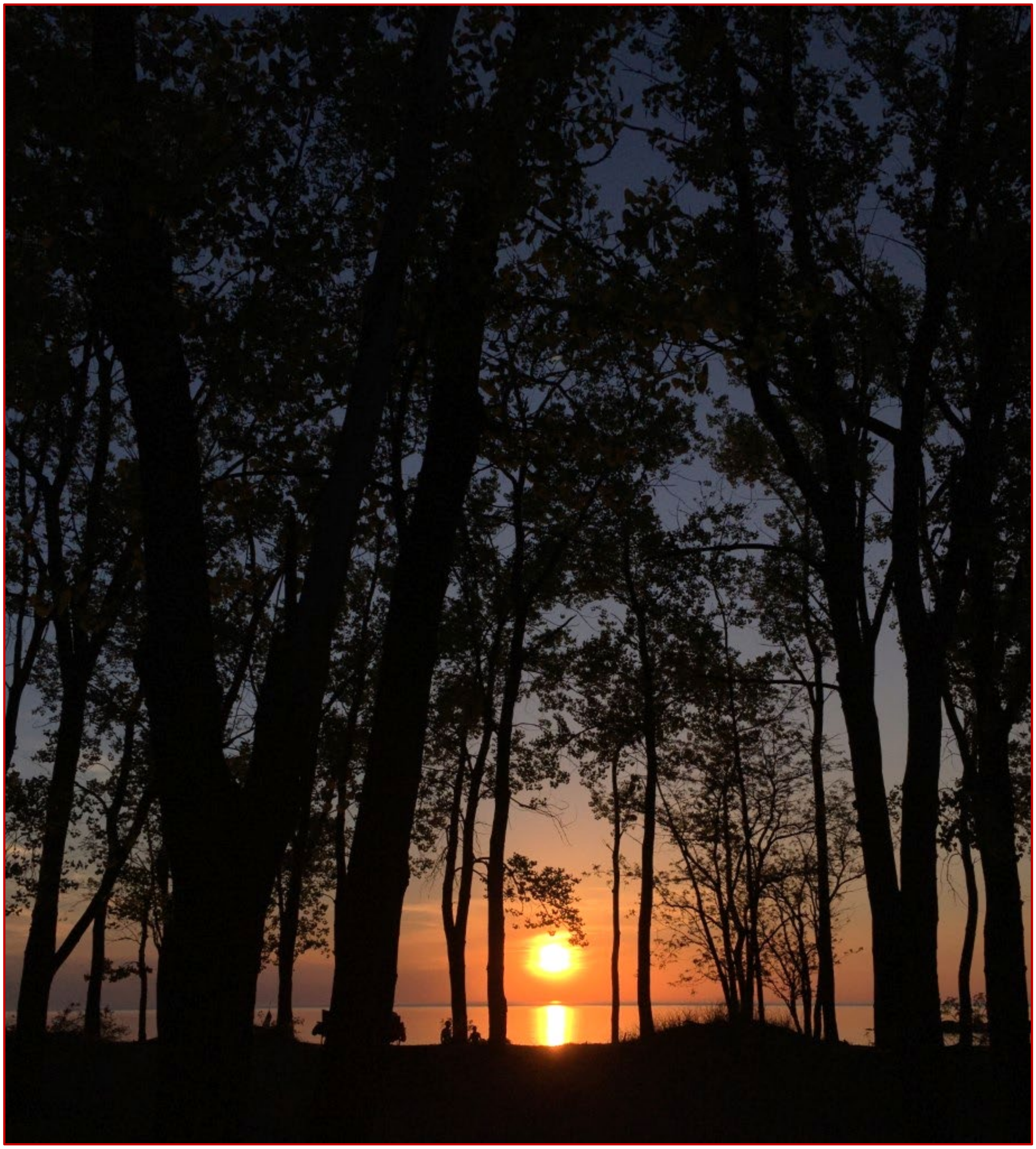
Evaluating Bluff Retreat and Sediment Supply on the Lake Erie Coast of Pennsylvania using Bayesian Network Modeling and Change-Detection Analysis



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Executive Summary

Overview

Erosional retreat of coastal bluffs across the Great Lakes basin impacts lakefront property owners and coastal stakeholders. This coastal hazard is associated with potential losses of $66 million of near-bluff property along 73 km of lakefront bluffs within Erie County, Pennsylvania. The Pennsylvania Lake Erie coast is dominated by unconsolidated Quaternary-age bluffs ranging in height from 1.5-55 meters above lake level. Overall, the coast can be considered a sand-starved system due to the small volumes of sand supplied to and moving within the littoral system.

Bluffs supply over 95% of the sand in transport within Pennsylvania's Lake Erie littoral zone and are thus critical to the littoral cell within which they lie (e.g., the western Erie County littoral cell; WECLC) and to littoral cells downdrift (e.g., the Presque Isle littoral cell). Because of this, a feeder-bluff conservation program could be adopted wherein eroding bluff sectors would be managed in their natural state to preserve the principal sediment supply to the littoral system and help reduce coastal erosion for tens of kilometers along and west of Presque Isle. Bluffs within municipal and state park properties centered on Elk Creek export significant sediment volumes to the littoral zone and may be appropriate for feeder-bluff designation.

This project uses a combination of coastal and stratigraphic mapping at selected field sites; wave climate and sedimentologic data; GIS change-detection analysis; and Bayesian statistical modeling to improve understanding of the relationships between coastal processes, hazards, and sediment supply associated with bluff retreat on the Lake Erie coast. The project quantifies relationships between physical processes and landscape responses that may help improve community resiliency against a major coastal hazard on the Great Lakes. Seven field sites of ~1-2 km in length were selected for Bayesian modeling of bluff retreat that relied on statistical analysis of 2007 and 2015 lidar data and numerous environmental parameters to determine the principal causes of bluff retreat. Linking these detailed-study sites and extending from the OH-PA state line to the downdrift end of the WECLC at Presque Isle State Park, GIS/lidar mapping was used to quantify 2007-2015 bluff contributions to the littoral sediment budget.

The project addresses two significant coastal-zone information gaps for Erie County bluffs in particular and for Great Lakes bluff coasts generally: (i) the need for a rigorous statistics-based understanding of the roles of different physical processes and bluff characteristics in bluff retreat, and (ii) the need for higher-resolution estimates of sediment volumes contributed by bluffs to the littoral zone using state-of-the-art geospatial methods.

This project used a high-resolution sediment-loss mapping approach for the first time on Pennsylvania coastal bluffs. Crest elevations were obtained at <1 m intervals, and bluff-face topographic changes (from which sediment losses were derived) were mapped every ~1 m^2, along the entire 33.5 km WECLC coast. These data represent a valuable addition to the regional geo-environmental knowledge base and allow improved understanding of bluff behavior and dynamics. The project used Bayesian Network statistical modeling to explain past bluff-retreat patterns and to simulate future bluff-crest retreat through 2065 at seven representative WECLC sites. The importance of bluff retreat as a contributor of sediment to the littoral transport system during average lake-level conditions was established using GIS change-detection analysis on a watershed by watershed basis.

Causes of Bluff Retreat

To evaluate the causes of bluff retreat along the WECLC, a Bayesian Network model was developed for seven 1-2 km long study sites representative of coastal conditions and watersheds within the WECLC. The overall modeling goal was to improve understanding of coastal processes driving bluff retreat and associated hazards on the Pennsylvania coast. Bayesian models in general are capable of explaining the location and magnitude of geohazards by defining joint-probability density functions that relate forcing variables and initial conditions to geologic events. Bluff retreat on the Erie County coast is suited to Bayesian analysis because bluff failure may be related to identifiable pre-existing conditions, there are a reasonable number of constrainable environmental processes, and long- and short-term bluff-retreat rate data are available.

The network model was built using geodata compiled from 20 m-spaced shore-normal DSAS transects, and other coarse-scale data sources, to explain historical change in bluff-crest location (1938-2007). It was then evaluated on its ability to predict "future" change over a recent (2007-2015) validation window. The model was subsequently used to simulate future crest locations for each of the seven WECLC sites (Sites 1STGL through 7BMDR) through 2025, 2040, and 2065. These time windows approximated (i) the average duration of individual-home ownership in the United States, (ii) a typical mortgage duration, and (iii) a time duration used in defining construction setbacks on the Pennsylvania coast. The Bayesian Network model initially relied on nine data inputs and one dependent-variable dataset (2007-2015 bluff-retreat rate). In total, 511 models were examined and the initial runs utilized:

(i) A long-term historical bluff retreat rate (1938-2007) as the *prior-behavior* parameter.
(ii) Six *initial-state* parameters of bluff height, bluff slope, bluff stratigraphy (expressed as geotechnical resilience), beach prism width, bluff toe elevation (expressed as beach thickness), and top-of-bedrock elevation.
(iii) Groundwater flux at the bluff face and wave energy (wave-impact hours) at the bluff toe. These were the two expected dominant *forcing agents* in the WECLC.

Using k-fold cross-validation, the optimal model was one in which eight of the nine possible inputs were used. These inputs included SPR resiliency, long-term retreat rate, bluff face slope, beach prism width, toe elevation, top-shale elevation, bluff height, and wave impact hours. Fitting the final model with all 414 transects, it correctly predicted the 2007-2015 retreat-rate bin 395 times, or for 95.4% of the transects (a *correct-classification rate* of 395 out of 414). This is a measure of the percentage of times the observed 2007-2015 retreat rate bin matched the bin with the highest predicted posterior probability. The predicted value was assumed to correctly match if the observed 2007-2015 retreat rate matched the bin with the largest predicted posterior probability. The prediction was also considered to be correct if the largest predicted posterior probability was tied among multiple bins (two bins in 80 cases, three bins in 9 cases) and the observed 2007-2015 retreat rate was among those bins. If ties were excluded, the model predicted 71.5% of the binned short-term rates correctly.

A method to assess model fit that considers the uncertainty in the model predictions is to average the predicted probability of being in the observed 2007-2015 retreat rate bin for each transect. This approach takes into account the confidence in predicting the correct short-term retreat rate, not just the percentage of times the correct short-term retreat rate is correctly predicted. When using the final model with all 414 transects, the *mean predicted posterior probability* of the observed 2007-2015 retreat rate was 84.1%. This value was used as a baseline to determine the importance of each input in the model. For the final 8-element model, the two most important inputs were long-term retreat rate (caused a 14.3% reduction in prediction probability if removed) and bluff face slope (caused a 13.8% reduction in prediction probability if removed). The third most important variable was toe elevation/beach height, which was also determined to be the best model via k-fold cross validation when only one input was used. This means that when building a 1-element model using any one of the nine geodata inputs, toe elevation/beach height was the best-performing input of the nine as a predictor of crest retreat.

The Bayesian Network model suggests that, in fundamental terms for property owners, long-term retreat rate, bluff face slope, toe elevation and beach-prism volume together explain most of the predicted 2007-2015 crest-retreat rates. Groundwater flux within the model appears to have only a minor influence because the model skill degrades when it is included. The reason for this is uncertain and may be due to imperfect quantification of the groundwater flux through WECLC watersheds.

The 8-element Bayesian Network model was used to simulate future positions of the bluff crest at each of the seven WECLC sites for the years 2025, 2040, and 2065 (using 2015 as the starting year). The plots for all three simulation periods show that, as has been true historically, simulated future retreat is spatially very variable between nearby transects and between field sites. Over the next 50 years, bluff-crest retreat at the seven WECLC sites may be expected to range from 1 to 15 m depending on location. That represents a range of crest retreat rates of 0.02 to 0.3 m/yr, within the range of values for historical bluff retreat. However, an implicit assumption here is that environmental conditions going forward do not vary any more than they have during the 1938-2015 timeframe used to build the Bayesian Network.

The 50-year simulation shows relatively consistent but greater future retreat for Site 1STGL, and for Sites 4LECP and 5YMCA (in the Trout Run watershed) compared to other sites. Simulated retreat averages ~8 m by 2065. Four sites (2RACK, 3EBSP, 6LSCC, 7BMDR) tend to show more within-site variability in amounts of simulated retreat by transect. Simulated retreat is, overall, generally similar across all sites, with the lowest simulated retreat occurring at Sites 2RACK, 3EBSP, 6LSCC, and 7BMDR. This is significant because the long-term historical record shows major retreat for Sites 1STGL and 2RACK in the Turkey Creek watershed (rates ~2X those of other WECLC sites): this trend weakens in the future simulations. The reason for this future (simulated) erosion reduction at historically high-erosion locations is unknown.

While the Bayesian Network model has certain limitations as a forward-predictor of bluff-crest location, it is valuable because it highlights the relative roles of the multiple environmental drivers involved in bluff retreat. It also highlights the most important variables that would be valuable for stakeholders to informally monitor as they consider moving to, or remaining on, a lakefront lot on the bluff top: long-term retreat rate and bluff-face slope, with negative correlations with bluff stability; and toe elevation and beach volume, with positive correlations with bluff stability.

Bluff Sediment Supply

Based on bluff-face topographic changes mapped using lidar data from 2007 and 2015, 8-year total-sediment and sand+ (sand to boulders) changes for the WECLC bluffs were net losses of 318,400 m^3 and 105,850 m^3, respectively. Lakefront bluffs in the Crooked Creek and Trout Run watersheds were the principal sediment-supply sources. Annualized, the bluffs supplied 39,800 m^3/yr of total-sediment (clay to boulders) and 13,250 m^3/yr of sand+ to the WECLC. Estimated sand+ yields were ~430 m^3/bluff km/yr averaged across the six WECLC watersheds. The 13,250 m^3/yr sand+ supply results in a small littoral-sediment transport rate by both ocean coast and Great Lakes standards given that sediment input from streams is minimal. The sand+ sediment supply reflects change within a longer ~12-year period of relatively low and steady lake levels (1999-2011) followed by a 3-year slow transgression (2012-2015).

The WECLC-average elevation change on the bluff face is ~0.3 m and varies across all six watersheds. Gains in elevation on the bluff face are a consequence of bluff-face deformation at slumps and of sediment storage lower on the bluff from upslope failures. Overall, the sediment-loss (erosion) volumes from the bluff face are about 20 times larger than the gain (accretion) volumes. The six HUC-12 watersheds fronting the WECLC supply significantly different quantities of bluff-derived sediment to the Pennsylvania sector of the Lake Erie littoral system, an attribute that was previously unknown. Rates and patterns of bluff retreat, total-sediment supply, and sand+ supply are regulated by several geo-environmental variables reviewed in Chapter 2, modeled using a Bayesian Network in Chapter 3, and quantified using change-detection analysis in Chapter 4.

Crooked Creek is the most important of the six WECLC watersheds in terms of normalized bluff sediment supply (m^3/bluff km/year), providing 53% to 220% more sand+ to the littoral zone than any other WECLC watershed. Given the undeveloped, unarmored and natural state of its lakefront, Erie Bluffs State Park in the eastern half of the Crooked Creek watershed is the best watershed-scale candidate in western Erie County for bluff conservation measures such as designation as a feeder bluff zone. Its sediment supply role is also important because it is responsible for providing material to the protective baymouth bar at Elk Creek in the next-downdrift watershed. Without this bar, fishing aesthetics, a sheltered shallow-water fish nursery, and other ecosystem services would be compromised.

The bluff-retreat sand+ volumes derived in this study provide a unique opportunity to understand sediment contributions from bluffs to the littoral zone during near-average and relatively stable lake levels. The data thus allow estimation of bluff retreat rates and sediment losses for average/stable lake-level periods that have occurred in the past (1944-1956; 1999-2011) and are likely to return in the future. Bluff change during 2007-2015 was responding, with a decades-scale process-response time lag, to environmental conditions beginning at least in 1999 and continuing through 2015.

A significant 0.76 m (~95 mm/yr) rise in lake levels that began in ~2012 and continued through 2020 may not be reflected in greater rates of bluff change for potentially another decade because of suspected time lags of at least a decade in the response of bluffs to lake-level change. It is expected that change rates, when ultimately determined for the 2012-2020+ period, will be greater than those reported in this study of the 2007-2015 era. They may approach or exceed rates determined for prior transgressive periods when sediment supply was ~five times larger than our 2007-2015 rates.

There are several coastal-management implications of our findings. Estimates of bluff contributions to littoral sand+ transport along the WECLC, based on the surface-differencing methodology, are 65-80% lower than previously estimated for the recent 20th/21st Century and earlier mid-20th Century eras. However, the small 2007-2015 volumes are interpreted to be representative of sand contributions to the littoral system during periods when lake level is near long-term average and a weak-transgressive trend is present (e.g., 1999-2015). Because of this, sediment budget assumptions used for coastal sand management and erosion mitigation at the next-downdrift littoral cell at Presque Isle State Park may need to be revised to account for the smaller, 2007-2015 era, sand+ input to that cell from the WECLC. Incorporating such a sediment-supply revision for the Presque Isle littoral cell would influence estimates of sand nourishment quantities required to mitigate beach erosion at Presque Isle over the coming decades.

Average and relatively stable lake-level periods, such as occurred during 1999-2015, may be opportune periods for artificial sand bypassing at large coastal structures such as Conneaut Harbor, OH, that are known to block net-eastward littoral sediment transport. During such periods, littoral sediment transport volumes along the WECLC would be low and thus the littoral sediment stream would benefit more from artificial-bypass inputs. Prior research shows that approximately 10,300 m^3/yr of sand naturally bypassed Conneaut Harbor prior to 1938 but may have been zero through at least 2006. This 10,300 m^3/yr is a large transport volume for the sand-starved Pennsylvania coast relative to volumes typically supplied by bluff retreat during transgressive and regressive intervals since the mid-20th Century.

Our estimates of bluff sand+ input to the WECLC contain uncertainty (±50%) but are inferred to be more precise than those of prior studies because of (i) better, although still imperfect, resolution of stratigraphic complexity, (ii) a DEM-differencing approach that allows higher-resolution mapping of topography and elevation changes across the bluff face at ~1 m point spacings, and (iii) better tracking of slump-supplied sediment accumulations (gains) on the bluff face that partially offset some (~5%) of the loss volumes. Our estimates of sand+ contributions to the littoral zone are lower than similar-era prior studies, and there are several possible reasons for this. The 8-year comparison may not have captured large but infrequent bluff sediment-supply events that would have a higher probability of being captured by analyses covering several decades. A likely decades-scale process-response time lag between lake level and bluff erosion means that the 2007-2015 bluff face may have been responding primarily to lower and more uniform lake levels during the 1999-2011 period. And lastly, a large part of our observation window occurred within a longer 12-year period of relatively low and stable, weakly-transgressive, lake levels (1999-2011) that had not previously occurred for over half a century.

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Evaluating Bluff Retreat and Sediment Supply on the Lake Erie Coast of Pennsylvania using Bayesian Network Modeling and Change-Detection Analysis

1 Study Description

Background and Context

Nationally, about 40% of the US population lives in coastal counties and migration to coastal counties has been increasing over time. Retreat of coastal bluffs across seven Great Lakes states, and across at least ten states on the Atlantic and Pacific coasts, impacts property owners and other coastal stakeholders. Bluff retreat is a coastal hazard affecting over $66 million of near-bluff property (ECDPS, 2012) along the City of Erie lakefront and adjacent municipalities in Erie County, Pennsylvania's only coastal county on the Great Lakes.

The Pennsylvania coast of Lake Erie is dominated by unconsolidated Quaternary-age bluffs ranging in height from 1.5-55 meters above lake level. The central coast in the vicinity of Erie includes a large shore-attached offshore sand spit or strandplain (at Presque Isle State Park) separated from the mainland bluffs by Presque Isle Bay. Overall, ~24% of the Pennsylvania coast is protected by engineering structures (Stewart, 2001), while beach nourishment and various biotechnical methods are also commonly used. The coast is considered a sand-starved system due to the small volumes of sand supplied to and moving within it (Knuth, 2001; Morang et al., 2011; Cross et al., 2016). The ~73 km mainland coast consists of bluffs dominated by unconsolidated fine-grained glacial and glacio-lacustrine material that is less than 2 my old.

Bluffs supply over 95% of the sand in transport within Pennsylvania's Lake Erie littoral zone (Knuth, 2001) and are thus critical to the littoral cell within which they lie (e.g., the western Erie County littoral cell; WECLC) and to littoral cells downdrift (e.g., the Presque Isle littoral cell). Because of this, a feeder-bluff conservation program could be adopted on the WECLC to preserve sediment supply to the littoral system and help reduce coastal erosion for tens of kilometers along and west of Presque Isle State Park. *Feeder bluffs* are defined as eroding landforms that deliver a significant amount of sediment to beaches and the littoral sediment budget (Shipman et al., 2014). If Pennsylvania were to consider a feeder-bluff conservation program similar to that used in Puget Sound, WA, for example, eroding bluff sectors could be managed in their natural state without erosion mitigation being attempted. This modeling and mapping project identifies bluff sectors in western Erie County with significant sediment losses along the Warren paleo-strandplain, located within municipal and state park properties centered on Elk Creek. These bluff areas would be appropriate for consideration as feeder bluffs to facilitate a resilient Lake Erie coast.

This project uses a combination of coastal and stratigraphic mapping at selected field sites; wave climate and sedimentologic data; GIS change-detection analysis; and Bayesian statistical modeling to improve understanding of the relationships between coastal processes, hazards, and sediment supply associated with bluff retreat on the Lake Erie coast. The project quantifies relationships between physical processes and landscape responses to help improve community resiliency against a major coastal hazard on the Great Lakes.

Study Area: The Western Erie County Littoral Cell (WECLC)

The westernmost 33.5 km of Pennsylvania coastline, lying updrift (southwest of) Presque Isle State Park, comprises the western Erie County littoral cell (WECLC) which is the focus area of this study (Fig. 1.1). Geomorphologic evidence and long-term records of coastal change compiled by the Pennsylvania Department of Environmental Protection (PA DEP) show that bluff erosion is pervasive along the entire WECLC. Hydrodynamically, the updrift cell boundary to the WECLC is defined by the 1.5 km long east breakwater at Conneaut Harbor, OH, which is part of a harbor complex known to inhibit natural littoral sediment transport from central coastal Ohio eastward into Pennsylvania (Morang et al., 2011; Cross et al., 2016). However, the WECLC as defined for this study excludes the easternmost 2 km of Ohio coast, with the updrift cell boundary instead being mapped as coincident with a small headland and park at the OH-PA state line that is not a barrier to littoral sediment transport. The eastern (downdrift) cell boundary of the WECLC was picked as the largest and most eastward groyne on the WECLC bluff coast, located at East Kelso Drive and Waldameer Park. This ~80 m long structure is associated with a wide accretional strandplain (~50,000 m^2 in area) on its updrift side, with the groyne tip being located ~225 m lakeward of the adjacent bluff crest. The groyne effectively marks where the neck of the Presque Isle peninsula joins the mainland and thus the updrift end of the Presque Isle littoral cell. The WECLC as defined here thus extends from the OH-PA state line (excluding ~2 km of Ohio bluff coast east of the Conneaut Harbor breakwaters) to the large groyne (a partial littoral-sediment barrier) at East Kelso Drive. It thus differs somewhat in along-coast extent from the west county littoral cell used by Knuth (2001).

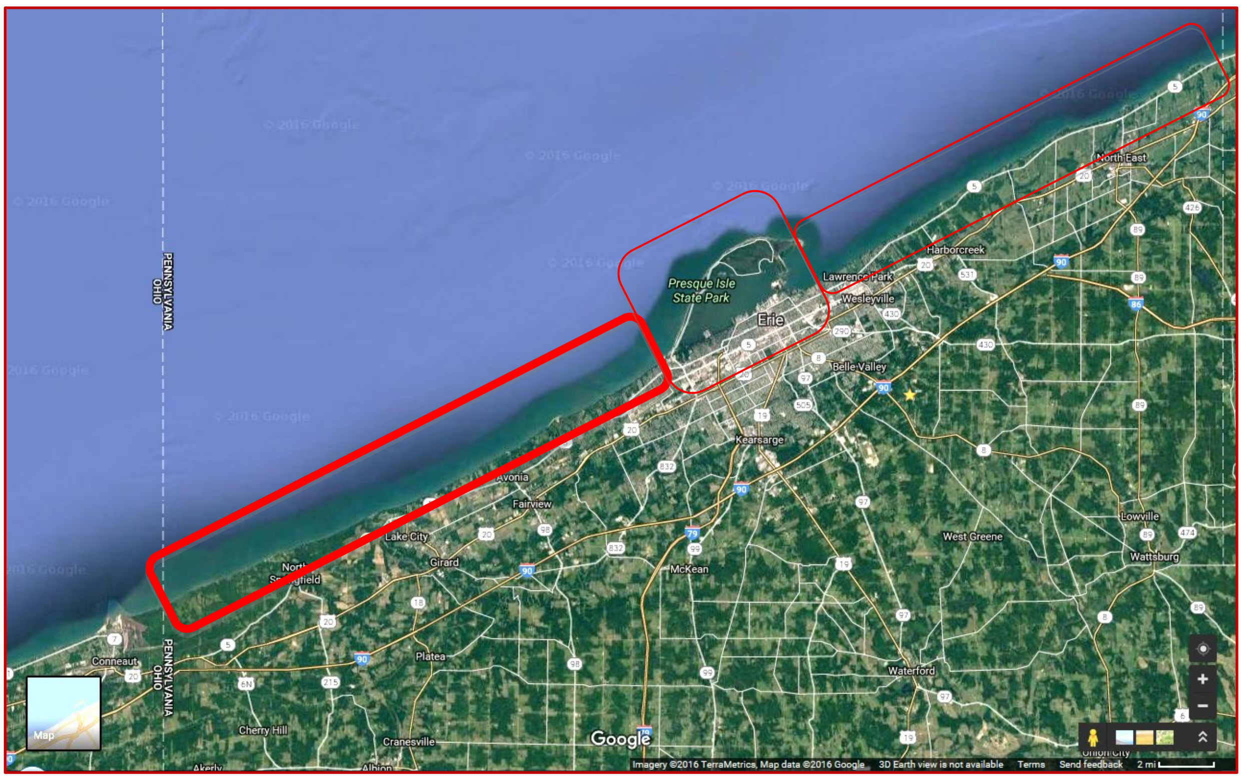


Figure 1.1: *Map of the Pennsylvania coast of Lake Erie and its three principal littoral cells. The 33.5 km WECLC (red rectangle on left) is located southwest (updrift) of the Presque Isle littoral cell which lies updrift of the eastern Erie County littoral cell (right side of image). Scale bar is ~3.2 km in length. (Image: modified from google.com/maps)*

During the 2007-2015 period of analysis for this study, Lake Erie water levels rose at an average rate of ~22.5 mm/yr, a significantly faster rate of transgression than occurs on oceanic coasts where sea level may rise at rates of ~2-6 mm/yr. The 2007-2015 period was part of a longer, but more variable, slight transgressive trend that began in the mid-1930s (time-coincident with the oldest bluff-position dataset used in this project – 1938), over which time-period lake levels rose at an average rate of ~6.5 mm/yr and during which there were several lower-amplitude cycles of transgression and regression. The long-term average lake level (1918-present) for Lake Erie is ~174.17 m MSL (above mean sea level), slightly lower than the Spring 2015 174.25 m reference used in this study.

Project Rationale

The WECLC project area comprises ~33.5 km of coastline dominated by unconsolidated glacial-till bluffs with relief of 1.5-38 m. Several large 3rd-4th order streams and numerous short 1st-2nd order groundwater-fed ravines traverse the bluffs. Low banks (<1.5 m of relief; PA DEP, 2013) and shore-protection structures typically define the lakeward edges of stream floodplains. Seven field sites of ~1-2 km in length were selected for Bayesian modeling of bluff retreat that relied on statistical analysis of high-resolution 2007 and 2015 lidar data and numerous environmental parameters to identify the principal causative agents of bluff erosion. Linking these detailed-study sites and extending from the OH-PA state line to the downdrift end of the littoral cell, WECLC-wide GIS/lidar mapping was used to quantify 2007-2015 bluff contributions to the littoral sediment budget. By mapping elevation differences across the bluff face between 2007 and 2015, the latter effort also revealed high-erosion areas and watershed associations important to future hazard and sand-supply management. The project allows improved understanding of bluff erosion hazards for coastal managers in a statistically meaningful way.

Project Focus Area I: Explaining the Causes of Bluff Retreat

The Pennsylvania Coastal Resources Management Program (CRMP) within PA DEP identifies beach erosion and bluff retreat as two of the most significant environmental problems on the Pennsylvania coast of Lake Erie. Coastal zone areas where the rate of bluff retreat creates a substantial threat to safety or structures are classified by PA DEP as Bluff Recession Hazard Areas (BRHAs) under the Bluff Recession and Setback Act (1980) (PA DEP, 2013). Within BRHAs, new construction and significant modifications to existing structures are subject to a minimum bluff setback distance (MBSD) requirement.

One of two principal objectives of this project is to use statistical modeling of easily-collected, remotely-sensed, topographic and environmental data to reduce uncertainty in our understanding of the behavior of eroding bluffs on a part of the Lake Erie coast that can be applied to other Lake Erie and Great Lakes settings. The process of bluff retreat is notably distinct from beach erosion because the loss of sediment is permanent. Beaches may gain and lose sandy sediments over various time scales (hours to centuries), but sand lost from a beach to the surf zone may return to the same beach or to downdrift beaches at a later time. Material eroded from Lake Erie bluffs typically consists of >70% silt and clay and <30% sand and gravel (Dawson and Evans, 2001; Morang et al., 2011; Jones and Hanover, 2014). Erosion can thus result in a permanent loss of ~70% of the bluff material to deepwater areas of the lake (below wave base). To manage retreating bluffs in the City of Erie and eight coastal municipalities, CRMP has monitored bluff change at specific control points (~0.5-1 km spacing) along the coast every ~4 years since the 1980s. Historically, the lack of a tall bedrock toe at the bluff contributes to high and variable retreat rates in the WECLC that average ~1 m/yr along its updrift sector, and ~0.5 m/yr along its downdrift sector (Fig. 1.2; ECDPS, 2012). Large rotational slumps along the tallest bluffs can result in 10s of meters of localized land loss over a several-week time period, while background soil creep can lead to more widespread but less significant land loss on a per-site basis.

On the perimeter of the Great Lakes, coastal retreat is a pervasive geologic process affecting cohesive clay-rich bluffs (Zuzek et al., 2003; Brown et al., 2005; Swenson et al., 2006; Cross et al., 2016; Davidson-Arnott, 2016). Understanding erosional behavior, and predicting future positions of a bluff crest, which is the standard map-reference landform, remains a scientific challenge (Trenhaile, 2009; Hapke and Plant, 2010; Castedo et al., 2012). This challenge exists primarily because:

(i) numerous interdependent variables influence episodic bluff retreat rates at any location, such as lake level, wave climate, groundwater flux, and bluff composition;
(ii) bluff behavior along a coast and over time can vary due to changes in internal geotechnical properties governed by geology;
(iii) temporal variability also occurs due to changes in external driving processes associated primarily with climate;
(iv) when a bluff fails, it typically enters a more stable phase for some period of time; and
(v) the pre-failure condition of the bluff can be a significant factor in subsequent bluff response to erosion stresses, both spatially and temporally.

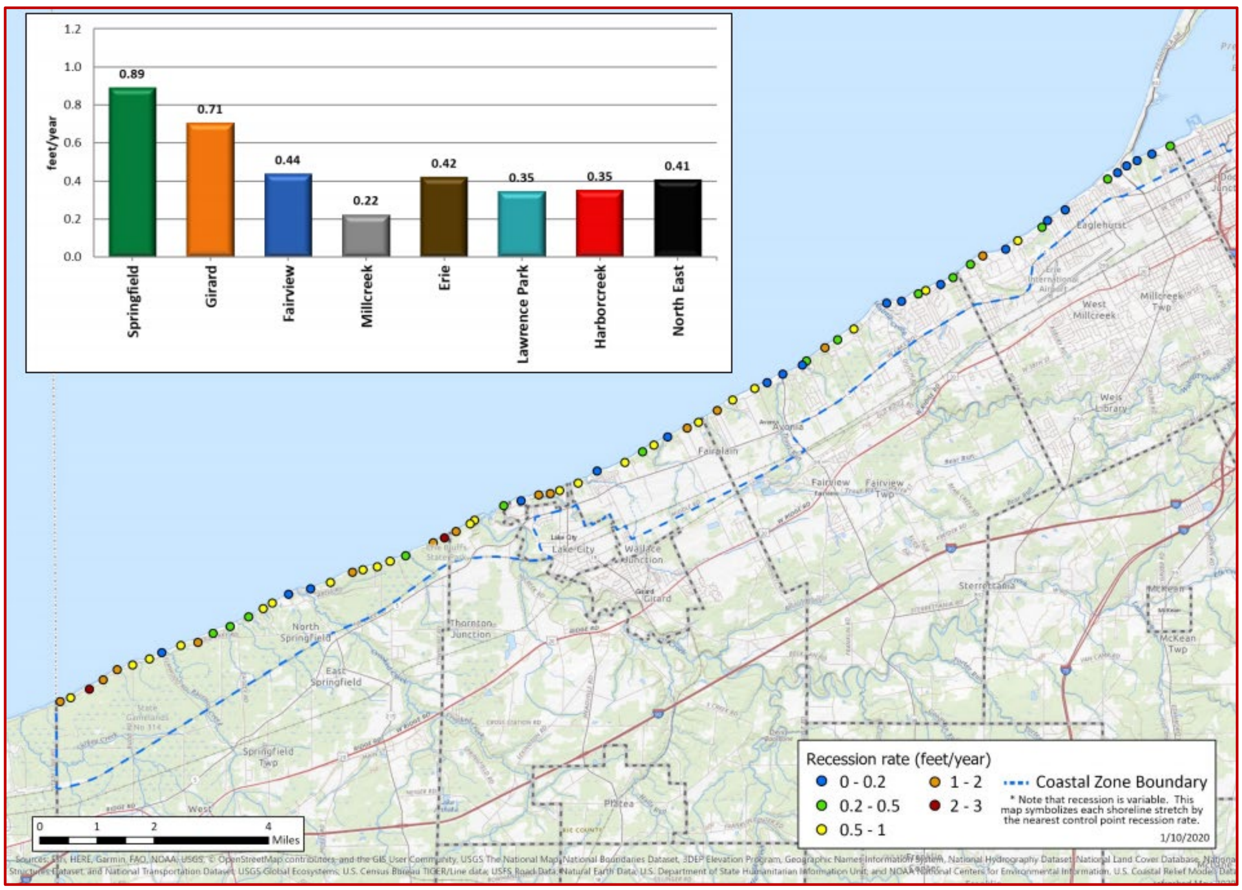


__Figure 1.2__: Bluff retreat in western Erie County, PA. Map data points show long-term average rates at PA DEP monitoring sites and vary from ~0.07 to ~0.9 m/yr. Insert graph shows municipality-average retreat rates for all Erie County municipalities: retreat rates are highest along the WECLC. (image: PADEP, 2020)

Project Focus Area II: Contributions of Bluff Retreat to the Littoral Sediment Budget

The second objective of this project is to provide a new, high-resolution and recent era, estimate of sediment input to the littoral zone due to bluff retreat. A new approach for Pennsylvania, using surface-differencing (change-detection analysis) of lidar-derived digital elevation models (DEMs) from 2007 and 2015, will allow higher-resolution mapping of bluff-face change than has been available prior to this time. Prior research (Knuth, 2001; Morang et al., 2011; Cross et al., 2016) on the littoral sediment budget for the Pennsylvania coast is resolution-limited because it relied on transect-based change mapping where transect spacings were relatively large and it was assumed that bluffs retreated in a simple parallel-retreat manner. In reality, bluff-crest retreat indicating sediment loss may be accompanied by storage (deposition) of material on the mid and lower bluff face, potentially resulting in overestimates of sediment contribution to the littoral zone when a parallel-retreat assumption is made.

In general, littoral sediment supplied by bluff retreat has been only coarsely resolved spatially and temporally. The temporal factor is important because decadal- and longer-scale bluff retreat rates likely vary with similarly scaled periods of lake-level rise (transgression; e.g. during 1938-2020) and fall (regression; e.g. 1953-1965). Recently, Cross et al. (2016) completed a regional sediment budget for the entire US shoreline of Lake Erie (OH-PA-NY) that will help improve interstate littoral sediment management. However, while understanding of the regional littoral sediment budget has improved over time, sediment inputs to the Pennsylvania system remain only coarsely resolved due to data limitations.

In Pennsylvania, sediment contributed to the littoral system by bluff retreat has historically been difficult to quantify because of an historical lack of suitable spatial and temporal scales in mapping data. Cross et al. (2016) calculated bluff sediment contributions (1876 through 2006) by binning bluff-crest retreat rates and elevations into 1 km sector averages; using a coarse (~ 5 km) and averaged stratigraphic dataset; and assuming that bluffs undergo parallel retreat (slab geometry) rather than considering geometries associated with multiple bluff failure mechanisms. Mechanisms are important because simply mapping crest retreat and elevation (and not bluff-face surface changes) over time will likely yield a sediment volume over-estimate due to the assumed slab failure geometry not accounting for sediment storage on the bluff. Recent and newly available high-resolution lidar topographic data used in this project will allow mapping of changes in the bluff crest location and in bluff-face topography. This (i) allows better quantification of bluff volumetric losses, and (ii) yields more-detailed information on spatial and temporal patterns of bluff failure.

Research Objectives

This project addresses two significant coastal-zone information gaps for Erie County bluffs in particular and for Great Lakes bluff coasts generally: (i) Obtaining a rigorous Bayesian statistics-based understanding of the roles of different physical processes and bluff characteristics in bluff retreat, and (ii) Developing a higher-resolution estimate of the sediment volumes contributed to the littoral zone through better mapping of bluff-face retreat using change-detection analysis.

The Bayesian Model component will improve understanding of coastal processes and hazards associated with bluff retreat on Great Lakes and oceanic coasts. It will quantify relationships between physical processes and landscape responses so that hazard forecasting and community resiliency may be improved. The bluff sediment budget component will assist coastal managers in their efforts to mitigate erosion problems along the WECLC and at Presque Isle State Park immediately downdrift.

Objective 1*: Develop and apply a multivariate Bayesian statistical network model of bluff retreat to the western Erie County littoral cell (WECLC). The model will provide a flexible predictive tool for explaining recent-to-historical bluff retreat and patterns, and for simulating future retreat magnitudes and patterns over multi-decade periods through 2065.*

Objective 2*: Generate up-to-date GIS/lidar-derived estimates of bluff-sourced (a) total sediment input (clays to boulders) to the WECLC that impacts both coastal water quality (turbidity, nutrients) and beach resources; and (b) littoral sediment input (sand to boulders; or "sand+") that represents the principal coarse sediment input to the WECLC and to the Presque Isle littoral cell immediately downdrift.*

Methods Summary Overview and Data Requirements

For Objective 1, a Bayesian statistical network approach (Pearl, 1988) uses multi-variate statistics to identify associations between several variables that may operate together to explain bluff retreat behavior. Recent successful Bayesian network model applications include cliff and landslide analysis (Lee et al., 2001, 2002), groundwater flow (Li and Jafarpour, 2010), and soil quality analysis (Back, 2007). Bayesian networks have been successfully tested by the US Geological Survey (USGS) to better-predict coastal change due to wave attack (US Pacific coast; Hapke and Plant, 2010) and sea-level rise (Atlantic coast; Gutierrez et al., 2011). A typical Bayesian network schematic, developed by Hapke and Plant (2010) for the southern California coast, is shown in Fig. 1.3.

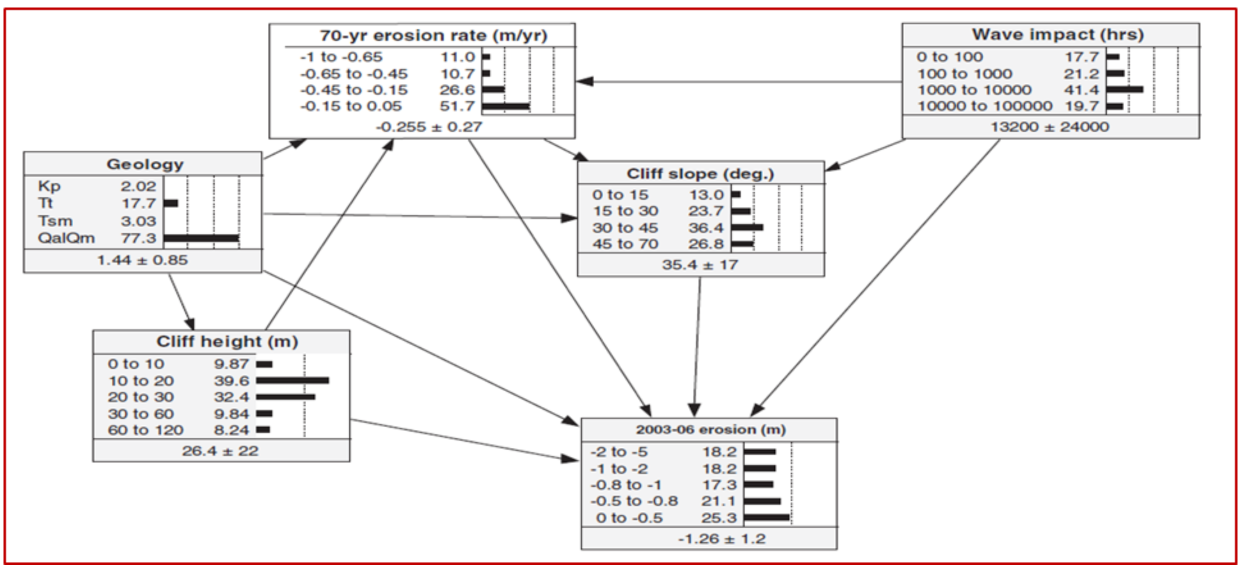


Figure 1.3: *Example schematic of a Bayesian Network model generated for bluff retreat on part of the southern California coast. Variables describe initial conditions (geology, cliff height, cliff slope), prior behavior (long-term bluff-crest retreat rate), and principal forcing agent (wave impact hours). (Image: from Hapke and Plant, 2010)*

The network approach used in this WECLC study models bluff retreat using a combination of input variables that comprised:

(i) Wave climate expressed as wave impact hours for the 2007-2015 era. These data were compiled from the US Army Corps of Engineers (WIS, 2020) using three selected synthetic wave gauges spaced at ~8 km intervals and in 15-17 m of water along the WECLC nearshore;

(ii) Bluff stratigraphy (geologic composition) expressed as bluff resiliency to erosion based on stratigraphic-layer thicknesses and a standard penetration resistance (expressed as blows-per-meter) geotechnical property;

(iii) Bluff elevation derived from the 2007 and 2015 lidar eras using a DSAS transects approach (Thieler et al., 2009);

(iv) Bluff slope derived from 2007 lidar using a DSAS transects approach;

(v) Short-term bluff-crest retreat rates (2007-2015) from lidar data using a DSAS transects approach to test (validate) the Bayesian model;

(vi) Long-term bluff-crest retreat rates from 1938 bluff-crest location data (provided by the US Army Corps of Engineers) and 2007 and 2015 lidar data using a DSAS transects approach;

(vii) Bluff-face groundwater flux using bluff-face area and estimated groundwater recharge derived from long-term average precipitation obtained from NWS records;

(viii) Bedrock toe/beach prism elevation from 2007 lidar mapping, 2015 oblique aerial photography available from PA DEP, and 2018 field measurements;

(ix) Beach width from 2007 lidar mapping and 2018 field measurements;

(x) Elevation of the top of bedrock above the backshore or lake level (if beach absent) from 2007 lidar, 2015 oblique aerial photography available from PA DEP, and 2018 field measurements.

For Objective 2, the project uses high-resolution topographic (lidar) and less-well resolved bluff stratigraphic data to develop an up-to-date and detailed assessment of the contributions of bluff retreat to the WECLC littoral sediment budget. This builds upon earlier work by Knuth (2001) and Cross et al (2016) that examined the littoral sediment budget through 2006 or earlier using a bluff face parallel-retreat approach. Using Digital Elevation Model (DEM) separation techniques for the 2007 and 2015 eras in LP360, in conjunction with field stratigraphic information, sediment gains, losses, and net change on the bluff face are estimated for six HUC-12 watersheds that comprise the study area. Bluff-face change along the WECLC is mapped in the area between the 2015 bluff crest (located at or landward of the 2007 bluff crest) and the toe of the bluff where it intersects the backshore or lake level at an average cell-wide elevation of 175.23 m. Inherent in the surface-differencing method is the opportunity to identify more-erosional (erosion hotspot) and less-erosional parts of the bluff face vertically and horizontally within each watershed (Fig. 1.4). Surface-differencing also allows mapping of bluff failure mechanisms and spatio-temporal patterns along the WECLC on the basis of visible patterns. This is a significant new 2-D (swath) mapping approach for documenting Lake Erie bluffs which have historically been 1-D mapped using a spaced-transect approach. The surface-differencing approach models topographic change using data that for this project comprised:

(i) A 2015 0.7 m-DEM surface developed from lidar data available from the Pennsylvania Spatial Data Access Clearinghouse (PASDA; pasda.psu.edu) for the coastal landscape located within 200 m of the bluff crest in the landward direction and extending to just lakeward of the shoreline;

(ii) A publicly available 2007 PAMAP Program lidar dataset from PASDA used to develop a 1m-DEM surface from PASDA with broadly similar specifications to the 2015 product;

(iii) Vertical elevation changes between the two DEM eras summed across six individual HUC-12 watersheds to estimate gains and losses of sediments to the littoral zone from the bluff face on a per-watershed and a per-unit bluff length basis;

(iv) 2007 and 2015 bluff crests mapped at 20 m intervals using DSAS at the project's seven study sites (Sites 1STGL through 7BMDR), and every ~20-40 m between sites, to provide the landward limit to the DEM-differencing procedure;

(v) Bluff toe elevation selected as the intersection of a 175.23 m plane with the bluff face, an average elevation for the bluff toe measured at study sites in 2018;

(vi) Bluff-face sediment texture and grain-size distribution data obtained from site visits and limited but representative prior research (D'Appolonia, 1978; Dawson and Evans, 2001; Knuth, 2001; Jones and Hanover, 2014) at Sites 1STGL and 2RACK; boring logs from a recent radio-tower installation at Site 4LECP (Terracon Consultants, Inc., 2018); bluff-face sediment logging at Site 5YMCA; and boring logs from bluff erosion-mitigation projects at Site 7BMDR and just east of the WECLC on Presque Isle Bay (ERE, 2017; Urban Engineers of Erie, Inc. 2004).

Figure 1.4: *Example of surface-difference mapping of a bluff face and beach strandplain on the WECLC coast. Cool colors denote erosion, and warm colors denote accretion between 2007 and 2015. Site is at the downdrift end of the WECLC where it adjoins the Presque Isle littoral cell. Scale bar is ~90 m (300 ft) in length. An online detailed version of this map is viewable at* https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

For both objectives, coastal site visits were conducted during 2018 and 2019, focusing on the study's seven 1-2 km long study sites used for Bayesian modeling. These seven sites covered ~30% of the 33.5 km of west-county coast and were selected to be representative of coastal variability along the entire WECLC using the following considerations:

(i) Knowledge of recent erosion rates (2012-2015), available from a prior Commonwealth of PA-funded study (Foyle, 2018);

(ii) Knowledge of long-term erosion rates (1938-2006), available from Cross et al. (2016);

(iii) Resolvable hydrogeology (groundwater flux in $m^3/m^2/yr$ estimated from annual precipitation, coastal surface-drainage characteristics, and bluff-face stratigraphy), adaptable from Foyle (2014);

(iv) Knowledge of relative coastal-structure density, mappable from PA DEP oblique coastal photography datasets available online for 2015 and 2017, and from 2007 and 2015 lidar;

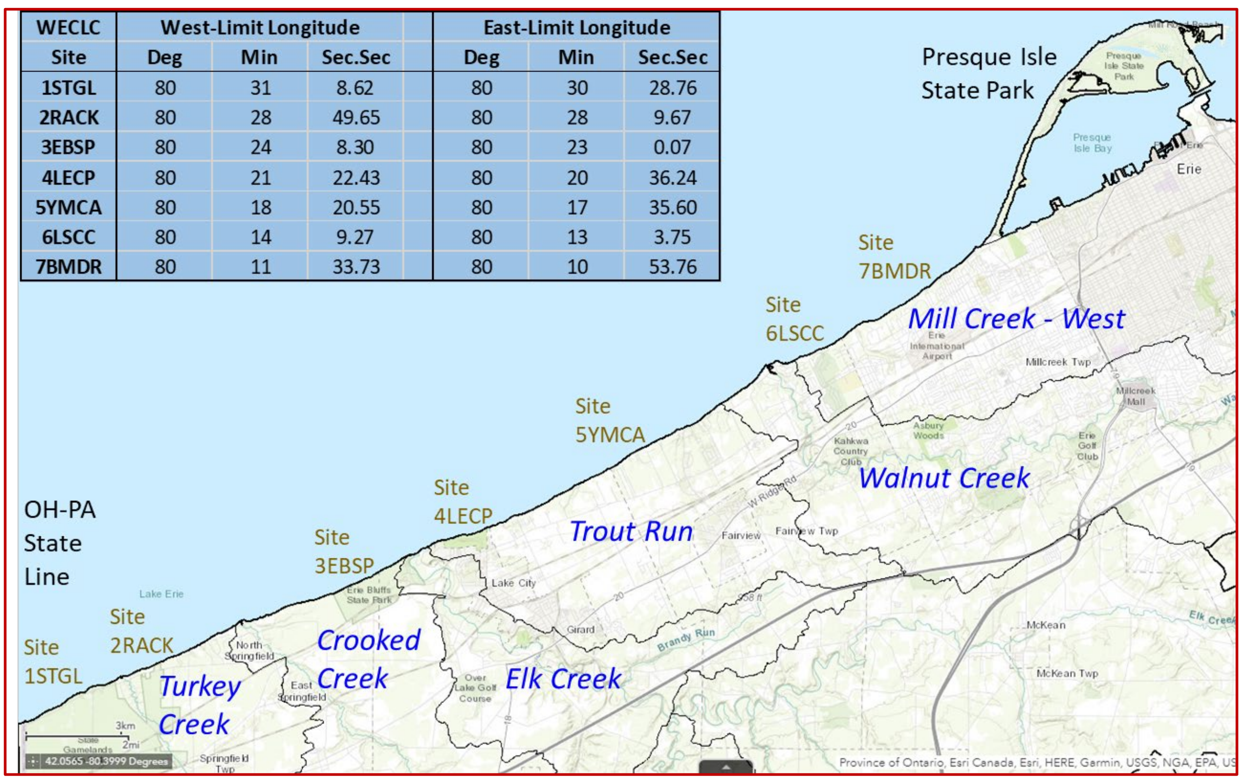
(v) Resolvable bluff stratigraphy, determined from prior published reports and logging at field-accessible sites;

(vi) Bluff-crest elevations, available initially from standard US Geological Survey 7.5-minute topographic quadrangles;

(vii) Degree of beach development, estimated initially from PA DEP oblique coastal photography datasets available online for 2015 and 2017;

(viii) Beach access logistics within each of the principal WECLC watersheds. Near-record high lake levels during 2018 and 2019 somewhat limited access to parts of Sites 2RACK and 4LECP.

Figure 1.5 shows the general locations of each of the seven field sites and the extent of the WECLC located southwest of Presque Isle State Park. Each site was field-mapped for bluff stratigraphy for resiliency estimations; for foreshore slopes and bluff/backshore contact elevations for wave impact hour estimations; for beach width, bedrock occurrence, and toe-elevations; and for hydrogeologic features, all used in the Bayesian modeling.



WECLC	West-Limit Longitude			East-Limit Longitude		
Site	Deg	Min	Sec.Sec	Deg	Min	Sec.Sec
1STGL	80	31	8.62	80	30	28.76
2RACK	80	28	49.65	80	28	9.67
3EBSP	80	24	8.30	80	23	0.07
4LECP	80	21	22.43	80	20	36.24
5YMCA	80	18	20.55	80	17	35.60
6LSCC	80	14	9.27	80	13	3.75
7BMDR	80	11	33.73	80	10	53.76

Figure 1.5: *General locations of seven 1-2 km WECLC field sites used for Bayesian network modeling within the broader WECLC littoral cell used for bluff-face sediment-input analysis. Six HUC-12 watersheds are shown. Insert shows site coordinates. Scale bar is ~3 km in length. (Image: pawalter.psu.edu)*

2 Coastal Geology, Stratigraphy, and Bluff Retreat

Introduction

Coastal cliffs (consisting primarily of "bedrock"), bluffs (primarily unconsolidated materials) and banks (steep, unconsolidated, low-relief slopes) account for ~80% of global coasts (Emery and Kuhn, 1982). Approximately 25% of the North American Great Lakes coastline consists of cohesive bluffs and low banks (Pope et al., 1999) that are very susceptible to present-day processes of weathering and erosion, and to future climate-influenced changes in bluff properties and lake levels that directly affect bluff stability (Foyle, 2018). Regional climate trends over the next several decades (Lofgren et al., 2002, 2011; Karl et al., 2009; Shortle et al., 2015) may lead to greater bluff instability due to (i) increased erosion associated with surface runoff across the bluff face and (ii) greater groundwater retention (mass) and seepage within the bluff leading to structural weakening. Conversely, an expected increase in regional evapotranspiration in the Great Lakes Basin may lead to lowered Lake Erie water levels, which would have a bluff-stabilizing effect because bluff-toe erosion by waves will be reduced. Predicted climate trends suggest hydrodynamic processes (waves, ice, currents) may become less important as drivers of bluff instability through the end of the century. However, subaerial processes (linked with surface water and groundwater) may become more important drivers. This process duality makes predicting sediment losses from bluff-adjacent lands over time more challenging.

Environmental Setting of the Pennsylvania Coast

Just over 40% of the entire Lake Erie perimeter consists of banks and bluffs that are dominated by unconsolidated glacial till and lacustrine sediments (Stewart, 1999; Geomorphic Solutions, 2010; Cross et al., 2016). In Pennsylvania, banks are defined as steep coastal slopes with elevations of less than 1.5 m above lake level (PA DEP, 2013). Bluffs and banks with sand contents in excess of 50% are very rare on the Lake Erie perimeter (Morang et al., 2011).

In Pennsylvania, the western Erie County littoral cell (WECLC) stretches ~33.5 km from the OH-PA state line northeastward to where Presque Isle joins the mainland bluff coast (Fig. 2.1). Lakefront bluffs account for ~88% (~29.6 km) of the 33.5 km, the remainder being creek mouths and associated floodplain banks (~7%; 2.3 km), and small ravines and access trails (~5%; ~1.6 km). The majority of the bluffs directly face the open lake, with a small fraction (1.5 km) being obliquely offset from the lake due to (i) accretion at creek mouths (Raccoon Creek, Avonia Creek, and Walnut Creek), (ii) suburban-developed lowlands at the bluff toe (near Powell Avenue), and (iii) beach accretion updrift of coastal structures (near East Kelso Drive). Coastal elevations range from 174.3 - 212.3 m above mean sea level (MSL), or 0-38 m above Spring 2015 lake level.

The WECLC nearshore lakebed consists of bedrock with little sediment cover. Nearshore bedrock occurring within the zone of wave breaking (less than 5-10 m water depth) can help reduce the rate of bluff retreat. This is because nearshore downcutting of the lakebed is reduced which in turn limits wave heights and thus wave energy that may be directed at the bluffs. Lakewide, approximately 46% of the Lake Erie perimeter nearshore consists of cohesive till, cohesive lacustrine clay, and cobble or boulder lag deposits (Stewart, 1999) that are susceptible to wave-induced downcutting during both high and low lake levels.

Along the Pennsylvania mainland coast of Lake Erie, cohesive bluffs in the WECLC locally overlie as much as 3 m (10 ft) of shale bedrock at the bluff toe. The shale bedrock toe is present along ~60 % of the WECLC coast, primarily in the Crooked Creek (includes Site 3EBSP), Trout Run (includes Sites 4EBSP and 5YMCA), Walnut Creek (includes Site 6LSCC), and Mill Creek-West (includes Sites 6LSCC and 7BMD) watersheds. In the Turkey Creek and Elk Creek watersheds, the bedrock surface lies as much as 2 m beneath lake level. The WECLC coast is a coarse-sediment starved system and was classified as a cohesive coast by the Lower Great Lakes Erosion Study (Stewart, 1999). The susceptibility of the WECLC coast to erosion is enhanced relative to other bluff-coast settings on the Great Lakes because the shoreline is a northwest-facing, windward coast subject to relatively large fetches and wave energies.

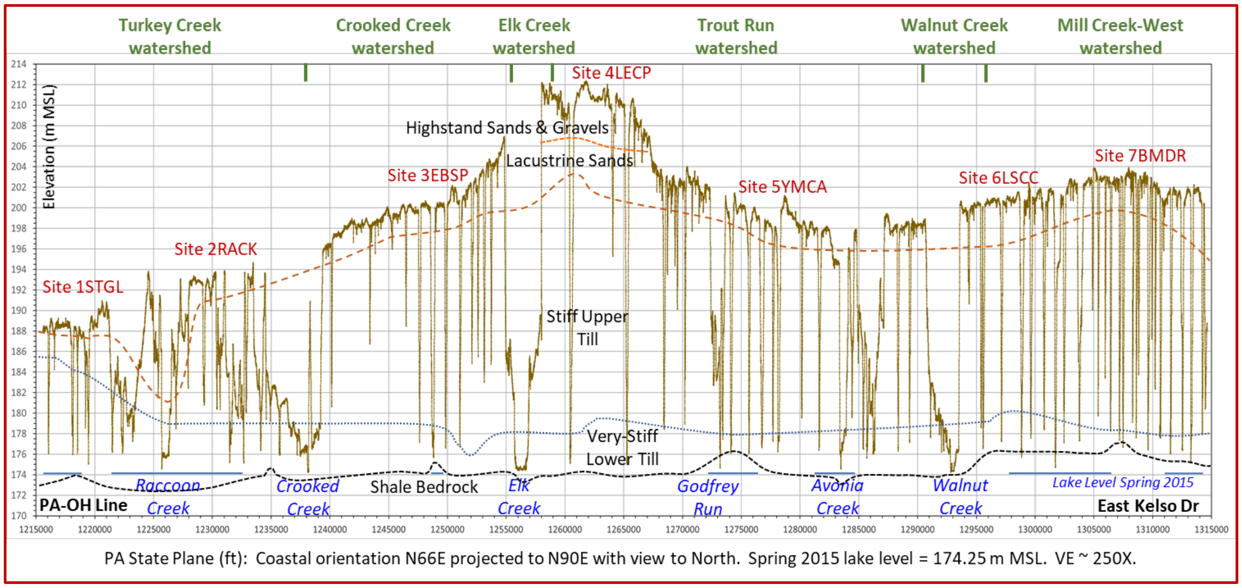


Figure 2.1: *Northward looking cross-section of the WECLC bluff coast showing bluff-crest elevations, major creeks and minor ravines, generalized stratigraphy, lakefront extent of HUC-12 watersheds, and study sites (1STGL - 7BMDR) used in Bayesian analysis. (bluff crest mapped using a 0.6 m sampling interval on 2015 lidar)*

Geologic Framework

The Pennsylvania mainland coast of Lake Erie is in general characterized by unconsolidated bluffs and banks ranging in elevation from 1.5 to 55 m above lake level (or, 175.5-229 m above mean sea level (MSL); Schooler, 1974; Foyle, 2018). The WECLC coastal sector is similar, with maximum bluff elevations of ~37.7 m above lake level (~212.3 m MSL). The bluffs are traversed by numerous creeks, such as Elk Creek and Walnut Creek (with ~250m wide floodplains), many of which incise through the unconsolidated sediments onto Devonian bedrock; small waterfalls are common at the shoreline in such settings. Small ephemeral groundwater springs drain active rotational slumps (tens of meters in width) and narrow ravines (meters to tens of meters in width; tens to hundreds of meters in length), while perennial springs drain larger, well-vegetated Holocene bowls that mark large former landslide areas. Beaches are generally narrow (averaged 8.9 m in width during 2007) and are present along ~75% of the WECLC. The maximum active-beach width of ~70 m occurs updrift of the large terminal groyne at East Kelso Drive that marks the downdrift limit of the WECLC.

Landward of the bluffs, an elevated low-gradient, lakeward-sloping, paleo-lacustrine plain extends several kilometers inland. Inland, this former lakebed abuts a late Pleistocene paleo-shoreline (typical elevation ~213 m MSL; Fig. 2.1) that marks the lakeward edge of the Warren beach ridge complex, which is in turn backed by an older, higher-elevation Whittlesey complex (~227 m; Schooler, 1974). Both of these complexes formed during latest-Pleistocene still-stands of lake level during a long-term drop in the level of Lake Erie (Holcombe et al., 2003). The coastal plain eventually terminates 5-10 km inland against the toe of a coast-parallel glacial-moraine escarpment at a typical elevation of ~245 m MSL. The crest of the escarpment (typically at ~450 m MSL) marks the southern edge of the Lake Erie watershed in Pennsylvania. East of Elk Creek at Site 4LECP in the Trout Run watershed, the Warren beach-ridge complex progrades northward over the paleo-lacustrine plain, extending to the bluff edge (Schooler, 1974). This sandy and gravelly complex is up to 8 m thick and associated with the highest bluff-top elevations in the WECLC. The beach-ridge complex is analogous to the modern Presque Isle strandplain and formed as a latest-Pleistocene coast prograded lakeward over the paleo-lacustrine plain that is now stranded tens of meters above modern lake level.

Offshore, Devonian-age shale bedrock (with thin sandstone beds) crops out on the lakebed over large areas of the surf zone and nearshore, and dips (~1:100 gradient) to the north-northwest. Sediment cover is patchy. Offshore of the Mill Creek-West watershed at the downdrift end of the WECLC (Fig. 2.1), as much as 4 m of sediment cover over bedrock marks a former position of the Presque Isle strandplain. Here, shallow bathymetry limits surf zone wave height during storm events and fosters partial dissipation of wave energy before waves reach the beach and bluff. This effect is likely most significant at the Mill Creek-West nearshore shoals, and also at similar but deeper shoals offshore of the Turkey Creek watershed at the updrift edge of the WECLC. Because of these two shoals bracketing the WECLC, deep nearshore water occurs closest to shore along the central part of the WECLC. Two dominant bedrock joint (fault) sets, oriented N40E and N55W, can be seen in the nearshore and surf zone on aerial imagery (pasda.psu.edu) and in PA DEP oblique aerial-photography datasets. At the bluff face, these joints cause localized changes in bedrock elevation and lakeward extent at the bluff toe. Richards et al. (1987) noted that enhanced groundwater transmissivity at these faults leads to heightened pore pressures that can contribute to localized failures in overlying glacial till sediments.

Bluff Stratigraphy

Detailed information on bluff stratigraphy in Erie County is scarce and is focused on a small number of specific research sites. Information on nearshore substrate properties for the Pennsylvania coast is even more scarce and poses a significant limitation for any future modeling of bluff stability. The Ohio DNR Office of Coastal Management maintains the LESEMP Map Viewer where coarse-resolution details on nearshore substrate coverage extend eastward into Pennsylvania coastal waters (http://coastal.ohiodnr.gov/erosion).

The principal sources of geologic information for western Erie County comprise studies completed by D'Appolonia (1978), Knuth (1983, 1985, 1987, 2001), Buyce (1987), Amin (1989, 1991, 2001), Knuth and Lindenberg (1994, 1995), Highman and Shakoor (1998), Urban Engineers of Erie, Inc. (2004), and Cross et al. (2016). Relevant stratigraphic information from easternmost Ohio is included in Dawson and Evans (2001) and Jones and Hanover (2014). While these publications provide differing degrees of stratigraphic and geotechnical information at specific coastal locations, the extrapolation of stratigraphy and geotechnical properties between sites remains challenging. More-generalized geologic and coastal-engineering summaries, and a broad-scale classification of bluff and nearshore materials, are available in Carter et al. (1987) and Stewart (1999). The former study categorized the Lake Erie coast into hazard-risk zones on the basis of susceptibility to coastal erosion: the WECLC was classified as a moderate-risk zone. In general, bluffs in the WECLC consist of a combination of one to five principal stratigraphic units:

- Devonian shale bedrock that crops out below lake level and locally occurs as high as 3m above lake level: the grey bedrock is interbedded with sandstones, well jointed, and resistant to erosion.
- two late Pleistocene glacial till units: a very-stiff, fractured, often stratified, typically grey, lower till is overlain by a stiff, less-well stratified upper till easily gullied by surface runoff (Fig. 2.2, Fig. 2.3).
- laminated and non-laminated lacustrine clays, silts and sands, ranging in color from grey to yellow-brown, the result of former glaciolacustrine lakebed deposition.
- latest Pleistocene paleo-strandplain sands and (pea) gravels deposited during former highstands of lake-level. An ancient analog of modern Presque Isle, these well-layered, friable strata are yellow-brown to brown in color.

Figure 2.2: *Typical appearance of glacial tills in the western part of the WECLC. Tills are dominated by silt and clay and contain cobbles and small boulders. They are overlain by thinner, tan-colored, usually well-bedded, lacustrine strata containing silts and sands. Runoff-and spring-caused rills and gullies are more common in the stiff upper till unit (left), while fracturing is restricted to the very-stiff lower till unit (right).*

Carter et al. (1987) showed that the Pennsylvania coast is effectively a cohesive coast dominated by clay-rich glacial tills overlain by proglacial lacustrine silts and sands. In the WECLC, bluffs are locally capped by sandy to gravelly highstand beach-ridge strandplain deposits (the Warren paleo-shoreline) near Elk Creek and range in elevation from low banks (~1.5 m) to ~38 m (Fig. 2.1). Shale bedrock crops out at and above lake level, particularly east of Elk Creek. Because of the bedrock toe, wave-induced erosion of unconsolidated bluff materials is reduced, and beaches are often absent or patchy where a bedrock toe is present. Slow rates of wave-induced erosion of the resistant bedrock toe mean that it retreats as a steep (>60^0; Foyle and Naber, 2011) cliff that fosters wave reflection, downward-directed wave shear stress, lake-bed scour, and consequently a limited opportunity for beach accumulation given a pre-existing shortage of littoral sand.

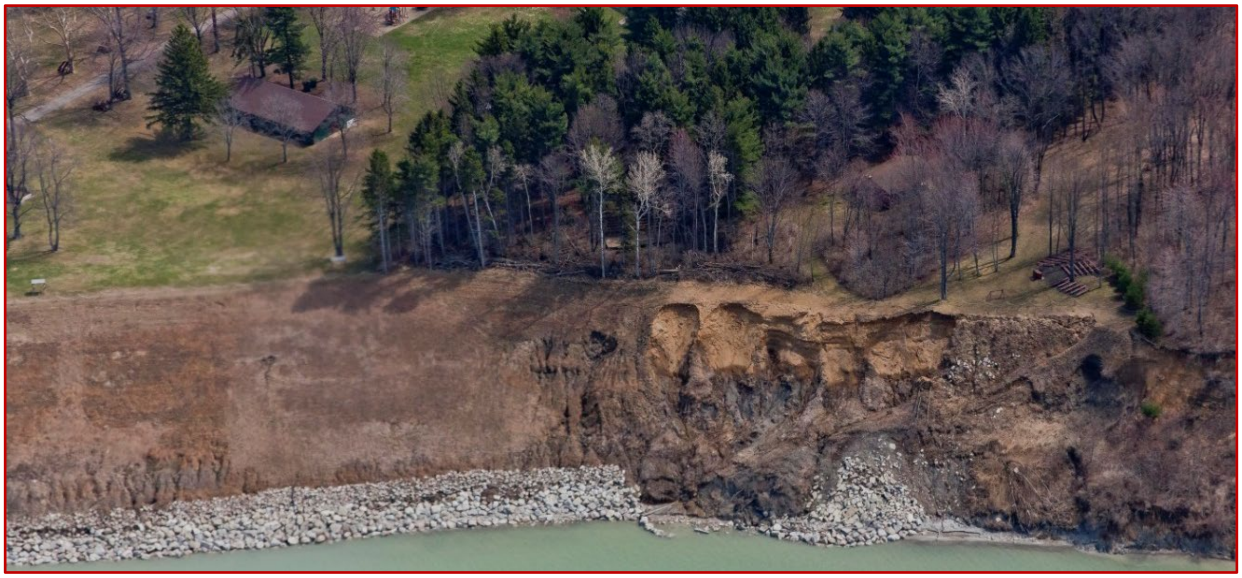


Figure 2.3: *Example of bluff failure and repairs along high bluffs. Small rotational slumps occur at the top of the bluff; and mud and debris slides occur in glacial tills on the lower half. The bedrock toe is absent. (2015 imagery, available from the PA DEP CRM Program at http://www.dep.pa.gov)*

Narrow beaches front most of the WECLC and are widest at stream mouths and updrift of groynes. Beaches are narrow because of a lack of natural sediment transport into the WECLC from west of the Conneaut breakwaters located ~2 km west of the OH-PA state line (Knuth, 2001; Cross et al., 2016). Periodic artificial sand bypassing across the Conneaut breakwaters partly mitigates this sediment-shortfall problem (Morang et al., 2011). Narrow beaches are also a consequence of sand and gravel contents being low (less than 30%) in the glacial till-dominated bluffs, and because localized sediment starvation occurs on the downdrift sides of shore-protection structures. Numerous creeks enter the WECLC but supply insignificant quantities of sand and gravel to the littoral zone. Knuth (2001) estimated that bluff erosion accounts for as much as 99% of the sediment supplied to the Pennsylvania littoral zone in general, with creeks accounting for the remaining 1%.

Devonian Bedrock

Bedrock occurring along the Erie County coast consists of members of the Upper Devonian Canadaway Formation. The Northeast Shale member is exposed at the lake shore to the east of Elk Creek, while the Girard Shale member is exposed at the mouth of Elk Creek and locally to the west at and below lake level (Knuth et al., 1981; Knuth, 2001; LERC, 2008). These Devonian rocks consist of grey shales and thin (< 0.1 m) interbedded sandstones (Sevon and Braun, 1997; Berg et al., 1980) and directly underlie Pleistocene glacial tills and pro-glacial lacustrine sediments (Fig. 2.4). There is a several-hundred million year gap in the rock record across the unconformity separating the Devonian from the Quaternary section. Bedrock elevation at the bluff face ranges from ~2 m below Spring 2015 lake level at the shoreline (~172.5 m MSL at Site 2RACK; Fig. 2.1) to almost 2.8 m above lake level (~177.2 m MSL at Site 7BMDR; Fig. 2.1). While the unconformity between bedrock and glacial till has along-coast topographic relief of a few meters, it also has significant relief in the shore-normal direction due to lake-bed erosion and stream incision over the past ~10,000 years. Bedrock relief is relevant for future bluff retreat rates because retreating bluffs may progressively intersect either higher- or lower-elevation regions of bedrock that are presently buried landward of the bluff face.

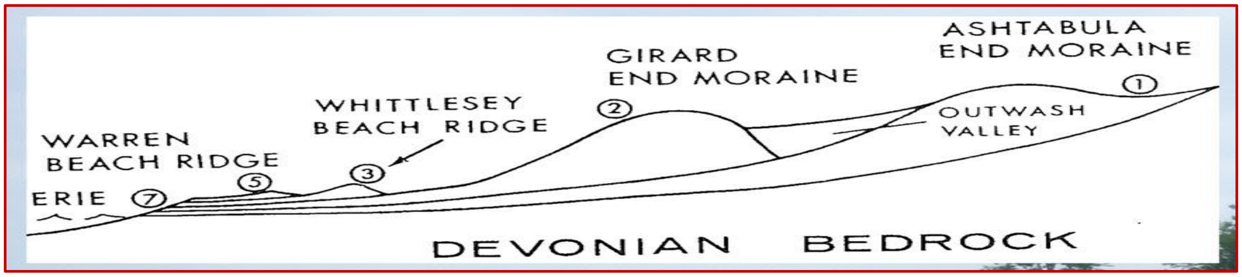


Figure 2.4: *Stratigraphic organization of the coastal plain adjacent to the WECLC. The entire stratigraphic sequence is shown schematically here, from Devonian bedrock near lake level to beach-ridge sands and gravels of the Warren paleo-shoreline that occur in the high bluffs of the Crooked Creek and Trout Run watersheds. The beach is not shown. The schematic (from Schooler, 1974) shows the generalized lakeward-stepping geologic framework for the Erie County coast that accumulated as Pleistocene ice retreated northward and lake-levels generally declined over the past ~12,000 years.*

Bedrock bedding dips gently southward with slopes in the 0 -5^0 range. Schooler (1974) showed that the top-bedrock unconformity generally increases in elevation southward. It is overlain by as much as 38 m of Pleistocene sediment at the bluffs (this report) that then thin to a few meters at the southeastern edge of the lacustrine plain inland. Gas well logs indicate that the Devonian-Quaternary unconformity has an average northward slope of ~1^0 (1.5:100) to the northwest (Foyle, 2014). In general, bedrock at the bluff face stabilizes the bluff because (i) the south-dipping sedimentary beds within the rock layers reduce the incidence of lakeward-directed bedrock slides and (ii) the bedrock toe limits wave impact on overlying unconsolidated bluff materials.

At the bluff face along the length of the WECLC, the undulating bedrock surface occurs from 2 m below to as much as 3 m above lake level (Foyle et al., 2020). It lies below lake level within the Turkey Creek watershed (Fig. 2.1), with the exception of a 400 m outcrop west of Holliday Road near Crooked Creek. Bedrock reappears on the beach east of Crooked Creek (~+0.25 m) in the Crooked Creek watershed and occurs intermittently along the shoreline of Erie Bluffs State Park. In the Elk Creek area, it drops below lake level between the east edge of Site 3EBSP and the east edge of Site 4LECP (Fig. 2.1). Bedrock then reappears in the Trout Run watershed east of Site 4LECP, remaining 0.2 to 0.3 m above lake level through Site 5YMCA (locally reaching ~+2.2 m above lake level) to just west of Avonia Creek. It is then above lake level (~+0.25 m) only intermittently between Avonia Creek and the eastern edge of the Trout Run watershed. It lies below lake level within the Walnut Creek watershed. From Site 6LSCC east of Walnut Creek to east of Site 7BMDR in the Mill Creek-West watershed, shale is well developed at the toe of the bluff, locally occurring at elevations of ~3 m above lake level in Site 7BMDR. From the east edge of Site 7BMDR to the large groyne at East Kelso Drive at the downdrift edge of the WECLC, bedrock lies below lake level and is hidden by the beach prism and by numerous properties with groynes and back-filled seawalls.

Quaternary Glacial Tills

The combined Quaternary cover of glacial tills, lacustrine deposits, and strandplain deposits varies in thickness along the coast and in the inland direction. Richards et al. (1987) show that between the bluff face and a line ~2 km inland to the southeast, isopach (thickness) contours range from ~7 m to ~30 m. Along the bluff crest, from southwest to northeast, the Quaternary section is thickest (27 – 38 m) on either side of Elk Creek where the Warren paleo-shoreline extends to the bluff edge. Here, strandplain deposits add to the Quaternary section in the eastern Crooked Creek and western Trout Run watersheds (Fig. 2.1). The Quaternary cover is thinnest at creek mouths (<2 m at Raccoon Creek, Crooked Creek, Elk Creek, Walnut Creek) due to fluvial downcutting during the Holocene. In general, the Turkey Creek watershed in the updrift part of the WECLC has the thinnest Quaternary cover (<15 m) among the six coastal watersheds in the study area.

The glacial till component of bluff stratigraphy in general accounts for ~70% (on average) of the bluff face along the entire WECLC, varying somewhat by watershed due to variability in bluff height, stream incision, and topography on the top-bedrock and top-till surfaces. Unconsolidated glacial till of latest Pleistocene age (17,000-22,000 years old) unconformably overlies bedrock and is the depositional record of as many as eight glacial advances into Pennsylvania that occurred during the past 2 million years (Richards et al., 1987). On the south side of Presque Isle Bay, at a remediated bluff-failure site, these deposits consist of medium-stiff gray silt with little sand (24% sand, 76% silt and clay; Urban Engineers of Erie, Inc., 2004). These percentages are in general agreement with those observed by D'Appolonia (1978), Amin (1989), and Knuth (2001) elsewhere on the coast. The tills have a high moisture content, poor drainage characteristics, a hydraulic conductivity (k) of ~5×10^{-5} cm/s, and a Standard Penetration Resistance of 26-100 blows/m (BPM; Urban Engineers of Erie, Inc., 2004).

Knuth (2001), based on mapping across Erie County, noted that the glacial till is generally composed of an upper unit (stiff upper till of this study) and a lower unit (very stiff, fractured lower till of this study) with an indistinct contact between the two (Figs. 2.5 and 2.6). The upper till unit is sometimes thinly stratified and is characterized by stiff to very stiff cohesive yellow-brown to gray clayey silt to silty clay with some gravel-shale fragments (Fig. 2.2). The lower till is similar but is a very stiff to hard well-bonded gray, clayey silt to silty clay, with flat angular shale fragments and occasional cobbles and boulders (Fig. 2.5). The two till units are likely to have significantly different geotechnical properties given their sedimentological differences (cohesiveness, grain size) and because the lower unit often has prominent vertical jointing that will induce failure mechanisms that will not necessarily occur in the upper till unit. In general, the till bluff face slopes lakeward at $35\text{-}60^0$ and has abundant rills and gullies cut by surface runoff and bluff-face seepage in areas where vegetation is scarce (Fig. 2.2).

Natural variability in bluff geotechnical properties is the norm and this influences their susceptibility to erosion by wave shear and impact stresses, longshore current-induced stresses, and sand abrasion. Kamphuis (1990) found that tills on the Canadian coast of Lake Erie are generally too strong to be eroded by wave-generated shear stresses alone, but that lower shear stresses could initiate erosion where granular abrasives are present (Trenhaile, 2009; Fig. 2.5).

Quaternary Lacustrine Sands and Silts

The glacial tills are capped by a transgressive erosional surface that was cut by a relative rise in lake level during the latest Pleistocene (Fig. 2.5). This low-relief erosional unconformity has meters of local relief and is overlain by transgressive lacustrine deposits (Schooler, 1974; Knuth, 2001). The erosional contact, because it also marks a significant change in hydrogeologic properties (compaction, porosity, hydraulic conductivity, saturation) between the glacial and lake sediments, is often the part of the bluff where springs occur and large rotational slumps bottom out (i.e., where the failure surface daylights).

Figure 2.5: *Typical appearance of coastal bluffs in the WECLC near Raccoon Creek (Site 2RACK) in the Turkey Creek watershed. The shale bedrock toe is absent but crops out on the lakebed below lake level. Note (i) the undulating beach topography which controls elevation of the bluff toe and (ii) the wave-abraded, rounded, appearance of near-vertical fracture openings at the bluff toe. For scale, orange-white banding on the prism pole are 30 cm thick, and the white folded stadia rod is 1.5 m in length.*

Just east of the WECLC in Presque Isle Bay, the lacustrine strata consist of loose, low shear strength, brown sand (83% fine sand, 17% silt and clay; Urban Engineers of Erie, Inc., 2004), have a moderate to high moisture content with a hydraulic conductivity of ~1×10^{-4} cm/s, and have a Standard Penetration Resistance of 10-33 BPM. Knuth (2001) describes this unit as consisting of soft to very stiff yellow-brown to gray, finely interbedded, clayey silts to silty clays with fine sand or silt partings and occasional shale fragments, deposited in a proglacial lake setting. Sevon and Braun (1997, 2000) state that the lacustrine deposits are the result of deposition of thinly interbedded clayey silt and silty clay in a proglacial lake setting. This sequence of lake sediments is inferred to be capped by a basal surface of forced regression (Foyle, 2014) that was cut by a relative stillstand or fall in lake level.

Quaternary Paleo-Strandplain Sands and Gravels

This stratigraphic unit occurs locally on the coast in the vicinity of Elk Creek in the eastern part of the Crooked Creek watershed and the western part of the Trout Run watershed. It is the geologically youngest and topographically highest of the Quaternary stratigraphic units at the coast. It is associated with the latest-Pleistocene age Warren beach-ridge paleo-strandplain, which is an ancient analog of the modern Presque Isle strandplain. The strandplain unit is described by Knuth (2001) as a sequence of loose to medium-compact, yellow brown to grayish brown, stratified sands and gravels. These ancient beach deposits, dominated by sand and gravel, contain layers comprised entirely of well-rounded pebbles (pea gravel) that mark former beach foreshore positions. In eastern Erie County, groundwater flow rates through this unit are significant (Foyle, 2014), and localized zones of focused groundwater flow in high-permeability layers can cause sapping and piping at the bluff face. This process is believed to be a strong contributing factor to the development of large rotational slumps in the upper section of the bluff.

Figure 2.6: *Toe of the coastal bluffs at Erie Bluffs State Park near Site 3EBSP in the eastern Crooked Creek watershed. The shale bedrock is hidden by the beach prism. Note (i) the sand, cobble and boulder composition of the beach and (ii) the almost man-made appearance of the two boulder-containing glacial till strata. For scale, the folded white stadia rod is 1.5 m tall.*

Coastal Hydrogeology

Groundwater in the coastal zone is present within both the Devonian shale bedrock and within the overlying Quaternary (primarily Pleistocene) sediments (Richards et al., 1987; Buckwalter et al., 1996). Away from joints and faults, bedrock is an effective basal aquiclude for the Quaternary surficial aquifer. Water levels in surficial aquifer wells are highest in March–April and lowest in September–October and lie at a median depth of several meters (Richards et al. 1987; Urban Engineers of Erie, Inc., 2004; Terracon Consultants, Inc., 2018). On the basis of grain-size characteristics, the hydraulic conductivity (k) of lacustrine sands and gravels typically ranges from 10^{-4} to 10^{1} cm/s, which is several orders of magnitude larger than for unconsolidated tills (typical range 10^{-9}–10^{-4} cm/s; Fetter, 2008). Thin gravel horizons in the glacial tills (5–10 cm thick; likely k values of 10^{-2} to 10^{1} cm/s), can function as concentrated local discharge zones at the bluff face. Hydrogeologic characteristics suggest that hydraulic gradients and conductivities, and groundwater flow velocities and volumes through the surficial aquifer are several times greater in the lacustrine and beach–ridge strata than in the glacial tills lower on the bluff (Foyle, 2018).

The surficial aquifer is locally absent from stream valley floors in the vicinity of the bluffs due to stream incision in response to lower lake levels during the latest Pleistocene through mid Holocene (Holcombe et al., 2003). Away from ravines draining the coastal watersheds of the WECLC, the surficial aquifer generally ranges in thickness from ~13 m in the Turkey Creek watershed at Site 1SGL, to ~37 m in the Trout Run watershed at Site 4LECP where beach–ridge complex sediments are present and bluffs attain elevations of almost 213 m MSL. Considering the general layer-cake and lakeward-thickening wedge geometry of the Quaternary stratigraphic section (Foyle, 2018) and the subdued surface topography, the geometry of the water table within the Pleistocene surficial aquifer is inferred to mimic the surface topography. Richards et al. (1987) and Buckwalter et al. (1996) proposed that groundwater circulation in the shallow aquifer system is strongly influenced by surface topography. Therefore, for the groundwater flux attribute used in Bayesian modeling in Chapter 3, groundwater divides are inferred to underlie watershed and sub-watershed divides. It is also inferred that the water table is expected to generally dip from inland areas down-gradient toward the coast and laterally toward stream valleys.

General Bluff Failure Mechanisms

Each of the unconsolidated stratigraphic units in the WECLC has distinct geotechnical properties (e.g., angle of repose, degree of compaction, surface micro-topography, shear strength, etc.). These properties control how a stratigraphic horizon, and the bluff face, visually appears and which type of failure mechanism is most likely to occur (Fig. 2.7). Vadose zone sediments (above the water table) at the top of the bluff often have the steepest slopes, usually 80-90^{0} with root-stabilized overhangs (90-120^{0}) occurring along short stretches (<50 m) of bluff top. Earth falls (individual grains to blocks of several cubic meters) are a common failure mechanism at this upper bluff location. Limited rill and gully development at the top of the bluff suggests that overland flow is an unimportant contributor to bluff instability on the upper bluff in these sandy sediments above the water table.

Below the elevation of the water table (in the phreatic zone), large (tens to hundreds of cubic meters) rotational and translational slumps (Varnes, 1978) are the most significant failure mechanisms (Fig. 2.7). They most commonly originate within the strandplain and lacustrine sections of the bluff. The headwall scarp marking the top of the failure surface of these slumps typically extends to the bluff top, while the toe of the failure surface typically daylights at or in the top of the glacial till (Fig. 2.5). Daylighting of the slip plane at the sand-till contact suggests that pore-water pressures are high at the base of the lacustrine section, partly due to the large contrast in hydraulic conductivity between it and the less permeable, more-cohesive, underlying glacial till section. Erosional chutes occur in the underlying glacial till when a rotational slump or debris fall on the upper bluff supplies debris that abrades the lower bluff during downslope transport. Subsequent groundwater seepage into these chutes can allow further development of topography. Distant from slumps, bluff face sections may fail gradually over time via thin (<0.3 m) earth flows, thin translational earth slumps, debris flows, and soil creep that often build small debris fans on the beach (Figure 2.7). In the westernmost parts of the WECLC where beaches are locally narrow and bedrock submerged, bluffs fail when wave undercutting and abrasion leave the lower till unsupported and it then fails along joint planes (topples; Fig. 2.8).

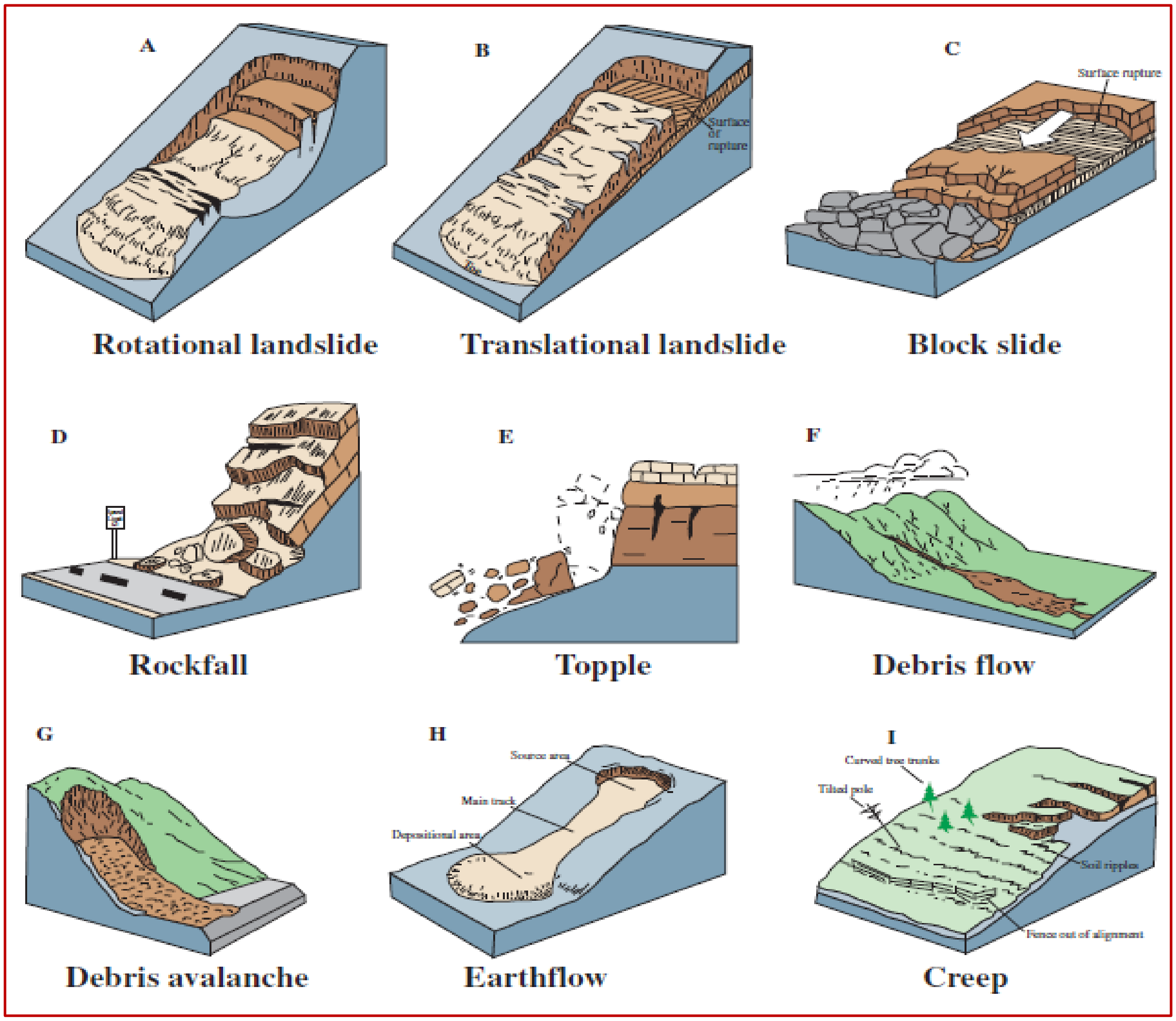


Figure 2.7: *Schematic diagram showing common bluff failure mechanisms. The scheme is based on composition, rate of movement, and water content of the materials involved in the failure. (Image: modified from Highland and Johnson, US Geological Survey Fact Sheet 2004-3072, 2004)*

The translational slump mechanism is associated with bluff failures in the WECLC that can extend for over a kilometer along the coast, for example at Site 4LECP (Fig. 2.9). They may be favored when the bluff toe is over-steepened by wave attack in areas where bedrock is absent from the bluff profile. Stepped benches extending tens to hundreds of meters along-coast with headwall heights of meters are typical dimensions. These failures, unlike rotational slumps, do not necessarily deliver as much debris to the bluff toe, beach, or lake. They have the appearance of sequential and organized (but incomplete) slump activity where benches often remain relatively intact (Fig. 2.9). The benched topography has the benefit of adding transverse topography to the bluff profile that reduces the opportunity for later development of incised rills and gullies fed by surface runoff. For property owners, this type of failure is more likely to result in less landward retreat of the bluff crest during a failure event, but also to result in a greater along-coast impact. This contrasts with the rotational slump response (Figure 2.7) of greater headwall retreat but lesser along-coast extent. This latter mechanism is more prevalent in tall bluffs where groundwater focusing at seeps and springs higher in the profile is more prevalent.

Figure 2.8: *View looking east and west along the low (~15 m) bluffs at WECLC Site 2RACK (Fig. 2.1). Where beaches are narrow and the bluff toe close to lake level, waves cut a wave-cut notch (left), leaving the very-stiff lower till unsupported and prone to failure (topples) along near-vertical joints within the till (right).*

Figure 2.9: *Translational slump (slide) with a relatively linear bluff-crest headwall. The failure is developed in glacial tills and overlying lacustrine sands at WECLC Site 4LECP (Fig. 2.1). Three headwall scarps and two narrow sub-horizontal benches are visible. The lowermost headwall scarp shows earth flow and soil creep activity. (2015 oblique aerial photo from the PA DEP CRM Program at http://www.dep.pa.gov)*

Lake-Level Trends

Lake levels are important because they help dictate how much wave energy reaches the bluff that, over time, drives retreat of the bluff crest. Over the 77-year time window used in this study (1938-

2015), average Lake Erie levels rose at a long-term rate of ~6.5 mm/yr (Fig. 2.10). While this was a long-term transgression overall, cyclicity was significant and there were five transgressive phases, each lasting ~10-15 years. There were four regressive phases, each lasting ~6-12 years. During the slightly shorter 1938-2007 period used to build the Bayesian model, lake level rose at a similar rate of ~4.5 mm/yr. During the shorter 2007-2015 validation period used in the Bayesian modeling (Chapter 3), lake level rose at an average rate of ~22 mm/yr, or about three times the long-term rate, and it was effectively a single transgressive phase if seasonal cyclicity is ignored. Considering these long-term and short-term transgressive periods, the trends but not necessarily the magnitudes were similar for both time periods used in the Bayesian modeling. Since 2015, lake levels have continued to trend towards new highs, with the 2019 annual average level of 174.84 m being 0.52 m higher than the 2015 annual average lake level. By June 2019, a record-high (as of December 2020) lake-wide monthly average lake level of 175.14 m (IGLD 1985) was attained.

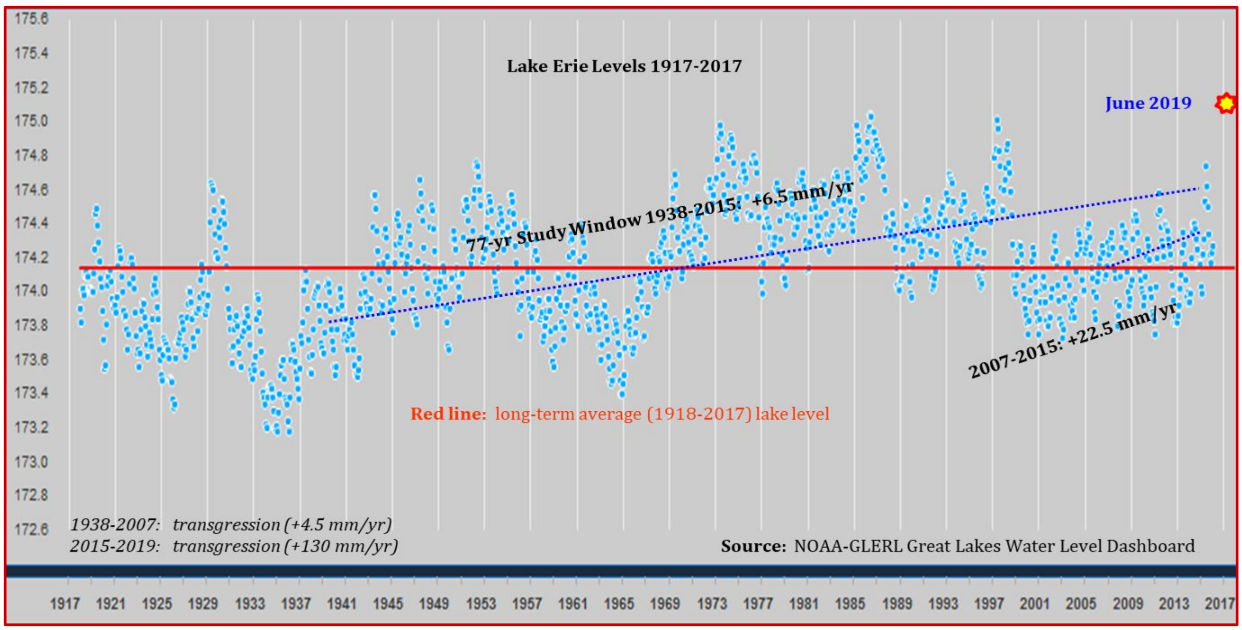


Figure 2.10: *Monthly lake level trends during this study. The red/yellow star shows the all-time-high monthly-average lake level for Lake Erie, set in June 2019. (Source: NOAA Great Lakes Water Level Dashboard, 2020)*

The response time of WECLC bluffs to changes in lake levels is uncertain and may occur over timescales of one to several decades. In the short term, parts of the bluff may respond immediately as waves erode the toe and local failures occur on the lower several meters of the bluff. Baird (2003) suggested that there may be as much as a 50-year time lag between change in lake levels on the Great Lakes and response of the bluff. Thus if process-response time lags are long (~50 years; Baird, 2003), bluff-retreat rates in western Erie County may still be high and responding to former high lake levels of the 1980s and may begin to decline over the next several decades. If process-response time lags are shorter (~10 years) as suggested by Knuth and Lindenberg (1995), then bluff-retreat rates may currently be low as they respond to the near-average lake levels of the early 2000s and have not yet begun to respond to higher lake levels of the post-2015 period.

Littoral Sediment Budget Background

About 24% of the Pennsylvania coast is protected by coastal engineering structures placed in the nearshore, on the beach, or on the lower bluff (Stewart, 2001). Coastal structures are significant because they influence the supply, movement, accumulation, and export of sandy sediments in the littoral zone. Morang et al. (2011) noted that a comprehensive coastal sediment budget was lacking for the Pennsylvania coast and that developing such a budget would be a key aspect of improving regional sediment management. A subsequent sediment budget for the US coast of Lake Erie (Cross et al., 2016) improved understanding of sediment budgets for Pennsylvania and for the region. In general terms, Pennsylvania's bluff coast is a sand-starved system due to the small volumes of sand supplied to, moving within, and exiting the system on the downdrift end. The entire coastal system can be defined by three large littoral cells that lie offshore of the western coastal reach (the WECLC of this study), the central coastal reach (Presque Isle littoral cell), and the eastern coastal reach (Knuth, 2001; Morang et al., 2011). The principal source of sand and gravel to the eastern Ohio, Pennsylvania, and western New York coast of Lake Erie is bluff retreat (Knuth, 2001; Morang et al., 2011; Cross et al., 2016).

The breakwaters at Conneaut Harbor, OH, define the updrift end of a littoral cell that includes 2 km of Ohio coast and the 33.5 km WECLC coast of this study. Natural sediment transport around the Conneaut breakwaters towards the Pennsylvania coast is minimal or absent (Knuth, 2001; Cross et al., 2016). Morang et al. (2011) estimated that littoral sediment transport around the Conneaut Harbor breakwaters and across the OH-PA state line may have been as high as 4,500-11,000 m^3/yr historically. Ohio DNR (Fig. 2.11) used bluff retreat rates (1990-2004) and general composition data (e.g., a sand and gravel content of 19%) to estimate that each kilometer of Ohio bluff coast supplies ~475 m^3/yr of sandy sediment to the Ohio littoral zone (Jones and Hanover, 2014). This suggests that the ~2 km of Ohio coast east of Conneaut is supplied with ~1000 m^3/yr of littoral sediment from bluff retreat. This volume, supplemented by any natural and anthropogenic bypassing of sand around Conneaut Harbor, then moves along the Pennsylvania coast. Because much of the bluff coast along the WECLC is similar (geotechnical properties; hydrodynamic forces; composition) to that of the eastern Ohio coast, it can be estimated that bluff erosion along the WECLC may supply ~16,000 m^3/yr of sandy material to the littoral system west of Presque Isle. This means that, during the late 20th to early 21st century, as little as 16,000 m^3/yr to as much as 28,000 m^3/yr of sandy material derived from bluff retreat may have entered the WECLC and then exited the downdrift (eastern) end to enter the Presque Isle Littoral Cell during an average year. This volume is augmented by any additional sand supplied from Pennsylvania streams, and by any onshore transport of shale debris from the nearshore. This number is similar to the 30,000 m^3/yr of potential littoral drift modeled to be arriving at the updrift end of Presque Isle by Nummedal et al. (1984). More recently, Cross et al. (2016) estimated bluff-supplied sand and gravel to the western Pennsylvania coast for the 1973/78-2006 period. Their estimate was 37,900 m^3/yr, of which an assumed 20% (7,600 m^3/yr) was lost offshore below wave base. Natural bypassing eastward around the Conneaut Harbor breakwaters was estimated to be 0 m^3/yr. This resulted in an estimated net 30,300 m^3/yr eventually entering the Presque Isle littoral cell downdrift of the WECLC during that time period.

Knuth (2001; reported in Cross et al., 2016) estimated that, between 1982 and 1988, the Conneaut, OH, to Presque Isle coast received a relatively large 58,650 m^3/yr of sand and gravel, almost exclusively from bluff retreat. Examining longer timeframes, Morang et al. (2011) estimated bluff-sediment inputs along Pennsylvania's western coastal reach over three multi-decade time periods using bluff-retreat data: 1875-1938, 1938-1973/1978, and 1973/1978-2006. They estimated that the volumes of sandy littoral sediment entering and transiting the WECLC and arriving at the updrift end of the Presque Isle littoral cell for those three periods were 47,000 m^3/yr, 61,000 m^3/yr, and 39,500 m^3/yr, respectively. The variability may relate to general trends in lake level (Fig. 2.10): the three time periods corresponded to general regression (a ~0.75 m fall; rate ~12 mm/yr), transgression (a ~0.75 m rise; rate ~20 mm/yr), and subsequent regression (a ~0.5 m fall; rate ~16 mm/yr), respectively. The estimates may support the premise that bluff retreat rates are lower during falling and low lake levels than during rising and high lake levels. A complicating factor in interpreting these numbers is that the Ohio coast also experienced a progressive increase in hard stabilization during the 1875-2006 time period (Fuller and Gerke, 2005).

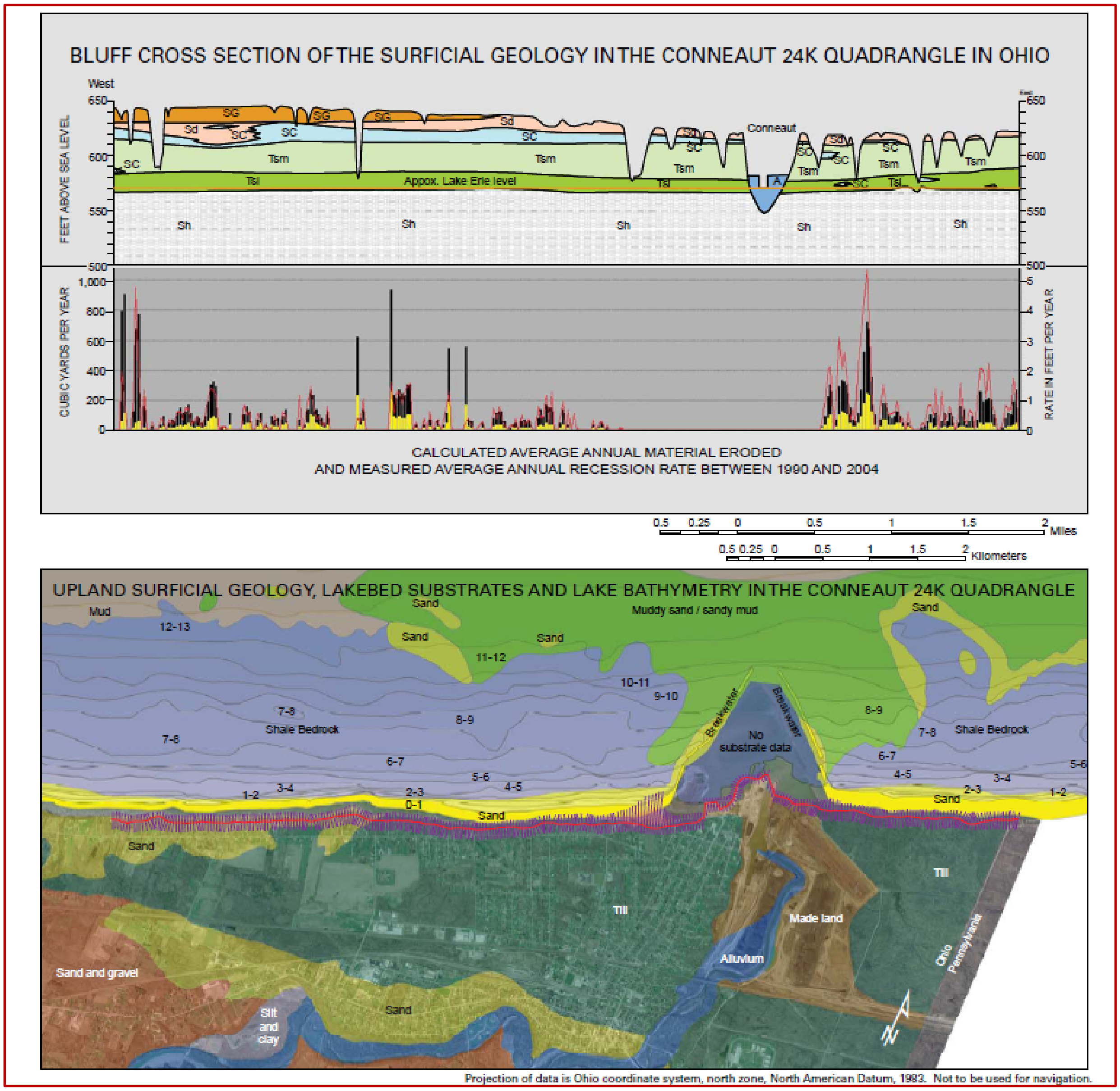


Figure 2.11: *Bluff-face stratigraphy, annual bluff retreat rates (1990-2004), sediment volumes input to the littoral zone, lake-bed and onshore geology, and bluff transect locations (33 m spacing) used for bluff mapping updrift of the WECLC in Ohio. (Image: modified from Jones and Hanover, 2014)*

To summarize, prior-research estimates show that late 20th to early 21st century sandy-sediment volumes entering the WECLC due to bluff retreat and leaving the downdrift end to enter the Presque Isle littoral cell ranged from 16,000-30,000 m³/yr (Nummedal et al., 1984; Knuth, 2001; Morang et al., 2011; Cross et al., 2016). These littoral sediment transport volumes on the WECLC coast are of sufficiently low magnitudes that artificial sand bypassing should be considered for any existing or planned large coastal structures that may trap littoral sediments (Foyle, 2018): infrequent artificial bypassing has already occurred updrift of the WECLC at Conneaut Harbor, OH.

Lakefront Bluff Retreat Background

As part of the compilation of data for the Bayesian modeling and sediment-input mapping components of the project, bluff attribute data were collected for all 470 transects at the seven WECLC study sites. The specific details on these bluff-related attributes are discussed further in Chapter 3 and Chapter 4. This section of the report describes general geo-environmental relationships, correlations, and spatial patterns that are revealed by comparing these attributes within sites and across the WECLC. In general, the correlations noted in this section, and variability in whether these correlations are positive or negative within and between sites, hint at the validity of using multivariate Bayesian modeling in Chapter 3 as a tool to identify process-response behaviors in bluff retreat. Qualitative comparisons of variables in this section do not identify a single variable (attribute) that can be consistently identified as the principal driver of bluff retreat across the WECLC.

Long-term annual rates of bluff-crest retreat (1938-2015; 1938-2007) for each of the seven WECLC sites, coupled with short-term rates (2007-2015; 8-yr) are shown in Fig. 2.12. The 77-yr and 69-yr rates are comparable to each other and larger than the 8-yr rates. This is likely a consequence of (i) the known periodicity of bluff retreat and (ii) slump recurrence intervals being near or greater that eight years and thus not being entirely captured in the 8-yr change comparison. Moving eastward along the coast, the 77-yr and 69-yr rates increase between Site 1STGL and Site 2RACK (highest at Site 2RACK) and then decrease towards Site 5YMCA. Rates are generally lowest at Site 6LSCC and then increase again (slightly) towards Site 7BMDR. Within each WECLC site, there is signification variation in the rates at each DSAS transect. The uncertainties in the annualized rates of bluff retreat for the 77-yr and 69-yr comparison periods are estimated to be approximately ±0.16 m/yr and ±0.18 m/yr, respectively.

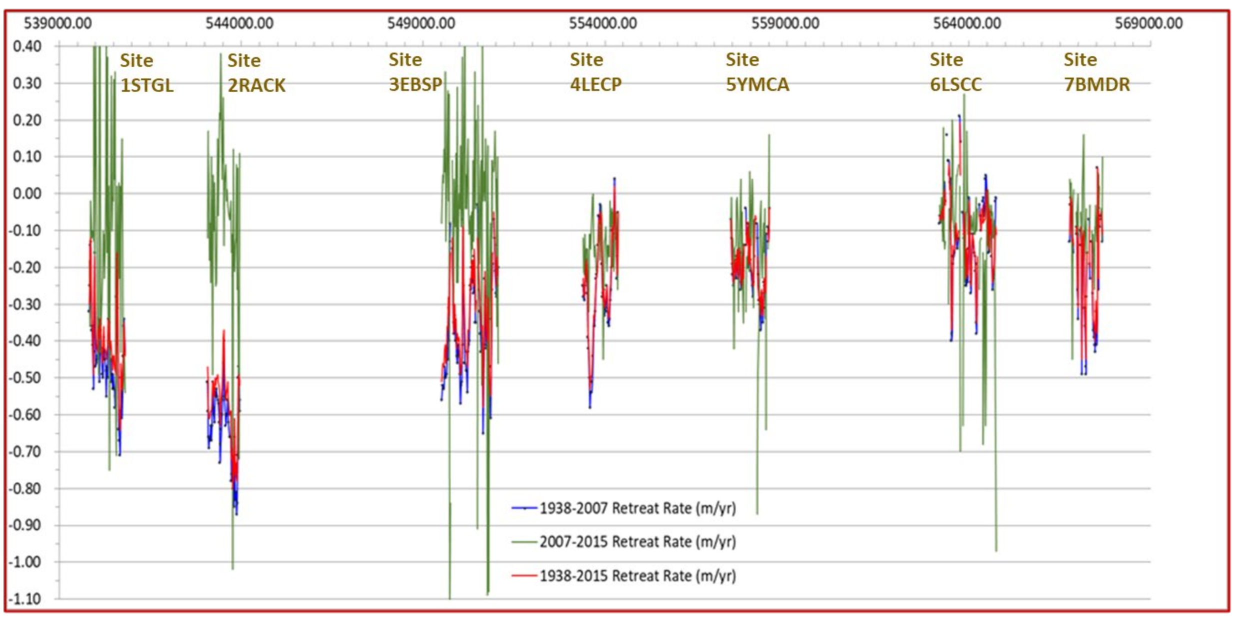


Figure 2.12: *Average annual bluff retreat rates (m/yr) at the seven WECLC study sites for 1938-2015, 1938-2007, and 2007-2015. The two latter rates are used in Bayesian modeling in Chapter 3. Each site comprises 50-80 data points per era, coordinates are in UTM meters, and negative numbers indicate retreat.*

The 2007-2015 annual retreat rates are noisier at each site than the long-term rates, with numerous occurrences of apparent bluff progradation at Sites 1STGL, 2RACK, and 3EBSP (Fig. 2.12). Apparent bluff progradation is likely a consequence of imprecise crest identification due to masking by bluff-edge trees. However, most of the progradation data points lie within the uncertainty range for these data, which for the 8-yr interval is ±0.17 m/yr (Chapter 3). Short-term rates slightly decrease eastward from Site 1STGL to Site 3EBSP (where rates are lowest), increase between Sites 3EBSP and 4LECP, and then decrease towards Site 7BMDR. Between sites, there is significantly less variation in the 2007-2015 retreat rates when compared with the long-term rates.

Examining the three datasets together, the 77-yr rates are slightly lower than the 69-yr rates. This suggests that the WECLC became slightly less erosional recently (2007-2015), particularly when this observation is considered with the overall-low short-term rates seen (although these could alternatively reflect slump-event periodicity). This transition may also mean that there has been some minor recovery from a littoral sediment shortfall in the WECLC that has been attributed to the construction and expansion of the Conneaut breakwaters beginning in 1829 (Morang et al., 2011; Cross et al., 2016). This recovery is possible if some sand is now being naturally bypassed east of the breakwaters to the eastern OH and western PA coasts. It is also possible that this minor change is attributable to intermittent artificial bypassing around the breakwaters. However, the rate differences between the two long-term eras are small enough that much of the difference may lie within the uncertainty in the datasets. Also notable in Fig. 2.12 is the difference between the long-term and short-term retreat rates spatially across the WECLC that might not be simply attributable to bluff-failure events not being captured in the eight-year comparison. Spatially, the rate differential increases between Sites 1STGL and 2RACK, and then decreases eastward along the remainder of the WECLC. The differential is largely due to change in the long-term rate, particularly in the western half of the WECLC (Fig. 2.12). The effect may be a consequence of the Conneaut breakwaters' impact on WECLC sediment supply having a multi-decade response time.

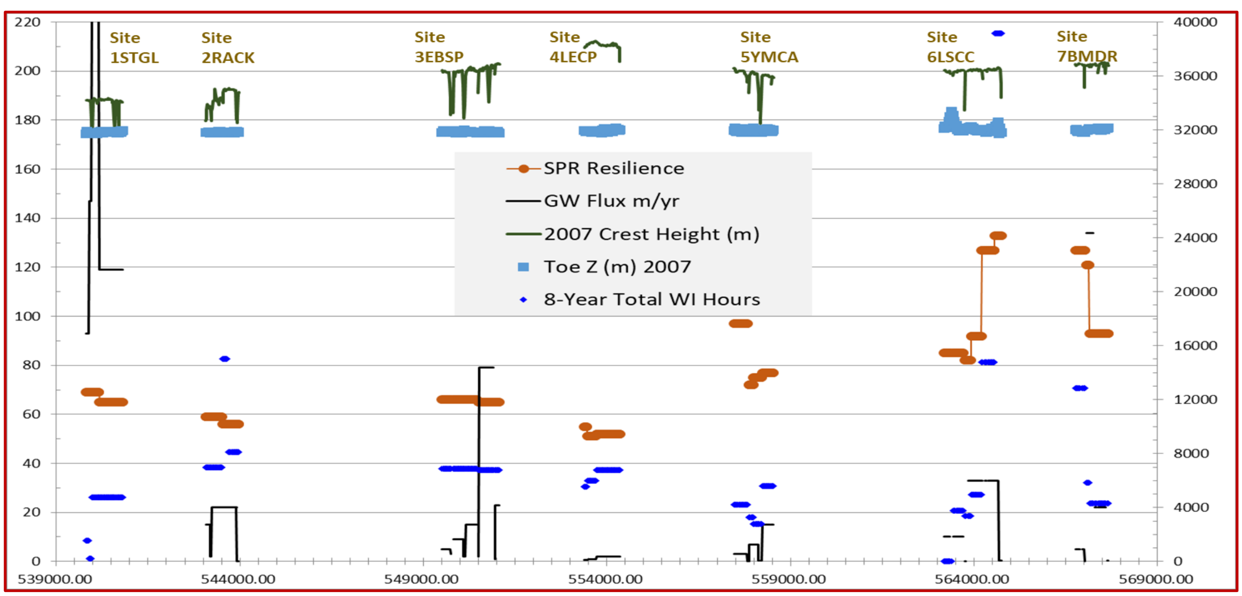


Figure 2.13: *Selected bluff-face attributes at the seven WECLC sites: bluff resilience, groundwater flux, crest height, and bluff-toe elevation (left axis); and 8-yr wave impact hours (right axis). Each of these attributes was considered for use in Bayesian bluff-retreat modeling discussed in Chapter 3. Coordinates are in UTM meters.*

Figure 2.13 plots the variation across the WECLC of five physical attributes associated with changes on the bluff face. These data are used in both the Bayesian modeling (described in Chapter 3) and the littoral-sediment input model (described in Chapter 4). The Resilience (SPR Resiliency) reflects the resistance of the bluff to erosion and is described in detail in Chapter 3. It ranges in value from ~51 to ~133 depending on the relative strengths and thicknesses of bluff strata present. It is lowest in the central part of the WECLC and increases to the west and more noticeably to the east. It is based on a relatively small number of data points per site, typically being mapped for each of two to six multi-transect WIH sectors within each WECLC site. The presence of shale bedrock at and above the shoreline can result in large jumps in the Resilience score, as can be seen for Site 6LSCC and Site 7BMDR near the downdrift end of the WECLC. This occurs because blows/m (BPM) values for shale bedrock are at least an order of magnitude greater than for the other unconsolidated strata in the bluff face.

Elevation of the top of bedrock (not shown here; see Chapter 3) increases eastward. The top of bedrock lies at its lowest elevations (172.5 – 174.2 m MSL; or 1.75 – 0.1 m below Spring 2015 lake level) at Sites 1STGL and 2RACK in the western WECLC. It then generally increases in elevation eastward to average 174 – 177 m MSL (or 0.25 m below - 2.75 m above Spring 2015 lake level) at Sites 6LSCC and 7BMDR.

Groundwater flux varies across each site and along the WECLC. The flux varies from tens to hundreds of cubic meters of groundwater discharge per square meter of bluff face per year. It varies due to changes in the sizes of the (ground) watersheds feeding the bluff face at the lakeward edges of each of 97 sub-watersheds, along with the discharge area of the bluff face associated with that sub-watershed. Low values of groundwater flux occur at bluff-face areas flanking ravines where much groundwater is deflected towards ravine slopes landward of the bluff face. Highest values of groundwater flux occur at Site 1STGL where inland surface drainage is poorly developed, and most groundwater is inferred to drain towards the bluff rather than being captured by incised surface drainage (ravines and creeks such as Turkey Creek).

The 2007 bluff crest height varies across the seven sites, generally increasing from west to east across the WECLC (Figs. 2.1 and 2.13). Crest heights range in elevation from ~175 m to ~212 m MSL, or from ~0.75 m (at ravine mouths) to ~38 m above Spring 2015 lake level. The highest bluff elevations occur at Site 4LECP in the Trout Run watershed in the center of the WECLC. Here, paleo-strandplain sands and gravels are exclusively present and overlie the lacustrine silts and sands that define the upper bluff in all other areas of the WECLC.

Toe elevation is relatively uniform across the WECLC where in general it increases from ~175 m MSL in the west to ~176 m MSL in the east (site-average values). Though difficult to resolve at the scale of Fig. 2.13, it varies within each site due to the presence or absence of beach, ranging in elevation from 174.5 - 176 m MSL on the western half of the WECLC, to 175 – 177 m MSL on the eastern half. The toe elevations, collected at 20 m-spaced DSAS transects, are lowest for Sites 1STGL and 2RACK, and highest at Sites 6LSCC and 7BMDR, where they locally reach ~177 m MSL due to the presence of a stepped wave-cut platform and low bedrock cliff (Fig. 2.13). Across the WECLC, toe elevations typically lie between 174.5 m and 177 m MSL, or 0.25 - 2.75 m above 2015 lake level.

Figure 2.13 shows wave-impact hours (WIH) at the bluff face ($R_{2\%}$ exceedance hours; Chapter 3) for the WECLC by site sector over the January 2007- December 2014 time period. At each WECLC site, two to six sectors were identified based on coastal orientation which strongly affects wave-energy delivery at the bluff given the generally planar nearshore bathymetry. Values are variable both within and between sites and are controlled by the degree of beach development (beach width and toe elevation; Chapter 3) and sector orientation to the long-term average wave-approach direction (~290⁰). Impact hours are lowest on the central third of the WECLC and highest on the eastern third, ranging from zero to almost 39,200 hours over the eight-year data period (1625 days; 203 days per year at Site 6LSCC). On average, the bluffs at the seven sites experience ~874 wave-impact hours (~36 days) per year.

Figure 2.14 shows total bluff retreat at each of the seven WECLC sites over the short (2007- 2015) and long (1938 – 2007; 1938 – 2015) terms. Uncertainties in mapped bluff-crest positions for these eras are ±1.4 m, ±12.5 m, and ±1.4 m, respectively (Chapter 3). Greatest retreat over the long term occurred on the western third of the WECLC at Sites 1STGL and 2RACK, generally ranging from 25 to 55 meters. On the eastern two-thirds of the WECLC, bluff retreat was noticeably less, ranging from 5 to 25 m. Changes in retreat magnitudes across the WECLC in the short-term data were not as apparent as in the long-term data, while uncertainty in the measurement (±1.4 m) led to apparent short-term progradation that was most noticeable at Sites 1STGL, 2RACK, and 3EBSP.

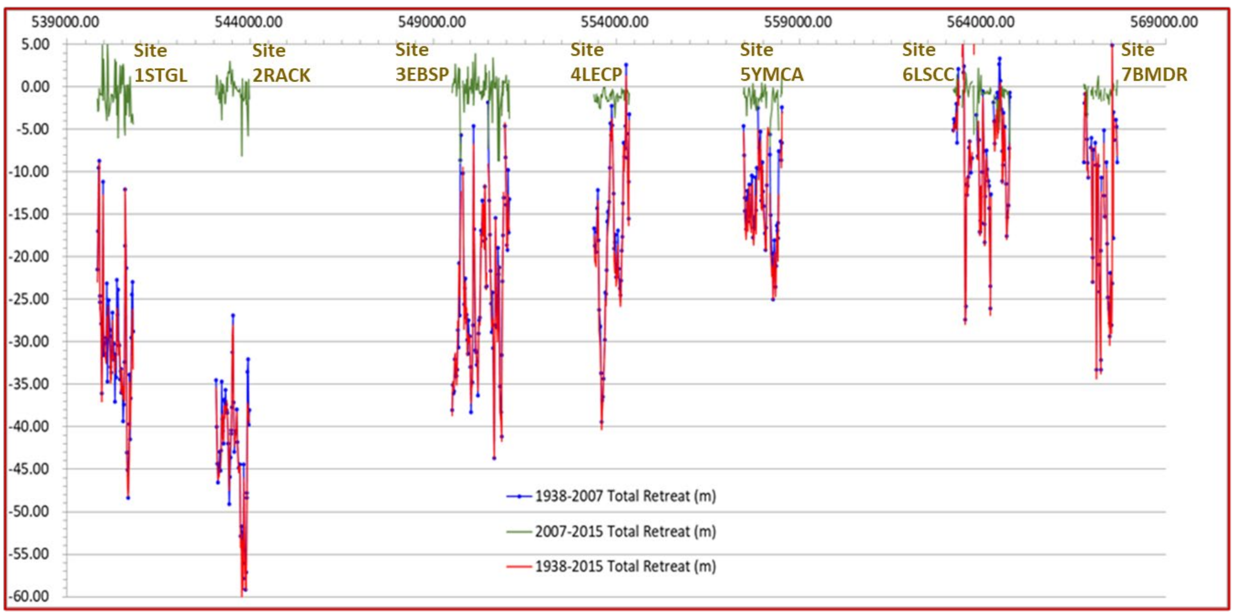


Figure 2.14: *Total amount of bluff retreat (m) at each of the seven WECLC sites for the 1938 – 2015, 1938 – 2007, and 2007 – 2015 time periods. Amounts are based on DSAS analysis of bluff-crest locations at 20 m spaced transects within each site. Each site comprises 50-80 data points per era, coordinates are in UTM meters, and negative numbers indicate retreat.*

Figure 2.15 shows additional bluff attributes also considered for Bayesian modeling (in addition to those shown in Figs. 2.12 and 2.13). Overall, beach width in the WECLC averages almost 9 m, increases from ~4 m to ~12 m eastward across the WECLC, and shows significant variation between DSAS transects within each site. Largest widths for the active beach are in general found at the downdrift end of the littoral cell, associated with groynes at Site 6LSCC and with beach accretion at and east of Site 7BMDR. Near Site 6LSCC, beach widths in excess of 50 meters occur along a wide floodplain on the east side of Walnut Creek that is no longer an active beach but does provide protection to the bluff toe from wave attack.

Bluff slopes decrease moving east across the WECLC from ~35⁰ to ~30⁰. Bluff slopes range from 12⁰ to 42⁰, with a mean of ~30⁰. Variation is significant within sites and has a range of ~20⁰ in the western WECLC and ~10⁰ in the eastern WECLC. In general, steeper slopes are known to be associated with greater bluff instability (Zuzek et al., 2003) and are more likely to fail in the future as the bluff attempts to revert to a gentler slope. The eastward decline in bluff slope accompanies an eastward increase in both beach width and thickness, suggesting that larger-volume beaches may be allowing bluff slopes to become more stable, perhaps because wave impact hours on the bluff are being reduced. Steeper bluff slopes in the western WECLC (Fig. 2.15) are associated with greater long-term (1938-2007) bluff-crest retreat (Fig. 2.14).

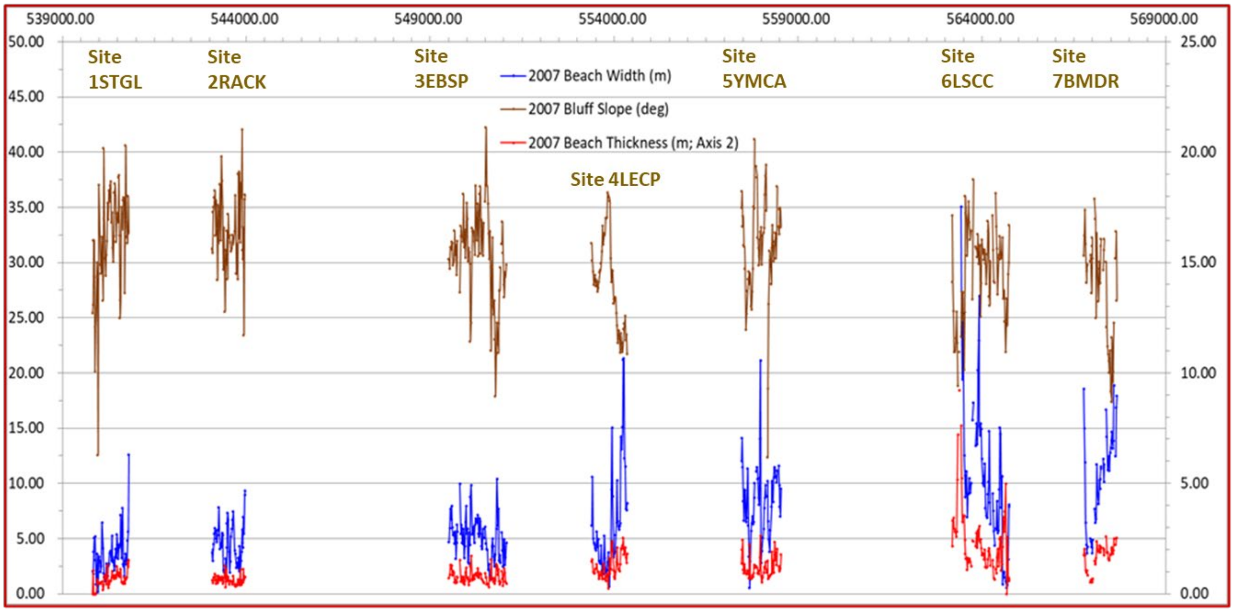


Figure 2.15: *Variability in 2007 beach width, 2007 bluff slope, and 2007 beach thickness (right axis) at WECLC study sites. The 2007-era attributes were expected to influence bluff retreat and were considered for use in Bayesian bluff-retreat modeling discussed in Chapter 3. Each site comprises 50-80 data points per era, and coordinates are in UTM meters.*

Beach thickness, a proxy for bluff-toe elevation, increases eastward from ~0.5 m to ~1.75 m, mirroring the trend in increasing beach width (Fig. 2.15). Combined, these two measures imply increasing beach volumes (beach prisms) moving eastward. This is a normal and common attribute seen in littoral cells, where the updrift part of a cell often has a less-positive sand budget than the downdrift part.

While explored more fully using Bayesian modeling in Chapter 3, generalized correlations between attributes can be observed qualitatively at specific WECLC sites by comparing Figures 2.12 through 2.15 above. These correlations vary in sign and strength between sites and illustrate the benefits of a multivariate-analysis approach to understanding bluff retreat (Bayesian modeling). In general, increasing beach width and bluff slope moving eastward across Site 1STGL show a positive correlation with long-term retreat rate (Fig. 2.12) and amount (Fig. 2.14), which also generally increase eastward across the site. The beach width:bluff retreat association is unexpected, suggesting that crest retreat may be forced by other variables here (Fig. 2.16). At Site 2RACK, a similar increase in long-term retreat moving eastward across the site is correlated (expectedly) with an increase in groundwater flux, wave impact hours, and crest height; and a decline in resiliency. Site 2RACK also has the greatest bluff retreat (rate and amount) among the seven sites and this is associated with the lowest top-of-bedrock elevation in the entire WECLC (~2 m below Spring 2015 lake level). Resiliency and beach-prism volume at Site 2RACK are the second-lowest among sites, while wave impact hours are the second-highest. Site 3EBSP shows a slight decline in long-term retreat moving eastward across the site, accompanied (unexpectedly) by a general decline in resilience and beach width. However, these trends are also accompanied (expectedly) by a decline in wave impact hours and an increase in bluff-toe elevation and top-of-bedrock elevation.

Site 4LECP shows a general decrease in long-term retreat moving eastward across the site. This is associated (unexpectedly) with an increase in wave impact hours, and (expectedly) with an increase in beach width and beach-prism volume. While the amount of retreat decreases eastward (Fig. 2.14), groundwater flux is very low but relatively constant, and resiliency increases slightly but remains among the lowest in the WECLC. Site 5YMCA has the second-lowest long-term retreat (rate and amount) among all sites, and this is accompanied intuitively by moderate to high resilience, among the lowest wave impact hours in the WECLC, a moderate beach-prism volume, and a very low groundwater flux. Increases in groundwater flux and wave impact hours moving eastward across Site 6LSCC are accompanied (unexpectedly) by relatively constant long-term retreat. These trends are also accompanied (unexpectedly) by a decline in beach width and beach-prism volume and, expectedly, by a decline in bluff-face slope and an increase in resiliency (due to an increase in the top-bedrock elevation). At Site 7BMDR, long-term retreat shows a slight decline moving eastward that is accompanied (unexpectedly) by an decline in resilience while being accompanied by an (expected) increase in beach width, a relatively high top-bedrock elevation, and a decline in bluff slope and wave impact hours..

Figure 2.16: *View looking west towards the OH-PA state line at WECLC Site 1STGL. Note ~14 m tall bluffs, stratigraphy-controlled bluff slopes, the narrow beach during 2018, and the bluff headland at the state line.*

The environmental variables reviewed above are examined further in Chapter 3. The goal in Chapter 3 is to identify defensible predictive associations between bluff features and processes (individually and in combination) and bluff behavior to quantitatively explain bluff retreat on the WECLC coast (Fig. 2.16). With the exclusion of 1938-2015 retreat rate (Fig. 2.12) and total retreat (Fig. 2.14), ten of the variables reviewed above are used in Chapter 3 in a Bayesian network analysis. The analysis aims to develop a predictive bluff-retreat model using the sub-set of variables that have the most skill at explaining retreat patterns while also being relatively convenient to compile from lidar-based and field measurements.

3 Bayesian Modeling of Bluff Crest Retreat

Introduction

The Bayesian model was developed for seven 1-2 km long study sites, selected to be representative of coastal conditions and the six HUC-12 watersheds within the WECLC. The overall modeling goal was to improve understanding of coastal processes driving bluff retreat and associated hazards on the Pennsylvania bluff coast (Fig. 3.1). The model quantifies relationships between physical processes and landscape responses (i.e., bluff-crest retreat over time) so that hazard understanding and community resiliency may be improved. Specifically, the aim of this part of the project was to: *Develop a multivariate Bayesian Network model of bluff retreat for the western Erie County littoral cell (WECLC) that would explain recent-to-historical bluff retreat patterns and simulate future retreat.*

Well-designed Bayesian models can explain and predict the location and magnitude of coastal hazards by defining joint-probability density functions that relate forcing variables and initial conditions to geologic events such as bluff retreat. Hapke and Plant (2010) applied a Bayesian approach to bluff retreat on the California coast and concluded that Bayesian methods are an effective tool in the prediction of bluff-crest positions and in the identification of erosional hotspots.

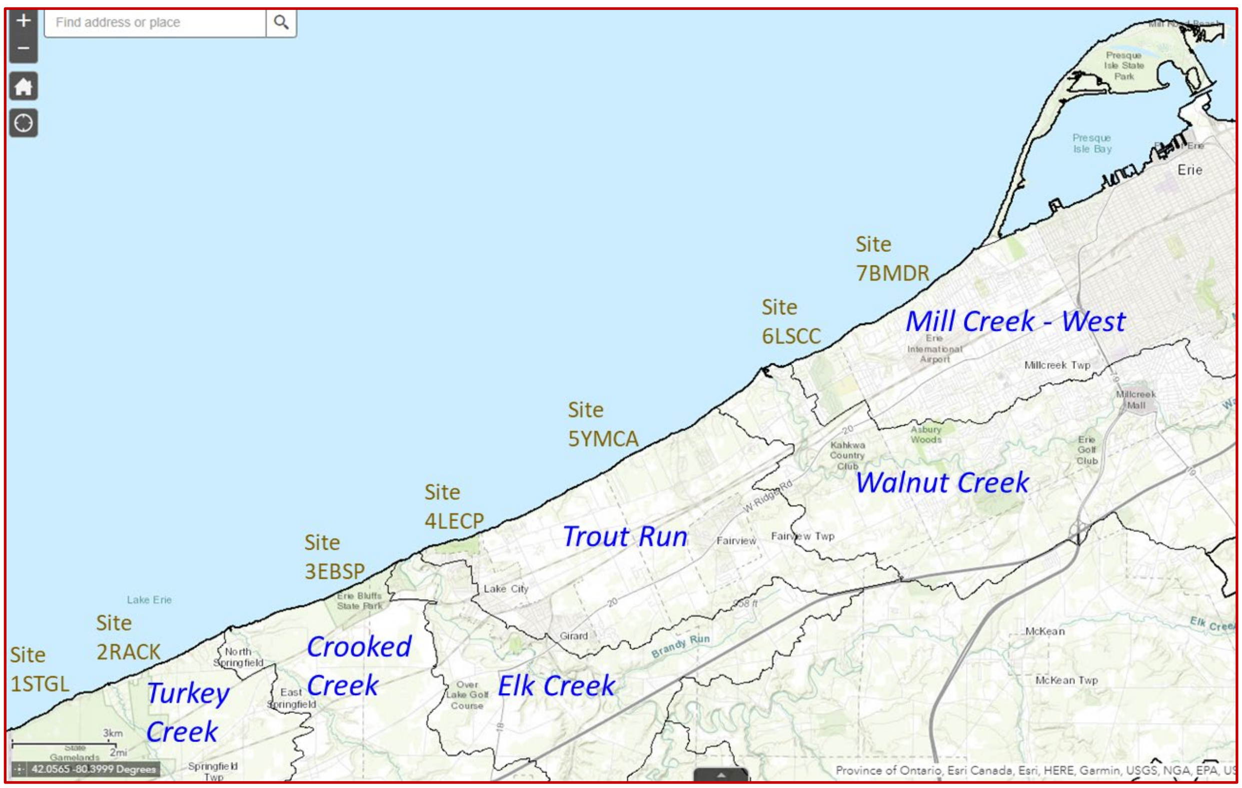


Figure 3.1: *Location map for the 33.5 km bluff coast in the western Erie County littoral cell (WECLC). The cell extends from the OH-PA state line to a large groyne where the Presque Isle isthmus joins the mainland. The map shows the seven field sites used for Bayesian modeling and the six principal HUC-12 watersheds within this part of the Lake Erie watershed. Bar scale is 3 km in length. (source: pawalter.psu.edu)*

Their model correctly forecast bluff retreat rates at over 70% of transects modeled over a multi-year period. Similar success rates were reported by Dahal et al. (2008) for landslide hazards in the

Himalayas (~88% of forecasts correct). Bluff retreat on the Erie County coast is suited to Bayesian analysis because bluff failure may be related to identifiable pre-existing conditions, there are a reasonable number of constrainable controlling processes, and long- and short-term bluff-retreat rate data are available. Seven field sites were selected for this analysis (Figs. 3.1, 3.2).

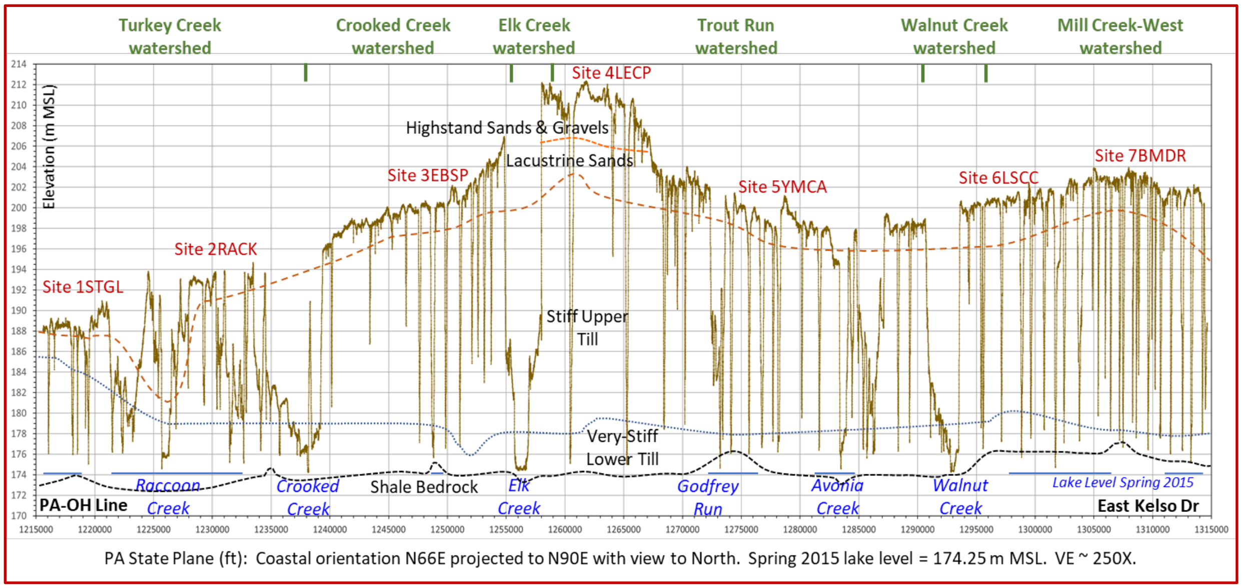


Figure 3.2: *Northward looking cross-section along the WECLC bluff coast showing bluff-crest elevations, major creeks and minor ravines, generalized stratigraphy, lakefront extent of HUC-12 watersheds, and study sites (1STGL - 7BMDR) used in Bayesian analysis. (bluff crest mapped using a 0.6 m sampling interval on 2015 lidar).*

Bayesian Statistical Modeling

The Bayesian Network model used in this study comprises two main components. The first is a directed network graph (Fig. 3.3) that shows how input variables (bluff height and wave impact hours, for example) are related to each other and to the "predicted" retreat rate (2007-2015) at the bluff crest. The network model allows for (i) discovery of how the model inputs are related to bluff-crest retreat rate, and (ii) the opportunity to look for possible interactions and feedbacks between variables. The second component of the model is a series of conditional probability density functions based on the observed data used as inputs. Inputs considered for use in the model were previewed in Chapter 2 where observed trends and correlations were briefly examined qualitatively. Table 3.1 lists the nine inputs examined for model inclusion with their basic statistics characteristics. The *Bayesian Geospatial Data Inputs* section describes the inputs in greater detail.

In this bluff-retreat application, geodata were compiled from shore-normal transects spaced at 20 m intervals along each of the seven 1-2 km long WECLC study sites. The observed data were binned so that discrete probability distributions were created based on the data that determine how the variables and retreat rate are causally related. The network model determines which variables we assume are related (connected nodes) and which variables we assume are independent (no connection). The Bayesian network model was built using the R statistical programing language (R Development Core Team, 2020) and the *bnlearn* package (Scutari, 2010). The output of the model was a discrete probability distribution for each field site location that predicted the probability of observing different retreat rates conditional on the observed input values. The modeling approach used here allowed a model fitting process to determine which variables were related rather than using a Bayesian Network model based on expert opinion. By allowing the model fitting process to create the connections between the variables using the observed data, connections between the variables unique to this particular region could be discovered, rather than assuming that connections that exist at different locations apply universally.

The goals were to build a statistical network model to successfully explain historical change in coastal bluff-crest location (1938-2007) and to then test the model's skill by evaluating its ability to predict "future" change over a recent (2007-2015) validation window. The model would then be used to simulate future crest locations for each of the modeled WECLC sites (1STGL through 7BMDR). The simulations would look out into the future for 10, 25, and 50 years (through 2025, 2040, and 2065, respectively). These time windows approximate (i) the average duration of individual-home ownership in the United States (nar.realtor), (ii) a typical mortgage duration, and (iii) a time duration used with bluff-crest retreat rates to define construction setbacks on the Pennsylvania coast (PA DEP, 2013). Building the model entailed using a combination of as many as nine, pre-identified, geospatial inputs plus a 2007-2015 bluff-retreat dataset (Fig. 3.3).

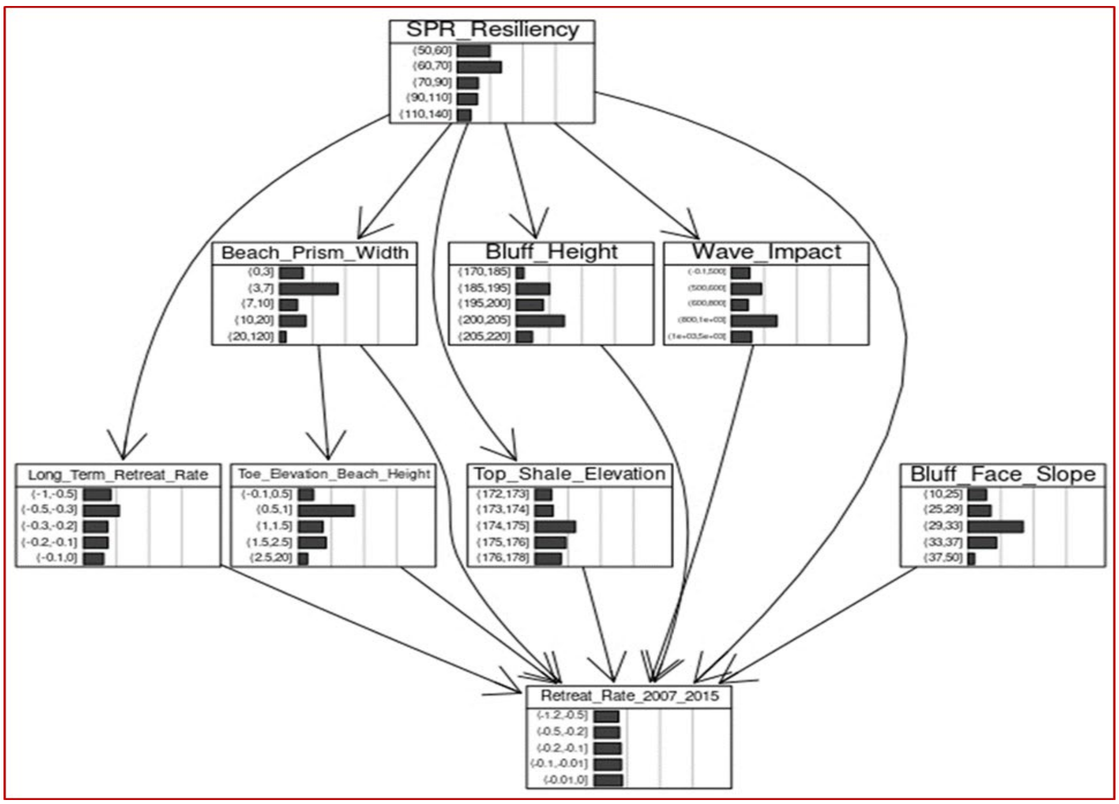


***Figure 3.3**: Final Bayesian Network model for bluff retreat on the WECLC coast showing the eight optimal variables used to predict "future" 2007-2015 bluff-crest retreat rates. Five bins with varying bin sizes for each variable ensure an optimal distribution coverage for each variable shown.*

In order to prepare the data for modeling, each observed input and the 2007-2015 retreat rate were turned into discrete categorical variables by placing each observation into one of five bins. The default binning option was to calculate the minimum and maximum of each input and create bin sizes that were of equal size spanning the range of observed values. However, for some inputs, this resulted in bins that contained zero observations due to extreme values at one end of the input range. Bayesian Network models are difficult to fit when bin counts are zero, so bin values were manually selected for each input (Table 3.1). The ranges of individual bins were selected to ensure that observations were roughly equally distributed among the bins while also allowing bins with larger counts when many observations were observed in the same range. The choice of five bins was based upon previous published work (Hapke and Plant, 2010) and, given the sample size, to minimize bins with small observed counts. Only transects in which all input variables and a 2007-2015 retreat rate were present were used during the model fitting process, resulting in 414 transects with usable data (88% of the entire 470-transect dataset). In Fig. 3.3, an arrow connecting two variables indicates that distribution of the values of the variable (where the arrow points) were observed to be conditional on the value of another variable (where the arrow starts). If no arrow exists between two variables, the variables were assumed to be independent. If more than one arrow enters a variable, a variable is dependent on more than one of the model variables.

Model Selection

To determine which combination of the nine possible inputs best modeled the 2007-2015 retreat rates using the Bayesian Network, k-fold cross validation was used (Scutari, 2010). This process allowed the observed data/geospatial inputs to be split into training and testing datasets. The entire dataset was randomly split into k=10 subsets and the model was fit using k-1 (nine) of the subsets in order to predict the 2007-2015 retreat rate of the remaining, test subset. For each run of the model fitting process, 369 transects consisted of the training data while the remaining 41 were used as the testing data. The k-fold cross validation was repeated 50 times in order to make sure that there was sufficient randomization in selecting which data were selected to fit the model, and which data were used to test the model such that the results would be reproducible. For each cross validation run, the model fit with the training data was used to predict the 2007-2015 retreat rate for the testing data. Comparing the predicted 2007-2015 retreat rate to the observed retreat rate of the testing data measured the quality of the model fit. The accuracy of the model fit was averaged over 500 (10 fold x 50) replications and can be used to compare models based on different variables.

Input parameters considered for the Bayesian Network model and associated data-bin boundaries

Model Parameter	*Min*	*Mean*	*Median*	*Max*	*Boundaries for 5 Bins*
Wave Impact Hours (hrs/yr)	0.0	873.90	848.10	4896.10	0.1-500-600-800-1000-50000
SPR Resiliency (blows per m)	51.00	76.06	66.00	133.00	50-60-70-90-110-140
Long-Term Retreat Rate (m/yr)	0	-0.31	-0.28	-0.87	Neg 0-0.1-0.2-0.3-0.5-1.0
2007-2015 Retreat Rate (m/yr)	0	-1.1	-0.09	-1.12	Neg 0.0-0.01-0.1-0.2-0.5-1.2
Bluff Height (m MSL)	174.8	197.8	200.0	212.2	170-185-195-200-205-220
Toe Elevation/Beach Height (m LL)	0.00	1.23	0.94	9.20	0-0.5-1.0-1.5-2.5-20
GW Flux (m^3/ m^2/yr)	0.10	36.91	15.00	222.00	0-5-10-20-50-250
Bluff Face Slope (degrees)	12.33	30.34	31.02	42.18	10-25-29-33-37-50
Top-Shale Elevation (m MSL)	172.50	174.80	174.80	177.20	172-173-174-175-176-178
Beach Prism Width (m)	0.18	8.88	5.78	117.27	0-3-7-10-20-120

Bold parameters are the input-variable finalists used in the eight-element Bayesian Network model

***Table 3.1**: Summary of the nine parameters considered, and the eight adopted, in the Bayesian Network model for the WECLC to predict 2007-2015 bluff retreat and simulate future retreat through 2025, 2040, and 2065.*

All possible models from among the nine possible model inputs were examined. This included all nine inputs individually, all combinations with two model inputs, all possible combinations with three model inputs, and so forth with the last model tested using all nine model inputs. In total, 511 models were examined. The total number of models examined included one model with all nine inputs, nine models each with one or eight inputs, 26 models each with two or seven inputs, 84 models each with three or six inputs, and 126 models each with four or five inputs. A Bayesian Network model was created for each combination of model inputs by forcing all inputs to influence the 2007-2015 retreat rate and at the same time allowing the model fitting process to learn any additional relationships between the remaining inputs using a hill-climbing model fitting process (Scutari, 2010). The k-fold cross validation procedure measured the percentage of incorrect classifications for the testing subset, averaged over the k=10 folds for each of the 50 cross-validation runs. The set of model inputs with the lowest percentage of incorrect classifications was determined to be the best model of those examined and was chosen as the final model (Fig. 3.3).

The percentage of incorrect classifications was calculated using the Bayesian Network model created by utilizing 90% of the observed data (k-1 folds, ~373 transects) to predict the remaining 10% (1 fold, ~41 transects) of the observed data. The percentage of the 41 transects for which the observed 2007-2015 retreat rate was predicted correctly, averaged over the 10 folds repeated over the 50 runs, was the percentage of incorrect classifications. This measure was used for comparing potential models, but not as a measure of overall model quality because only a portion of the data were used to fit each Bayesian Network model. The average percentage of incorrectly classified transects generated from cross-validation are typically higher than the percentage observed when the entire data set is used.

Assessing Model Fit

After the final model was selected, overall model fit was assessed by comparing the predicted 2007-2015 retreat rate to the observed retreat rate for all 414 transects used to fit the model. The output of the Bayesian Network is a posterior probability distribution that describes the probability of short-term retreat rates being in each of the five bins. The posterior probability distribution describes the probability of an observed set of inputs resulting in one of the 2007-2015 retreat rate bins (m/yr: -1.2 to -0.5; -0.5 to -0.2; -0.2 to -0.1; -0.1 to -0.01; and -0.01 to 0). If the short-term retreat rate bin with the highest posterior probability matched the observed 2007-2015 retreat rate bin, the model was determined to correctly classify the transect. If there was a tie among the bins with the highest posterior probability, and the observed 2007-2015 retreat rate bin was among the tied bins, the model also was determined to correctly classify the transect. The quality of the model fit was determined by calculating the percentage of correctly classified transects.

Measuring Variable Importance

In order to determine the importance of the model inputs in the final model, the posterior probability distribution for the 2007-2015 retreat rate was estimated using the full dataset for all transects. The predictive ability of the final model was determined by calculating the average predicted posterior probability for the observed 2007-2015 retreat rate bin over all 414 transects. The average predicted posterior probability was calculated by taking the posterior probability distribution found in the 2007-2015 retreat rate bin that matched the observed short-term retreat rate bin and then averaging those values over all 414 transects. A value of one would indicate that the model fit perfectly. In other words, the posterior probability is 100% in the bin that matches the observed 2007-2015 retreat rate bin for that observation. To measure variable importance for each input in the final model, the model was fit again without that input and the average predicted posterior probability was calculated again. The percent reduction in the average predicted posterior probability compared to the full, final model was calculated. The model inputs with the largest reduction in average predicted posterior probability were considered the most important inputs in the final model.

Bayesian Geospatial Data Inputs

The Bayesian Network model initially relied on nine data inputs and one dependent-variable dataset (2007-2015 bluff-retreat rate). Six of these parameters were obtained directly from lidar-derived digital elevation models (DEMs), while four (resiliency, wave impact hours, top-bedrock elevation, groundwater flux) relied on a combination of DEMs, published geotechnical reports, field work, and aerial imagery in their estimation. The initial runs of the model used:

(i) A long-term historical bluff retreat rate (1938-2007) as the *prior-behavior* parameter.
(ii) Six *initial-state* parameters of bluff height, bluff slope, bluff stratigraphy (expressed as geotechnical resilience, or resistance to erosion), beach prism width, bluff toe elevation (expressed as beach thickness), and top-of-bedrock elevation.
(iii) Groundwater flux (at the bluff face) and wave energy (expressed as wave-impact hours) at the bluff toe. These were the two expected dominant *forcing agents* in the WECLC.

The model was tested to determine the optimal number of input variables and validated using the 2007-2015 change in bluff-crest positions mapped at shore-normal DSAS transects (Digital Shoreline Analysis System, an Arc-GIS extension; Thieler et al., 2009) from lidar DEMs. As described above, data-bin ranges for the model maximized the distribution for each variable and are listed in Table 3.1 along with the maximum, minimum, median, and mean values for each. The final model results and outcomes are discussed further in the Results and Discussion sections, following review of the model inputs below.

In this project, the Bayesian statistical network approach (Pearl, 1988) uses multivariate statistics to identify associations between geo-environmental variables that may operate together to explain and predict bluff retreat patterns and magnitudes. The network approach models bluff retreat using a combination of *a priori* input variables suspected to have at least some control on bluff retreat along the Erie County (WECLC) coast. Nine input variables were initially used in the model and later reduced to eight of the most-impactful variables. All are described in detail below and summarized in Table 3.1.

Wave Climate

Wave climate dictates wave heights at the shoreline (Fig. 3.4) and the severity of erosion on the lowermost bluff face. Erosion occurs due to the mass of impacting waves, scouring by entrained materials in the wave, removal of protective beach cover at the base of the bluff, and hydraulic- and air-blasting that occurs within fractures and voids in the bluff face. Prior work by Amin (1989, 1991, 2001) in westernmost Erie county suggested that wave-induced erosion on bluffs (near Site 1STGL of this study) was focused on the lowermost 2 m of the bluff face.

For this study, wave hindcast data modeled from the wind field were retrieved from the US Army Corps of Engineers WIS website (WIS, 2020) for three synthetic wave gauge stations equally spaced at ~8km intervals along the WECLC in water depths of 13-16m (Fig. 3.5). WIS Station 92039 was located due north of Site 1STGL, Station 92036 due north of Site 3EBSP, and Station 92034 due north of Site 5YMCA. Hourly wave statistics for the Jan 2007- Dec 2014 time period (data were not available for 2015) were obtained from each station (Fig. 3.6). Because the average approach angle of deepwater waves on this coast was from ~290^{0}, data from Station 92039 was applied to all sectors in Sites 1STGL, 2RACK, and 3EBSP. Station 92036 was used for all sectors in Sites 4LECP and 5YMCA, while Station 92034 was used for all sectors in Sites 6LSCC and 7BMDR. Deepwater wave climate during the 2007-2014 time period was considered a good proxy for wave climate for the duration of the study (1938 - 2015).

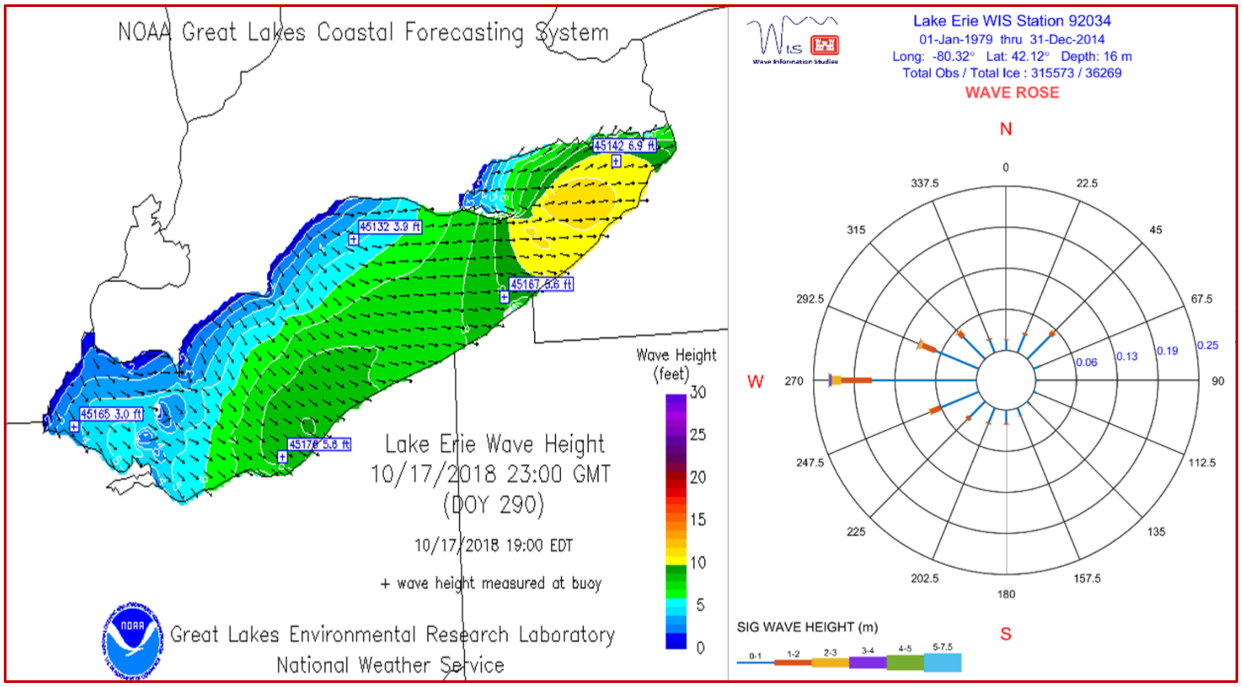


Figure 3.4: *Example of autumn storm conditions on Lake Erie and the WECLC coast at WIS Station 92034. When the associated wave parameters (H_{m0}=3m, T=7.1s, L_0=78m a=290^0; described in text) are applied to a typical WECLC beach with B_f = 11^0 using the Stockdon et al. (2006) equation, the estimated R2% run-up value is 2.3 m. This is significantly greater than the average bluff toe elevation of ~1.2 m above still lake level at the seven WECLC sites. Average H_{m0} (2007-2014) for the WECLC is ~0.6 m.*

Because of the spatial scale of the wave field data, wave-climate data could not be used to resolve changes occurring at individual 20m-spaced DSAS transects at each site but were better suited to resolving differences between sectors (within sites), and between the seven sites due to changes in coastal orientation. Each of the seven sites comprised two to five sectors, determined by changes in coastal orientation which affect wave-energy delivery to the bluff. Significant deepwater wave height (average of the highest 33% of waves, in meters), wave period (in seconds), and wavelength (in meters) were extracted from the WIS datasets. Significant wave height was increased by ~10% to account for water depths at the synthetic gauge sites not being as deep as wave base for larger storm waves in the 70,080-hr dataset from each gauge. The waves were also refracted towards the shoreline from their hourly approach angle towards the ~N65^{0}E (sector and site dependent) orientation of the shoreline using equations from Komar (1998).

Wave run-up was the hydrodynamic metric derived from the WIS statistics (Fig. 3.7). Wave run-up is defined as the wave set-up (η; mean water surface elevation relative to still lake level) due to wind stress, plus the swash run-up (S), which is the variation in the water-beach contact elevation about the swash-backwash mean (Melby, 2012). A best-practice $R_{2\%}$ methodology (Stockdon et al., 2006; Ruggiero et al., 1996, 2001) was used to determine the hourly 2%-exceedance elevations for the morphodynamically intermediate-to-reflective geometries of WECLC beaches. The $R_{2\%}$ metric represents run-up of the highest 2% of waves, measured in meters above still lake level. The hourly $R_{2\%}$ values were then compared with bluff-toe elevation to determine annual cumulative wave-impact hours (and run-up elevation) on the bluff for each transect within each site sector. For each of these impact-hour events, waves were high enough to extend as much as ~2 m up the bluff face (Fig. 3.8).

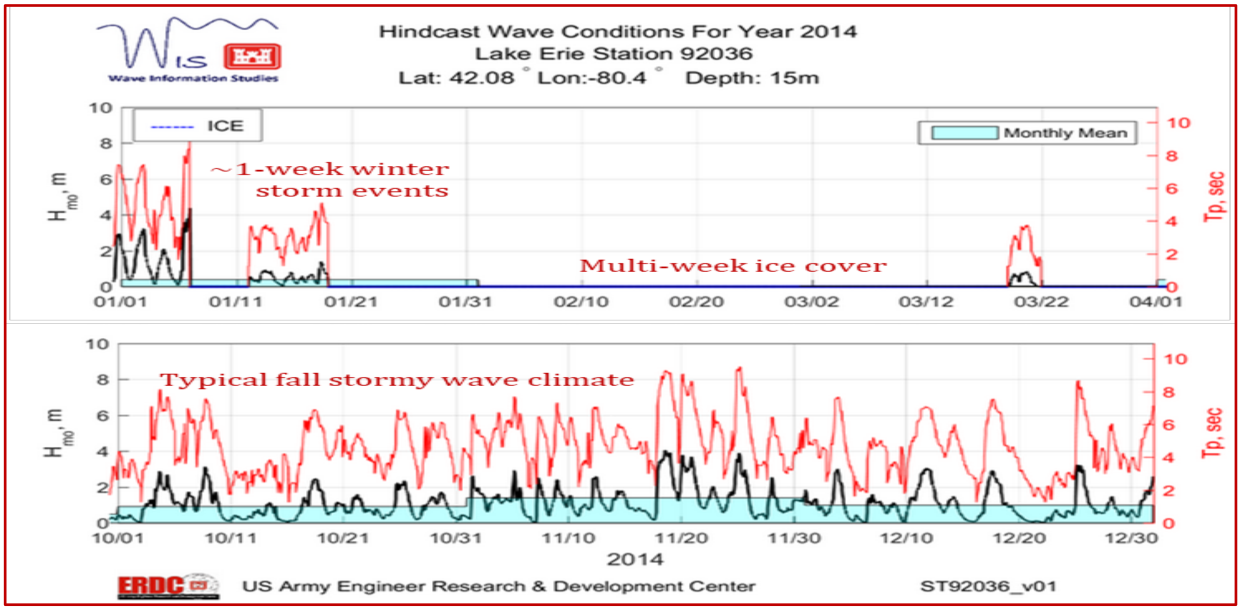


***Figure 3.5**: Partial WIS plot showing typical winter-spring and fall-winter (2014) wave climate for WIS Station 92036 located offshore of the Elk Creek watershed and Sites 4LECP and 5YMCA. Significant wave height and period show seasonal and shorter-term variability. (Image: WIS, 2020)*

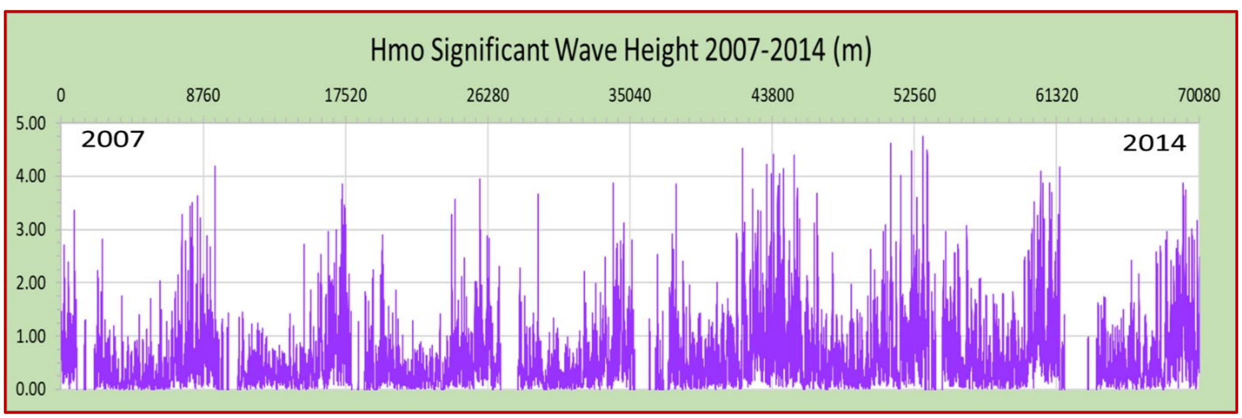


***Figure 3.6**: Eight years (70080 hours) of offshore significant wave heights (meters; 2007-2014) from WIS Station 92036 located offshore of the Elk Creek watershed. Zero-values are mostly caused by seasonal ice cover. The pattern is somewhat similar for Stations 92034 and 92039 (Foyle et al. 2020).*

The general form of the $R_{2\%}$ equation from Stockdon et al. (2006) was used to convert the WIS hourly deepwater significant wave height (H_{m0}) and wavelength (L_0) data, and field-measured beach foreshore slope (β_f), into vertical wave run-up events at the shoreline. The foreshore slope (β_f) is the mean slope of the wave-wetted part of the beach profile measured within 2σ above and two SDs below still lake level, where σ is the standard deviation in the offshore significant wave height values. The numerical value for σ is commonly approximated as one half of the significant wave height (Melby, 2012). At WECLC site sectors, β_f was therefore measured during the 2018 field season on a swath of beach between ~0.6 m above and ~0.6 m below still lake level because the average H_{m0} during 2007-2014 was ~0.6 m (WIS, 2020).

$$\mathbf{R2\%} = 1.1 \left[\left[(0.35Bf\,(Ho/Lo)^{0.5} \right] + \left[\frac{(HoLo\,(0.563Bf^{2} + 0.004))^{0.5}}{2} \right] \right]$$

Figure 3.7: *The general form of the $R_{2\%}$ run-up equation appropriate for use on a wide range of beach geometries ranging from dissipative to reflective. The first term-group quantifies wave set-up (η), while the second term-group quantifies swash run-up (S) (Stockdon et al., 2006).*

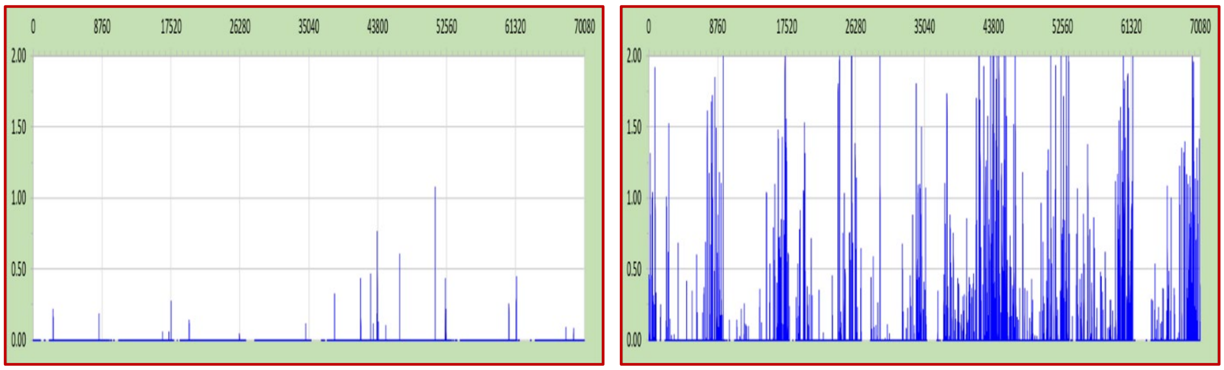


Figure 3.8: *Predicted wave impact hours (WIH events) and vertical run-up elevations at the bluff toe at the Site 1STGL-West and Site 2RACK-East sectors between January 2007 and December 2014. Site 1STGL-West experiences a smaller number of impact hours at the bluff toe (WIH=216 hrs; 0.3% of the 8-yr period) than Site 2RACK-East (WIH=8105 hrs; 11.6% of 8-yr period) due to differences in average coastal orientation and toe elevation (Foyle et al. 2020).*

Periods of shore and lake-ice, identified as periods of 0 m wave heights (Fig. 3.5, Fig, 3.6) and run-up values (Fig. 3.8) in the WIS dataset, frequently reduced daily impact hours to zero during most winter seasons. For each year of observation, seasonal wave run-up elevations were measured from an average seasonal high lake level and an average seasonal low lake-level baseline that varied annually and were obtained from the NOAA Great Lakes Water Level Dashboard (2020). The 2007-2014 wave impact hours ranged from 0 to 4896 hrs/yr (averaged), with a mean and median of 873.9 hrs/yr and 848.1 hrs/yr, respectively.

Bluff Stratigraphy & SPR Resiliency

The stratigraphic (sedimentologic) composition of the WECLC bluffs are discussed in detail in Chapter 2. Stratigraphy is important in modeling bluff retreat because it influences the resiliency, or resistance to erosion, of the bluffs to wave attack, groundwater flux through the bluff face, and surface run-off. Stratigraphy varies in the along-coast direction, particularly in terms of whether shale bedrock occurs above lake level, how thick the glacial till and the lacustrine stratigraphic units are, and whether highstand sands and pea gravels are present at the top of the bluff. The generalized bluff stratigraphy along the length of the WECLC is summarized in Fig. 3.9. The stratigraphic data, compiled from publications and fieldwork between 1978 and 2018, is inferred to be a good proxy for stratigraphic make-up of the bluffs since 1938. Effects due to variability in unit thicknesses and slopes of internal stratigraphic surfaces inland from the bluff face were unmappable for the project and inferred to be small.

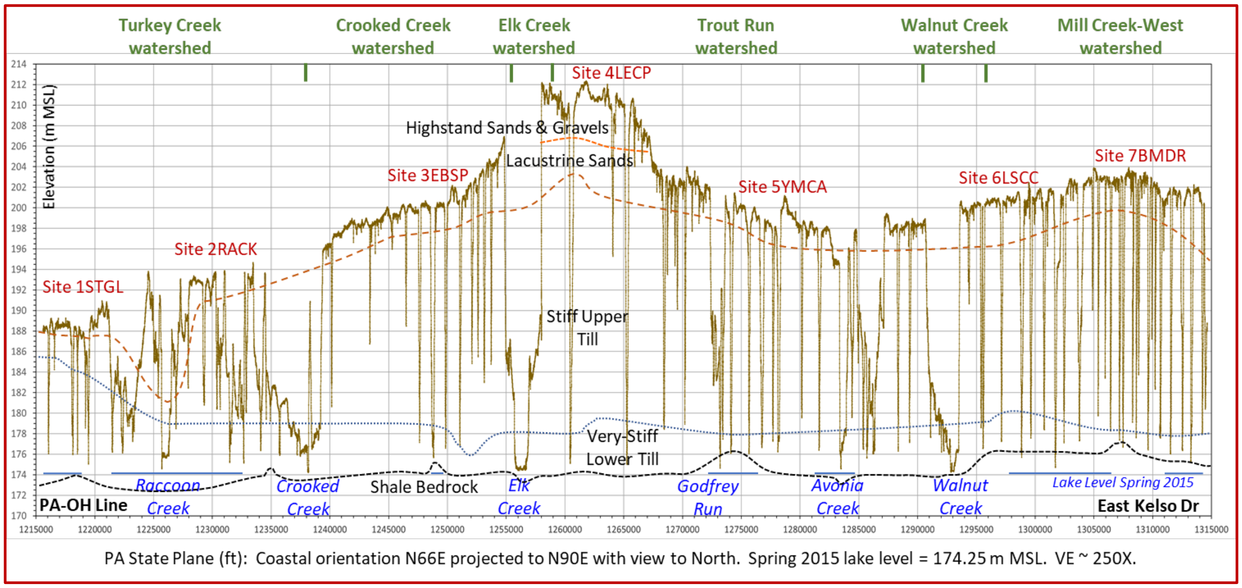


***Figure 3.9**: General stratigraphic layering in the WECLC bluffs from Site 1STGL downdrift to Site 7BMDR. Of significance is the presence or absence of shale bedrock above lake level, and the relative thicknesses of the overlying glacial till, lacustrine, and highstand strata. Cross-section is approximate, due to limited coring data.*

Stratigraphy was largely compiled from available published literature and reports, and from field observations during 2018. The principal sources of site-specific geology in western Erie County comprised studies by D'Appolonia (1978), Knuth (2001), Buyce (1987), Amin (1989, 1991, 2001), Knuth and Lindenberg (1994, 1995), Highman and Shakoor (1998), Dawson and Evans (2001), Urban Engineers of Erie, Inc. (2004), Jones and Hanover (2014), Cross et al. (2016), and Terracon Consultants, Inc. (2018). From these sources, geotechnical and stratigraphic information was reconstructed in the areas of Site 1STGL, Site 2RACK; Site 4LECP; Site 5YMCA; and Site 7BMDR using an erosion-mitigation project just downdrift of the WECLC in the Presque Isle littoral cell.

In the Bayesian model, bluff stratigraphy (geologic composition) was expressed as bluff resiliency to erosion based on stratigraphic-layer thicknesses and standard penetration resistance data (SPR in blows-per-meter (BPM)) for each of one to five stratigraphic horizons present at all sites. It ranged in value from 51 to 133 BPM. The resiliency of the bluff could not be resolved to DSAS transect scale (20 m) but was determined for site sectors (groups of DSAS transects within a site). The SPR Resiliency is dependent upon the weighted thickness of the stratigraphic units present times the value of the respective SPR geotechnical property, with the SPR value converted from its normal expression in blows per foot to blows per meter. Numerical SPR data were retrieved and averaged from several of the publications listed above, and the resultant SPR Resiliency for each stratigraphic unit was as follows (Fig. 3.10):

(i) Highstand paleo-strandplain sands and gravels = 26 BPM;
(ii) Transgressive glacio-lacustrine silts and sands = 35 BPM;
(iii) Medium-stiff (upper) till = 69 BPM;
(iv) Very stiff fractured (lower) till = 158 BPM;
(v) Devonian shale bedrock = 836 BPM;

The stratigraphic complexity of the bluff was therefore significant considering the differences in the geotechnical resistance of units present. The least resilient material was present only at Site 4LECP in the Trout Run watershed, while the most resilient material (shale) was absent (located below lake level) at Sites 1STGL and 2RACK in the Turkey Creek watershed (Fig. 3.9). SPR resiliency ranged from 51 to 133 BPM, with a mean and median of 76.1 BPM and 66.0 BPM, respectively.

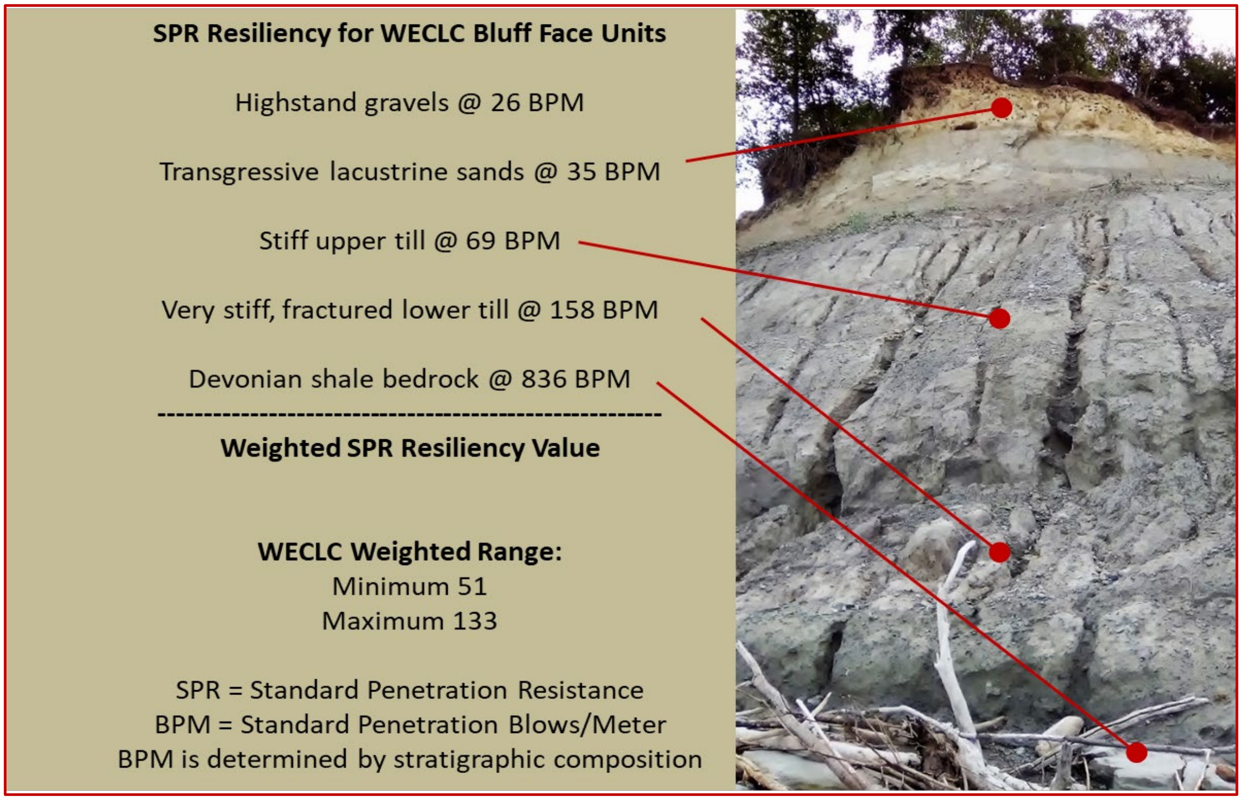


***Figure 3.10**: SPR Resiliency of a sector of bluff face was estimated from published Standard Penetration Resistance tests of the stratigraphic units present, weighted by their average thickness within that bluff sector. WECLC-wide average BPMs are based on data compiled from up to 6 sites. (Image: Foyle et al., 2020).*

Bluff-Crest Retreat Rates: 1938-2007, 1938-2015 2007-2015

Bluff-crest retreat rates were calculated for the historical 1938-2007 prior-behavior period and for the short-term 2007-2015 independent validation period using the US Geological Survey's DSAS ArcGIS extension (Digital Shoreline Analysis System; Thieler et al., 2009). DSAS was used with DEM analysis to calculate several bluff statistics used in both the Bayesian model and in the littoral sediment input model (Chapter 4). DSAS uses a shore-normal transect spacing selected by the user (20m for this study) to position transects that typically extend in the shore-normal direction from a shore-parallel baseline located either onshore or offshore (this study). Transects are extended to intersect all mapped linear coastal features of interest, specifically the 2007 and 2015 shorelines; the 2007 and 2015 bluff toes; and the 1938, 2007, and 2015 bluff crests in this study. Transect lengths were chosen such that they extended from the baseline (offshore) to a point landward of the most-landward (2015) bluff crest. Modifications to individual transect orientations were possible when the DSAS-cast transects were not oriented sufficiently crest-normal. Crest-oblique transect orientations can lead to overestimates in the total amount of bluff retreat and the annual retreat rate for selected time intervals. Specific transects were removed where they crossed non-bluff areas (ravines, floodplains and marinas).

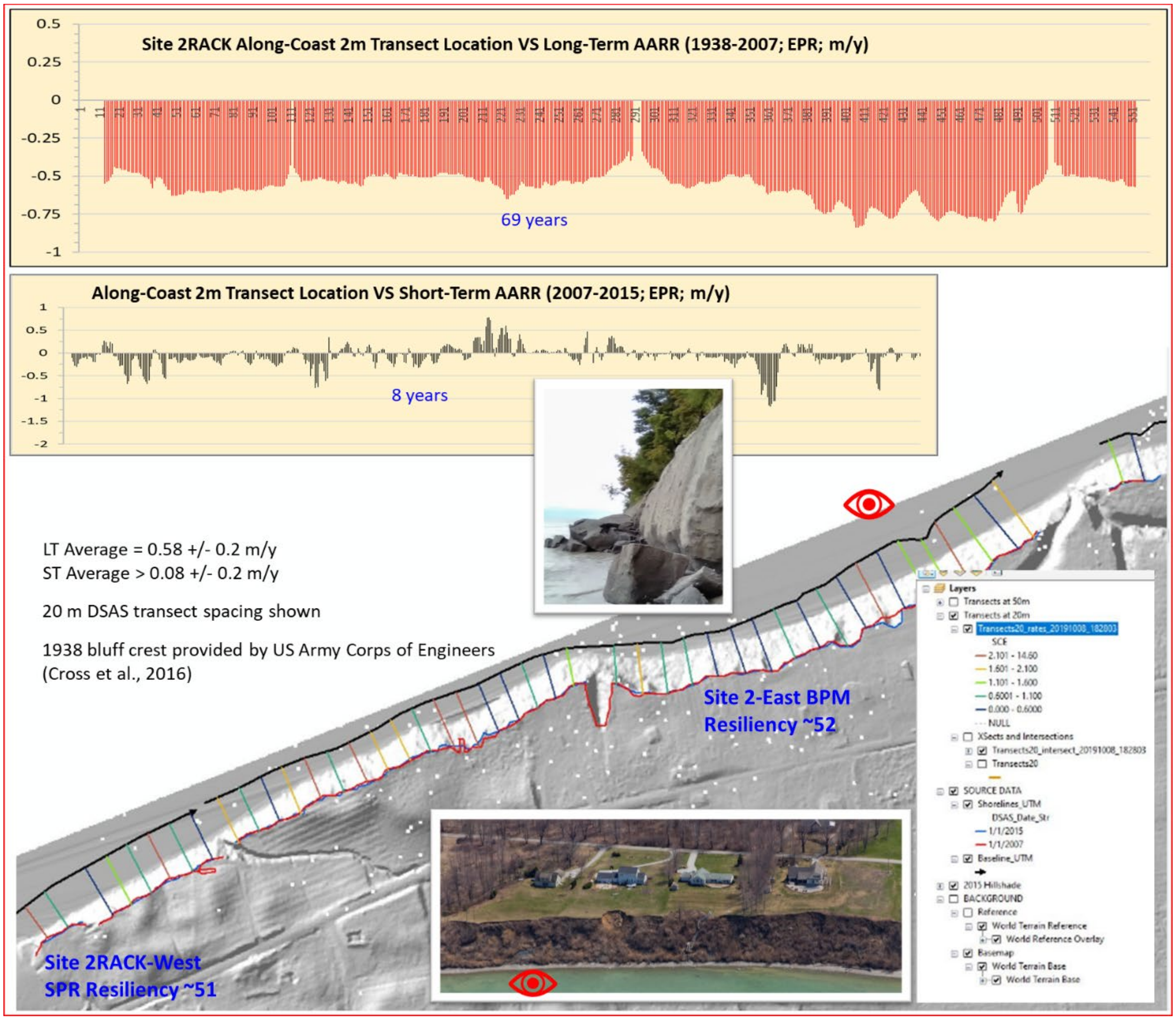


***Figure 3.11**: Sample DSAS-derived bluff-crest retreat visualization for Site 2RACK in the western part of the WECLC. Long- and short-term retreat rates (2m DSAS transect spacing), typical blocky bluff-failure pattern for the lower till, DSAS baseline (black), transects (20m DSAS spacing shown; color-coded by retreat rate), closely-spaced 2007 and 2015 bluff crests, SPR Resiliency sector values, and oblique aerial photo of part of the site are shown. Base map is a 2015 DEM hillshade map. (Image: Foyle et al. 2020).*

At the georeferenced points where each DSAS transect intersected shoreline, toe, and crest line-features, UTM Easting (X), Northing (Y), and elevation (Z) data were compiled by DSAS into a database along with additional information such as slope, horizontal distance, and vertical relief between features. DSAS then calculated end-point change rates (EPRs) for pairs of different-aged line features and, where there were three or more line-features intersected by a transect, linear-regression-fit retreat rates (LRRs). This permitted estimation of long-term (1938-2007; 1938-2015) and short-term (2007-2015) bluff-crest retreat rates needed for Bayesian and littoral-sediment input analyses. Bluff-crest retreat rates for 1938-2007, 2007-2015, and 1938-2015 were thus calculated at 20 m intervals along the coast at each of the seven Bayesian sites for a total of 470 measurements. The 1938-2007 rate represented the “prior behavior” input variable to the Bayesian model, while the 2007-2015 rate was the validation-period change rate that was used to assess the model’s prediction skills. Figure 3.11 shows apparent progradation of the bluff crest in the short-term (2007-2015) data at Site 2RACK that is also notable at Site 1STGL and Site 3EBSP. Because the majority of these low-positive change rates are not associated with real progradation at the bluff crest and lie within the uncertainty value for the estimated bluff crest positions (see below), they were discounted to a value of zero change.

Retreat rates calculated by DSAS for the long-term and short-term bluff-crest pairs contained positional uncertainty. This uncertainty was related to the imperfect accuracy of the DEM model built from lidar ground strikes, and to user uncertainty when identifying and mapping the bluff-crest on the historical aerial photographs (1938 era; Cross et al., 2016) and on the DEMs. The total uncertainty in the position of the 1938 bluff crest was estimated by Cross et al. (2016) to be ±10-15 m and included cartographic errors and crest-ID errors (Moore, 2000). The 2007 DEM was created using Inverse-Distance Weighted (IDW) interpolation to produce a raster surface model from a lidar point dataset stated to have a horizontal accuracy of ±0.77 m RMSE (±1.52 m at the 95% confidence level). Uncertainty in the location of linear features in the interpolated raster is greater than the published point-data uncertainty. The 2015 DEM was similarly derived from a lidar point dataset shown to have horizontal accuracy of ±0.18 m RMSE (±0.36 m at the 95% confidence level; pasda.psu.edu). Crest-ID errors when delineating the bluff crest on the DEM were estimated to potentially be as high as ~±0.8 m, based on final editing at a screen scale of 1:1200. The total horizontal uncertainty for the 2007 and 2015 bluff crests was equal to the DEM and crest-ID uncertainties summed in quadrature, or ±0.77-1.1 m and ±0.18-0.82 m, respectively.

When comparing crest positions at any transect in order to derive total retreat between data years, the horizontal uncertainties for each data year were summed in quadrature. Thus, the uncertainties for the amount of bluff-crest movement (NSM term in DSAS) during the 1938-2007, 1938-2015, and 2007-2015 comparison periods were ±12.5 m, ±12.5 m, and ±0.8-1.4 m, respectively. The uncertainties in the annualized rates of bluff retreat (EPR term in DSAS) for the three comparison periods were ±0.18 m/yr for the 69-yr interval, ±0.16 m/yr for the 77-yr interval, and ±0.1-0.17 m/yr for the 8-yr interval, respectively. Long-term (1938-2007) crest retreat rates ranged from 0 to 0.9 m/yr, with a mean and median of 0.31 m/yr and 0.28 m/yr, respectively. These are comparable to long-term retreat rate averages derived by Cross et al. (2016) of ~0.34 m/yr for the WECLC over a 128-yr (1878-2006) time period. Short-term (2007-2015) retreat rates ranged from 0 to 1.12 m/yr, with a mean and median of 0.11 m/yr and 0.09 m/yr, respectively.

1938 Bluff Crest Position

The 1938 bluff crest was provided as a line feature for inclusion in the project GIS by the US Army Corps of Engineers (W. Cross, Buffalo District). It is the same dataset used in the Cross et al. (2016) US Army Corps of Engineers report that examined the 1878-2006 sediment budget for the United States shoreline of Lake Erie. The bluff crest was originally mapped from 1938 historical aerial photography by the US Geological Survey and was also used by Hapke et al. (2009) in an analysis of bluff retreat in Erie county. Crest elevations were not available. Prior to mapping the bluff-crest from 1938 raster photography, photographs were georeferenced onto a modern earth projection. This included identifying common points between the 1938 photographs and georeferenced 2006 aerial photographs. The bluff-crest identification procedure is fully described by Cross et al. (2016) who estimated the total horizontal uncertainty in the 1938 bluff-crest position to be ±10-15 m.

2007 Bluff Crest Position

The 2007 lidar point datasets (LAS) were obtained from Pennsylvania Spatial Data Access (pasda.psu.edu). Published vertical accuracy for the LAS data is ±18.5 cm RMSE or better in open bare-earth areas, which is equivalent to ±36 cm at the 95% confidence level. In vegetated areas, the published vertical accuracy drops to ±72.5 cm at the 95% confidence level. The horizontal accuracy was ±0.77 m RMSE (±1.52 m at the 95% confidence level).

The 2007 lidar data was acquired at a nominal point spacing of 1.4 m. The IDW DEM used for this study was produced from the subset of classified lidar ground points with 1-meter (3.2 ft) cell size in order to facilitate direct comparison with the higher resolution 2015 DEM described below. Due to raster interpolation, vertical accuracy of the DEM is degraded compared to the point dataset, particularly in localized areas where ground point density is low due to terrain shadowing and dense vegetation cover. Without independent testing against ground control points, this additional uncertainty cannot be definitively quantified.

2015 Bluff Crest Position

The 2015 lidar point datasets (LAS), acquired on April 29 2015, were also obtained from Pennsylvania Spatial Data Access (pasda.psu.edu). Published vertical accuracy for the LAS data is ±9.1 cm RMSE or better in open bare-earth areas, which is equivalent to ±17.8 cm at the 95% confidence level. Vertical accuracy in densely vegetated areas was not assessed and is not reported in the metadata. The horizontal accuracy was ±0.18 m RMSE (±0.36 m at the 95% confidence level).

The 2015 lidar data was acquired at a nominal point spacing of 0.7 m. The IDW DEM was produced from the subset of classified lidar ground points with 1-meter (3.2 ft) cell size. Vertical accuracy of the derived DEM is affected by the same factors described above for the 2007 DEM, and as such varies locally and cannot be definitively quantified.

Bluff-Crest Elevation

Bluff crest elevations were derived from the 2007 and 2015 lidar DEMs, using the DSAS transects approach described above (Thieler et al., 2009). The 2007 bluff crest was inferred to be a good proxy for the 1938 crest height that was an initial state for the system in the Bayesian model (1938 crest height was not available). The approach yielded X-Y coordinate and Z elevation data for the crest every 20 m along a site where DSAS transects intersected this line feature. The 2007 crest elevation was also used as an input variable for the 2007-2015 validation period. Bluff-retreat measurements by Foyle (2014) in eastern Erie county showed that higher bluff-crest elevations were weakly correlated with higher bluff-crest retreat rates. The 2007 bluff-crest elevations ranged from 0.5 to 37.7 m above Spring 2015 lake level, with a mean and median of 23.5 m and 25.1 m, respectively.

Bluff-Toe Elevation (Beach Prism Thickness)

The bluff toe is the contact (a GIS line feature) between the beach (or backshore), the lake surface, or a wave-cut shale platform, with the steeper bluff face. Its elevation is controlled by lake level or by the thickness of the beach prism or bedrock platform where they abut the bluff face. The difference between the bluff-toe elevation and lake level is also the beach prism thickness (in most cases), which was a derivative input variable used for the model. The thicker the beach prism, the greater the bluff-toe elevation. Toe elevations were derived from the 2007 and 2015 lidar DEMs at DSAS transects that provided X-Y-Z data for the toe and crest every 20 m along a site. The 2007 bluff toe was inferred to be a good proxy for the 1938 toe height that was an initial state for the system (1938 toe height was not available). In the Bayesian analysis, the 2007 toe elevation was also used as an input variable for the 2007-2015 validation period. It was expected that higher bluff-toe elevations, due to the presence of a thicker beach prism or wave-cut bedrock platform, would be inversely correlated with bluff-crest retreat rates. The bluff toe at the seven WECLC sites lay at an average elevation of 1.2 m above Spring 2015 lake level. It ranged in elevation from 0 m (at lake level; no beach) to 9.2 m (outlier) above lake level, with a median value of 0.9 m.

Bluff Slope

Bluff slopes were derived from the 2007 and 2015 lidar DEMs using the DSAS transects approach (Thieler et al., 2009). For the Bayesian model, the 2007 slope was used as an initial state for the validation period and as a reasonable proxy for the 1938 initial state because 1938-era data were not available. The calculated slope was the average slope along a transect determined from the vertical (elevation) and horizontal distances between the crest and the toe of the bluff. This was a convenient geometric simplification of the sometimes complex slope patterns seen along parts of the WECLC. The complexity is related to bluff stratigraphy, because different stratigraphic layers have different geotechnical properties. Complexity also occurs due to groundwater flux through the bluff face which varies by watershed. For example, groundwater discharge at Site 2RACK often leads to a stepped bluff profile that results from relatively rapid retreat of the upper bluff's lacustrine sediments that are saturated with groundwater (Fig. 3.12). The underlying glacial tills retreat at a slower rate, and sediment slumps at the top of the bluff partly accumulate on a glacial till bench and are not immediately supplied to the beach.

The 2007 bluff slope was used in the Bayesian model because steeper bluff slopes have been correlated with greater bluff-crest retreat rates elsewhere (Emery and Kuhn, 1982; Zuzek et al., 2003). In the failure-cycle model of Zuzek at al. (2003), bluffs retreat over time as they cycle between steep, unstable phases and less-steep, more stable phases (Fig. 3.12). The 2007 bluff slope ranged from 12.3^0 to 42.2^0, with a mean and median of 30.3^0 and 31.0^0, respectively.

Bluff-Face Groundwater Flux

Detailed estimations of groundwater flux through the WECLC bluffs are difficult due to uncertainty in the characteristics of ground-watersheds in the shallow subsurface and to limited hydrogeologic data for Erie County. Groundwater flux through the bluff face was estimated for the several Lake Erie sub-watersheds that occur within each of the seven Bayesian sites. Simply, the flux was estimated at sub-watershed scale (not transect scale) using the average bluff-face area for a sub-watershed (m^2) divided into the volume of annual precipitation inferred to be directed to groundwater recharge and towards the bluff face. Where sub-watersheds were few in number at a site, estimating the groundwater flux for each WIH sector improved resolution. Large groundwater fluxes reduce bluff cohesiveness, particularly for the upper bluff where the relatively high hydraulic conductivities of lacustrine and paleo-strandplain strata allow faster flow compared with underlying glacial till strata. Foyle (2014) noted a strong correlation between bluff retreat rates and groundwater flux expressed as discharge per square meter of bluff face (m^3/m^2) and, in particular, as discharge per meter of bluff length (m^3/m; Fig. 3.13).

Long-term mean annual precipitation for coastal Erie County is ~105 cm/year (NOAA NCDC 2020), which includes ~300 cm/year of snowfall. Analysis of stream flow and precipitation data by Buckwalter et al. (1996) in four watershed sites in French and Raccoon Creeks showed that, on average, about 30% of precipitation becomes stream base flow, 32 % becomes surface runoff contributing to stream flow, while about 38 % becomes a combination of evapotranspiration (23 %) and groundwater flow (15 %). For the Raccoon Creek site exclusively, these numbers were 17% for base flow, 20% for runoff, and 63% for evapotranspiration plus groundwater flow with the latter being undifferentiated. Because the lower reaches of stream ravines incise to bedrock near the shoreline, groundwater flow out of the surficial Pleistocene-age coastal aquifer must exit the groundwater system primarily as discharge through the bluffs if it is not directed laterally to creekside springs and stream baseflow. On high-elevation beach–ridge terrain areas with no significant surface drainage, such as in the Crooked Creek and Trout Run watersheds and in approximately half of the WECLC's ninety-seven Lake Erie sub-watersheds, as much as 77% of precipitation may discharge through the bluff face, given that surface runoff and base flow capture by streams are insignificant. Conversely, in sub-watersheds with well-developed surface drainage systems that draw groundwater towards stream axes, as little as 15% of precipitation may discharge as groundwater flux through the bluff face.

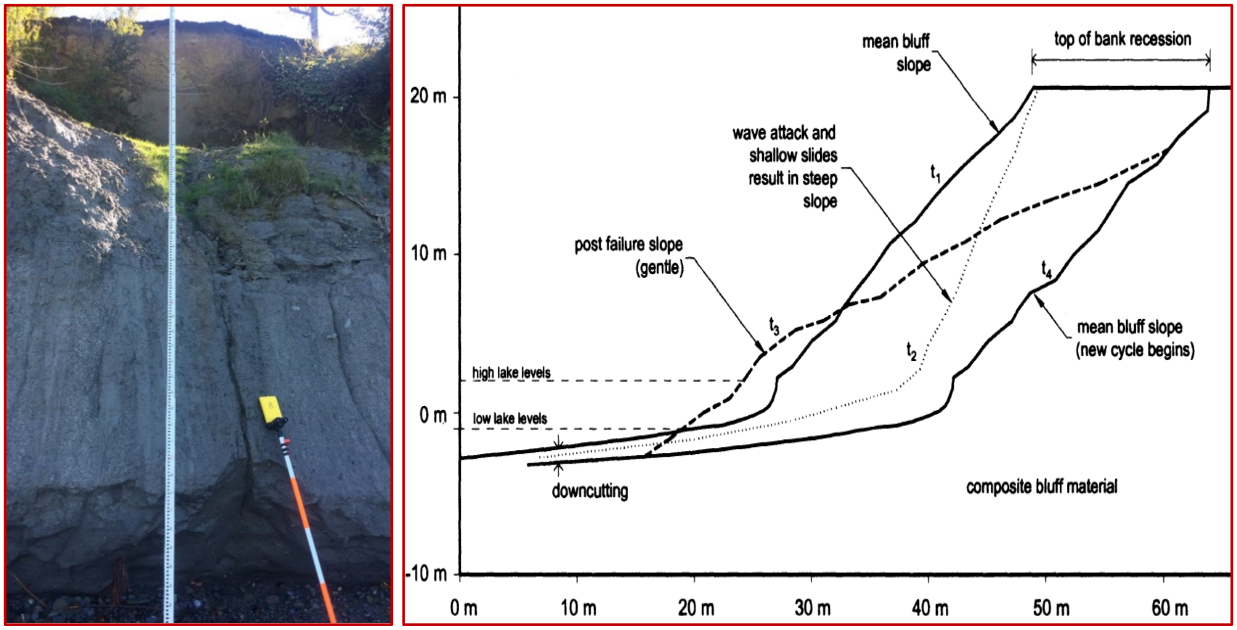


Figure 3.12*: (Left) Bluff retreat in the WECLC where the bluff face has a marked stepped profile due to preferential retreat of the upper bluff (lacustrine sediments) driven by groundwater flux (30 cm color bands on prism rod). Note the wave-cut notch at the base of the stadia rod. (Right) Schematic showing the repeating failure cycle that results in extended periods of bluff-crest stability (time-1 to time-2) alternating with shorter periods of significant crest retreat (time-2 to time-3) identified by Zuzek et al., 2003. The post-slump slope at time-3 is an intermediate stable state, but renewed toe erosion will ultimately steepen the slope and cause renewed failure at time 4-5. (Profile image: modified from Zuzek et al., 2003)*

The bluff face at different sectors and sites on the WECLC coast thus experiences spatial variation in groundwater discharge determined by the presence or absence of surface drainage systems within the sub-watersheds. Where surface drainage was absent, average annual precipitation was multiplied by a recharge factor of 77% to model the annual volume of groundwater recharge due to precipitation that exits the bluff for that sub-watershed (Foyle, 2014). For sub-watersheds with well-developed surface drainage, the average annual precipitation was multiplied by a recharge factor of 15% to model the volume of precipitation that recharges the groundwater system and then exits the bluff. For very large, low-gradient watersheds with well-developed drainage extending for several kilometers inland of Route 5, the average annual precipitation was multiplied by a conservative recharge factor of 0.1% because of uncertainty in the flow directions, geometries, and inter-connectedness of ground-watersheds across these larger tracts of the subsurface.

When estimating the groundwater flux, it was assumed for simplicity that groundwater exited all unconsolidated stratigraphic layers in the bluff face at similar rates. This assumption avoids modeling complications associated with differences in hydraulic conductivity and gradient between the glacial tills and the overlying lacustrine sands and paleo-strandplain beach ridge deposits (Chapter 2). The bluff face area through which groundwater exited was estimated by subtracting the average top-of-bedrock elevation (when bedrock is present) or bluff-toe elevation from the average 2007 bluff-crest elevation for each sub-watershed, and multiplying this by the along-coast length of that sub-watershed. Because of limitations in hydrogeologic data resolution, flux estimates can only be resolved to the site sector or sub-watershed scale and not to the 20 m DSAS transect scale. While annual precipitation for Erie County is cyclical and over the 77-yr project window increased by about 25% (NOAA NCDC, 2020), groundwater fluxes estimated from current precipitation are inferred to be a reasonable proxy for fluxes during the 1938-2007 period. Groundwater fluxes at the bluff face ranged from 0.1 $m^3/m^2/yr$ to 222 $m^3/m^2/yr$, with a mean and median of 36.9 $m^3/m^2/yr$ and 15.0 $m^3/m^2/yr$, respectively.

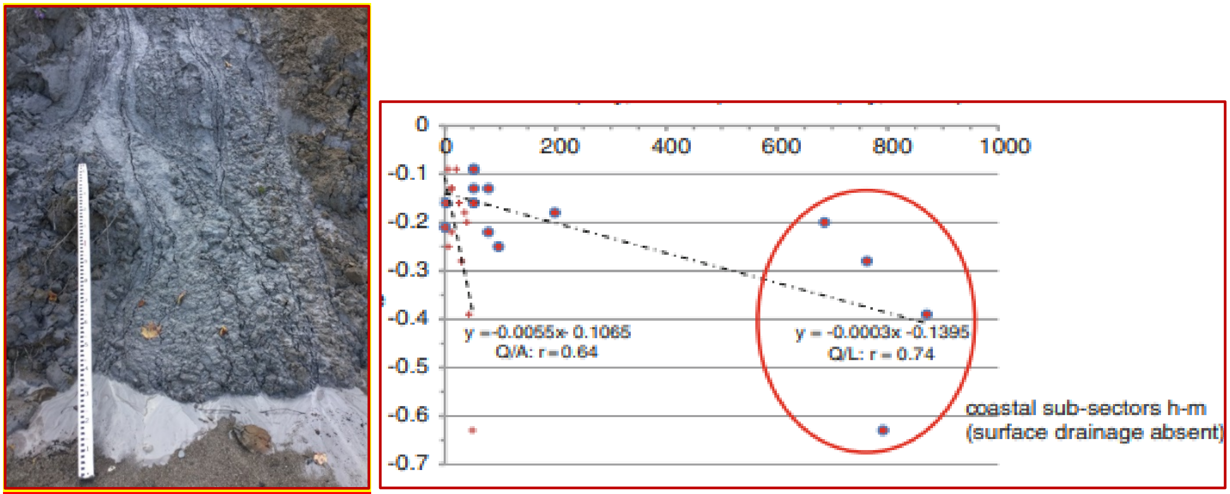


Figure 3.13*: (Left) Mudflow due to groundwater flux through glacial tills in the WECLC (1 cm tick marks on folded 1.5 m stadia survey rod). (Right) Average annual groundwater discharge (Q in* m^3/yr*) per meter of bluff length (X-Axis: Q/L circles in* $m^3/m/yr$*) and average annual discharge per square meter of bluff face (X-Axis: Q/A crosses in* $m^3/m^2/yr$*) versus average bluff-crest retreat rate (Y-Axis: in m/yr) for coastal areas in eastern Erie County. Sectors with well-developed surface drainage systems (abundant streams) have Q/L values that cluster in the less-negative EPR region of the graph while sectors lacking surface drainage (paleo-strandplain beach-ridge areas) have a greater Q/L and cluster in the more-negative region of the graph (Image: modified from Foyle, 2014).*

Top-of-Bedrock Elevation

The elevation of the top of bedrock (Devonian shale) at the toe of the bluff across each of the seven WECLC sites was difficult to resolve from the 2007 and 2015 DEMs alone. The face of the bedrock is typically near-vertical, and it is only at a few locations that the overlying glacial tills have eroded sufficiently to leave behind a shale-bedrock shelf due to groundwater-induced bluff failure (Fig. 3.14). Therefore, for both the Bayesian sites and the intervening bluff areas along the entire WECLC, the top-bedrock elevation also relied on using online 2015 and 2017 oblique coastal aerial photography datasets from PA DEP. Fall 2018 field measurements and presence/absence observations at Sites 1STGL through 7BMDR were also utilized to help map the top-shale elevation. The elevation of the top of bedrock should not have varied significantly over the 1938-2018 time window and is thus inferred to be a good proxy for the top-bedrock elevation input variable used in the Bayesian model.

Bedrock elevation at the bluff toe ranged from ~2 m below Spring 2015 lake level of 174.25 m (~172.5 m MSL at Site 2RACK) to 2.9 m above lake level (~177.2 m MSL at Site 7BMDR; Figs. 3.9, 3.14). Both mean and median top-bedrock elevations were 174.8 m. While the unconformity between bedrock and overlying glacial till thus has along-coast topographic relief of ~5 m, it also has significant relief in the shore-normal direction due to lake-bed erosion in the surf zone and stream incision landward of the bluff face over the past ~10,000 years. However, over the 2007-2018 time period, the amount of bluff face retreat should not result in significant change to the top-bedrock elevation. The elevation of the top of bedrock is a variable that is expected to influence bluff retreat due to its contribution to greater geotechnical resilience (Fig. 3.10).

The presence of bedrock adds a highly wave-resistant material to the toe of the bluff that is difficult to remove by wave action, compared to having a bluff toe consisting of glacial till (Fig. 3.14). Thus, over-steepening of the lower bluff face is much less likely to occur in areas where shale is present. This in turn will reduce the propensity for bluff-face failure due to wave-caused oversteepening. The relative elevation of the top of bedrock is important because waves impinging on the bluff toe will have some value (0 – 2 m) of wave run-up onto the bluff face. The taller the bedrock strata are, the less likely it is for waves to erode unconsolidated glacial tills and overlying strata (Fig. 3.9). Dawson and Evans (2001) noted that in Painesville-on-the-Lake, Ohio, long-term bluff retreat rates declined by ~50% once the top of bedrock reached elevations greater than 1.5 m above lake level.

Beach Prism Width

The three-dimensional beach prism in profile (looking along the coast) extends from the shoreline to the toe of the bluff, with its top surface being the walkable beach and its base being bedrock or glacial till. Among the 470 DSAS transects across the seven WECLC sites, the average beach-prism thickness at the bluff toe was mapped from the 2007 DEM to be 1.23 m. A wide and thick (tall) beach prism has the effect of moving the toe of the bluff landward and to a higher elevation where it is less likely to be impacted by vertical wave run-up. Beach prism width, along with bluff-toe elevation (or prism thickness) discussed above, is thus important because a wider beach allows a greater opportunity for dissipation of wave energy, before it impacts the bluff, due to wave-bore infiltration and frictional losses.

In the WIH equation (Fig. 3.7), a beach-foreshore slope (β_f) is used, which is the slope measured on that part of the beach profile bounded vertically by the mean significant wave height centered on the still water line (Melby, 2012). While foreshore slope is utilized in the WIH calculations, it does not directly account for width of the berm and backshore, which are located between the foreshore and the bluff toe. It was therefore suspected that the beach prism width may affect bluff retreat rates as it can dictate how much protection a beach provides the bluff toe. Beach width measured from the DEM was judged a somewhat reasonable proxy for beach width as an initial state for the 1938-2007 time period. It was also used as an initial-state input for the start of the 2007-2015 validation period. The 2007 beach prism width ranged from 0.18 m to 117.3 m, with a mean and median of 8.9 m and 5.8 m, respectively.

Beach width measurements were compiled from the 2007 DEM at 20m-spacing DSAS transects for each of the seven WECLC sites. These data were supplemented with several (~150-200 m spacing) 2018 field measurements at each site. The latter generally yielded narrower widths, due to increased lake levels in 2018 relative to 2007, and due to the opportunity for some downdrift beach migration to have occurred in the 11-year time interval between the two datasets. A complication at Site 6LSCC was that the bluff toe in 2018 was separated from the shoreline by a stepped wave-cut shale platform. On the 2007 DEM this would appear visually as the landward (backshore) part of the 2007 beach that would have been present.

Figure 3.14: *(Left) Bedrock bluff toe extending 2.3 m above (and overhanging) the backshore at WECLC Site 7BMDR. This site has the highest top-bedrock elevations and the second-highest groundwater fluxes among all seven WECLC sites. Note the smooth lowermost 40 cm of the bedrock toe indicating abrasion by sediment-charged wave run-up. Orange and white bands on the prism pole are 30 cm tall, and 1 cm tick marks are visible on the extended stadia rod.*

Ruggiero et al. (1996, 2001) found that bluff or dune erosion on Pacific Northwest coasts proceeds at faster rates when the bluff or dune toe lies closer to sea level. Similarly, Lee (2008) documented that bluff-crest retreat rates on the UK North Sea coast and elsewhere are inversely proportional to the volume of beach material present. In east-central Ohio, short-term bluff retreat rates were found to be 67% lower when beaches were wider than 30 m and/or lake levels were lower (Mackey and Haines, 1998; Dawson and Evans, 2001). Conversely, Foyle (2014) found that beach development in eastern Erie County had little correlation with bluff retreat rates. This is possible because the presence of a wide beach fed by littoral drift can provide bluff-toe protection but may alternatively be the result of recent bluff failure at that location.

Bayesian Network Model Results

Model Selection

Using k-fold cross-validation, the best model examined was the one in which eight of the nine possible inputs were used (Fig. 3.15; Table 3.2). These inputs included SPR Resiliency, Long-Term Retreat Rate, Bluff Face Slope, Beach Prism Width, Toe Elevation/Beach Height, Top-Shale Elevation, Bluff Height, and Wave Impact Hours (Table 3.2, Row 8). The average percentage of incorrectly classified transects was 60.4% for the 8-element model, which had the lowest number of incorrect classifications among models, leading to its selection as the final (optimal) model. Models with five inputs (60.5%) and seven inputs (60.8%) produced similar results (Table 3.2; Rows 5 & 7). The similarity of these numbers indicated the predictive performance of all three models was similar. However, the goal was to select the model with the best predictive ability, therefore the model with the lowest percentage of incorrect classifications was selected. The average percentage of incorrectly classified transects was used only for model selection and not as a measure of goodness of fit because not all of the data collected was used to fit the model at any one time. The cross-validation results indicated that the model using all nine inputs resulted in overfitting the data. That is, while it fit the data used to build the model well, it did a poor job with predictions when presented with new data.

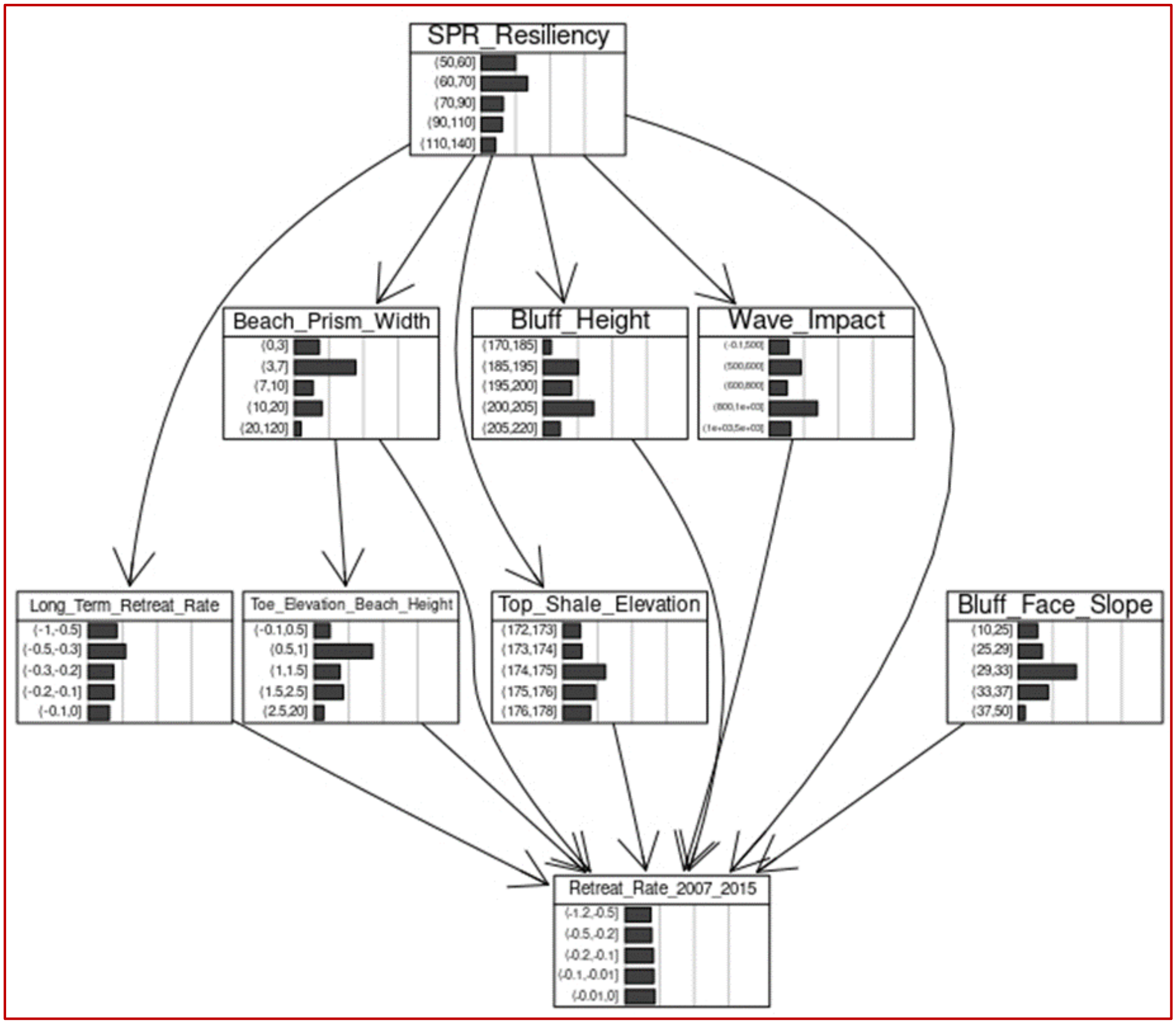


Figure 3.15: *Final Bayesian Network model for bluff retreat on the WECLC coast showing the eight optimal variables used to predict 2007-2015 retreat rates and simulate future (2025, 2040, 2065) bluff-crest locations. Review Table 3.1 for data details.*

In addition to the forced relationships between the eight inputs and the 2007-2015 retreat rate, the model fitting process also found relationships between SPR Resiliency and Long-Term Retreat Rate, Beach Prism Width, Bluff Height, Wave Impact Hours, and Top Shale Elevation. This means that SPR was the least important variable, largely due to the fact that information contained in the SPR value was mirrored in the other five variables. Among this group, dependency would be expected between SPR Resiliency and Top Shale Elevation because calculation of the numerical value for the resiliency input is influenced by the presence and thickness of shale bedrock that is an order of magnitude more resilient than the unconsolidated strata. Beach Prism Width was found to relate to Toe Elevation/Beach Height. The direction of the arrow indicates that, for example, the distribution of the probability of being in a given bin for Toe Elevation/Beach Height is conditional on the Beach Prism Width. This relationship is also to be expected because greater-volume beach prisms are associated with thicker beach deposits which causes a vertical elevation change for the toe-beach contact. The probability of being in a given Toe Elevation/Beach Height bin at a transect can be shown to depend on the bin the transect is in for Beach Prism Width. It is not a causal relationship, but more akin to a correlation. The lack of an arrow between different inputs in Fig. 3.15 indicates the probability distributions of those inputs are roughly independent of each other. This means that there was no information in the dataset to establish a dependency.

Influence of model-input combinations on Bayesian Network model success		
# of Inputs	***Incorrect Class %***	***Model Input Variables***
1	63.2	Toe Elevation/Beach Height
2	63.7	SPR Resiliency, Bluff Face Slope
3	62.8	Toe Elevation/Beach Height, Bluff Height, Wave Impact Hours
4	61.0	Beach Prism Width, Toe Elevation/Beach Height, Top-Shale Elevation, Bluff Height
5	60.5	Long-Term Retreat Rate, Bluff Face Slope, Beach Prism Width, Toe Elevation/Beach Height, Wave Impact Hours
6	61.3	SPR Resiliency, GW Flux, Long-Term Retreat Rate, Toe Elevation/Beach Height, Top-Shale Elevation, Bluff Height
7	60.8	SPR Resiliency, GW Flux, Bluff Face Slope, Beach Prism Width, Toe Elevation/Beach Height, Bluff Height, Wave Impact Hours
8	***60.4***	***SPR Resiliency, Long-Term Retreat Rate, Bluff Face Slope, Beach Prism Width, Toe Elevation/Beach Height, Top-Shale Elevation, Bluff Height, Wave Impact Hours***
9	63.2	SPR Resiliency, Long-Term Retreat Rate, Bluff Face Slope, Beach Prism Width, Toe Elevation/Beach Height, Top-Shale Elevation, Bluff Height, Wave Impact Hours, Groundwater Flux

***Table 3.2**: Summary of the nine parameters considered, and the eight adopted (in bold), in the final Bayesian Network model for the WECLC to predict 2007-2015 retreat rates and simulated future bluff locations.*

Assessing Model Fit

Fitting the final model with all 414 transects, the final model correctly predicted the 2007-2015 retreat-rate bin 395 times, or for 95.4% of the transects. In other words, the model correctly predicted 95.4% of the binned short-term retreat rates correctly. This included ties: if ties were excluded, the model predicted (395-80-9)/414 or 71.5% of the binned short-term rates correctly. The predicted value was assumed to correctly match if the observed 2007-2015 retreat rate matched the bin with the largest predicted posterior probability. The prediction was also considered to be correct if the largest predicted posterior probability was tied among multiple bins (two bins in 80 cases, three bins in 9 cases) and the observed 2007-2015 retreat rate was among those bins. Figures 3.16 to 3.19 show the observed (bars) and predicted bins (dots) for 2007-2015 retreat-rate for all 414 participating DSAS transects at each of the seven WECLC sites used in the model. The plots have a "toothy" appearance with many common values because the average value of each of the five retreat-rate bins (predicted and observed) was plotted.

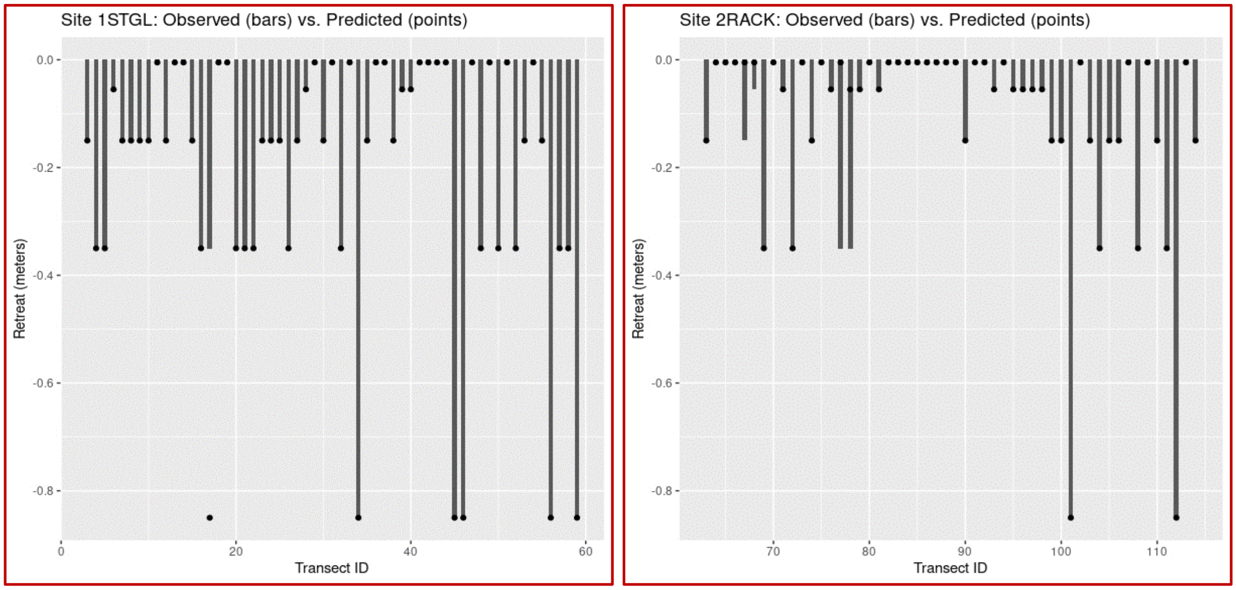


Figure 3.16*: Observed (bars) and predicted bins (dots) for 2007-2015 retreat rate for participating DSAS transects at WECLC Sites 1STGL (left) and 2RACK (right), both in the Turkey Creek watershed.*

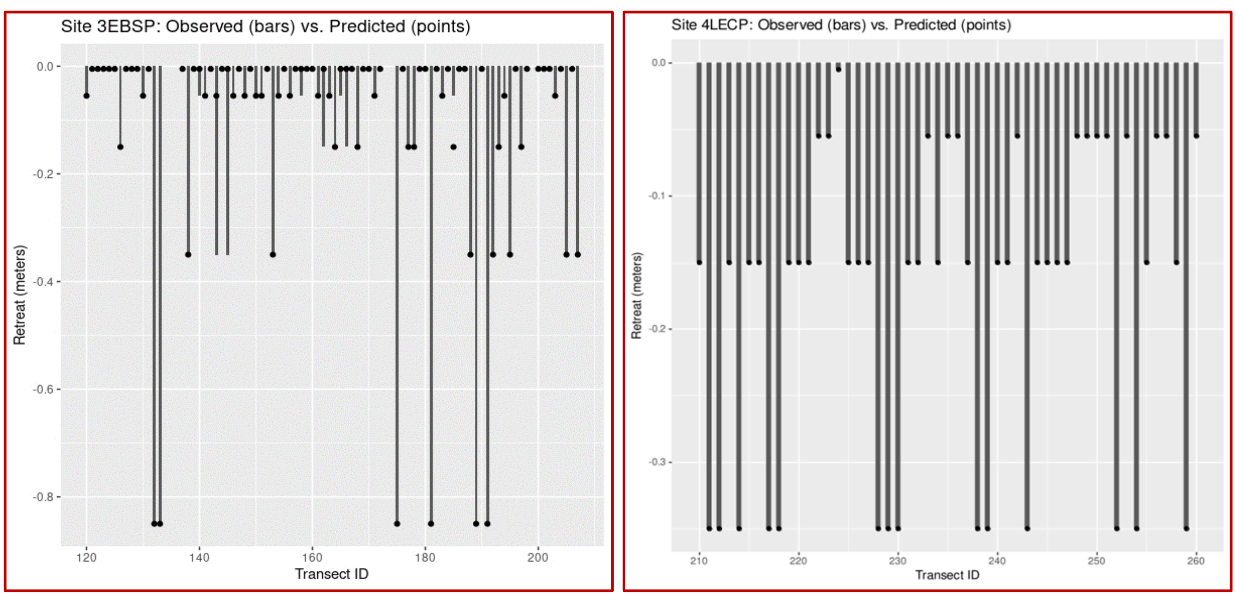


Figure 3.17*: Observed (bars) and predicted bins (dots) for 2007-2015 retreat rate for participating DSAS transects at WECLC Site 3EBSP in the Crooked Creek watershed (left) and Site 4LECP in the Trout Run watershed (right). Note different retreat-rate and distance (transect-ID) scales on these two plots.*

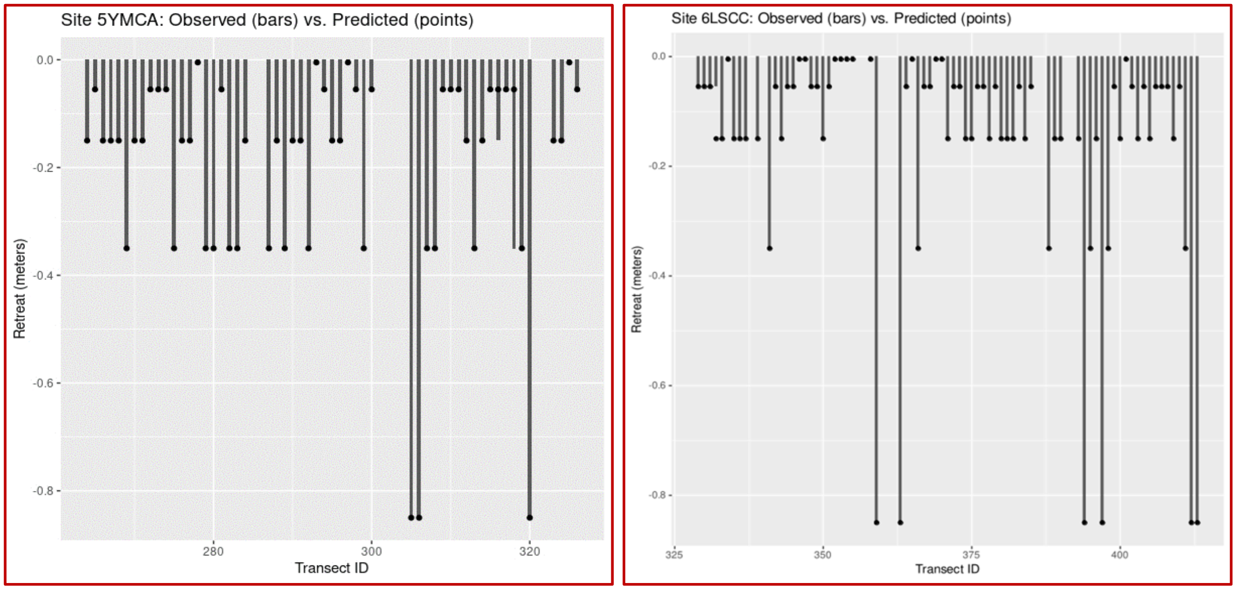


***Figure 3.18**: Observed (bars) and predicted bins (dots) for 2007-2015 retreat rate for participating DSAS transects at WECLC Site 5YMCA in the Trout Run watershed (left) and Site 6LSCC in the Walnut Creek and Mill Creek-West watersheds (right). Note different distance (transect-ID) scale on these two plots.*

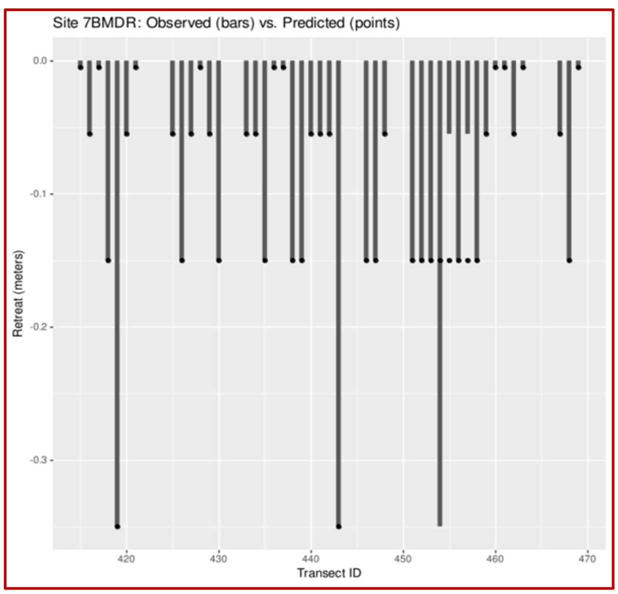


***Figure 3.19**: Observed (bars) and predicted bins (dots) for 2007-2015 retreat rate for participating DSAS transects at WECLC Site 7BMDR in the Mill Creek-West watershed at the downdrift end of the WECLC.*

Observed and predicted retreat rates of 0-0.01 m/yr are relatively common at Sites 2RACK and 3EBSP. Many of these near-zero-change transects are associated with apparent bluff-crest progradation due to crest-mapping uncertainty discussed earlier. This uncertainty can be partly ascribed to such effects as masking of the bluff crest by dense bluff-edge vegetation, and to lower lidar ground-strike densities in the 2007 dataset, which leads to a slightly less precise DEM. Most of the apparent-progradation rates fall within the uncertainty in the 2007-2015 retreat-rate estimates (±0.17 m/yr) and these transects' observed retreat rates are consequently treated as locations of zero net bluff-crest change. Elsewhere, observed and predicted 2007-2015 retreat rates match best at Site 4LECP where 100% of observed and predicted retreat rates were coincident. Across all WECLC sites, the transects showing retreat of ~0 m/yr indicate a modeling limitation: a longer (than 8-year) validation period may have better distinguished real zero-change transects from low-retreat and apparent-progradation transects. Observed-rate and predicted-rate data voids for transects in Figs. 3.17 – 3.19 represent locations where at least one of the eight model inputs or the 2007-2015 retreat rate was missing from the model dataset (12% of transects; 56 of 470 transects).

Measuring Variable Importance

When using the final model with all 414 transects, the average predicted posterior probability of the observed 2007-2015 retreat rate bin was 84.1%. This value was used as a baseline to determine the importance of each input in the model because this was the average predicted posterior probability value for the final model. Table 3.3 shows the percent reduction from 84.1% when the average predicted posterior probability of the observed 2007-2015 retreat rate bin was calculated without any one of the eight model inputs. For the final 8-element model, the two most important inputs were long-term retreat rate (causes a 14.3% reduction in prediction probability if removed) and bluff face slope (causes a 13.8% reduction in prediction probability if removed). For example, if long-term retreat rate is removed from the model, the average predicted posterior probability is reduced by 14.3% to 69.8%. This result indicates that without long-term retreat rate, the resulting Bayesian Network model has a combination of fewer correctly classified transects and more uncertainty among those predictions. The percentage reductions in model skill are specific to this 8-element model and would assume different values if the model consisted of a different number of inputs (such as those shown in Table 3.2)

Bayesian Network Discussion

As with any model fitting process, there is a danger of over-fitting a model by using all the available input (or predictor) variables that may have a role in describing the system. Such a model will have a high variance (medium.com, 2020) and will try to explain every input value, including outliers. In other words, it will try to learn the training data too well and will have difficulty generalizing to new data. Conversely, a model may under-fit the data and consequently may not explain all the input values (the model has a high bias). It will have difficulty learning the training data, has to make a lot of assumptions, and also will have difficulty generalizing to new data (medium.com, 2020). While the former typically results in a model that fits the observed data very well, the predictions the model produces for new or test data can be inaccurate. The optimal situation is to balance and reduce variance and bias so that the model can explain most of the inputs and can adapt well to new data. When datasets are very large, the paradigm of using a training dataset (long-term retreat rate, bluff height, etc.) to fit the model and a separate test dataset to select a final model fit is a widely accepted approach to balance model accuracy and over-fitting (e.g., Van Westen et al., 2003). When the size of the dataset is not large, as in this bluff-retreat application, the use of k-fold cross validation emulates the training/test model fitting approach.

The use of k-fold cross validation for model selection usually results in a final model that selects a simpler model over more complicated models with similar predictive power (Table 3.2). In this bluff-retreat application, the k-fold cross validation approach selected a final model that contained eight of the possible nine model inputs. Since k-fold cross validation contains a random component, how the data set is randomly split into *k* (here 10) subsets, the statistic used to measure model quality (here, percentage of incorrect classifications) can vary from run to run. By averaging the percentage of incorrect classifications over 50 runs, this not only minimizes the effect of the random portion of the procedure, it also allows for the model selection process to be reproducible.

Sensitivity analysis to identify reduction in prediction probability for specific variables removed	
Model Input Variable	***Reduction in Prediction Probability***
Long-Term Retreat Rate	14.3%
Bluff Face Slope	13.8%
Toe Elevation/Beach Height	9.7%
Beach Prism Width	9.1%
Top-Shale Elevation	5.3%
Wave Impact Hours	4.6%
Bluff Crest Height	4.0%
SPR Resiliency	0.3%

***Table 3.3**: Summary of sensitivity analysis of the eight adopted model-input parameters showing effects of removing a single input on the average predicted posterior probability of the model.*

The output of the Bayesian Network model is the predicted posterior probability of being in each of of the five 2007-2015 retreat-rate bins: (-1.2,-0.5),(-0.5,-0.2),(-0.2,-0.1),(-0.1,-0.01) or (-0.01,0) m/yr. There are multiple ways to measure the accuracy of the final Bayesian Network model selected. The most straightforward way is to count the percentage of times the observed 2007-2015 retreat rate bin matched the bin with the highest predicted posterior probability. Treating ties among multiple bins as correct if the observed bin is among a small number (e.g., two) of ties, 95.4% of the transects were correctly classified (395 out of 414 transects).

A second method to assess model fit that takes into account the uncertainty in the model predictions is to average the predicted probability of being in the observed 2007-2015 retreat rate bin for each transect. This approach takes into account the confidence in predicting the correct short-term retreat rate, not just the percentage of times the correct short-term retreat rate is correctly predicted. For the final model, the mean predicted probability of the observed short-term retreat rate was 84.1%. The predicted probabilities ranged from 14.3% to 100%, with 100% indicating that the observed short-term retreat rate was the only possible predicted short-term retreat rate. 287 of the 414 (69.3%) transects predicted the observed short-term retreat bin with accuracy greater than 99.99%.

The difference between these measures of overall model fit (95.4% correct classification rate and 84.1% average predictive probability) and the average percent incorrect classifications from the k-fold cross validation for the final model (60.4%) appears to be contradictory. However, it is important to note that criteria for model selection via k-fold cross validation as used is not a measure of overall model quality. Model selection is a separate analysis from evaluating the final model. Additionally, under k-fold cross validation, if there is a tie among the short-term retreat rate categories with the highest probability, the cross-validation process randomly selects one of the tied categories. This process of tie-splitting increases the number of incorrect classifications even though the model may be performing well. As the percentage of incorrect classifications is being used only for model selection (Table 3.2), only the relative values between the models are important, not the magnitude of the values.

The two most important variables, in terms of reduction of prediction probability, in the final 8-element model are the long-term retreat rate and the slope of the bluff face (Table 3.3). The third most important variable is toe elevation/beach height, which was also determined to be the best model via k-fold cross validation when only one input was used (Table 3.2, Row 1). The latter statement means that when building a 1-element model using any one of the nine geodata inputs, toe elevation/beach height is the best-performing input of the nine when predicting the amount of crest retreat. In comparison, the reduction in average prediction probability (Table 3.3) measures the importance of an input of interest when it is removed but all other inputs remain in the model. The discrepancy between what appears to be the "most important" input using these two metrics demonstrates the complexity in multi-variate modeling of 2007-2015 retreat rates and that increasing the complexity of the Bayesian Network changes the importance of the inputs.

The Bayesian Network model suggests that, in fundamental terms for property owners, long-term retreat rate, bluff face slope, toe elevation and beach prism volume together explain most of the predicted 2007-2015 crest-retreat rates (Table 3.3, Rows 1-4). Groundwater Flux within the model appears to have only a minor influence because the model skill degrades when it is included (Table 3.3, Row 9). The reason for this is uncertain and may be due to imperfect quantification of the groundwater flux through WECLC watersheds. Long-Term Retreat Rate in the 8-element model remains the most important input variable. This validates the historical practice of using long-term retreat rates to predict future retreat rates on coastlines in general. A possible reason for this is that long-term retreat rate is fundamentally a consequence of interactions among all processes driving bluff retreat over time.

Sensitivity analysis indicates that no one model variable can be defined as the principal driving or "best" factor for predicting 2007-2015 retreat rates. If removal of long-term retreat rate (in Table 3.3) resulted in a very large reduction in prediction probability (e.g., greater than 50%), it would have indicated not that it was a very important variable but that the model was over-fit and a simpler model would have been more appropriate. Given that all of the values in Table 3.3 are less than 15%, this indicates that a multivariate approach to modeling the complex system driving retreat is appropriate. Inputs near the bottom of Table 3.3 are still critical inputs, as they were deemed sufficiently important to include in the model during the k-fold cross-validation selection process. It is important to realize that the 8-element model is the best-fit model for all WECLC sites. It may or may not work as well as some other model for any one particular WECLC site. However, Figs 3.16-3.19 suggest that the 8-element model does work better in some sites than in others.

Bayesian Network Forward Simulations: 2025, 2045, and 2065

Methods

Based on the results presented in Table 3.2, the 8-element model developed above is the best of those examined, and the output can be used to simulate future positions of the bluff crest at each transect used in the model. The output of the final Bayesian Network model shown in Figure 3.15 is the posterior distribution of the probability of each site transect's annual retreat rate being within each of the five rate bins. For example, Transect 5 (at WECLC Site 1STGL; Fig. 3.16) has the posterior probability distribution shown in Table 3.4. Future annual bluff-crest retreat can be simulated by sampling from this posterior probability distribution. For Transect 5, there is an ~50% chance that the retreat will be between -0.5 and -0.2 m/yr and an ~50% chance that it will be between -0.1 and -0.01 m/yr. There are also small, non-zero probabilities that the retreat could occur at rates in three other bins (-1.2 to -0.5 m/yr; -0.2 to -0.1 m/yr; -0.01 to 0 m/yr). Rounding results in an essential 50/50 split between the (-0.05, -0.2) and (-0.1, -0.01) retreat-rate bins.

Posterior probability distribution of retreat rates at a sample transect					
	Rate Bin	***Rate Bin***	***Rate Bin***	***Rate Bin***	***Rate Bin***
Rate (m/yr)	-1.2 to -0.5	-0.5 to -0.2	-0.2 to -0.1	-0.1 to -0.01	-0.01 to 0
Probability (%)	<0.01	49.99	<0.01	49.99	<0.01

Table 3.4*: Summary table showing sample posterior probability distribution for Transect 5 at WECLC Site 1STGL in the Turkey Creek watershed.*

To simulate 10 years of retreat, ten samples from the above posterior probability are randomly generated. The simulated annual retreat can be obtained in either of two ways. The first is to use the midpoint of each bin as the simulated annual retreat. This would result in 0.85, 0.35, 0.15, 0.05, and 0.005 m/yr of retreat for each bin, respectively. A second approach would be to sample a random measured retreat from all the observed retreats within a bin. This is called a bootstrap sample. For example, if for one year in Transect 5, the bin that was selected for the simulated retreat was (-0.5 to -0.2 m/yr), an observed retreat from this bin would be randomly selected, -0.35 m/yr for example. All observations in each bin are equally likely to be sampled. In order to better simulate possible bluff-crest retreat, the second method is preferred and utilized in this simulation. To simulate the total 10-year retreat, the annual retreat is summed over the 10 samples.

Bluff crest retreat is simulated for 10, 25, and 50 years for each transect at each of the seven WECLC sites, representing total retreat by the years 2025, 2040, and 2065, respectively (using 2015 as the starting year). The 10-yr observation window is a convenient time period in terms of public perception of coastal hazards because it is coincident with the median duration of individual-home ownership in the United States (10-13 yrs; nar.realtor). Twenty-five years is the approximate duration of an average residential mortgage, while the 50-yr time window looks out for the number of years used to determine the minimum bluff-setback distance for residential properties within Pennsylvania's Bluff Recession Hazard Areas (PA DEP, 2013). Each transect was randomly sampled 500 times: this was chosen to be appropriate because it allowed for a reasonable number of results without using an excessive model-run time. To summarize the 500 simulated retreats, a crest-retreat box plot was generated for each transect within each of the seven WECLC sites.

Results

For each transect at each of the seven WECLC sites, the simulated total bluff crest retreat (in meters) is presented as a box plot for 10, 25, and 50 years in the future. The median simulated retreat is represented by the center line in each box, the box represents the middle 50% of simulated retreats, and any outliers are represented by dots. The 50-yr retreat simulations are shown below in Figs. 3.20-3.23. Fig 3.24 shows a topographically more realistic 10-transect moving average of total retreat over 50 years, superimposed on mean retreat by transect, for each of the seven WECLC sites. The 10-yr and 25-yr simulated retreats are shown separately in Chapter 3-Appendix Figures A3.25-A3.28 and A3.30-A3.33. The 10-transect moving averages for the 10 yr and 25 yr time windows are shown in Appendix Figures A3.29 and A3.34.

Ten-transect moving averages are shown in Figs. 3.24, A3.29, and A3.34 for several reasons. Along-coast extents of slump failures range from ~5 m to ~1000 m in length over the long term (tens to hundreds of years) and from ~5 m to ~200 m over shorter time periods (decades). Realistically, the simulated retreat at any given transect will rarely occur in isolation from nearby transects, spaced every 20 m on either side. This is a phenomenon not considered in the Bayesian Network model, because interactions between transects are not directly examined. Also, the larger the simulated failure event or total retreat at a transect, the more likely it is for a larger number of adjacent transects to be influenced (i.e., also show enhanced change in crest position). For example, 39.5 m of simulated retreat over 50 years at Transect 101 in Fig. 3.24 is unlikely to be accompanied by zero meters of retreat at adjacent Transect 102. These occurrences of major retreat and minor retreat on adjacent DSAS transects are also visible elsewhere in Figs. 3.20-3.23, A3.25-A3.28, and A3.30-A3.33. The 10-transect moving average smooths the crest-retreat line feature across multiple transects such that the crest appears topographically more realistic.

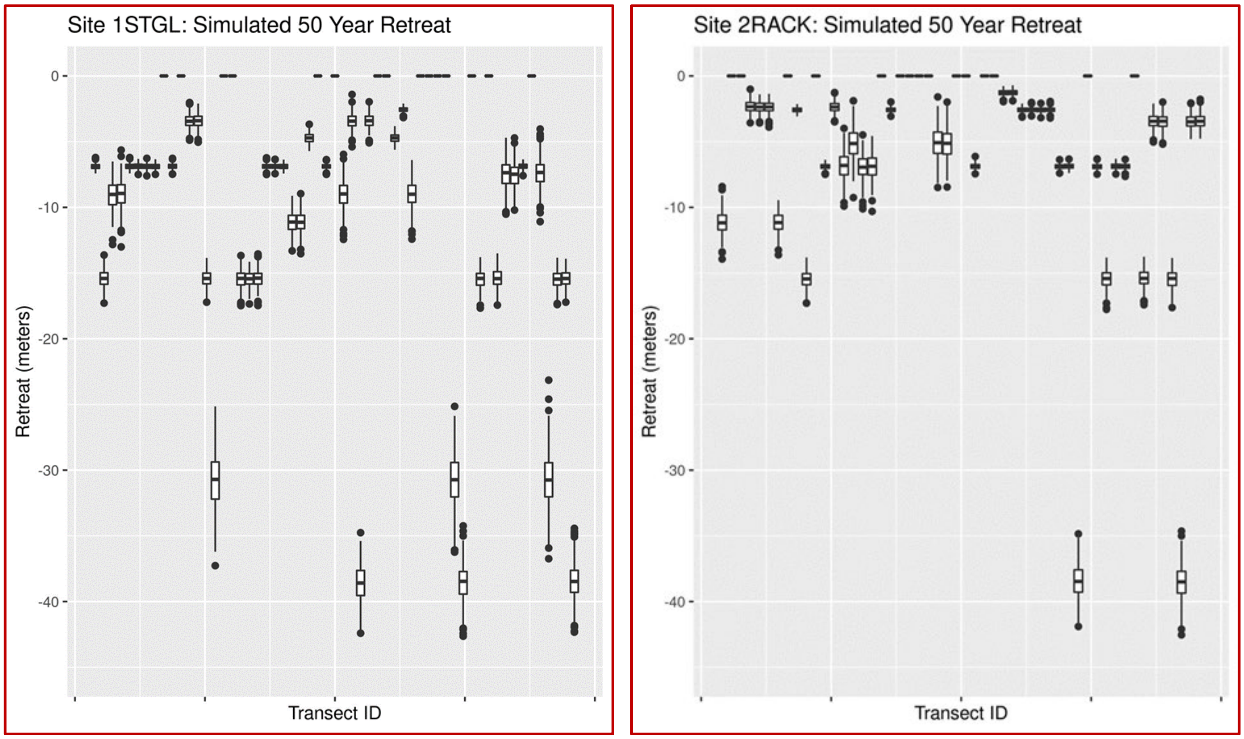


Figure 3.20: *Simulated 50-year bluff retreat by DSAS transect at WECLC Site 1STGL (left) and Site 2RACK (right) in the Turkey Creek watershed. See text for symbology explanation.*

The 10-transect averaging also circumvents another limitation of the Bayesian model: that ~zero-change transects will continue to illustrate ~zero change over decades and that major-change transects will continue to illustrate major change over those same decades. This implicit modeling assumption is contrary to current understanding of bluff retreat, where periods of enhanced crest retreat lead to lower-slope, more stable bluffs (resulting in a lowering of retreat rates over subsequent years) and vice versa (Zuzek et al., 2003; Fig. 3.12). Over the decadal timeframes for the simulations, a 10-transect moving average (assumed 200 m event dimension/20 m transect spacing) was assumed appropriate as a smoothing mechanism to better represent natural topographic conditions and crest irregularity. Figures 3.24, A3.29, and A3.34 therefore plot 10-transect moving averages as well as the noisier mean individual-transect retreats.

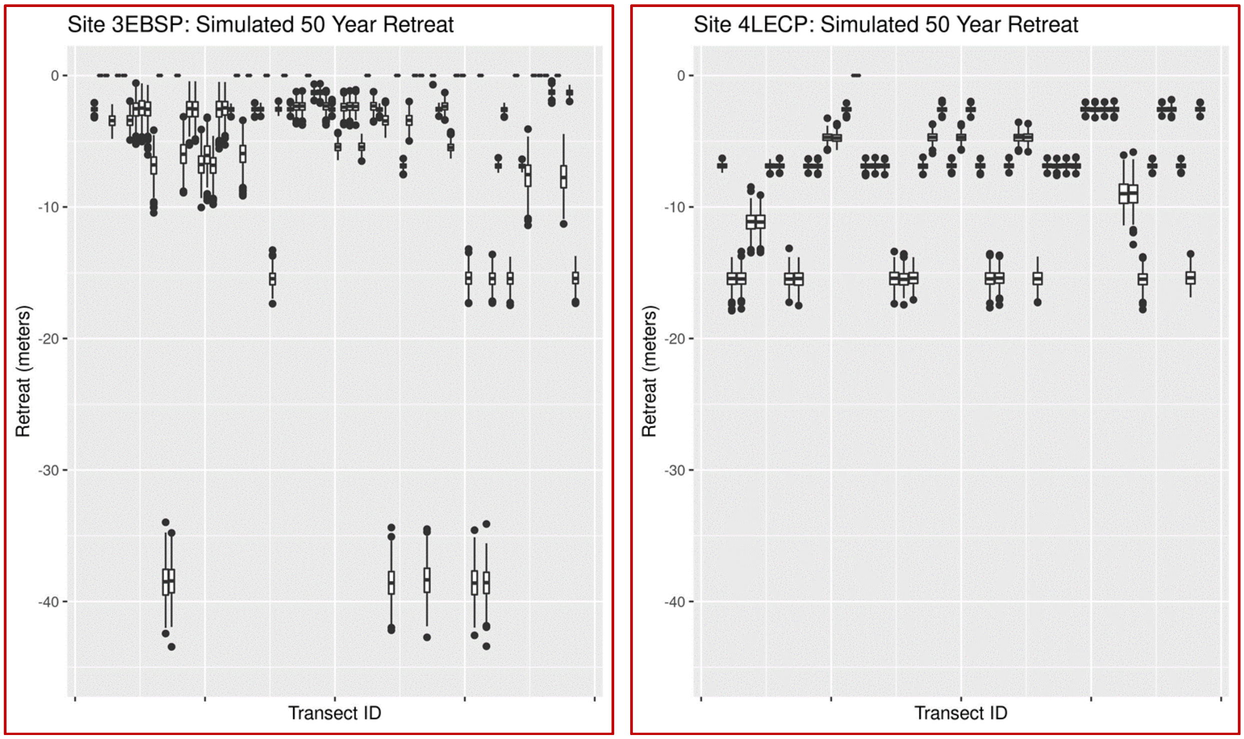


Figure 3.21: *Simulated 50-year bluff retreat by DSAS transect at WECLC Site 3EBSP (left) and Site 4LECP (right) in the Crooked Creek and Trout Run watersheds, respectively. See text for symbology explanation.*

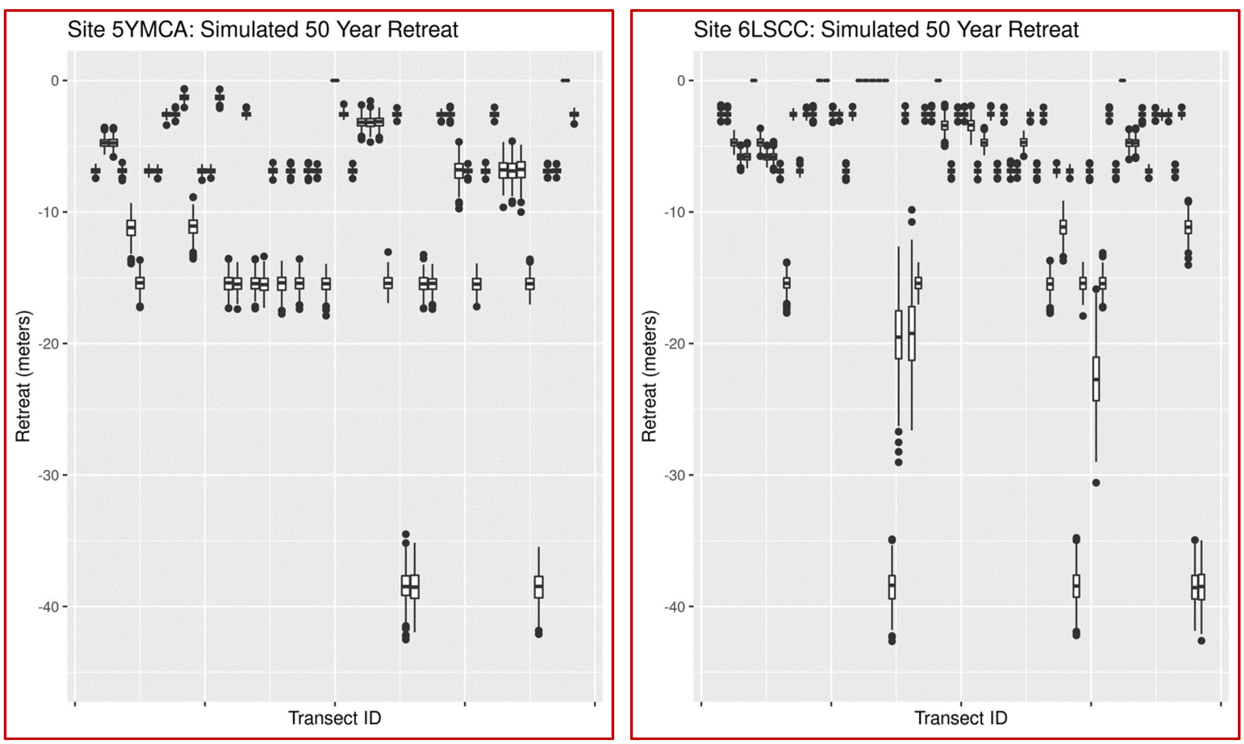


Figure 3.22: *Simulated 50-year bluff retreat by DSAS transect at WECLC Site 5YMCA (left) and Site 6LSCC (right) in the Trout Run and Walnut Creek/Mill Creek-West watersheds, respectively. See text for symbology explanation.*

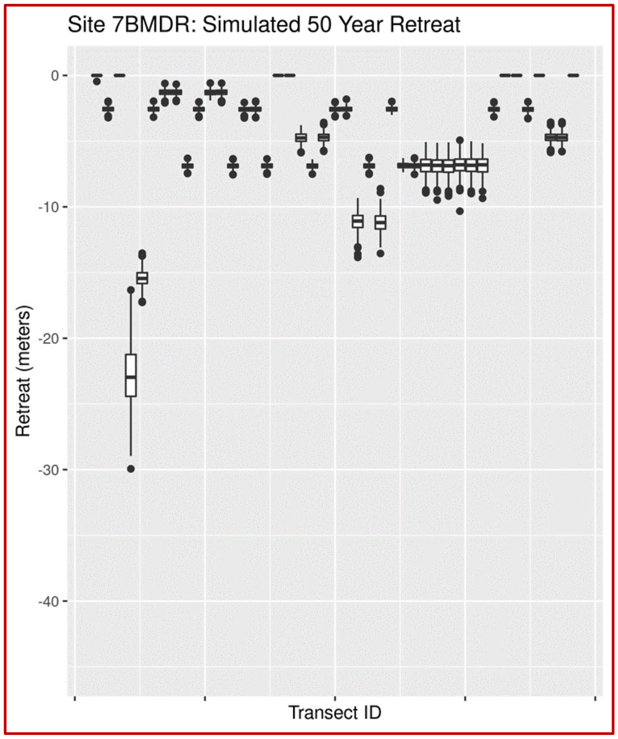


Figure 3.23: *Simulated 50-year bluff retreat by DSAS transect at WECLC Site 7BMDR in the Mill Creek-West watershed. See text for symbology explanation.*

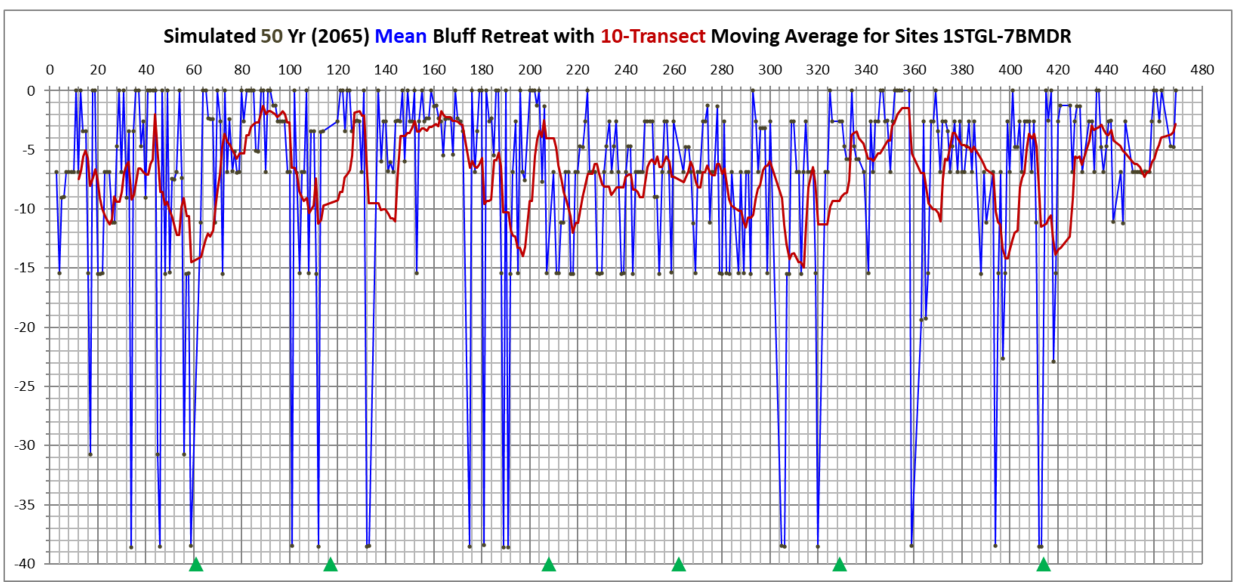


Figure 3.24: *Simulated mean retreat (meters) and 10-transect moving-average by DSAS transect for 50 years of bluff retreat at each of the WECLC Sites (multi-km gaps between sites are not shown). WECLC site boundaries are indicated by triangles on the x-axis. If this plot is "birds-eye viewed" as an east-west map with Lake Erie at the top, the scale of crest retreat appears dramatic because the retreat (y) axis is exaggerated ~100X.*

Forward Simulation Discussion

Given the high level of accuracy in correctly predicting the observed 2007-2015 retreat rate by the Bayesian Network model (84.1% *mean predicted probability*; 95.4% *correct-classification rate*), much of the variation in simulated retreat rates through 2065 shown in Figs. 3.20-3.23 is due to natural variation in retreat rates observed in each of the 2007-2015 retreat rate bins for each transect. Transects with narrow simulation box plots indicate that the model was able to predict the observed 2007-2015 retreat rate with a high level of accuracy at that location, while transects with wide box plots have more uncertainty. For example, Transect 5 (Fig 3.20; third from left) from Site 1STGL has a wide spread of possible 50-year simulated retreat. It similarly has a wide spread for the 10-year and 25-year simulations (Figs. A3.25, A3.30). In general, the plots for all three simulation periods show that, as has been true historically, simulated future retreat is spatially very variable between nearby transects and between field sites.

Fig 3.24 suggests that, over the next 50 years, bluff-crest retreat at the 7 WECLC sites may be expected to range from 1 to 15 m depending on location, using the 10-transect moving average (Fig. 3.24). That represents a range of crest retreat rates of 0.02 to 0.3 m/yr, within the range of values for historical bluff retreat (Fig. 2.12). However, an implicit assumption here is that environmental conditions going forward don't vary any more than they have during the 1938-2015 period (the timeframe used to build the Bayesian Network).

Ten-transect moving average plots (Figs. 3.24, A3.29, A3.34) reduce some of the spatial noise in the decade to multi-decade simulations of mean retreat. Focusing on the 50-year simulation in Fig. 3.24, relatively consistent but greater future retreat can be seen for Site 1STGL, and for Sites 4LECP and 5YMCA (Transects 200-300; in the Trout Run watershed) compared to other sites. Simulated retreat averages ~8 m by 2065. Four sites (2RACK, 3EBSP, 6LSCC, 7BMDR) tend to show more within-site variability in by-transect amounts of simulated retreat. Simulated retreat is, on average, generally similar across all sites, with the lowest simulated retreat occurring at Sites 2RACK, 3EBSP, 6LSCC, and 7BMDR. This is significant because comparing Fig. 2.14 (Chapter 2) and Fig. 3.24 above, the long-term record of major retreat for Sites 1STGL and 2RACK in the Turkey Creek watershed (relative to other WECLC sites) weakens in the future simulations. Figure 2.14 suggests that historical bluff retreat at Site 2RACK was over twice as great as that occurring at all other WECLC sites but 1STGL. The reason for this future (simulated) erosion reduction at historic rapidly eroding locations is unknown.

There are limitations in the Bayesian Network model that potentially limit its skill at simulating future bluff-crest locations during any of the three time windows analyzed. A significant number of transects in the dataset we used had zero or near-zero short-term (2007-2015) retreat rates. These transects forced the model to predict ~zero meters of future retreat during subsequent simulations. These zeroes are a consequence of limited real bluff-crest change in the 2007-2015 observed data at DSAS transects, and of crest-mapping uncertainty (small) when picking the bluff crest locations from lidar data. If a greater (e.g., 5X) transect density was available, then more advanced distributions of the input variables across more transects could be used in the model to better describe short-term retreat rate variability. Similarly, a longer observation window than the 8-year window used in this study could help to better identify small amounts of annual retreat because they get summed over the longer time window. Currently, small amounts of retreat on some transects were probably not detected in what was originally perceived to be a sufficiently large time window with which to model.

Other potential limitations relate to groundwater flux and to assumed independence of retreat amounts between transects. Groundwater flux, initially suspected to be an important variable driving bluff retreat, resulted in a less robust Bayesian Network model when it was included as an input variable (Table 3.2). While this initially suggests that groundwater flux was unimportant relative to other model variables, it may simply be a consequence of imperfect quantification of the groundwater flux through WECLC watersheds: this warrants further investigation in any subsequent modeling. There is significant variability in simulated future retreat between transects at all sites relative to the dimensions of typical bluff-failure events. Realistically, the simulated retreat at any given transect will rarely occur in isolation from nearby transects. Also, the larger the simulated failure event or total retreat at a transect, the more likely it is for a larger number of adjacent transects to be influenced. This is a phenomenon not considered in the Bayesian Network model, because interactions between transects are not directly examined. The 10-transect moving average used in Figs. 3.24, A3.29, and A3.34 is an attempt to circumvent this limitation but it remains a network model limitation.

The 10-year moving average approach to smooth the simulated retreat by transect circumvents another limitation of the Bayesian model in its current application: that ~zero-change transects will continue to illustrate ~zero change over decades and that major-change transects will continue to illustrate major change over those same decades. Prior research on bluff-retreat geometries by Zuzek at al. (2003) suggests that this scenario is unlikely to occur if bluff retreat follows a cyclical failure pattern over many decades.

A final potential limitation on the accuracy of simulated bluff retreat is that the simulations over 10 to 50 years can be undermined by unpredictable future changes in environmental conditions that are outside the bounds of variability that occurred during the 1938-2007 period used to build the model. For example, if lake level rises or falls at rates or magnitudes outside the bounds of historical lake level over the 1938-2007 period, the amount of wave attack at the bluff toe could be significantly different and thus affect future retreat such that it does not match the simulations. Similarly, littoral sediment supply from updrift in Ohio may change over the next several decades due to natural or artificial bypassing. This may lead to larger beach prisms along the WECLC, which would reduce the number of wave impact hours at the bluff toe and cause simulated and real future retreat to diverge.

The Bayesian Network model provides a more quantitative understanding of how the Lake Erie bluff system works along the WECLC and potentially along the entire PA bluff coast. Because bluff retreat is controlled by many factors with spatial and temporal variation and internal feedbacks, simulated future crest positions, especially when multi-transect averaged, may provide more useful results than simple forward projection of the long-term average annual retreat rate. This Bayesian approach to predicting future crest locations is statistically stronger than the common practice of solely using long-term retreat rates to predict future crest location: the R^2 value for a model considered during the model-selection phase that predicted 2007-2015 retreat using the study's long-term retreat rate was just 0.02, almost zero predictive power.

Given that the Bayesian Network model has certain limitations as a forward-predictor of bluff-crest location, it is nevertheless valuable because it highlights the relative roles of the many environmental drivers involved in bluff retreat. It also highlights the most important variables that would be valuable for stakeholders to informally monitor as they consider moving to, or remaining on, a lakefront lot on the bluff top (Table 3.3): long-term retreat rate, inversely correlated with bluff stability; bluff-face slope, inversely correlated with bluff stability; toe elevation, positively correlated with bluff stability; and beach volume, positively correlated with bluff stability.

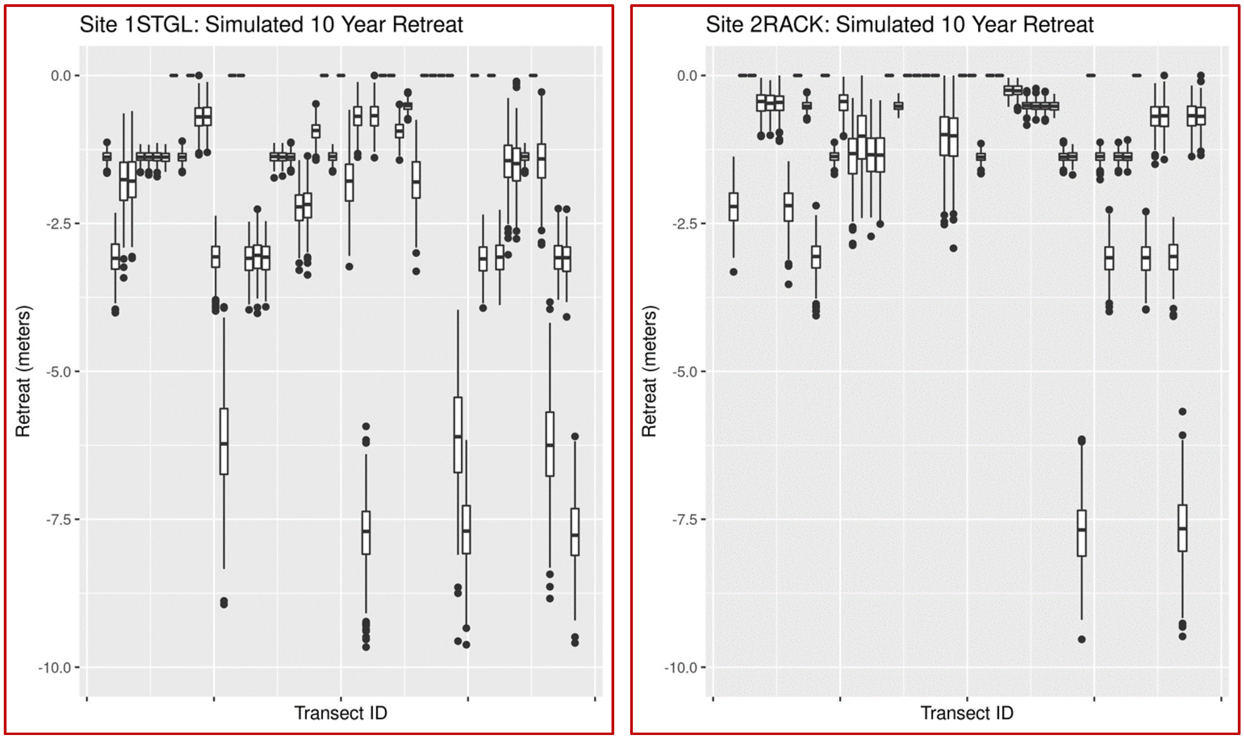


***Figure A3.25**: Simulated 10-year bluff retreat at WECLC Site 1STGL (left) and Site 2RACK (right) in the Turkey Creek watershed. See text for key.*

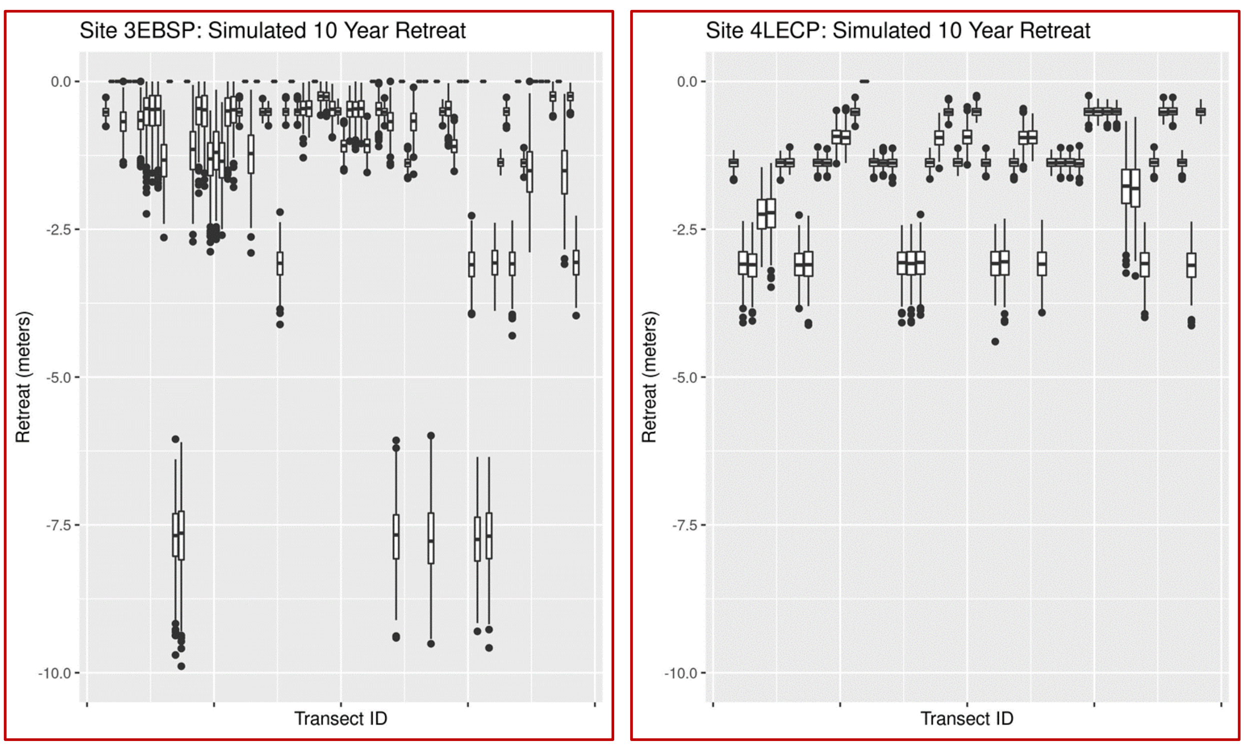


***Figure A3.26**: Simulated 10-year bluff retreat at WECLC Site 3EBSP (left) and Site 4LECP (right) in the Crooked Creek and Trout Run watersheds, respectively. See text for key.*

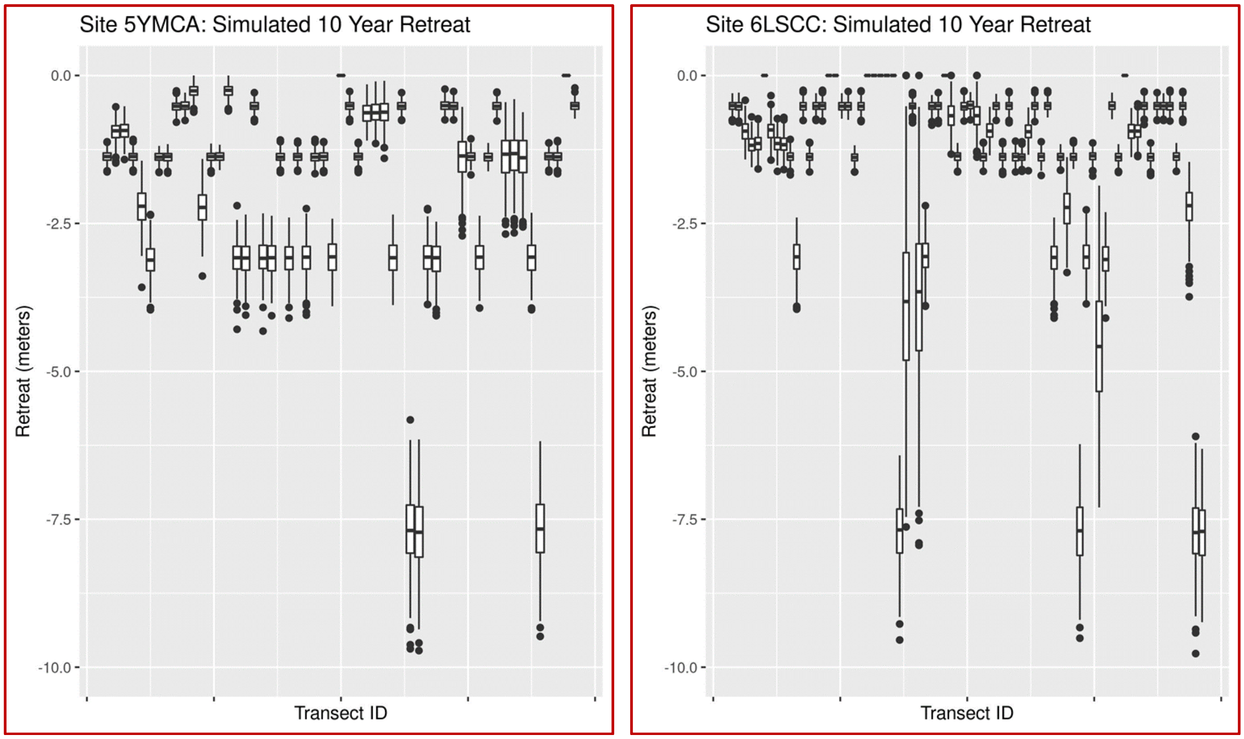


Figure A3.27: *Simulated 10-year bluff retreat at WECLC Site 5YMCA (left) and Site 6LSCC (right) in the Trout Run and Walnut Creek/Mill Creek-West watersheds, respectively. See text for key.*

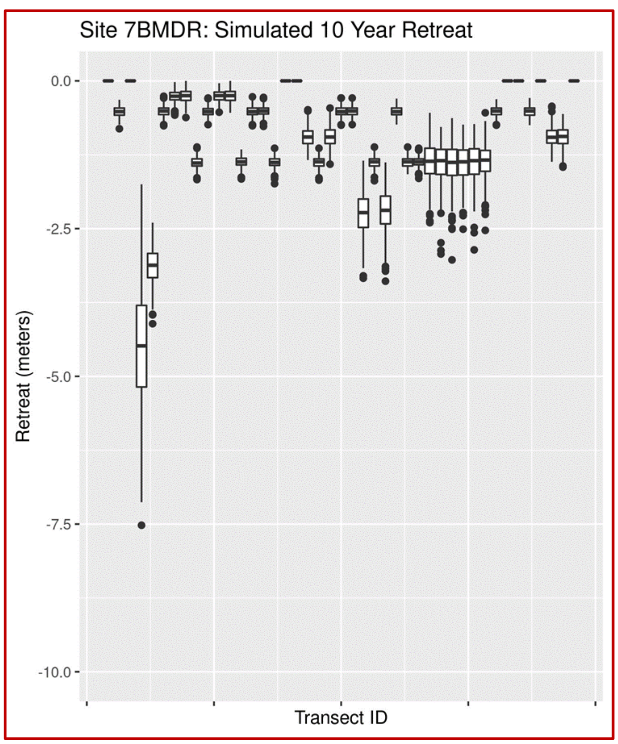


Figure A3.28: *Simulated 10-year bluff retreat at WECLC Site 7BMDR in the Mill Creek-West watershed. See text for key.*

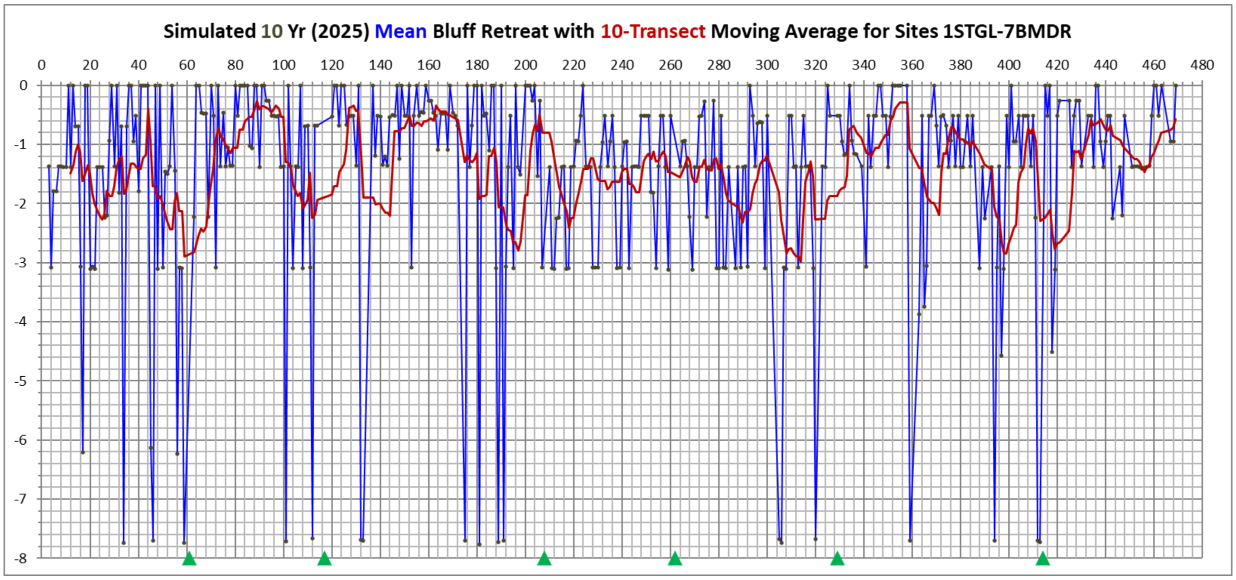


Figure A3.29: *Simulated mean retreat (meters) and 10-transect moving-average by DSAS transect for 10 years of bluff retreat at WECLC Sites 1STGL to 7BMDR (gaps between sites are not shown). WECLC site boundaries are indicated by green triangles on the x-axis. If this plot is "birds-eye viewed" as an east-west map with Lake Erie at the top, the scale of crest retreat appears dramatic because the retreat (y) axis is exaggerated ~500X.*

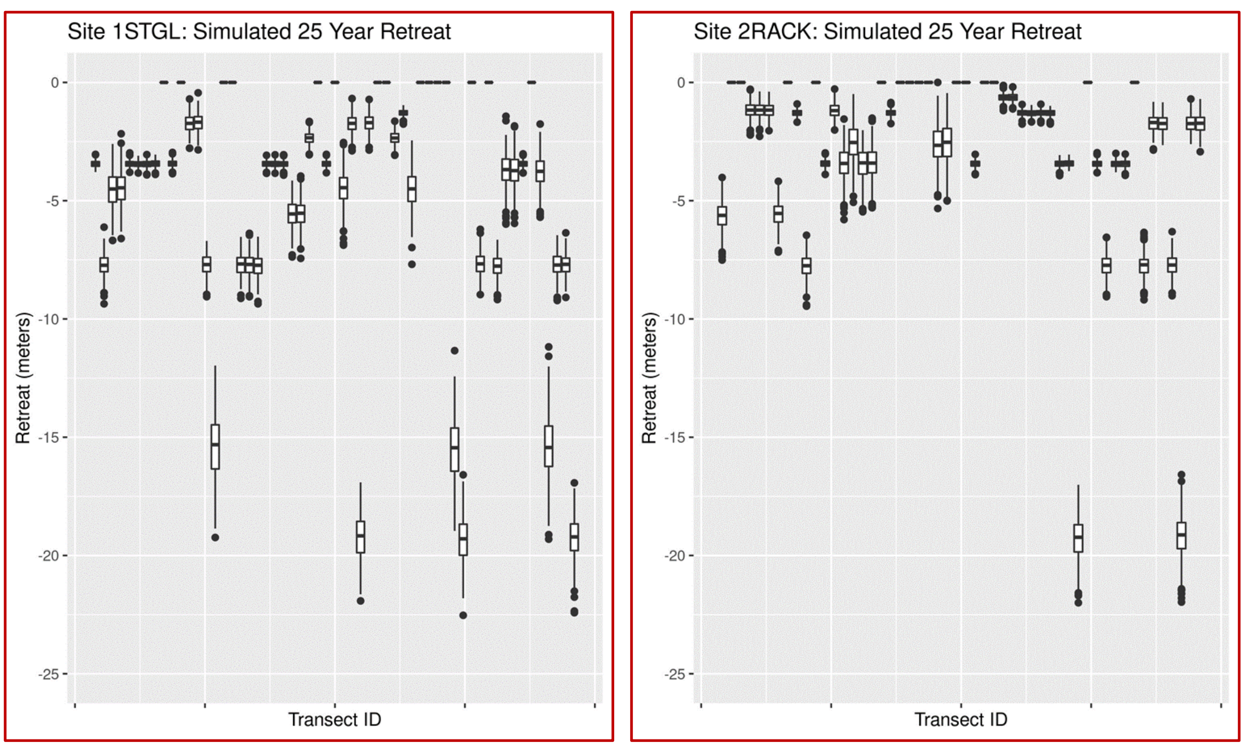


Figure A3.30: *Simulated 25-year bluff retreat at WECLC Site 1STGL (left) and Site 2RACK (right) in the Turkey Creek watershed. See text for key.*

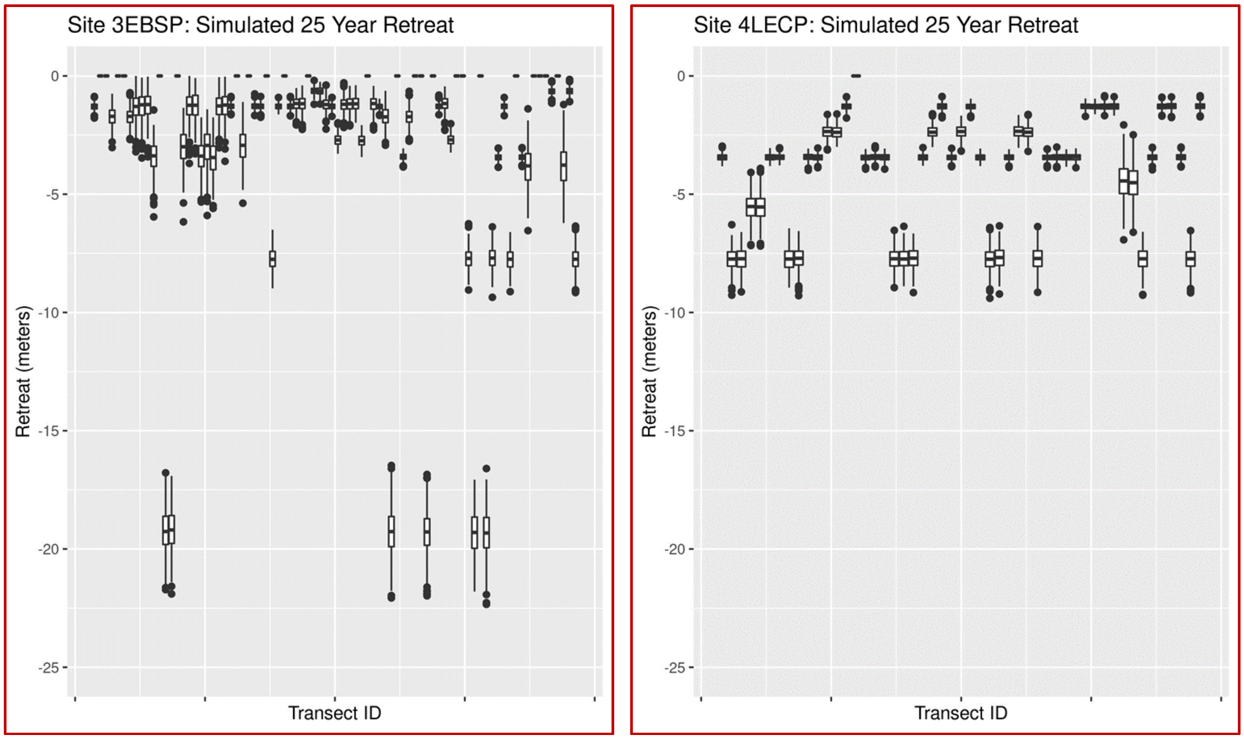


Figure A3.31: *Simulated 25-year bluff retreat at WECLC Site 3EBSP (left) and Site 4LECP (right) in the Crooked Creek and Trout Run watersheds, respectively. See text for key.*

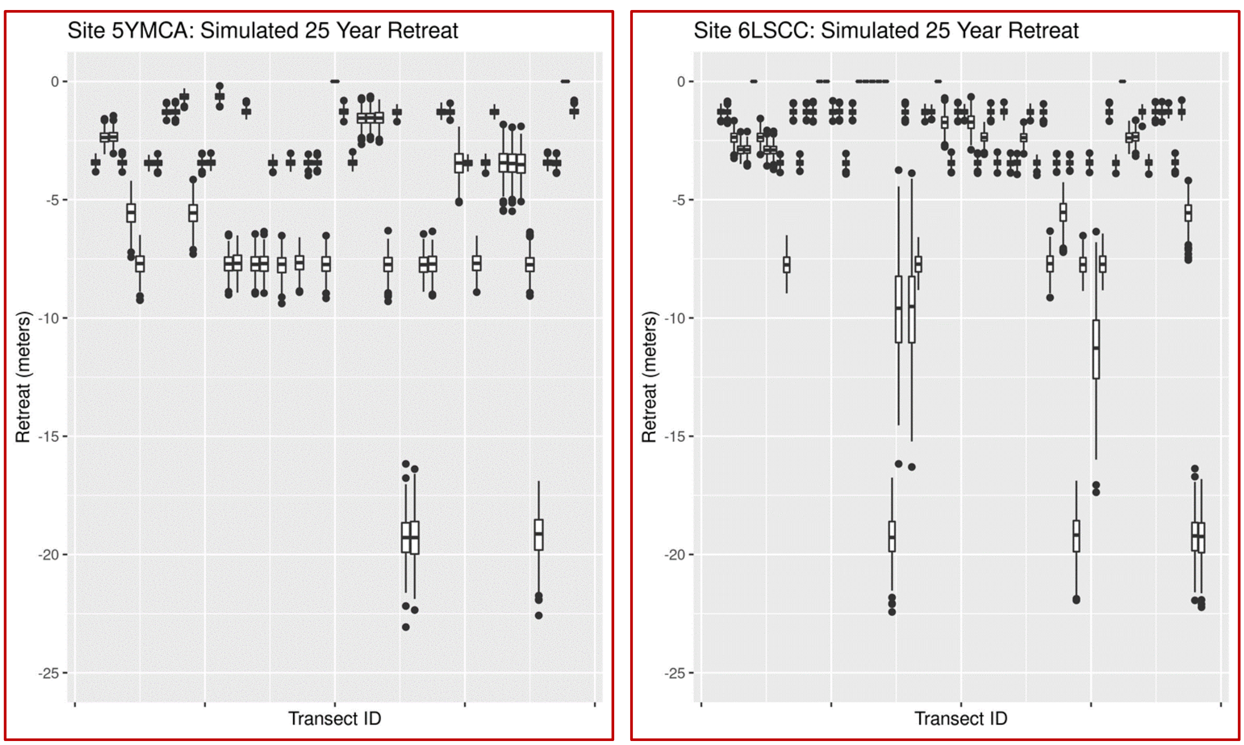


Figure A3.32: *Simulated 25-year bluff retreat at WECLC Site 5YMCA (left) and Site 6LSCC (right) in the Trout Run and Walnut Creek/Mill Creek-West watersheds, respectively. See text for key.*

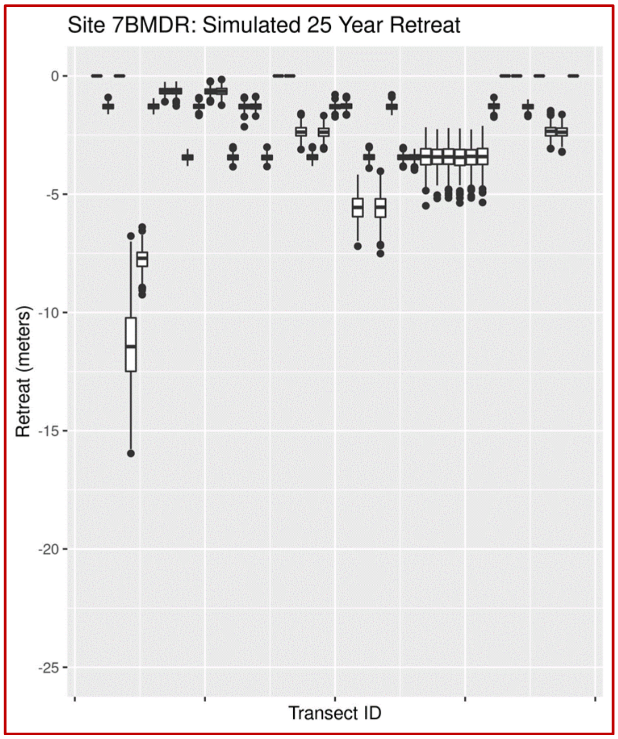


Figure A3.33: *Simulated 25-year bluff retreat at WECLC Site 7BMDR in the Mill Creek-West watershed. See text for key.*

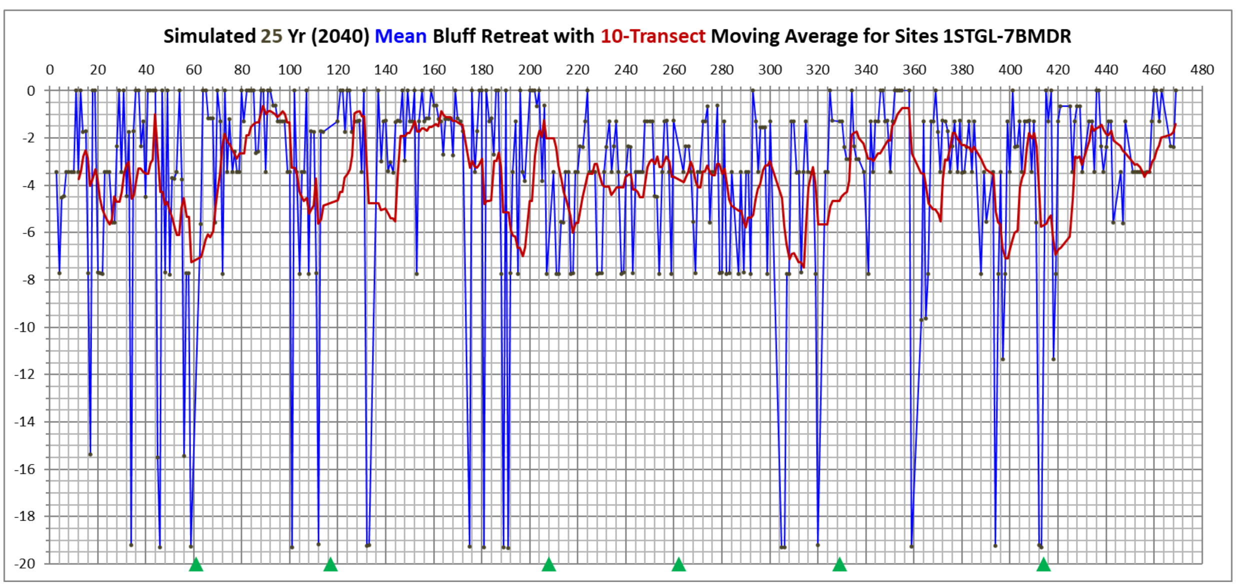
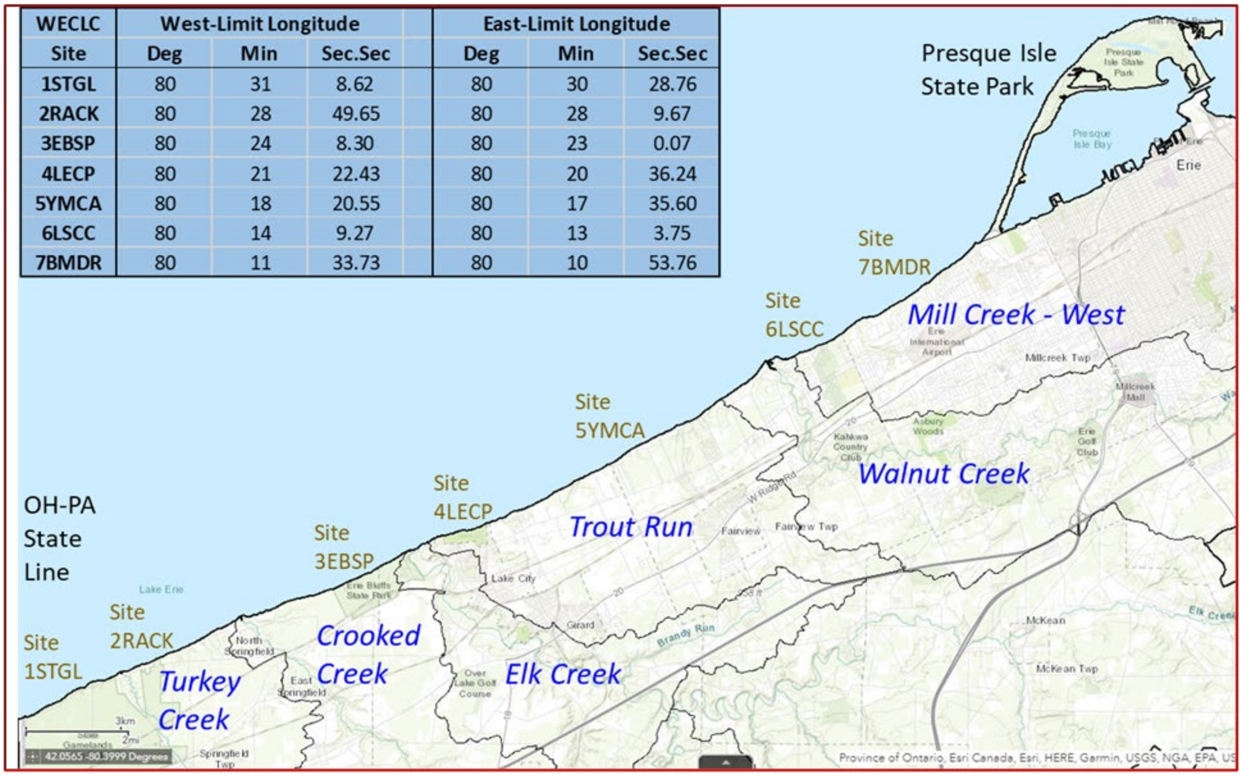


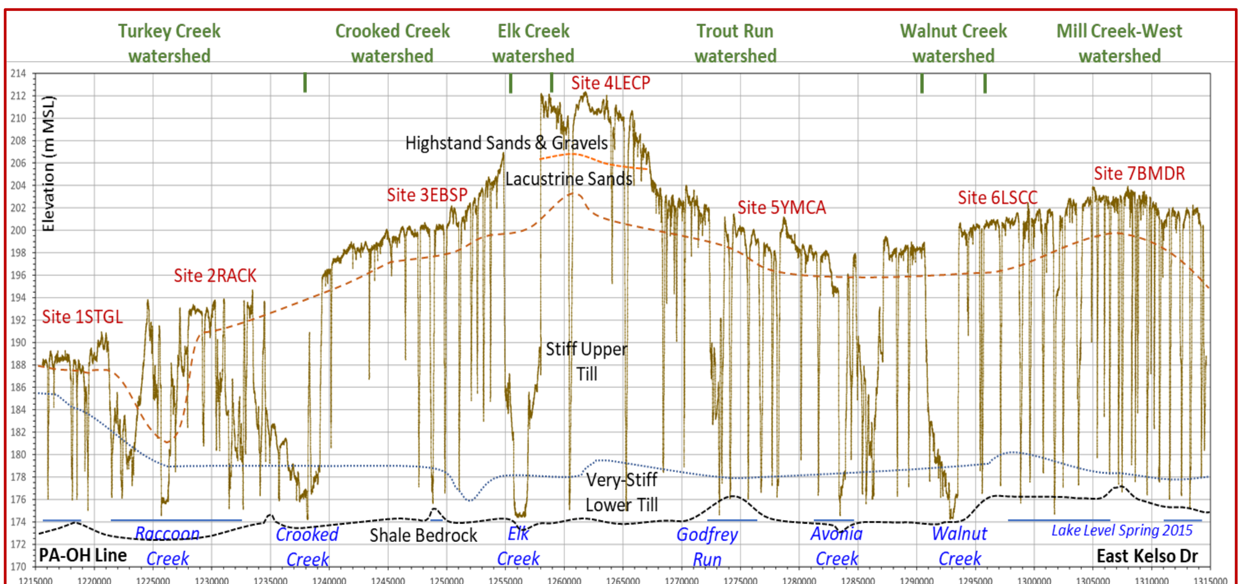
Figure A3.34: *Simulated mean retreat (meters) and 10-transect moving-average by DSAS transect for 25 years of bluff retreat at WECLC Sites 1STGL to 7BMDR (gaps between sites are not shown). WECLC site boundaries are indicated by green triangles on the x-axis. If this plot is "birds-eye viewed" as an east-west map with Lake Erie at the top, the scale of crest retreat appears dramatic because the retreat (y) axis is exaggerated ~250X.*

4 Bluff Contributions to the Littoral Sediment Budget



WECLC Site	West-Limit Longitude			East-Limit Longitude		
	Deg	Min	Sec.Sec	Deg	Min	Sec.Sec
1STGL	80	31	8.62	80	30	28.76
2RACK	80	28	49.65	80	28	9.67
3EBSP	80	24	8.30	80	23	0.07
4LECP	80	21	22.43	80	20	36.24
5YMCA	80	18	20.55	80	17	35.60
6LSCC	80	14	9.27	80	13	3.75
7BMDR	80	11	33.73	80	10	53.76

***Figure 4.1**: Location map of the WECLC littoral cell. Scale bar is ~3 km in length. (Image: pawalter.psu.edu)*



PA State Plane (ft): Coastal orientation N66E projected to N90E with view to North. Spring 2015 lake level = 174.25 m MSL. VE ~ 250X.

***Figure 4.2:** Northward looking topographic cross-section of the WECLC coast showing bluff-crest elevations, major creeks and minor ravines, generalized stratigraphy, lakefront extent of HUC-12 watersheds, and study sites (1STGL-7BMDR) used in Bayesian analysis. (crest mapped using a 0.6 m sampling interval on 2015 lidar).*

Introduction

The bluff sediment-input analysis uses the seven field sites used in the Bayesian modelling of bluff retreat (Sites 1STGL-7BMDR; Chapter 3) as well as inter-site coastal areas to cover all 33.5 km of the WECLC coastline (Figs. 4.1, 4.2). Sediment volumes lost from the bluffs, or stored temporarily on the mid and lower bluff, and bluff-failure mechanisms and patterns were derived from comparison of 2007 and 2015 lidar DEMs available from the Pennsylvania Spatial Data Access portal (pasda.psu.edu, 2020). A GIS approach using ArcGIS (Esri.com), LP360 (GeoCue.com), and DSAS (Digital Shoreline Analysis System; Thieler et al., 2009) allowed estimation of total (all grain sizes) and littoral (sand size and coarser) sediment volumes released to Lake Erie under the modern era's transgressive lake-level conditions.

GIS was used to analyze lidar data from 2007 and 2015 to obtain bluff-crest and bluff-face location, geometry, and spatial change information for the sediment budget analysis described here. These data-years were chosen because they are two of the better lidar datasets available and because Lake Erie is currently in a transgressive phase, like it has been (overall) during the 1938-2015 period (NOAA Great Lakes Water Level Dashboard, 2020). The lidar data used for this sediment budget analysis were collected along the Lake Erie coast between Ohio and New York during 2006-2008 and 2015 (pasda.psu.edu). By nature, lidar yields a high-accuracy (~20 cm vertical accuracy at the 95% confidence level), high-resolution digital elevation model of the ground, thus providing detailed information about watersheds, topography, and vegetation that may influence the potential for bluff sediment loss. Digital raster elevation models were created from the native lidar point clouds and GIS spatial analysis tools (ArcGIS, DSAS, LP360) were then used to compute differences between elevation models (change detection analyses). For the three-dimensional data used, needed volumetric computations, hydro-flattening, hydro-enforcement, and profile and transect generation were performed in ArcGIS using third-party extensions (DSAS, LP360). An online version of the small-scale surface-difference maps reviewed below shows bluff-face changes in greater detail and is viewable at:
https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

From the online map in particular, it is immediately apparent that the greatest sediment losses from the WECLC bluff face occur within the Crooked Creek watershed west of Elk Creek (Fig. 4.1). Volumetric losses at the high end of the surface-differencing scale, of 10-30 ft^3 per square meter (cell), are much more prevalent on the bluff face of this watershed than they are in any of the other five watersheds. The majority of sediment loss appears to be from the top (landward) half of the bluff, indicating a decline in bluff slope over the 8-yr observation period that may result in reduced crest-retreat rates in the future. These and other observations are discussed below on a watershed-by-watershed basis.

Bluff Sediment Gains, Losses, and Contributions to the Littoral Zone

On a global basis, unconsolidated bluffs on ocean, lake, and bay coasts, from Pacifica (CA) to the Chesapeake Bay, MD, are either in a state of temporary stability or in a state of erosion (Foyle, 2018). The presence of a bluff-like geometry on a coastline is indicative of erosional geologic processes, whether that geometry is at the scale of a storm-event 0.25 m beach scarp cut by waves on the Outer Banks of North Carolina, or at the scale of the ~210 m rocky Cliffs of Moher on the Atlantic coast of Europe.

There are no natural processes that allow bluffs to recover sediment they have lost via subaerial erosion (driven by groundwater discharge and surface runoff) or "marine" erosion (caused by wave and ice attack). This irreversible-erosion characteristic is very different from sandy beach coasts that often gain sediment during calmer-sea summer months and lose sediment during stormy-sea winter months. A second principal difference between sandy-coast beaches and silty-clayey bluff coasts is that typically 60% or more of the material lost from a bluff on the Lake Erie coast is so fine grained that it is quickly transported and deposited offshore beyond the reach of wave resuspension. Thus, it cannot be returned, tank-tread fashion, to the bluff as normally happens on sandy beaches during summer months. The sand and gravel component of a bluff, typically <30% of the sediment mass, may be transported downdrift in the littoral system, or returned to the base of the bluff to build a wider beach, but cannot be transported vertically to repair (refill) an eroded bluff face or allow the crest to prograde lakeward to its former location.

Bluffs do not gain sediment on the bluff face, nor experience crest progradation, unless there has been human intervention associated typically with landscape fill, cut and fill for trails and roadways, near-crest elevation lowering, and building construction. This apparent sediment gain most commonly occurs in association with development at the bluff crest and occasionally on the bluff face (Fig. 4.3). Other unique patterns of accretion on the bluff face, typically of limited dimension with a strong linear or curvilinear fabric, commonly occur (Fig. 4.3). These are the result of processes such as deposition of material eroded from higher on the bluff face, or from the crest, that slides to a lower elevation on the face where it may accumulate temporarily (months to decades). Apparent sediment accretion may also be due to vertical-upward movement of part of the bluff face when a rotational slump geometrically results in localized elevation gain on the downslope end of its curvilinear failure plane. Bluffs may gain material at the toe due to arrival of material lost from higher on the bluff, from beach accretion that covers the bluff toe, or from coastal engineering efforts.

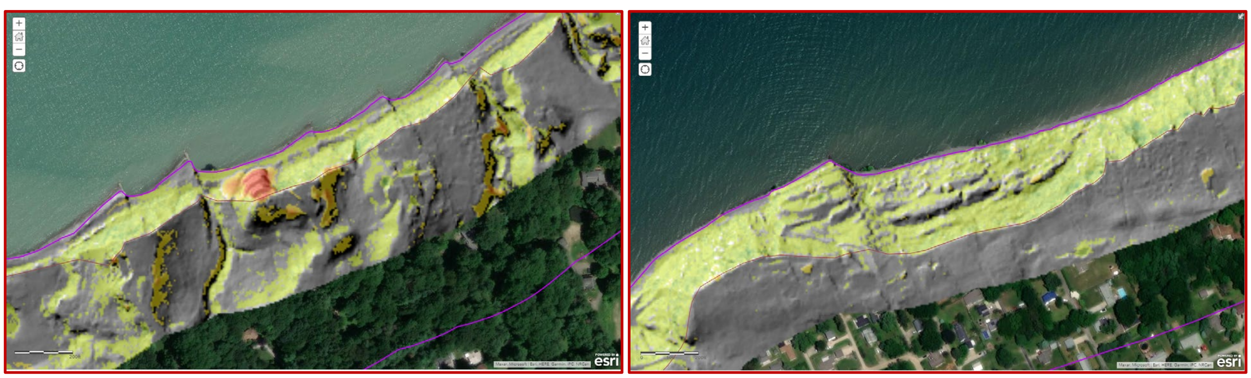


Figure 4.3*: Bluff-face changes in the Trout Run watershed. Left: Apparent accretion on the bluff face due to home construction and lot improvements east of Avonia Creek. Terracotta-colored arcuate pattern reflects meters of anthropogenic elevation gain on and lakeward of the bluff crest. Right: Curvilinear bluff-face topographic patterns due to temporary storage of slump material on the bluff face and buckling of the bluff face associated with rotation along a large translational slide just east of Lake Erie Community Park. (see Figure 4.4 for figure key; scale bar is ~60 m (200 ft) in length)*

Surface Differencing Methodology (Elevation-Change Map)

A surface-differencing procedure from which bluff-face erosion and accretion patterns were identified, and sediment gain and loss volumes estimated, was completed for the bluff face in each of the six HUC-12 watersheds within the WECLC using lidar data sets from 2007 and 2015. The volumetric analysis procedure involved use of ESRI ArcGIS Pro (Esri.com), the ArcGIS extension DSAS (Thieler et al., 2009) that permits transect generation and analysis, and the ArcGIS extension

LP360 (GeoCue.com) that permits lidar and photogrammetric point-cloud processing of large geospatial datasets.

Raster DEMs at 3.281 ft (1 m) resolution were produced from the 2007 and 2015 lidar point datasets using only points classified as bare-earth and applying IDW interpolation in LP360. The same grid was used for both datasets despite differences in nominal point spacing to facilitate raster differencing. The 2007 DEM was subtracted from the 2015 DEM to produce a raster of elevation change over the 8-year time period. The resulting difference rasters were clipped at the bluff toe and bluff crest, as described below.

The difference raster was initially a seamless product extending along the entire WECLC coast. HUC-12 watershed boundaries obtained from pawalter.psu.edu were then used to clip the difference raster to the six watersheds. This allowed watershed-based computation of sediment gains and losses on the bluff face. The elevation-difference raster values were then multiplied by cell area (~1 m^2; or ~10.76 ft^2) to produce volumes. All positive changes were aggregated as gain; all negative changes were aggregated as loss. Zonal statistics were calculated in ArcGIS Pro to produce the gain, loss, and net-volume changes for each watershed. Because GIS map work used the State Plane coordinate system, elevation (ft), distance (ft) and volume (ft^3) map data were subsequently converted to metric units in Chapter 4 tables and text for comparison with DSAS-derived data; however, maps and sections retain non-metric units.

Surface Differencing Data Needs

2015 DEM

Because the bluff crest along the WECLC is either stable or retreats erratically over time, the landward limit of bluff-face volumetric change analysis was picked as the 2015 bluff crest as mapped from the 2015 DEM. In some areas, the 2015 crest occurred at the same location as the 2007 crest, indicating that local erosion did not occur on the uppermost bluff in these areas over the eight-year timeframe. The 2015 lidar data, collected in April 2015 and available from Pennsylvania Spatial Data Access (pasda.psu.edu), was used to produce a DEM. Vertical accuracy was ±9.1 cm RMSE, equivalent to ±17.8 cm at the 95% confidence level. The vertical accuracy in vegetated areas was not stated in the metadata. The horizontal accuracy was ±0.18 m RMSE (±0.36 m at the 95% confidence level) and meets the requirements of NSSDA at the 95% confidence level (1.96 x RMSE). Lidar flight lines were flown with a nominal average lidar point spacing of 0.7 m, while the DEM had an ~1 m (~3.2 ft) spacing between points.

2015 Bluff Crest

The location and elevation attributes for the 2015 bluff crest were mapped from the 2015 DEM using the following procedures for (i) the Bayesian study sites (Sites 1STGL to 7BMDR; ~10 km in total length) and (ii) the intervening WECLC bluff regions (~23 km in total length).

The bluff crest was identified from the 1-meter resolution bare-earth DEMs produced using IDW interpolation in LP360, as described in Chapter 3. From the DEM, a 2015 bluff-slope map was produced in ArcGIS Pro. Visual inspection indicated that the bluff face was commonly characterized by a sharp break in slope at both the crest and toe. A slope of 18^0 or greater was empirically determined to represent the bluff face. The break from flat or gently sloping (<18^0) terrain landward of the crest to steeper slopes (>18^0) on the bluff face was delineated as the bluff crest. A raster polygon was then used to enclose areas where slopes were greater than or equal to 18^0. This was then edited, and the polygon separated into crest and toe line features. The crest-line feature was then used with DSAS to estimate bluff retreat when compared with the 2007 crest location, and to mark the landward limit of bluff-face surface differencing. The 2015 toe line feature was used with DSAS primarily to derive additional bluff-face slope and beach-prism width/thickness values as part of the Bayesian modeling (Chapter 3).

For the inter-site coastal reaches, the 2015 bluff crest was manually digitized on-screen and edited at 1:1200 scale. The crest in these inter-site reaches may be offset as much as ±0.75 mm (at map scale; or ±0.9 m real-world distance) from the difference-map edge at 1:1200 screen scale. The goal in these inter-site areas was to accurately capture bluff-face change, and to map bluff-crest location as a means to delimit the landward extent of that change. As a result, the accuracy of the bluff-crest mapping in these inter-site areas may be somewhat less than that within the seven Bayesian-study sites (Sites 1STGL through 7BMDR; Chapter 3). The bluff crest was in general digitized on-screen every ~10-40 m using the 18^0 slope criterion described above. This was supplemented if needed using the line where the sunlit hillshade swath denoting the bluff face (apparent sun to northwest) transitioned to the darker swath denoting the flatter coastal plateau just inland. Given that the horizontal error for the 2015 DEM was ±0.18 m RMSE, the resultant positional error for the 2015 crest, when these two uncertainties were summed in quadrature, was ±0.9 m in these inter-site areas. This level of accuracy was comparable to or better than prior work on the Lake Erie coast (WCR, Inc., 2004; Hapke et al., 2009; Foyle, 2014).

2007 DEM

The 2007 lidar dataset was used to identify the lakeward extent of the surface-difference map coverage at the bluff toe. Available from Pennsylvania Spatial Data Access (pasda.psu.edu), the 2007 lidar was produced to meet a vertical accuracy of ±18.5 cm or better RMSE specification for PAMAP in clear bare-earth areas. The ±18.5 cm RMSE is equivalent to an accuracy of ±36 cm (at the 95% confidence level). In vegetated areas, the vertical accuracy was ±72.5 cm (at the 95% confidence interval). In both cases, the vertical accuracy meets the requirements of NSSDA at the 95% confidence interval (1.96 x RMSE). The 2007 data had a horizontal accuracy of ±0.77 m RMSE (±1.52 m at the 95% confidence level). Lidar flight lines were flown with a nominal average lidar point spacing of 1.4m, while the DEM had an ~1 m (3.2 ft) horizontal ground resolution.

2007 Bluff Crest

Mapping of the 2007 bluff crest followed the same general procedure as that outlined above for the 2015 bluff crest.

2007 Bluff Toe

The 2007-2015 surface-difference map was clipped at its lakeward edge to include only the bluff face landward of the 2007 bluff toe. This entailed using a bluff toe elevation of 175.23 m to exclude sediment-volume changes on the beach (backshore) below that elevation. Located ~1 m above Spring 2015 lake level, this elevation was derived by averaging bluff-toe elevations that were field-surveyed at several locations within each of Sites 1STGL through 7BMDR during 2018. This cut-off elevation was used in preference to that derived from lidar, which yielded a higher average toe elevation of 175.58 m. The latter cut-off elevation was perceived to be less ideal because the bluff face just above the toe of the bluff may not always have been intercepted by lidar ground strikes because of near-vertical slopes in some areas. The bluff-toe elevation from the DEM (175.58 m) could therefore over-estimate the toe elevation and be less desirable as a cut-off datum. The clipping procedure, using the 2007 and 2015 DEM surfaces clipped at the 175.23 m toe elevation and the (variable-height) crest of the bluff, respectively, permitted capture of the majority of bluff-face change between the toe and crest. Minor accretion that may have occurred below and lakeward of the 175.23 m datum's intercept with the 2007 DEM may not have been completely captured using this procedure. Such limited accretion can occur due to temporary accumulation of slump material on the backshore in areas where the beach prism is small.

2007-2015 Surface-Difference Raster Map

Beyond the bluff-crest and bluff-toe delineation, additional localized clipping of the difference map was completed to remove (i) anomalous artifacts such as apparent sediment gain due to construction and landscape modifications on the bluff face (Fig. 4.3), (ii) volume changes within ravines that traverse the bluff crest, and (iii) bluff-face volume changes in areas where wide creek floodplains, coastal progradation, residential development at the toe of the bluff, or marina facilities separated the bluff from the littoral zone. In the latter situation, material lost from the bluff face would not be supplied to Lake Erie for many decades. Examples of areas where this was most notable occurred at Crooked Creek and Avonia Creek (progradation and floodplains; Fig. 4.4), Walnut Creek (marina and floodplain), Pittsburgh Avenue (historical bluff-toe community), and at East Kelso Drive (wide strandplain updrift of the WECLC's terminal groyne).

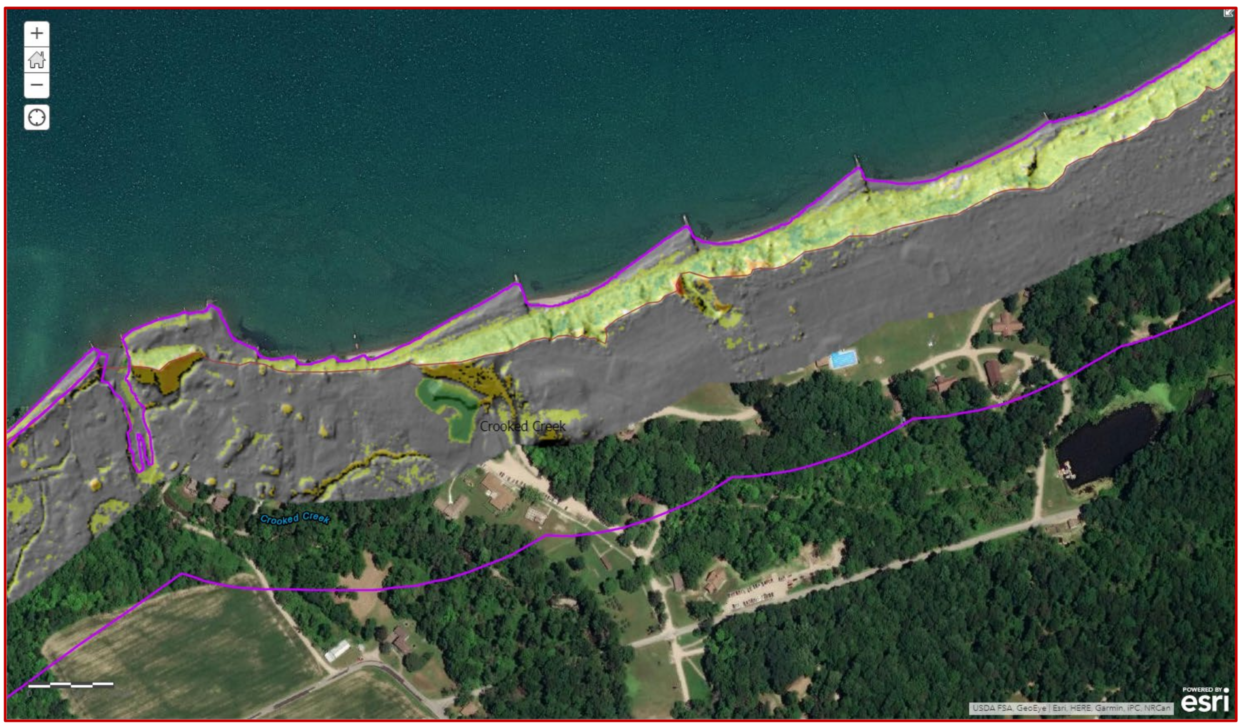


Figure 4.4: *Clipped section of the 2015 raster DEM hillshade from the western part of the WECLC at Crooked Creek and YMCA Camp Fitch. The DEM is overlain by the color elevation-difference raster map for the bluff face, and it is underlain by recent aerial imagery. Elevation changes on the bluff face (sediment gains and losses between 2007 and 2015) are shown as a colored swath bounded by the 2015 bluff crest (thin brown line) and the toe of the bluff that lies at an average elevation of 175.23 m (~1 m above Spring 2015 lake level). Darker colors on the bluff face indicate more erosion, lighter colors less. Bluff-face topography and spatial patterns in erosion severity can be seen at larger (zoomed-in) scales. The purple line marks the clipped coastal edge of the Crooked Creek HUC-12 watershed. Scale bar is ~90 m (300 ft) in length.*

Each data point on the difference raster map had a vertical isopach (elevation change) value that reflected the vertical separation between the 2007 and 2015 DEM surfaces at that location. GIS was used to integrate the vertical elevation change (Z) for all sample points with the bluff-face slope area associated with each to tally the volume of erosion and accretion over the entire bluff face for the eight-year time interval. The net difference between the erosion value (larger) and the accretion value (smaller) was then calculated and reflected the net volume of total sediment (all grain sizes) contributed to the littoral zone, both over the 2007-2015 time period and on an average-annual basis. The average bluff-face stratal composition for each HUC-12 watershed was then used to subdivide the whole-face volume change for a watershed into sub-volumes associated with each of one to five stratal units present (shale bedrock to paleo-strandplain sands and gravels). This allowed each stratigraphic unit's total sediment contribution to be resolved into clay-plus-silt and sand-to-boulder components (discussed below).

Given that the DEM surfaces have vertical uncertainties of ±18.5 cm RMSE (2007) and ±9.1 cm RMSE (2015), respectively, the propagation of those uncertainties in the surface-differencing result (elevation change) can be estimated. The error for each DEM-surface was summed in quadrature, so that the uncertainty in the result (elevation change at a point) was equal to the square root of the sum of the squares of the errors in the DEM elevations being subtracted. The vertical uncertainty for the 2007-2015 difference map was thus ±0.2 m. The resultant volume uncertainties were subsequently estimated by multiplying the ±0.2 m uncertainty by the area of the WECLC bluff face. To illustrate patterns of bluff-face change and associated volume changes in figures and online maps, color-coded elevation-change data bins were used.

Benefits of Surface-Difference Mapping in GIS

The *surface-difference* (isopach or elevation-change) map approach used in this report to estimate changes in bluff-face topography and volumes over time uses high-density point sampling across the entire bluff face. It differs from the *crest retreat-times-surface-area* or *profile-integration* method typically employed on the Lake Erie coast. For example, prior sediment budgeting by Jones and Hanover (2014) for parts of the Ohio coast, by the US Army Corps of Engineers (Morang et al., 2011; Cross et al., 2016) in a basin-wide Lake Erie sediment study, and by Knuth (2001) on the Pennsylvania coast, used this latter approach. The *surface-difference* approach in this project is similar to that used, for example, by the U.S. Geological Survey for a major landslide sediment-supply study in the Monterey Bay National Marine Sanctuary on the California coast (Hapke, 2005). Effectively, surface differencing is the equivalent of isopach-map generation that is commonly used across the geosciences (e.g., Foyle et al., 1999).

The *surface-difference* approach is advantageous in areas where the bluff does not retreat with an assumed "slab" geometry from toe to crest. While bluffs conceptually follow such a parallel-retreat geometry over time scales of decades to centuries (Zuzek et al., 2003; Foyle, 2018), this geometry is rare at year to decade time scales unless the stratigraphic make-up of the bluff favors linear slab failure (or tabular debris slides) that extend from toe to crest. Such failure modes are favored where internal bluff stratigraphy has a face-parallel geometry, stratal units are individually cohesive, and sloped bedding planes are failure surfaces (Fig. 4.5). This is not the case for the near-horizontally layered bluffs on the WECLC coast, where some parts of the bluff fail while others do not or do so to a different degree. There is temporary storage of some of the slumped material on the slope immediately below the failure zone, often lower on the bluff face nearer the bluff toe, on the adjacent backshore, or in the surf zone if a beach is absent. Considering geometries further, active toe retreat may steepen the lower bluff face while not having any immediate impact on crest retreat. Similarly, groundwater discharge may induce failure on the mid and upper bluff with no mappable change on the lower bluff but with notable crest retreat. Consequently, at the time scales of this project, the slab failure mode is very unlikely to occur. Instead, there are irregular wedge-shaped (at translational slides) or spoon-shaped (at rotational slumps) failures that do not necessarily occupy the entire bluff profile from top to bottom. The surface-differencing approach is well suited to capturing the volume changes associated with these non-planar and spatially variable failures prevalent on the layered WECLC bluffs.

The *surface-difference* approach is also useful when different bluff lithologies exist because a cubic meter of sediment lost can, given stratigraphic complexity, be associated with a specific lithology that has a sand-to-boulder (i.e., *"sand+"*) grain size distribution that is different from other stratigraphic layers. The approach also allows for continuous areal data coverage (despite some limitations in lidar coverage) rather than relying on identifying crest changes at transects spaced at 20-1000 meter intervals along a coastline. The bluff sediment input estimates to the Lake Erie littoral zone from Cross et al. (2016), and from Jones and Hanover (2014; eastern Ohio) and Knuth (2001; western Pennsylvania) all assumed simple parallel bluff retreat over multi-year observation periods and used the *crest retreat-times-surface-area* (*profile-integration*) method. While this assumption of parallel retreat is applicable for many bluff morphologies over long timescales, it can lead to overestimates of bluff sediment supply to the WECLC because slump material can be temporarily stored on the bluff, slump failures can be restricted to the lower bluff (wave-driven failures) or to the upper bluff (groundwater driven failures), and an erosion-resistant bedrock toe may prevent parallel retreat.

Figure 4.5*: Steeply-dipping tabular strata on ~30 m tall bluffs (cliffs) along the Atlantic coast of southwestern France near St. Jean de Luz. The bluffs follow a slab-failure mode due to the seaward slope of, and strong cohesion within, each stratal layer. One meter of bluff-crest retreat has a high probability of being accompanied by 1 m of retreat over the entire bluff face from crest to toe. The remains of a German WWII gun emplacement rest on the wide wave-cut platform. (Image: N. Osinski; google.com/maps)*

Sediment Contribution to the Littoral Zone

For each of six HUC-12 watersheds, and for the entire WECLC, the methodology used to calculate *total-sediment supply* and *sandy sediment supply* to the littoral zone (beach, surf zone, and nearshore) from eroding bluffs is described below. The sediment volumes are presented as volumes for the eight-year observation period, as annualized volumes, and as normalized volumes gained and lost per kilometer of lakefront and bluff crest over an average one-year time frame between 2007 and 2015.

Of the two sediment-volume metrics, *total-sediment supply* includes grain sizes that range from clay particles to boulders (diameters of 0.001 – 250+ mm). Because small sediment grains such as clays (diameters <0.004 mm) and silts (diameters <0.0625 mm) are sufficiently small to remain suspended in the water column for days to weeks, these grains are largely exported from the littoral zone for deposition in the open lake below wave base from where they cannot return to the coast. For example, clay particles would need about three weeks to settle through a 20 m column of still freshwater, about the average depth of Lake Erie. Because of this, and because of their ease of resuspension and renewed transport in shallow water, these sediments do not contribute significantly to beach sediment volumes on coasts in general. They may, however, be trapped to build wetland substrates and estuary-mouth floodplains, particularly on ocean (salt- or brackish-water) coasts. In these non-lake settings, salinity-induced flocculation and fecal-pellet formation convert dispersed grains into clumps that settle out of the water column faster. As a result, they are more likely to be deposited in the littoral system and are less prone to resuspension and removal once deposited. On the Lake Erie coast, flocculation is insignificant, and fecal-pellet formation is likely orders of magnitude less significant than in oceanic estuaries and coastal wetlands. On lake coasts, these fine-grained clays and silts are notable because they contribute to a temporary decrease in coastal water quality. This is visible as increased turbidity in the water column following storm events and periods of high-flow stream discharge, when suspended fine sediments can reduce water-column photosynthesis by restricting light penetration for hours to days.

For the above reasons, *sandy sediment* volumes are therefore used when calculating sediment gains and losses from the littoral zone for erosion mitigation, dredging, and resource-planning purposes. This *sand+* material is sufficiently coarse (grain diameters of 0.062 – 250+ mm) that it is deposited faster and therefore closer to shore, and it is less likely to be lost offshore during subsequent storm events. It is therefore the principal material that builds recreational beaches on most of the world's and Great Lakes coasts. On the world's coastlines, this sandy material is continuously recycled within the littoral system in water depths shallower than 10-20 m depending on coastal wave climate (depth of closure concept; Brutsché et al., 2016). Consequently, sediment lost from a beach during one season may be returned during the next or subsequent seasons. A fundamental difference between sediment cycling on bluff and sandy coasts is that sediment lost from bluffs cannot be returned by natural processes. This is because the fine sediments deposited offshore below wave base cannot be returned to the beach, nor can those temporarily in the nearshore and surf zone be transported back up the bluff face to their original locations. The same principle applies for sand-to-boulder sized materials: once lost from the bluff face, there is no natural process to return these materials to their former strata within the bluff.

Sediment Contribution to the WECLC by Individual HUC-12 Watershed

This section summarizes the gains, losses, and spatial-change patterns of sediment volumes moving on the WECLC bluffs between 2007 and 2015. The goals are to (i) document the recent-era quantities of sand and gravel supplied to the littoral system through bluff retreat, and (ii) identify spatial patterns of sediment loss from, and storage on, the bluff face. Understanding these aspects of bluff behavior can be useful in determining the relative importance of specific watersheds as host locations for *feeder bluffs* (Shipman et al., 2014) that play an important role as sediment sources for sand-poor littoral systems generally. Quantifying sediment volumes being supplied to the WECLC is also critical as context for understanding beach-erosion problems in the Presque Isle littoral cell immediately downdrift. On an average annual basis, WECLC bluffs contributed 39,800 m^3 of total-sediment and 13,250 m^3 of sand+ sediment to the littoral zone. The total-sediment volumes are ~77% lower than estimates of turn-of-century rates by Morang et al. (2011) and Cross et al. (2016).

The sand+ volumes are ~65% lower. The average annual sand+ yield was 430 m^3/bluff km/yr, comparable to turn-of-century yields estimated for the Ohio coast by Jones & Hanover (2014) and outlined in Chapter 2. Comparing watersheds, the greatest amounts of bluff-face elevation loss ranged from 1.0 m (Elk Creek) to 2.4 m (Walnut Creek). The greatest amount of elevation gain, due to sediment storage or bluff-toe deformation, ranged from 1.8 m (Walnut Creek) to 3.1 m (Trout Run). Volume losses on the bluff face were ~20 times greater than volume gains (Table 4.1).

Results are described for each of the WECLC's HUC-12 watersheds (Fig. 4.6), moving eastward along the coast. Volume changes for the six watersheds are summarized in Table 4.1 (total clay-boulders sediment) and Table 4.2 (sand-boulders sediment, or sand+). The sand+ volumes are derived by multiplying each watershed's total-sediment volume loss by the average sand+ content and the percent-area of each of one to five stratal units on the bluff face (Table 4.3). A larger-scale zoomable version of the surface-difference maps reviewed in this section is available online at:

https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

The online map is referenced extensively in the watershed descriptions that follow. Bluff-face changes are quoted in two forms: the online map uses tan to green color-coded bins to show total-sediment volume changes expressed in cubic feet per unit area (pixel, m^2) of bluff face. In the text, these units are converted to metric-unit elevation changes (m) by dividing the map's volume-change bin values by 35.32 ft^3/m^3. On all maps, darker colors denote greater change.

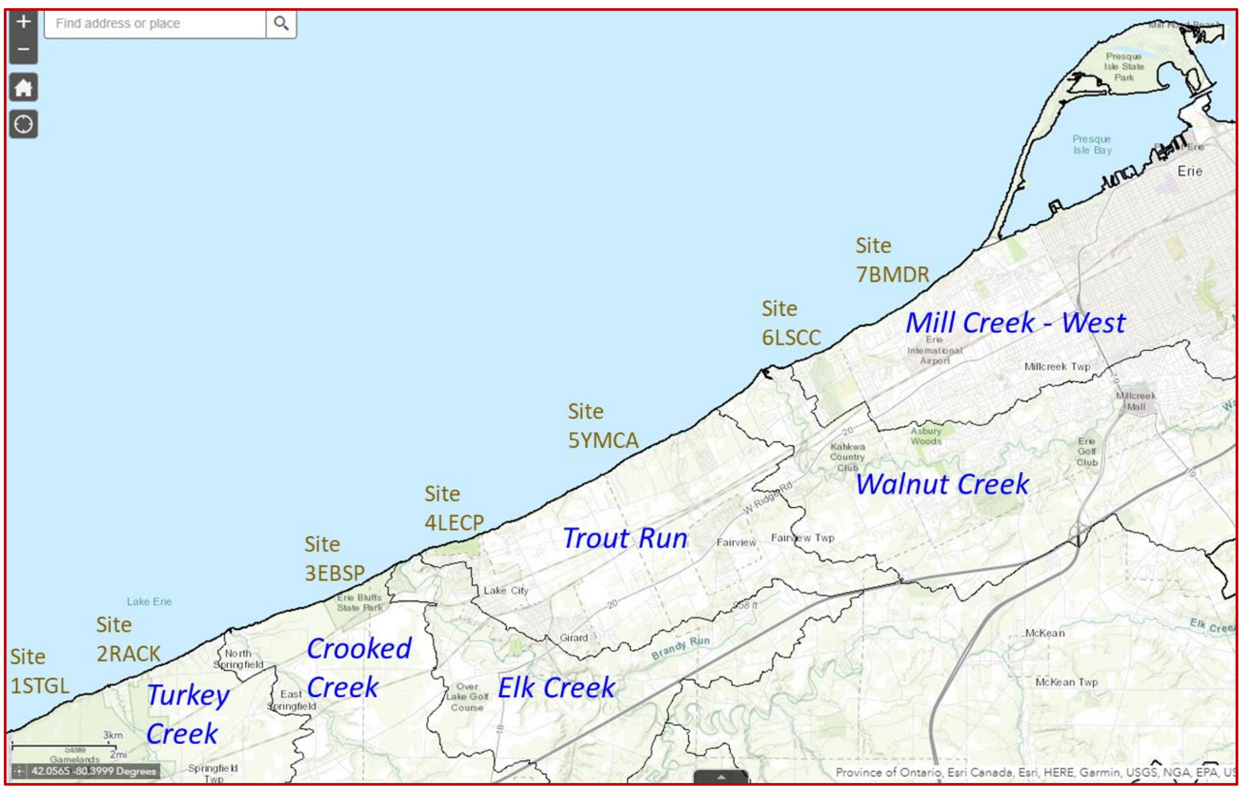


Figure 4.6: *Location map for the 33.5 km bluff coast in the western Erie County littoral cell (WECLC). The cell extends eastward from the OH-PA state line (small headland) to a large (terminal) groyne where the Presque Isle isthmus joins the mainland. The map shows the seven field sites used for Bayesian modeling (Chapter 3) and the six principal HUC-12 watersheds within this part of the Lake Erie watershed. The HUC-12 watersheds contain 97 smaller sub-watersheds (not shown). Bar scale is 3 km in length. (source: pawalter.psu.edu)*

Total-sediment volume gains, losses, and net change for the WECLC bluffs by HUC-12 watershed								
HUC-12 Watershed & Lakefront Length (km)	***8-Yr Gain*** *m³*	***8-Yr Loss*** *m³*	***8-Yr Net Change*** *m³*	***Annual Gain*** *m³/yr*	***Annual Loss*** *m³/yr*	***Annual Net*** *m³/yr*	***Volume Storage on bluff***	***Normalized* Bluff Change*** *m³/km/yr*
Turkey Creek 7.5	3,036	-43,995	-40,959	380	-5,499	-5,120	6.5%	**-683; -742**
Crooked Creek 5.9	1,999	-94,703	-92,704	250	-11,838	-11,588	2.1%	**-1,964; -2069**
Elk Creek 0.55	2	-618	-616	~0	-77	-77	0.3%	**-140; -1,027**
Trout Run 10.3	7,293	-115,053	-107,760	912	-14,382	-13,470	5.9%	**-1,308; -1327**
Walnut Creek 2.8	694	-15,421	-14,727	87	-1,928	-1,841	4.3%	**-658; -1151**
Mill Creek–West 6.8	2,966	-64,589	-61,623	371	-8,074	-7,703	4.4%	**-1,133; -1223**
WECLC Total			**-318,400**			**-39,800**		**-980; -1250**
*Normalized to cubic meters per lakefront kilometer per year; and to cubic meters per lakefront-bluff kilometer per year. Lakefront bluffs comprise 14% (Elk Creek) to 98.5% (Trout Run) of each watershed's total lakefront Bluff-face volume estimates are accurate to ±50% due to uncertainty in the DEM-differencing procedure								

Table 4.1*: Total-sediment volume changes for the WECLC Bluff Face by HUC-12 Watershed (2007-2015).*

Sand+ volume gains, losses, net and normalized change for the WECLC bluffs by HUC-12 watershed*							
HUC-12 Watershed & Lakefront Bluff Length (km)	***8-Yr Gain*** *m³*	***8-Yr Loss*** *m³*	***8-Yr Net Change*** *m³*	***Annual Gain*** *m³/yr*	***Annual Loss*** *m³/yr*	***Annual Net*** *m³/yr*	***Normalized Annual Net* Sand+ Supply to WECLC*** *m³/lake-km/yr; m³/blf-km/yr*
Turkey Creek 6.9	877	-12,715	-11,837	110	-1,589	-1,480	**-197; -215**
Crooked Creek 5.6	666	-31,536	-30,870	83	-3,942	-3,859	**-654; -689**
Elk Creek 0.075	~1	-224	-224	~0	-28	-28	**-51; -373**
Trout Run 10.15	2,480	-39,118	-36,638	310	-4,890	-4,580	**-445; -451**
Walnut Creek 1.6	213	-4,734	-4,521	27	-592	-565	**-202; -353**
Mill Creek-West 6.3	1,047	-22,800	-21,753	131	-2,850	-2,719	**-400; -432**
WECLC Total			**-105,850**			**-13,250**	**-400; -430**
See Table 4.3 for calculations: Sand+ volume = Total-sediment volume x watershed Sand+ percent from Table 4.3 *Normalized to cubic meters per lakefront kilometer per year; and to cubic meters per lakefront-bluff kilometer per year Bluff-face volume estimates are accurate to ±50% due to uncertainty in the DEM-differencing procedure							

Table 4.2*: Sand+ sediment volume changes for the WECLC bluff face by HUC-12 watershed (2007-2015).*

The percent sand+ content for the bedrock shale through paleo-strandplain sand and gravel strata was compiled and averaged from published and project data from thirteen sites. Stratal grain size compositions were obtained for sites located just updrift of the WECLC in easternmost Ohio, along the WECLC, and just downdrift of the WECLC in Presque Isle Bay. The percentage of sand+ estimated for shale adopted a *shale factor* of 30% from Cross et al. (2016) that was used in that study to estimate the volume of beach-retained material that results from a given volume of physically weathered/eroded shale bedrock. Information on sand+ contents used in Table 4.3 was compiled from Carter (1975), D'Appolonia et al. (1978), Knuth (2001), Dawson and Evans (2001), Urban Engineers of Erie, Inc. (2004), Jones and Hanover (2014), Cross et al. (2016), Environmental Remediation & Recovery, Inc. (2017), project fieldwork, and Terracon Consultants, Inc. (2018).

Stratigraphic characteristics used in Sand+ volume calculations by watershed in Table 4.2						
HUC-12 Watershed	**Turkey Creek**	**Crooked Creek**	**Elk Creek**	**Trout Run**	**Walnut Creek**	**Mill Creek - West**
8-Yr Total Net Bluff Sediment Change m^3	**-40,959**	**-92,704**	**-616**	**-107,760**	**-14,727**	**-61,623**
Highstand Gravels: % of Bluff Face Area	0%	0%	8.5%	4.8%	0%	0%
Average Sand+ Content %	88%	88%	88%	88%	88%	88%
8-Yr Highstand Sand+ Volume Loss in m^3	0	0	46	4,552	0	0
Lacustrine Sands: % of Bluff Face Area	9%	10.5%	8.5%	8.2%	10%	17.5%
Average Sand+ Content %	69%	69%	69%	69%	69%	69%
8-Yr Lacustrine Sand+ Volume Loss in m^3	2,544	6,716	36	6,097	1,016	7,441
Stiff Upper Till: % of Bluff Face Area	38%	70.5%	66.5%	69.8%	52%	63.5%
Average Sand+ Content %	29%	29%	29%	29%	29%	29%
8-Yr Upper Till Sand+ Volume Loss in m^3	4,514	18,953	119	21,813	2,221	11,348
Very Stiff Lower Till: % of Bluff Face Area	53%	18.5%	16.5%	16%	34%	11.5%
Average Sand+ Content %	22%	22%	22%	22%	22%	22%
8-Yr Lower Till Sand+ Volume Loss in m^3	4,776	3,773	22	3,793	1,102	1,559
Shale Bedrock: % of Bluff Face Area	0%	0.5%	0%	1.2%	4%	7.5%
Average Sand+ Content %	30%	30%	30%	30%	30%	30%
8-Yr Bedrock Sand+ Volume Loss in m^3	0	1,391	0	388	177	1,387
Average Sand+ Percent for all Bluff Strata	**28.9%**	**33.3%**	**36.3%**	**34.0%**	**30.7%**	**35.3%**
8-Yr Sand+ Loss from all Bluff Strata in m^3	**11,834**	**30,833**	**223**	**36,643**	**4,516**	**21,735**
Net Sand+ Loss to WECLC in m^3/yr	**1,479**	**3,854**	**28**	**4,580**	**565**	**2,717**
Sand+ Loss to WECLC *m^3/lakefront km/yr* *m^3/bluff-km/yr*	**197 214**	**653 688**	**51 371**	**445 451**	**202 353**	**400 431**

Note small rounding errors when compared with Table 4.2.
Average Sand+ contents are derived from the literature and bluff-face logging: Carter (1975), D'Appolonia et al. (1978), Knuth (2001), Dawson & Evans (2001), Urban Engineers of Erie, Inc. (2004), Jones & Hanover (2014), Cross et al. (2016), Environmental Remediation & Recovery, Inc. (2017), WECLC project fieldwork (2018), and Terracon Consultants, Inc. (2018).
Bluff-face volume estimates are accurate to ±50% due to vertical uncertainty in the DEM surfaces.

Table 4.3: *Stratigraphic characteristics used in Sand+ volume calculations by watershed in Table 4.2.*

Because of vertical uncertainty in the DEM surfaces used to estimate topographic and volume changes, total and sand+ sediment volumes quoted in this section have a possible volumetric uncertainty of as much as ±50%. This arises because the DEM vertical uncertainty of ±18.5 cm

RMSE for the 2007 data and ±9.1 cm RMSE for the 2015 data yields an uncertainty of ±0.2 m for the 8-year elevation-change numbers. Elevation change averaged across the entire WECLC bluff face was almost 0.3 m over the 2007-2015 observation period.

Turkey Creek Watershed

Coastal Geography

https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

Turkey Creek watershed comprises 7.5 km of bluff coast at the updrift (southwestern) end of the WECLC (Fig. 4.2). It extends from the OH-PA state line near State Line Road eastward to Crooked Creek. The watershed includes Site 1STGL and Site 2RACK used in Bayesian modeling (Chapter 3). Raccoon Creek is the largest of seventeen Lake Erie sub-watersheds within the Turkey Creek watershed and traverses the bluff crest to drain into Lake Erie near Elmwood Home Road (Fig. 4.7). Twelve ravines, all less than 200 m in length, also traverse the bluff crest. Other than at the twelve ravine mouths, the ~200 m wide floodplain of Raccoon Creek, and the ~400 m wide west-bank floodplain of Crooked Creek, the coast comprises bluffs that generally increase in elevation eastward (Fig. 4.2).

Figure 4.7(a): *Map showing the 7.5 km lakefront edge of the Turkey Creek watershed (extent delimited by orange markers). It extends from a headland at the OH-PA state line near State Line Road eastward to Crooked Creek. Seventeen Lake Erie sub-watersheds (grey line features) define this watershed. Scale bar is 0.6 km in length. (source: pawalter.psu.edu)*

The bluffs are lowest along the western edge of the watershed at Site 1STGL, lying at an elevation of ~188 m MSL, and reach an elevation of almost 195 m MSL at Site 2RACK near Elmwood Home Road (Fig. 4.7(b)). Bluffs are highest in the eastern part of the watershed, just east of Eagley Road (Fig. 4.7(c)). Here, they locally reach an elevation of ~194 m along a 1.3 km stretch of hummocky (hilly) landscape that extends eastward to west Holliday Road. Sub-watersheds with well-developed surface drainage systems have wide meandering floodplains that incise into the glacial tills. Along the eastern half of the watershed, this results in pronounced hummocky coastal topography between Raccoon Creek and Crooked Creek (Fig. 4.2, Fig 4.8). The easternmost part of the watershed is defined by 0.4 km of the Crooked Creek floodplain east of Haskell Drive.

The Turkey Creek HUC-12 watershed comprises seventeen Lake Erie sub-watersheds (Fig. 4.7(a)). There is an alternating pattern of sub-watersheds that do not have well developed surface drainage systems (ten watersheds) and those that do have well-developed surface drainage systems. For the former, a large percentage of the precipitation input is directed to groundwater recharge and ultimately to discharge at the bluff or bank face. State Gamelands 314 contains nine of the sub-watersheds in the western half of the watershed.

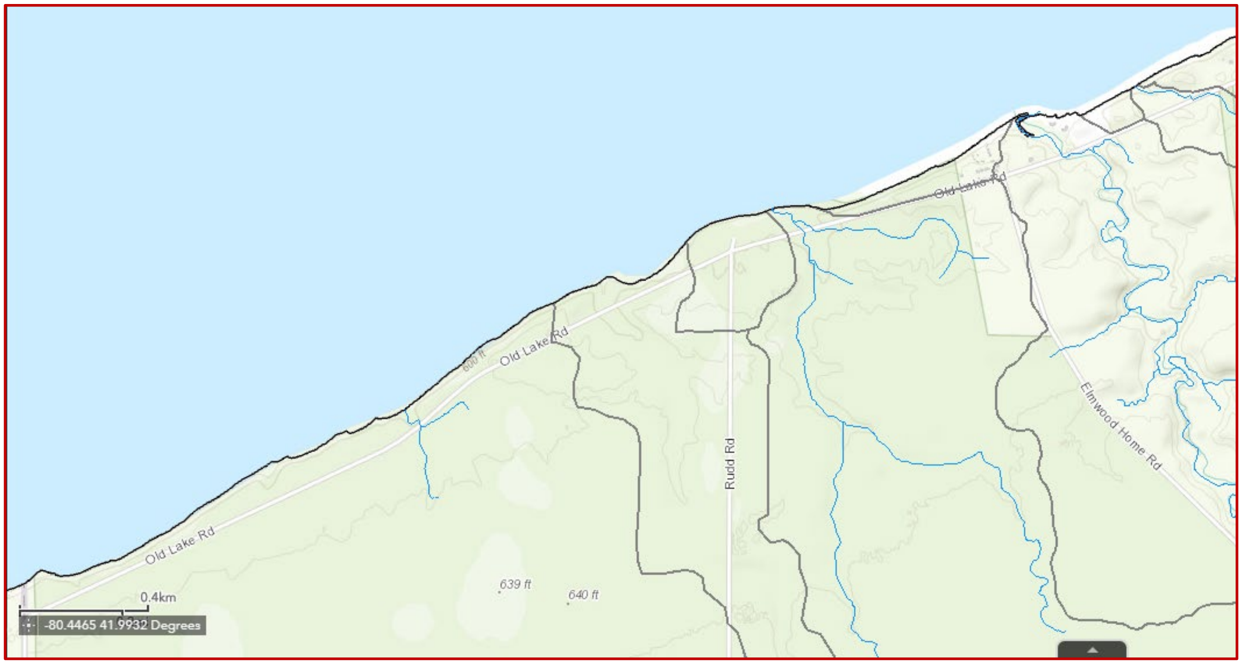


Figure 4.7(b)*: Map showing the western 4 km lakefront edge of the Turkey Creek watershed, extending eastward from the OH-PA state line near State Line Road to Old Lake Road at Raccoon Creek Park. Eight Lake Erie sub-watersheds (grey line features) define this stretch of coast. Scale bar is 400 m in length. (source: pawalter.psu.edu)*

Bluffs along the Turkey Creek lakefront have the lowest overall elevations in the WECLC, being almost 20 m lower than the tallest WECLC bluffs located in the Trout Run watershed at Site 4LECP. Bluff stratigraphy is dominated by the lower glacial till and upper glacial till units, with a thin veneer of lacustrine sands. Shale bedrock does not occur above lake level except at an outcrop that reaches ~1 m above lake level and extends intermittently for ~400 m just west of Holliday Road (Fig. 4.2). Concave-to-lake bluff-crest (cuspate) erosional indentations with along-coast extents of 5-30 m are common along the bluff crest in this watershed (Fig. 4.9(b); Fig. 4.9(c)). These are indicative of rotational slumps whose headwalls lie at the bluff crest and whose curved failure surfaces typically daylight on the mid bluff. At Site 2RACK, the failure surfaces daylight at the glacial till-lacustrine sand contact. This commonly results in a pronounced step or bench on the mid to upper bluff as groundwater-saturated lacustrine sands retreat at a faster rate than the subjacent glacial tills. Just over half of the seventeen sub-watersheds in the Turkey Creek watershed have weakly developed drainage systems that suggests that groundwater flux plays an important role in bluff retreat.

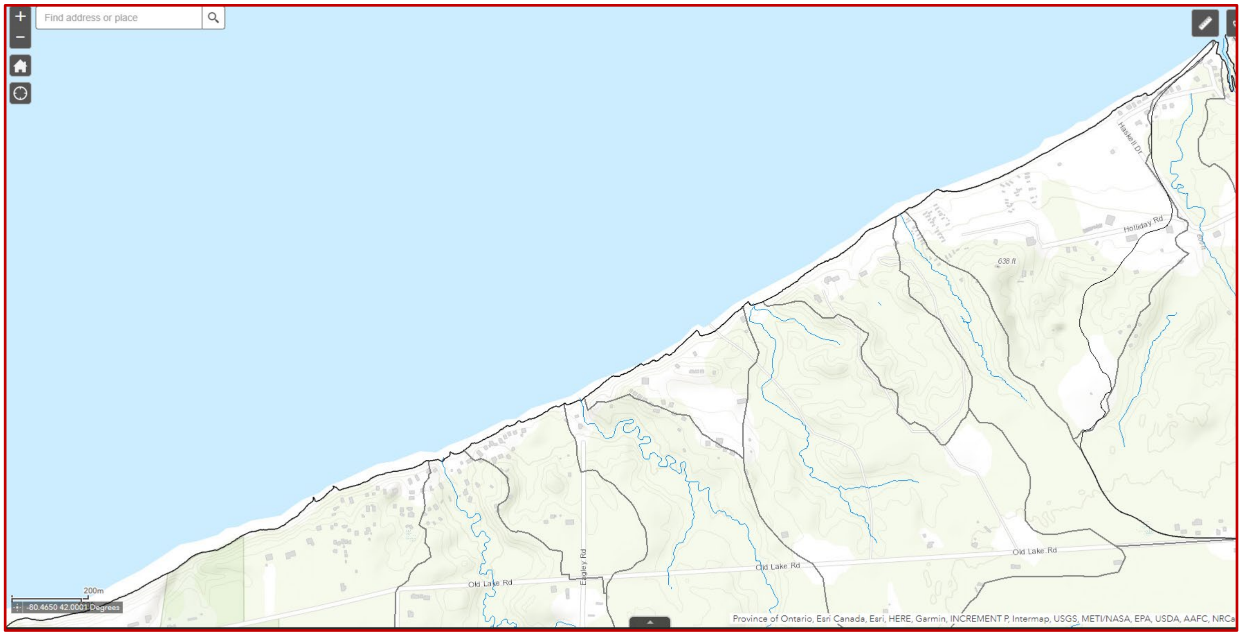


Figure 4.7(c)*: Map showing the eastern 3.5 km lakefront edge of the Turkey Creek watershed, extending from just east of Raccoon Creek to Crooked Creek near Haskell Drive. Nine Lake Erie sub-watersheds (grey line features) define this stretch of coast. Scale bar is 200 m in length. (source: pawalter.psu.edu)*

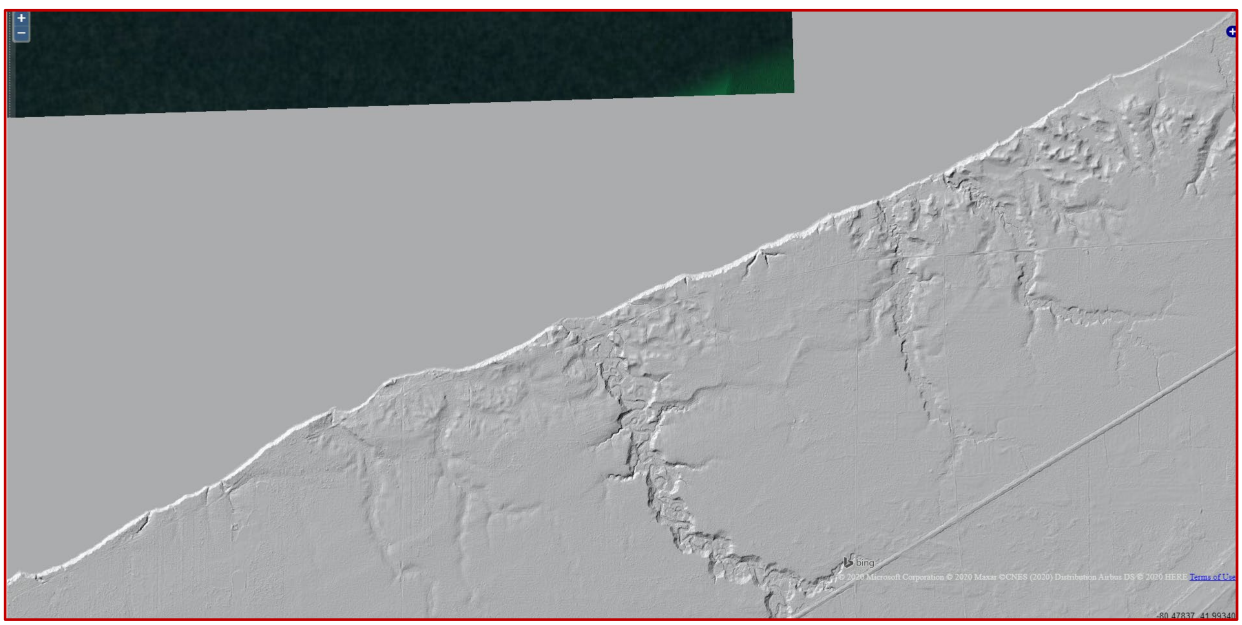


Figure 4.8*: Section of the 2007 DEM hillshade for the Turkey Creek watershed. Raccoon Creek traverses the landscape in the center of the image, and the mouth of Crooked Creek is just visible at the top-right. Lakeward-facing bluffs appear as a pronounced lighter-toned curvilinear feature. Approximate map scale is 1:43,000. (map: pasda.psu.edu/uci/DataSummary.aspx?dataset=1247)*

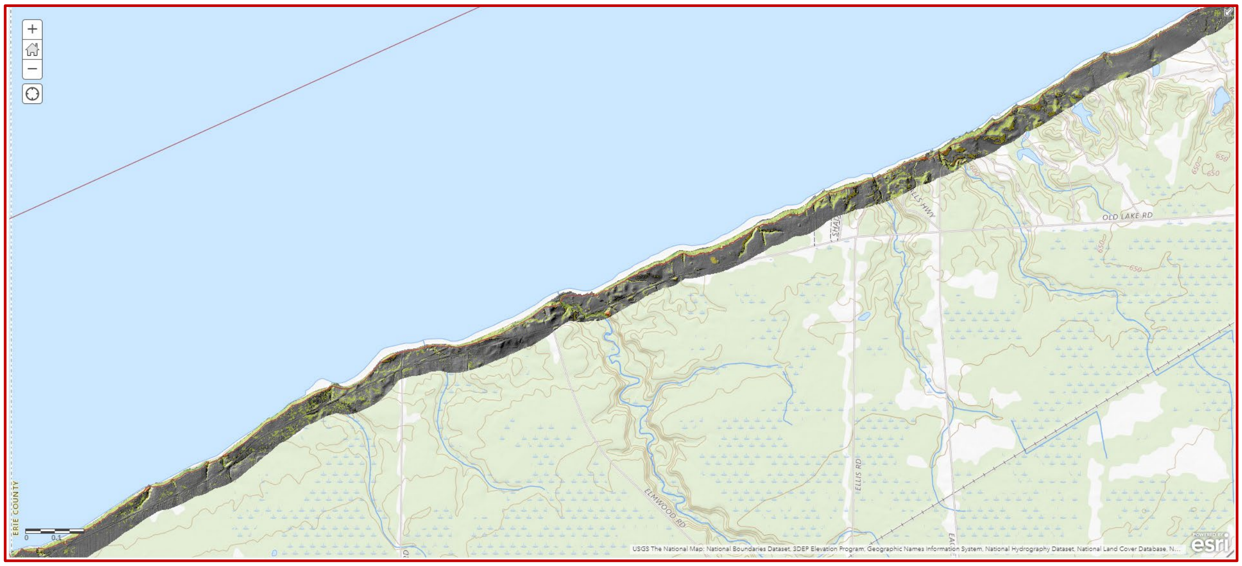


__Figure 4.9(a)__: Lidar surface-difference raster map (2007-2015) for the 7.5 km Turkey Creek watershed's bluff face, overlain on a 150 m-wide DEM hillshade strip. On the bluff-face (narrow colored strip), cool shading denotes sediment losses while rare warm shading denotes sediment gains. Beach areas lakeward of the bluff toe, and ravines and creeks traversing the bluff crest, are excluded from sediment volume calculations. Refer to the online map for greater detail and legend. Scale bar is ~322 m (0.2 miles) in length.

__Figure 4.9(b)__: Lidar surface-difference raster map (2007-2015) for the western 3.75 km of the Turkey Creek watershed's bluff face. Refer to the online map for greater detail and legend. Scale bar is ~183 m (600 ft) in total length.

Shoreline Engineering

Approximately thirty-five engineering structures occur in this watershed, comprising twenty-three groynes, eleven seawall sections totaling ~1100 m in length, and one jetty on the west bank of Crooked Creek (Table 4.4). Groynes and seawalls are limited to the eastern four kilometers of the watershed, being absent west of Raccoon Creek along the State Gamelands 314 shore. Groynes occur primarily in groyne fields, such as a four-element field at Raccoon Creek and a nine-element field between Eagley Road (Halls Hwy) and Crooked Creek (Fig. 4.9(b); Fig 4.9(c)). Groynes have spacings of 10-90 m and lengths ranging from 6 to 33 m. Sand and cobble fillets on the updrift (southwest) sides of the groynes are ~50-70% full.

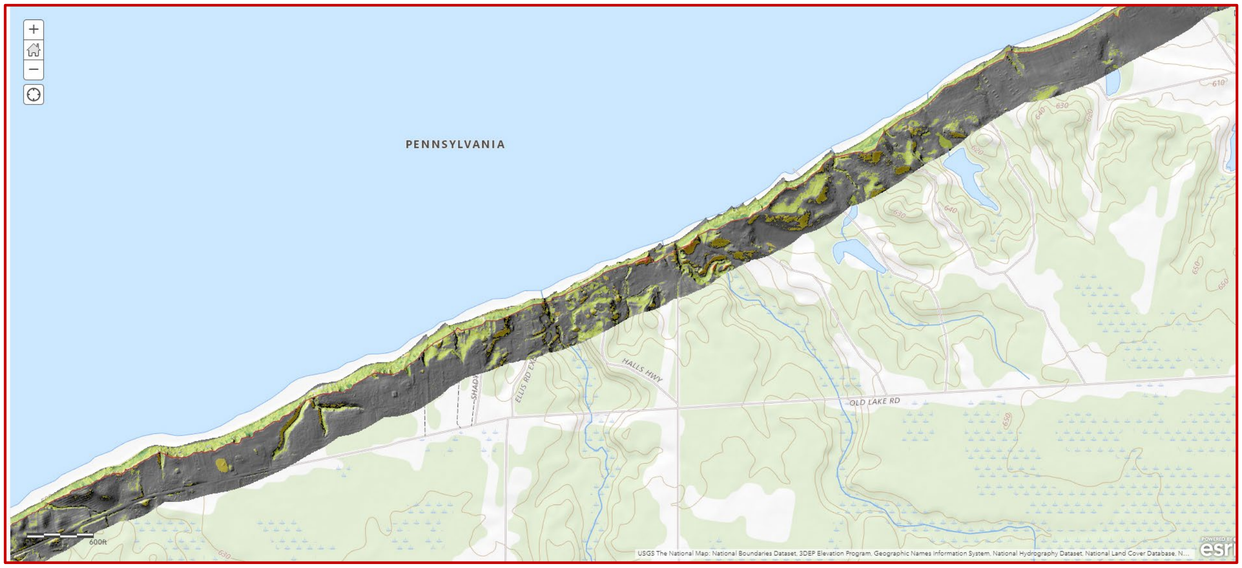


Figure 4.9(c): *Lidar surface-difference raster map (2007-2015) for the eastern 3.6 km of the Turkey Creek watershed's bluff face (easternmost 0.15 km at Crooked Creek is not viewable at this scale). Refer to the online map for greater detail and legend. Scale bar is ~183 m (600 ft) in total length.*

Coastal Engineering Structures and Structure Spatial Density in the WECLC by HUC-12 Watershed*

Watershed & Shore Length	Groynes	Groynes/km	Seawalls (m)	Seawalls (m/km)	Jetties	Total Structures
Turkey Creek 7.5 km	23	3.1	11 (1100 m)	147	1	35
Crooked Creek 5.9 km	13	2.2	5 (205 m)	35	1	19
Elk Creek 0.55 km	0	0	0	0	0	0
Trout Run 10.3 km	38	3.7	11 (400 m)	39	2	51
Walnut Creek 2.8 km	27	9.6	6 (330 m)	118	2	35
Mill Creek – West 6.8 km	66	9.7	19 (1770m)	260	0	85

*Structures identified from 2015 lidar, 2015 PADEP CRMP oblique coastal photography dataset, and 2018 site visits

Watershed Bluff Stratigraphy

The coastal stratigraphy for the Turkey Creek watershed comprises Devonian shale bedrock in the nearshore and surfzone; sands, gravels, and small shale slabs defining the beach prism between the shoreline and the bluff toe; and very stiff lower till, stiff upper till, and lacustrine sand horizons on the bluff face. Depending on location, the glacial tills make up 60 to 90% of the bluff face. Highstand beach-ridge sands and pea gravels that occur in the Trout Run watershed, downdrift to the northeast, are absent from this watershed. The highest bluffs in the watershed lie at ~194 m

MSL, at Site 2RACK near Raccoon Creek. Shale bedrock is present below lake level, in the surf zone and nearshore along the entire watershed. Shale bedrock crops out on the bluff face only locally, for ~400 m near the eastern edge of the watershed (Fig. 4.2).

Watershed Bluff-Face Change Trends

Practically the entire 7.5 km of bluffs in this watershed are erosional (Fig. 4.9). During the 2007-2015 time period, about 20% of the bluff face shows up to 0.3 m of erosion (i.e., a loss of up to 0.3 m^3 per unit area on the online map), while over 60% shows 0.3-0.6 m of erosion. The remaining ~20% shows 0.9 m or more of erosion (0.9 m^3 per unit area). Erosional areas occur across the entire bluff face, from crest to toe, and across the watershed with no pronounced pattern. In general, the bluff face west of Rudd Road is more erosional than bluff-face areas to the east. Areas with erosion of more than 0.3 m are well developed on the central two-thirds of the bluff face, indicating significant sediment removal from glacial till on the low to mid bluff face (due toe erosion and slope instability), and lesser sediment removal from lacustrine sands from the upper bluff face (likely due groundwater discharge). In general, erosion of greater than 0.6 m is more common near the bluff crest than near the bluff toe, occurring primarily within rotational-slump features ranging in length from 10 m to 45 m with a downslope extent of 15-20 m. Significant erosion near the bluff crest, such as over 0.9 m of elevation loss on the bluff just east of Eagley Road, indicates a reduction in bluff-face slopes over the 8-year period within these erosional features (Fig. 4.9(a)). Figure 4.9(b) shows that the most significant areas of localized erosion in excess of 3 ft (0.9 m) occur in two small 125 m and 170 m coastal embayments located between the OH-PA state line and Rudd Road in State Gamelands 314 (western third of the watershed).

Large-change areas occurring on the lower bluff face are not necessarily associated with crest retreat during 2007-2015. Their occurrence indicates bluff-face steepening between the bluff toe and mid-face, which leads to greater slope instability and a higher propensity for future crest retreat. This is a common phenomenon just east of Raccoon Creek (Site 2RACK) where the very-stiff till on the lower bluff is routinely undermined by wave scour. A near-horizontal wave-cut notch up to 0.5 m deep (into the bluff face) typically develops and the vertical lower bluff face then fails when near-vertical fractures at the head of the notch propagate to the top of the till (Fig. 2.8). This results in large blocks of till, on the order of 10 m^3 in volume, toppling onto the narrow beach. Additionally, higher-erosion swaths lie several meters landward of the bluff toe (Fig. 4.9) indicating sediment loss from the stiff upper till that typically overlies the 2-3 m tall very-stiff lower till. Failure of the lacustrine sands overlying the till due to groundwater flux (sapping) locally leads to significant mid-bluff erosion and development of an erosional bench at the top of the glacial tills (Fig. 3.12).

Large translational slides, while seen in the Trout Run and Mill Creek-West watersheds, are not a style of bluff failure in the Turkey Creek watershed (Fig. 4.9; online map). As a consequence, rotational slumps with along-coast lengths of 8 to 45 m are the dominant large-volume failure mechanisms. Background chronic but slow soil creep, common in all WECLC watersheds, is also common here. Block falls, where large blocks of till topple off the bluff face, are common just east of Raccoon Creek in particular. This style of bluff failure is evident in the field but difficult to resolve on the surface-difference map shown in Fig. 4.9. The difficulty occurs because the steep bluff face at these sites does not always provide good lidar returns. However, the failure mechanism does result in bluff-toe retreat, elevation loss just landward of the toe due to block removal, and ultimately though not necessarily over the eight-year observation period, retreat of the bluff-crest.

Minor apparent aggradation occurs along descending-elevation ridge lines that form where the sides of ravines transect the lakefront bluff. The ravine aggradation anomalies result from a lower density of lidar ground strikes in one or both lidar datasets, the geometry of the lidar survey flight paths, and TIN-interpolation artifacts along these knife-edge features. These anomalies are consequently excluded from sediment gain/loss calculations.

The top part of the bluff, within 2-4m of the bluff edge (Fig. 4.9; online map) shows aggradation in several areas within State Gamelands 314 west of Raccoon Creek. This aggradation on the bluff face occurs because the bluff face in this area has a stepped profile where capping lacustrine sands are eroding faster than the glacial tills defining the mid and lower bluff. Over-steepening of the lacustrine sands leads to slumping. Some of the slumped or earth-fall material accumulates on an erosional near-horizontal bench that results from retreat of the sand horizon landward across the underlying till surface due to differential rates of erosion. Springs and groundwater seeps at the sand-till contact enhance lacustrine-sand instability and the stepped-profile appearance. The volume of aggradation on these bluff-face benches partly offsets background erosion on the bluff face as a whole. It is retained in the sediment volume calculations because it represents a redistribution of sediment on the bluff face and not an immediate loss to the littoral system.

Watershed Sediment Gains and Losses from the Bluff Face

Based on comparison of lidar-derived DEMs shown in Fig. 4.9 and the online map, the Turkey Creek watershed shows ~3,040 m^3 of total-sediment gain, ~44,000 m^3 of total-sediment loss, and a net change of about -40,960 m^3 over the 2007-2015 time period (Table 4.1). Annualized, the net change is a loss of 5,120 m^3 of total-sediment from the bluff face per year, or just over 740 m^3/bluff km/yr. This total-sediment material ranges in grain size from clay particles to shale pebbles and cobbles, to igneous boulders formerly encased within the glacial till.

Integrating this total-sediment volume with watershed stratigraphy and typical grain-size compositions of WECLC bluffs (Table 4.3), lakefront bluff retreat in the Turkey Creek watershed yielded just under 11,850 m^3 of sand+ over the eight-year period. This is equivalent to an average supply of 1,480 m^3/yr of sand+ material to the littoral zone per year (Table 4.2; 40,959 m^3 total-sediment x 28.9% sand+ content x 0.125). Normalized to the volume of littoral sand supply per kilometer of lakefront bluff, the sand+ sediment yield is almost 220 m^3/bluff km/yr, the lowest normalized supply among the six WECLC watersheds. This sand+ sediment is sufficiently coarse to remain primarily in the littoral stream and is the material used to build and replenish a large component of the beach volumes in the WECLC and in the Presque Isle littoral cell immediately downdrift.

Crooked Creek Watershed

Coastal Geography

https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

This watershed comprises 5.9 km of bluff coast located downdrift (NE) of the Turkey Creek watershed and updrift (SW) of the Elk Creek watershed (Fig. 4.2). It extends from Crooked Creek (near Holliday Road) to Elk Creek on the eastern boundary of Erie Bluffs State Park (Fig. 4.10). Located in the western half of the WECLC, the watershed includes Site 3EBSP used in Bayesian modeling (Chapter 3). Crooked Creek, at the west edge of the watershed, and Duck Run within Erie Bluffs State Park, are the largest of twelve Lake Erie sub-watersheds within this HUC-12 watershed (Fig. 4.10(a)). Eleven ravines traverse the bluff crest, eight of which occur in Erie Bluffs State Park. Other than at the eleven small ravine mouths (including Duck Run), and the larger mouth of Crooked Creek, the coast comprises bluffs that increase in elevation eastward. The bluffs are lowest at the western edge of the watershed, lying at an elevation of ~196 m MSL on the eastern flanks of the Crooked Creek floodplain, which extends for ~310 m east of the mouth of Crooked Creek. The bluffs are tallest at the eastern edge of the watershed at Erie Bluffs State Park, reaching an elevation of ~207 m MSL. The latter elevations are due to the presence of highstand beach-ridge strata that are absent outside of the eastern Crooked Creek and western Trout Run watersheds. A geomorphologically unique, three-sided erosional remnant of former bluff occurs as an isolated pyramid near Lou's Lane in the center of the Crooked Creek floodplain (186 m in elevation; 10 m of relief; 2,400 m² in area; Fig. 4.10(b), Fig. 4.11).

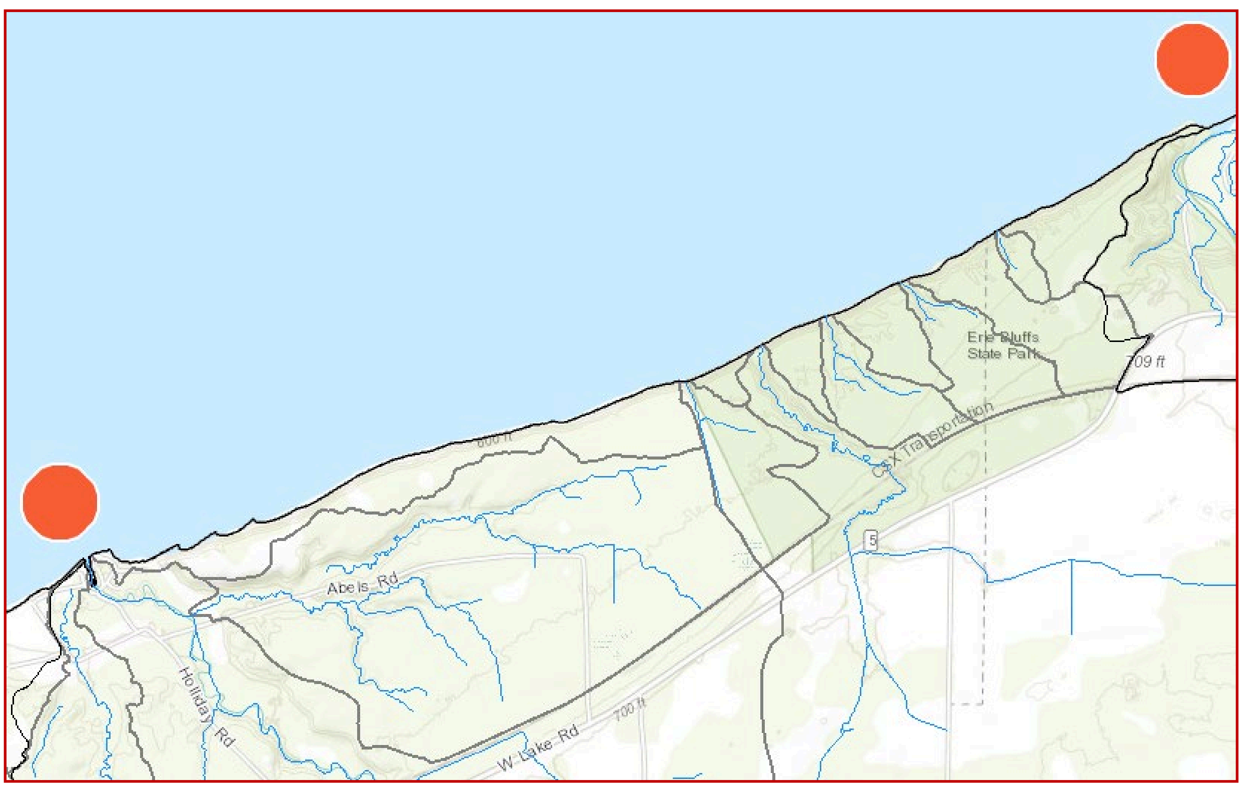


***Figure 4.10(a)**: Map showing the 5.9 km lakefront edge of the Crooked Creek watershed (extent delimited by orange markers). It extends from Crooked Creek near Holliday Road eastward to the mouth of Elk Creek just east of Erie Bluffs State Park. Twelve Lake Erie sub-watersheds (grey line features) define this stretch of coast. Approximate map scale is 1:31,000. (source: pawalter.psu.edu)*

Figure 4.10(b)*: Map showing the western 2.9 km lakefront edge of the Crooked Creek watershed, extending eastward from the mouth of Crooked Creek at Crooked Creek Lane to the western edge of Erie Bluffs State Park. Two Lake Erie sub-watersheds (grey line features) define this coast. Note the absence of surface drainage within the narrow lakefront sub-watershed. Approximate map scale is 1:15,000. (source: pawalter.psu.edu)*

Figure 4.10(c)*: Map showing the eastern 3.0 km lakefront edge of the Crooked Creek watershed, extending the length of Erie Bluffs State Park to Elk Creek at the eastern end of the watershed. Ten Lake Erie sub-watersheds (grey line features) define this stretch of coast. Approximate map scale is 1:15,000. (source: pawalter.psu.edu)*

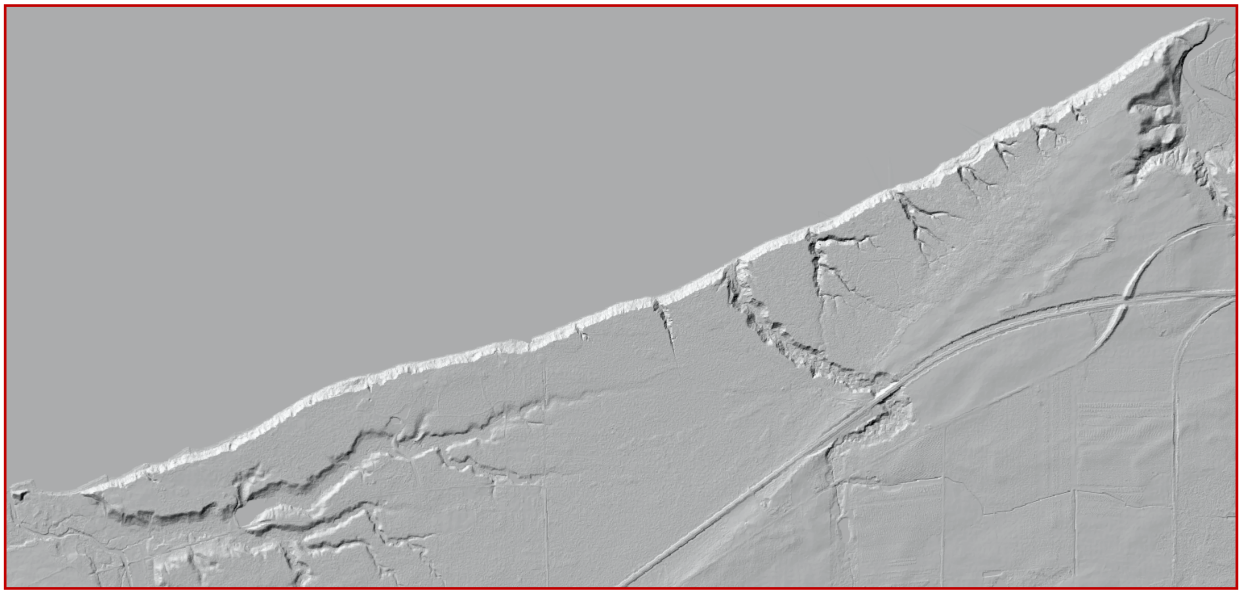


***Figure 4.11**: Section of the 2007 DEM hillshade for the Crooked Creek watershed. Crooked Creek traverses the landscape on the lower-left where a bluff remnant is isolated on the floodplain. Duck Run traverses the center of the image, and Elk Creek occurs at the top-right. Lakeward-facing bluffs appear as a pronounced lighter-toned linear feature. Approximate map scale is 1:31,000. (map: pasda.psu.edu/uci/DataSummary.aspx?dataset=1247)*

The Crooked Creek HUC-12 watershed comprises twelve Lake Erie sub-watersheds (Fig. 4.10(b); Fig. 4.10(c)). There is an alternating pattern of watersheds that do not have well developed surface drainage systems (one large and five small watersheds) and those that do have well-developed surface drainage systems (two large and four small watersheds). For the former, a large percentage of the precipitation input is directed to groundwater recharge and ultimately to discharge at the bluff or bank face. Ten of the twelve sub-watersheds are located within Erie Bluffs State Park.

Strongly concave-to-lake bluff-crest (cuspate) erosional indentations with along-coast extents of 8-130 m are common along the bluff crest in this watershed (Fig. 4.12(b); Fig. 4.12(c)). Translational slides are rare, and they are restricted to the eastern half of the watershed in Erie Bluffs State Park. Concave failures associated with rotational slides are shorter in the westernmost third of the watershed (along Abels Road) than elsewhere in the watershed. The largest rotational slides occur at the fifth and seventh ravines east of the western boundary of Erie Bluffs State Park, with lengths of 90 m and 175 m, respectively (Fig. 4.12(c)). The only example of a translational slide occurs near the third ravine. With an along-coast extent of 95 m, this translational slide does not have notable benches and headwalls on the bluff face, in contrast to those in the Trout Run watershed to the east. These patterns indicate low-magnitude, episodic and infrequent failures (slides) over time on curved failure surfaces that occur as background to more continuous (chronic), lower-magnitude soil creep. The visually sharp (on 2015 lidar and aerial imagery) stretches of cuspate crest lines indicate continuing erosion due primarily to rotational slumps. A typical precipitous drop onto the bluff face, of 1-4 m based on observations across the study area, is the result of a steep (>70^0) slump headwall cut into the upper bluff's lacustrine sands. These near-crest silty sand to gravel horizons are less cohesive (~2 kg/cm^2; Dawson and Evans, 2001) than underlying glacial tills (~4 kg/cm^2) and characteristically have steep slopes that may exceed 90^0 along non-vegetated stretches.

***Figure 4.12(a)**: Lidar surface-difference raster map (2007-2015) for the 5.9 km Crooked Creek watershed's bluff face overlain on a 150 m-wide DEM hillshade strip. On the bluff-face (narrow colored strip), cool shading denotes sediment losses while rare warm shading denotes sediment gains. Beach areas lakeward of the bluff toe, and ravines and creeks traversing the bluff crest, while shown here, are excluded from sediment volume calculations. Refer to the online map for greater detail and legend. Scale bar is ~322 m (0.2 miles) in length.*

***Figure 4.12(b)**: Lidar surface-difference raster map (2007-2015) for the western 2.9 km of the Crooked Creek watershed's bluff face. Note the relative scarcity of ravines crossing the bluff crest. Refer to the online map for greater detail and legend. Scale bar is ~183 m (600 ft) in length.*

Shoreline Engineering

Approximately nineteen engineering structures occur along this coast. They comprise one jetty on the east bank of Crooked Creek, thirteen groynes, and five short seawall sections totaling ~205 m in length (Table 4.4). Groynes and seawalls are limited to the western half of the watershed and are absent from the Erie Bluffs State Park shore. Two notable groyne fields occur, one seven-element field at Crooked Creek, and one four-element, large-groyne, field at YMCA Camp Fitch east of Lou's Lane (Fig. 4.10(b)). At these two fields, groynes have spacings of 30-40 m and 190-205 m, respectively. Average groyne lengths are 14 m and 42 m, respectively. Sand and cobble fillets on the updrift (southwest) sides of the groynes are ~50-70% full.

***Figure 4.12(c)**: Lidar surface-difference raster map (2007-2015) for the eastern 3.0 km of the Crooked Creek watershed's bluff face at Erie Bluffs State Park. Note the relative abundance of ravines (eight) crossing the bluff crest. Refer to the online map for greater detail and legend. Scale bar is ~183 m (600 ft) in total length.*

Watershed Bluff Stratigraphy

The coastal stratigraphy for the Crooked Creek watershed comprises Devonian shale bedrock in the nearshore and surfzone; sands, gravels, and shale slabs defining the beach prism between the shoreline and the bluff toe; occasional occurrences of shale bedrock at the bluff toe overlain by very-stiff till; and stiff till and lacustrine-sand strata on the bluff face. Highstand beach-ridge sands and pea gravels that occur in the Trout Run watershed immediately downdrift are absent from this watershed. The highest bluffs in the watershed lie at ~207 m MSL (Fig. 4.2).

Shale bedrock is present just below lake level (174.25 m in April 2015) in the surf zone and nearshore along the entire watershed. From just east of the YMCA Camp Fitch groyne field to the western boundary of Erie Bluffs State Park (Fig. 4.12(b)), shale bedrock occurs just above lake level. Where the beach prism is patchy or absent, the bedrock appears as a wave-cut platform with bedrock extending up the bluff face for as much as 0.25 m. Where the beach prism is present, the shale platform is hidden. Locally, the shale reaches almost a meter above lake level along eastern Abels Road, before diving below lake level at the western boundary of Erie Bluffs State Park. The shale then reappears along Erie Bluffs State Park, locally rising to ~0.5 m above lake level as an ~100 m length of wave-cut platform north of the Elk Creek access road at the eastern edge of the Crooked Creek watershed.

Watershed Bluff-Face Change Trends

The entire 5.9 km of bluff in this watershed is erosional (Fig. 4.12), and the online map shows that erosion is much more pervasive (both areas and volumes) than in the Turkey Creek watershed.

Over 60% of the bluff-face area shows at least 0.3 m of elevation change during the 2007-2015 time period, while ~30% shows greater than 0.6 m of elevation change. The >0.6 m erosion patches are best developed on the top half of the bluff face across the watershed, indicating significant sediment removal from the upper till and lacustrine-sand stratigraphic horizons. In general, erosion is more common near the bluff crest, occurring primarily within rotational-slump features ranging in length from 10 m to 140 m that indicate concomitant retreat of the bluff crest and a reduction in bluff-face slopes over the 8-year period (Fig. 4.12(a), Fig 4.12(b)). In general, greater-erosion swaths cover more surface area of the bluff face here than almost all the other WECLC watersheds (Trout Run excluded), indicating greater sediment losses. Significant erosional patches are also notable at the YMCA Camp Sherwin groyne field, just east of Crooked Creek, despite relatively wide protective beaches at this location. More-pronounced erosional swaths are more common in the eastern half of the watershed along the tall bluffs at Erie Bluffs State Park (Fig. 4.2, Fig. 4.12(c)).

Large volume-change areas on the lower bluff face are more prevalent in the eastern half of the watershed at Erie Bluffs State Park (Fig. 4.12(c)), indicating that the toe of these bluffs became steeper over the eight-year period. This may lead to greater crest retreat in the future. Bluffs in the western half of the watershed often became less steep over the same time period because greater amounts of sediment loss occurred on the upper half of the bluff face (Fig 4.12(b)). Change patterns better visible on the online map suggest that volumetric losses per unit crest length are lower in the western half of the watershed and higher in the eastern half.

Minor apparent aggradation occurs along descending-elevation ridge lines that form where the sides of ravines transect the lakefront bluff face. The ravine aggradation anomalies result from a lower density of lidar ground strikes in one or both lidar datasets, the geometry of the lidar survey flight paths, and TIN-interpolation artifacts along these knife-edge features. These data-artifact anomalies are excluded from sediment volume calculations.

Watershed Sediment Gains and Losses from the Bluff Face

Based on comparison of lidar-derived DEMs shown in Fig. 4.12 and the online map, the Crooked Creek watershed shows ~2,000 m^3 of total-sediment gain, ~94,700 m^3 of sediment loss, and a net change of about –92,700 m^3 over the 2007-2015 time period (Table 4.1). Annualized, the net change is a loss of almost 11,600 m^3 of total sediment from the bluff face per year, or ~2,070 m^3/bluff km/yr. This total-sediment material ranges in grain size from clay particles to shale pebbles and cobbles, to igneous boulders formerly encased within the glacial till.

Integrating this total-sediment volume with watershed stratigraphy and typical grain-size compositions of WECLC bluffs (Table 4.3), lakefront bluff retreat in the Crooked Creek watershed yielded an average of ~3,860 m^3/yr of sand+ material to the littoral zone per year (Tables 4.2 and 4.3; 92,704 m^3 total-sediment x 33.3% sand+ content x 0.125). Normalized to volume of littoral sand supply per kilometer of lakefront bluff, the sand+ sediment yield is almost 700 m^3/bluff km/yr. Notably, this is the highest normalized rate among all WECLC watersheds and is 53-220% greater than those other watersheds. This sand+ sediment is sufficiently coarse to remain primarily in the littoral stream and is the material used to build and replenish a large component of the beach volumes in the WECLC and in the Presque Isle littoral cell immediately downdrift.

Elk Creek Watershed

Coastal Geography

https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

This watershed comprises a 0.3 km (300 m) wide creek mouth and its flanking floodplain located between bluff slopes at the mouth of Elk Creek, located downdrift (NE) of the Crooked Creek watershed and updrift (SW) of the Trout Run watershed. This watershed's lakefront extends from the bluff ridge line on the western bank of the Elk Creek estuary eastward across a large baymouth bar to a 50-80 m (locally, almost 400 m) wide east-bank floodplain at the toe of the bluffs at Elk Creek Road. It then extends up onto the bluff plateau to the western edge of the Trout Creek watershed. The entire watershed's ~550 m of coast thus consists of the creek estuary, a floodplain just above lake level, and flanking bluff slopes that face the creek channel as they turn inland (as a re-entrant) from the lakefront (Fig. 4.13).

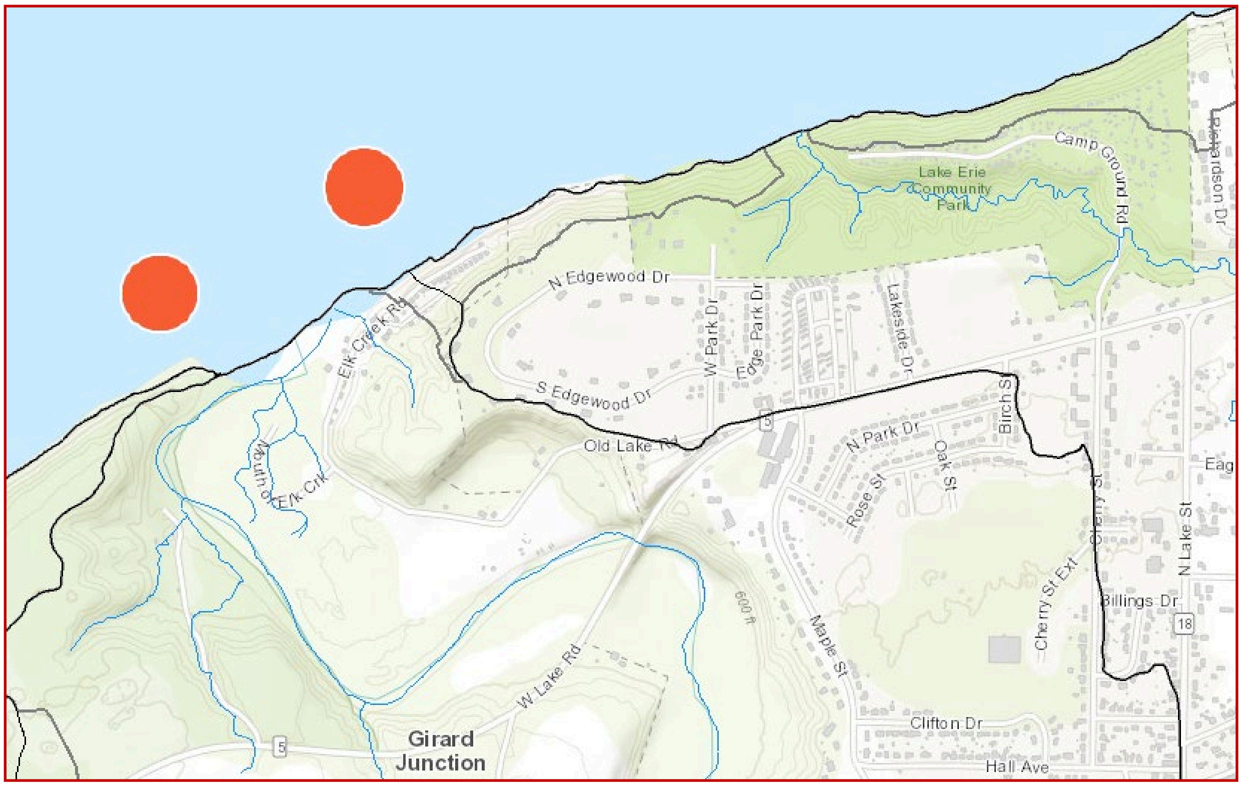


***Figure 4.13**: Map showing the short ~0.55 km lakefront edge of the Elk Creek watershed (extent delimited by orange markers). It extends from a bluff ridge line on the west edge of Elk Creek at Erie Bluffs State Park to the bluffs on the east edge near North Edgewood Drive (Elk Creek Road). Approximate map scale is 1:18,000. (source: pawalter.psu.edu)*

Most sediment eroded from the bluffs in this sector are either fed directly to Elk Creek before being transported to the coastal littoral zone or are stored on tiered bluffs and not supplied to the beaches. The latter case arises because the eastern edge of the Elk Creek watershed, and the westernmost 0.5 km of the Trout Run watershed, have a "tiered bluff" geometry (PA DEP, 2013). An upper bluff face is separated from a lower bluff face by a plateau (tableland) as much as 150 m in width. This plateau is either a remnant of a) a large prehistoric slump, or b) a prehistoric floodplain of Elk Creek, formed when lake level was 10-15 m higher than present. In littoral sediment-input calculations, sediment losses from creek-facing bluffs and from the upper tiered bluff face are excluded because sediment is not directly supplied to the littoral system on timescales of decades. Only 75 m of bluff face, on the east side of the Elk Creek watershed, face Lake Erie and are capable of supplying sediment to the littoral system from any erosion on the bluff's lower tier.

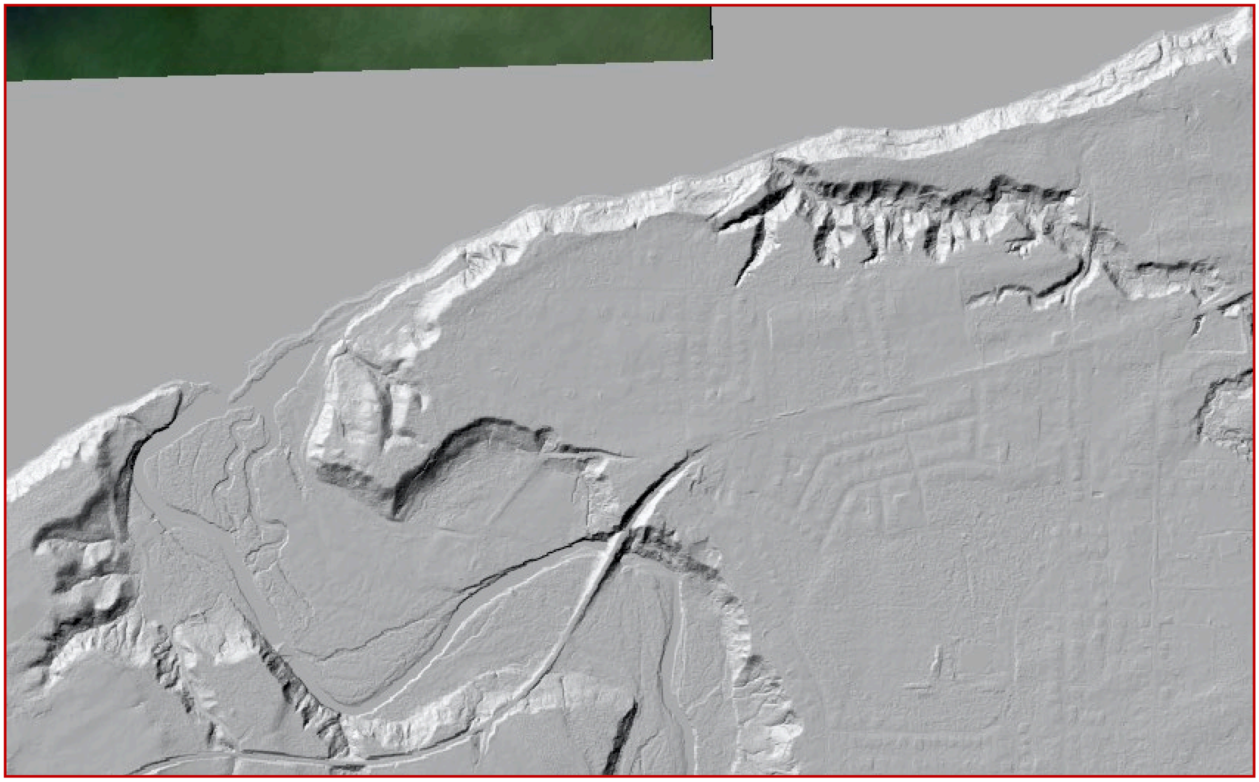


Figure 4.14: *Section of the 2007 DEM hillshade for the Elk Creek watershed. Elk Creek has cut a wide (~400 m) valley and floodplain over the past several thousand years. Lakeward-facing bluffs appear as lighter-toned linear features due to "apparent sun" low-angle illumination from the north-northwest. The lake surface is represented by a simple, flat, featureless surface at an elevation of ~174.5 m. Site 4LECP is on the top-right of the image. Approximate map scale is 1:18,000. (map: pasda.psu.edu/uci/DataSummary.aspx?dataset=1247)*

Shoreline Engineering

Other than minor bank stabilization on the floodplain, engineering structures are absent from the mouth of Elk Creek and its adjacent floodplain (Table 4.4). A large baymouth bar (~300 m in length; Figs. 4.14, 4.15) partially blocks and deflects the creek mouth for most of the year, and occasionally and temporarily blocks the creek during low-flow periods. This dynamic feature changes geometry frequently, depending on storm activity, sediment supply, and lake level. It is supplied with silt, sand, gravel, and shale slabs by Elk Creek and by littoral transport from the Crooked Creek watershed just updrift. As is typical of similar baymouth bars on ocean coasts, periodic breaching, regrowth, and migration of the bar in the downdrift direction permit episodic sediment transfer across the creek mouth to supply a wide (~65 m) beach on the downdrift shore. During storm conditions, coarse sediment is also transported out into the surf zone for temporary deposition and subsequent transport back onshore to the beach at Elk Creek Road (Fig. 4.13).

Watershed Bluff Stratigraphy

The coastal stratigraphy for the mouth of the Elk Creek watershed consists of Devonian shale bedrock in the nearshore, surfzone and creek floor. Onshore, silts, sands, gravels, and shale slabs define the beach prism and floodplain between the shoreline and the bluff toe. Very-stiff till, stiff till, and lacustrine-sand strata make up the valley-facing bluff face. The bluffs just east of Elk Creek in the Trout Run watershed are also capped by Warren paleo-shoreline deposits (Schooler, 1974), and are among the highest bluffs in the entire WECLC at ~212.3 m MSL. Shale bedrock does not occur above lake level on this short stretch of coast and is estimated to lie at an elevation of ~173 m at the mouth of Elk Creek. This is partly due to its removal by erosion as Elk Creek incises the bedrock by moving laterally back and forth within its floodplain, incising to depths of 1-2 m below lake level. The absence of bluff-toe shale is also due to bedrock lying at a lower elevation generally in this part of the WECLC.

Figure 4.15: *Lidar surface-difference raster map (2007-2015) for the short 0.55 km Elk Creek watershed and adjacent coast to the west (Crooked Creek Watershed and Erie Bluffs State Park) and east (Trout Run watershed and Lake Erie Community Park). The 150 m wide grey-tone strip is the 2007 lidar-derived DEM hillshade. On the bluff-face (narrow color strip), cool shading denotes sediment losses while rare warm shading denotes sediment gains. Sediment gains and losses from the floodplain and Elk Creek-facing bluffs are excluded from sediment volume calculations. Refer to the online map for greater detail and legend. Scale bar is ~183 m (600 ft) in total length.*

Watershed Bluff-Face Change Trends

The 75 m of lakeward-facing bluffs within this watershed limit bluff-face sediment contributions to the littoral zone. The short stretch of bluff is located on the east flank of Elk Creek, within a small and narrow sub-watershed to the west of North Edgewood Drive (Figs. 4.13, 4.16). This small sub-watershed within the Elk Creek watershed abuts the Trout Run watershed just to the east. Erosion of 0-0.3 m dominates the bluff face, and no notable accretion occurs. Patchy erosion of 0.3-0.9 m occurs on ~25% of the bluff face, concentrated on the mid to upper bluff over an area of less than 1000 m^2, indicating bluff steepening over the 2007-2015 time period. Erosion and accretion artifacts are common within the estuary because of channel migration, growth and decay of the baymouth bar, and changes in lake level between 2007 and 2015. Accretion on the wide beach just downdrift of the creek mouth is notable but is excluded from sediment-volume calculations because this change does not occur on the bluff face. Sediment losses from the creek-facing bluffs on the east side of the creek valley and from the upper tier of the bluff face are apparent in Figs. 4.15 and 4.16, where less than 0.1 m of elevation change occurs near Elk Creek Road. The sediment volumes from the upper tier are excluded from the sediment-budget calculations because sediment is not directly supplied to the littoral system at these locations.

Figure 4.16: *Larger-scale view of the mouth of Elk Creek. Bluff-face changes between 2007 and 2015 are shown in shades of green (narrow color coastal strip). The purple lines enclose the coastal edge of the Elk Creek watershed used in surface-difference mapping. Only the lower bluff-face tier on the top-right of the image (part in the Elk Creek watershed, part in the Trout Run watershed) supplies sediment to the littoral system. Refer to online map for greater detail and legend. Scale bar is ~90 m (300 ft) in total length.*

Watershed Sediment Gains and Losses from the Bluff Face

Based on comparison of lidar-derived DEMs (Fig. 4.16; online map), the Elk Creek watershed shows almost zero sediment gain, ~620 m^3 of sediment loss, and a net change of ~620 m^3 over the 2007-2015 time period (Table 4.1). Annualized, the net change is a loss of about 80 m^3 of total-sediment from this short stretch of bluff face per year, or almost 1,030 m^3/bluff km/yr. This total-sediment material ranges in grain size from clay particles to shale pebbles and cobbles, to igneous boulders formerly encased within the glacial till.

Integrating this total-sediment volume with watershed stratigraphy and typical grain-size compositions of WECLC bluffs (Table 4.3), lakefront bluff retreat in the Elk Creek watershed yielded an average of ~30 m^3/yr of sand+ material to the littoral zone per year (Tables 4.2 and 4.3; 616 m^3 total sediment x 36.3% sand+ content x 0.125). Normalized to volume of littoral sediment supply per kilometer of lakefront bluff, the sand+ sediment yield is just over 370 m^3/bluff km/yr. This sand+ sediment is sufficiently coarse to remain primarily in the littoral stream and is the material used to build and replenish a large component of the beach volumes in the WECLC and in the Presque Isle littoral cell immediately downdrift.

Trout Run Watershed

Coastal Geography

https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

This watershed contains 10.3 km of bluff coast located downdrift (NE) of the Elk Creek watershed and updrift (SW) of the Walnut Creek watershed (Fig. 4.2). It extends from the east edge of the Elk Creek floodplain (Elk Creek Road) to the west edge of the Walnut Creek floodplain (near Eaton Road). Located along the central third of the WECLC, the watershed includes Sites 4LECP and 5YMCA used in Bayesian modeling (Chapter 3). Other than eighteen small ravine mouths and the relatively large Avonia Creek floodplain, almost the entire watershed's coast comprises bluffs (Fig. 4.2). The bluffs between Elk Creek Road and Culbertson Drive in the western third of the watershed comprise the tallest bluffs (~212 m MSL) in the entire WECLC due to the presence of highstand beach-ridge strata that are absent from other watersheds.

The Trout Run HUC-12 watershed comprises twenty-eight Lake Erie sub-watersheds (Fig. 4.17). There is an alternating pattern of watersheds that do not have well-developed surface drainage systems (fourteen generally small watersheds) and those that do (fourteen generally larger watersheds). For the former, a large percentage of the precipitation input is directed to groundwater recharge and ultimately to discharge at the lakefront bluff or bank face.

Bluffs along the westernmost 0.25 km of the Trout Run watershed have a "tiered bluff" geometry (PA DEP, 2013). At this location, an upper bluff face is separated from a lower bluff face by a plateau (tableland) as much as 70 m in width. This plateau is likely a remnant of a) a large prehistoric slump, or b) a prehistoric floodplain of Elk Creek formed when lake level was ~10-15 m higher than present. Both bluff tiers show evidence of erosion in the 0.3-0.6 m range. In sediment-volume calculations, sediment losses from the upper bluff face are excluded because sediment is stored on the plateau and not supplied to the littoral system on timescales of decades. In the central part of the watershed at the west side of Avonia Creek (Fig. 4.18), an accretional beach fillet as much as 60 m in width has accumulated on the updrift side of the groyne and jetty at the creek mouth and protects the bluff toe from wave attack. Sediment losses from the adjacent 125 m stretch of bluff are also excluded from sediment-volume calculations because sediment lost from the bluff gets stored on the beach backshore and is not released to the littoral system.

Concave-to-lake bluff-crest (cuspate) indentations with along-coast extents of several meters to 100 m are common in this watershed. Also common in the western quarter of the watershed where bluffs are highest are much larger, straight to curvilinear stretches of bluff edge indicative of translational slides. Examples of these translational slides that are 200 m and 1000 m in length occur at Lake Erie Community Park (Fig. 4.17(b)), and about 1 km east of the park at Ailes Avenue, respectively. Such large translational slides, active for decades to centuries, have at least one relatively continuous bench-headwall pair preserved on the bluff face that appears as crenulated topography on lidar and aerial imagery. This geometry indicates sequential failures (slides) over time, combined with more continuous, lower-magnitude soil creep. These visually sharp (on lidar and aerial imagery) stretches of cuspate and curvilinear crest lines indicate continuing erosion due to rotational slumps and translational slides in particular. A precipitous drop onto the bluff face of 1-4 m is the result of a steep (>70^0) slump headwall cut into lacustrine strata, or into overlying beach-ridge pea gravels, on the uppermost several meters of the bluff face. These near-crest sand and gravel horizons are less cohesive (~2 kg/cm^2; Dawson and Evans, 2001) than underlying glacial tills (~4 kg/cm^2) and characteristically have slopes that may exceed 90^0.

Shoreline Engineering

Approximately fifty-one engineering structures occur along this coast (one jetty at Richardson Drive and one at Avonia Creek; at least thirty-eight groynes; and eleven seawall sections totaling almost 400 m in length (Table 4.4). Three notable groyne fields occur at Godfrey Run, Wilson Drive, and Avonia Creek. At these locations, five to twelve groynes in each field have spacings of 8-150 m and range in length from 6-30 m. Near-filled to full sand and cobble fillets occur updrift (southwest) of most of the groynes.

Watershed Bluff Stratigraphy

The coastal stratigraphy for the Trout Run watershed comprises Devonian shale bedrock in the nearshore and surfzone; sands, gravels, and shale slabs defining the beach prism between the shoreline and the bluff toe; and occasional shale bedrock at the bluff toe overlain by very-stiff till, stiff till, and lacustrine sand horizons on the bluff face. Between Elk Creek and Serene Road/Nursery Road (Fig. 4.17(b)), which includes Site 4LECP, highstand beach-ridge sands and pea gravels cap the stratigraphic section. The bluffs at this location are thus capped by Warren paleoshoreline deposits (Schooler, 1974), and are the highest bluffs in the entire WECLC at ~212.3 m MSL.

Like all watersheds in the WECLC, shale bedrock is present just below lake level, in the surf zone and nearshore along the entire watershed. Along ~50% of the watershed, shale bedrock occurs above lake level at elevations of as much as 1 m. Between Serene Road/Nursery Road (just downdrift of Site 4EBSP; Fig. 4.17(b)) and Beach Drive/Hartley Road (just east of Site 5YMCA; Fig 4.17(c)), shale generally defines the lowermost part of the bluff face. Within this stretch, at Serene Road the shale defines the lowermost ~0.5 m of the bluff face, while at Godfrey Road the shale defines the lowermost ~0.25 m of the bluff face (Fig. 4.17(b)). To the east, near Hartley Road and Site 5YMCA, the shale increases in elevation, defining the lowermost ~1-2 m of bluff face (Fig. 4.17(c)). Further east, the shale decreases in elevation to near lake level and is frequently hidden by the beach prism. It locally reappears ~0.5 m above the backshore (for less than 100 m of coastline) at Melhorn Road and at Stephany Road just west of Avonia Creek (Fig. 4.17(c)). Further east, shale extends up the bluff face ~0.5 m between Lord Road and Pinegate Road/Eaton Road, then declines in elevation, disappearing beneath a thickening beach prism at the easternmost end of the watershed (Fig. 4.17(c)).

Watershed Bluff-Face Change Trends

The entire 10.3 km of bluff in this watershed is erosional and sediment storage on the bluff face is small and localized (Fig. 4.19; online map). About 75% of the bluff-face shows 0-0.3 m of elevation change during the 2007-2015 time period, while ~15% shows ~0.3-0.9 m of elevation change. Change in excess of 0.9 m occurs in small linear patches most commonly located near the bluff crest, particularly in Lake Erie Community Park and near Fairplain Road. These large-erosion patches on the top half of the bluff face indicate sediment removal from the upper till, lacustrine-sand, and beach-ridge pea gravel strata. Erosion in general is greater near the bluff crest across much of the watershed, typically occurring within elongate translational slides and shorter rotational-slump features that indicate retreat of the bluff crest (Fig. 4.19(a); online map). Between Fairplain Road and just east of Beach Drive (including the Site 5YMCA area) large swaths of elevation loss occur on the top half of the bluff face: this is one of the watershed's most significant erosional areas. The most severe erosion in the watershed occurs along an ~600 m stretch within Lake Erie Community Park where 0.3 to 0.9 m of elevation loss occurs. At the tiered-bluff area at the western edge of the watershed (Fig. 4.19(b)), and at the west side of Avonia creek where the bluff is set back from the present shoreline (Fig. 4.19(c)), bluff-face sediment losses occur but are consistently low (<0.3 m) compared to unshielded bluff areas elsewhere across the watershed.

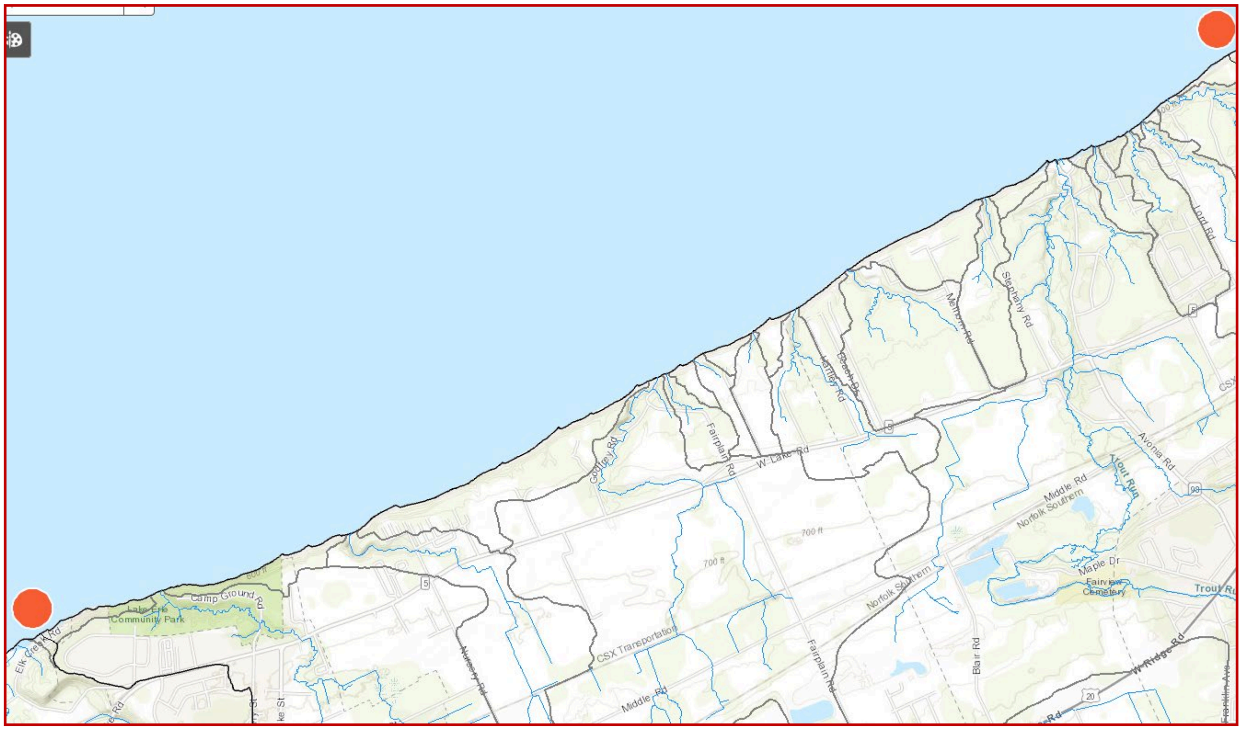


Figure 4.17(a)*: Map showing the 10.3 km long lakefront edge of the Trout Run watershed (extent delimited by orange markers). It extends from the east edge of the Elk Creek floodplain near Erie Bluffs State Park to the west edge of the Walnut Creek floodplain near Eaton Road. Twenty-eight Lake Erie sub-watersheds (grey line features) define this stretch of coast. Approximate map scale is 1:60,000. (source: pawalter.psu.edu)*

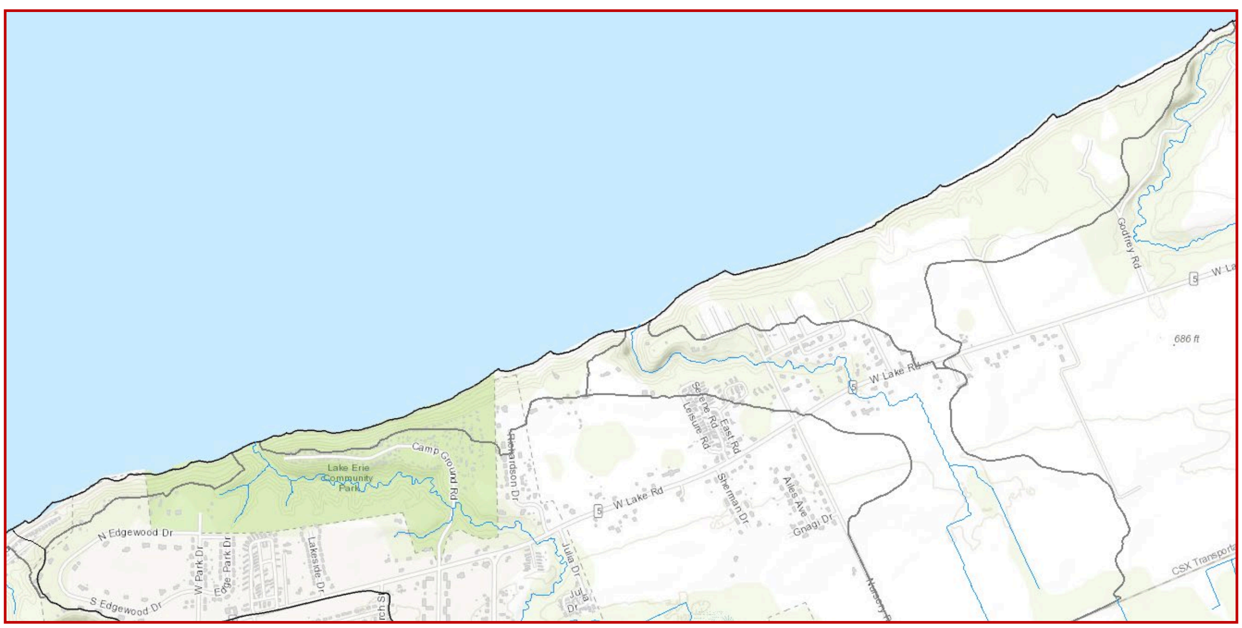


Figure 4.17(b)*: Map showing the western 5.15 km lakefront edge of the Trout Run watershed, extending eastward from North Edgewood Drive to Godfrey Road at Godfrey Run. Five Lake Erie sub-watersheds (grey line features) define this stretch of coast. Approximate map scale is 1:30,000. (source: pawalter.psu.edu)*

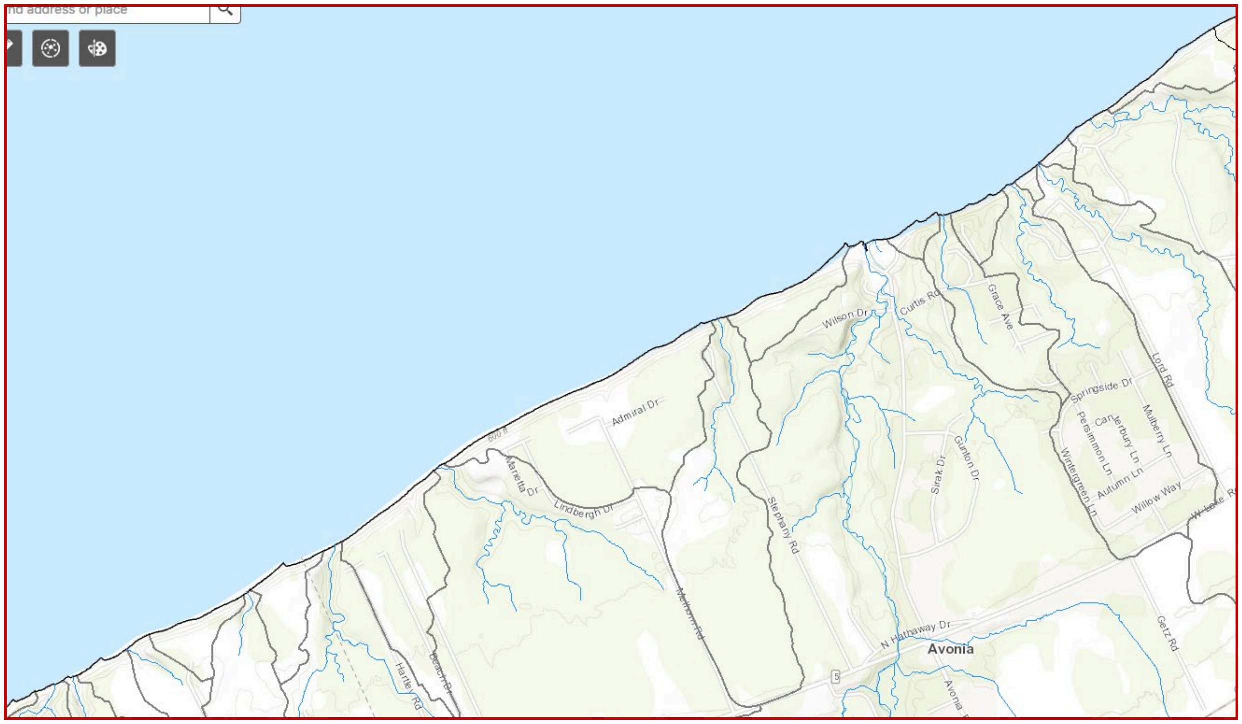


***Figure 4.17(c)**: Map showing the eastern 5.15 km lakefront edge of the Trout Run watershed, extending northeastward from Godfrey Road Run to near Eaton Road. Twenty-three Lake Erie sub-watersheds (grey line features) define this stretch of coast. Approximate map scale is 1:30,000. (source: pawalter.psu.edu)*

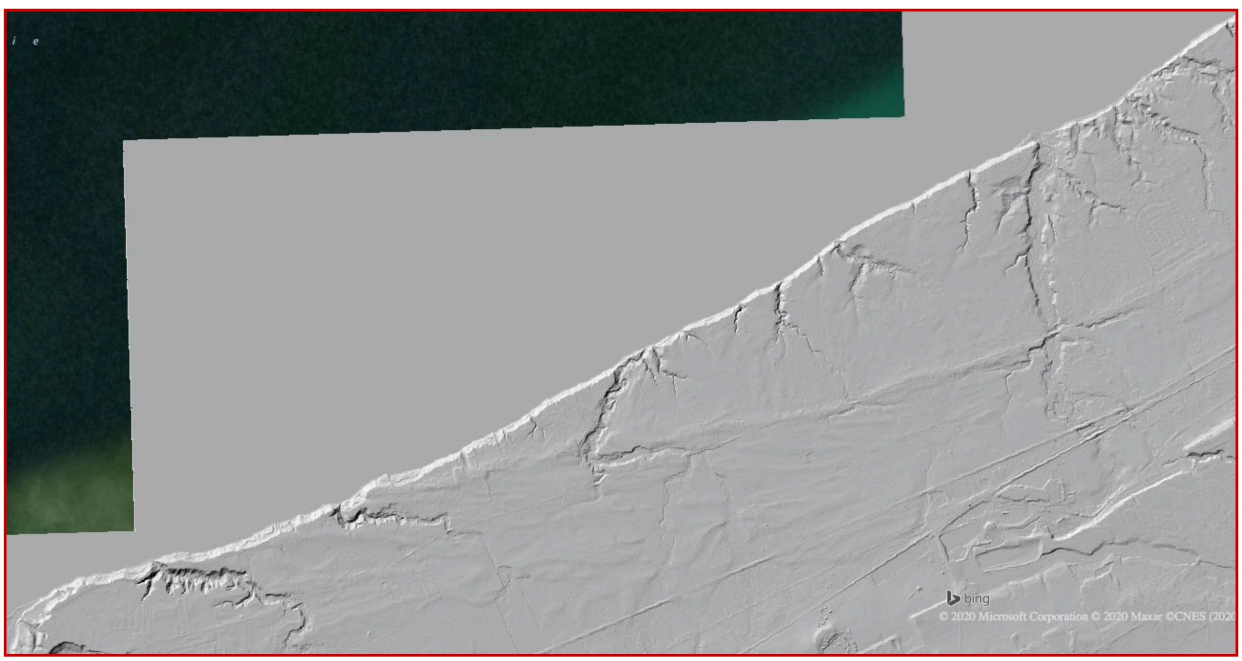


***Figure 4.18**: Section of 2007 DEM hillshade for the Trout Run watershed. Elk Creek traverses the landscape at the bottom-left of the image. Avonia Creek traverses the landscape near the right edge of the image. Lakeward-facing bluffs appear as lighter-toned curvilinear features due to "apparent sun" low-angle illumination from the north-northwest. The lake surface is represented by a simple flat, featureless surface at an elevation of ~174.5 m. Approximate map scale is 1:60,000.(map: pasda.psu.edu/uci/DataSummary.aspx?dataset=1247)*

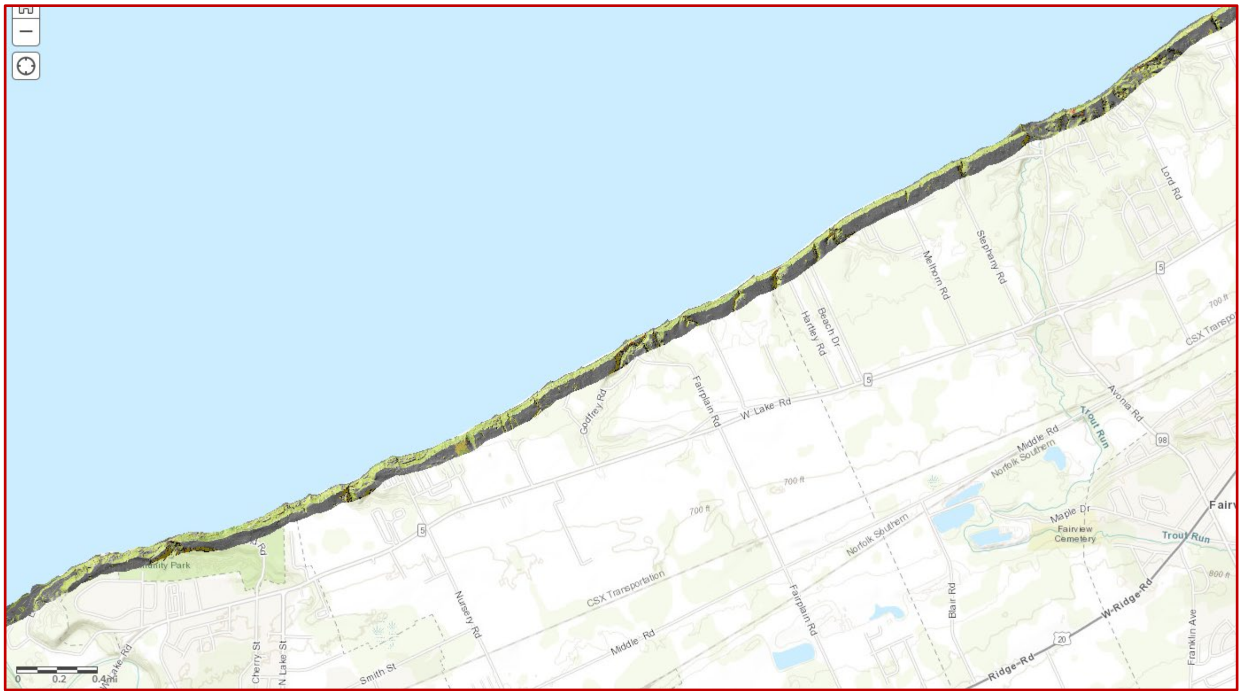


Figure 4.19(a): *Lidar surface-difference raster map (2007-2015) for the 10.3 km Trout Run watershed's bluff face overlain on a 150 m-wide DEM hillshade strip. On the bluff-face (narrow colored strip), cool shading denotes sediment losses while warm shading denotes sediment gains. Beach areas lakeward of the bluff toe, and ravines and creeks traversing the bluff crest, while shown here, are excluded from sediment volume calculations. Refer to online map for greater detail and legend. Scale bar is ~644 m (0.4 miles) in length.*

Figure 4.19(b): *Lidar surface-difference raster map (2007-2015) for the western 5.15 km of the Trout Run watershed's bluff face. Refer to online map for greater detail and legend. Scale bar is ~322 m (0.2 miles) in length.*

Figure 4.19(c): *Lidar surface-difference raster map (2007-2015) for the eastern 5.15 km of the Trout Run watershed's bluff face. Refer to online map for greater detail and legend. Scale bar is ~322 m (0.2 miles) in length.*

Large-change areas also occur lower on the bluff face, are not necessarily associated with crest retreat during 2007-2015, and are not as continuous in the along-coast direction. These occurrences indicate bluff-face steepening between the bluff toe and mid-face, which leads to greater slope instability and a propensity for future crest retreat. A large example (>0.9 m of elevation change over an ~450 m^2 area) occurs near Camp Ground Road at Site 4LECP and is inferred to be associated with erosion of a debris fan built with sediment lost from slumping higher on the bluff face prior to 2007. Ground movement associated with large translational slides (i.e., vertical displacement along hundreds of meters of bluff) is common on these bluffs between 2007 and 2015 (Fig. 4.19(b)), while bench and headwall evidence from the 2007 DEM also suggests a pre-2007 history of slope movement. Several areas have mid-slope zones of no sediment loss to net sediment gain whose areal dimensions indicate movement of much of the bluff face. The largest translational slide zones occur at Site 4LECP (three 5-20 m wide swaths ranging in length from 75-800 m; Fig. 4.19(c)); at Nursery Road/Culbertson Drive (25 m x 250 m); and at Marietta Drive/Melhorn Road (5 m x 200 m) east of Godfrey Run (Fig. 4.19(c)). Rotational slumps with notable elevation losses occur at the North Edgewood Drive (0.6-0.9 m) and Richardson Drive - Leisure Road areas (>0.9 m; Fig. 4.19(b)), with several individual slump failure areas as large as 200 m^2.

Minor apparent aggradation occurs along descending-elevation ridge lines that form where the sides of ravines transect the lakefront bluffs. The ravine aggradation anomalies result from a lower density of lidar ground strikes in one or both lidar datasets, the geometry of the lidar survey flight paths, and TIN-interpolation artifacts along these knife-edge features. A notably large bluff-face aggradation feature occurs at Grace Avenue just east of Avonia Creek (Fig. 4.19(c)). This anomaly has over 6 m of elevation change and is due to building construction and installation of retention walls and fill on the bluff face. These data-artifact and anthropogenic anomalies are excluded from sediment volume calculations.

Watershed Sediment Gains and Losses from the Bluff Face

Based on comparison of lidar-derived DEMs (Fig. 4.19 and online map), the Trout Run watershed shows ~7,300 m^3 of total-sediment gain, ~115,050 m^3 of sediment loss, and a net change of about –107,750 m^3 over the 2007-2015 time period (Table 4.1). Annualized, the net change is a loss of 13,470 m^3 of total sediment from this stretch of bluff face per year, or almost 1,330 m^3/bluff km/yr. This total-sediment material ranges in grain size from clay particles to shale pebbles and cobbles, to igneous boulders formerly encased within the glacial till.

Integrating this total-sediment volume with watershed stratigraphy and typical grain-size compositions of WECLC bluffs (Table 4.3), lakefront bluff retreat in the Trout Run watershed yielded an average of almost 4,600 m^3/yr of sand+ material to the littoral zone per year (Tables 4.2 and 4.3; 107,760 m^3 total-sediment x 34.0% sand+ content x 0.125). Normalized to volume of littoral sediment supply per kilometer of lakefront bluff, the sand+ sediment yield is just over 450 m^3/bluff km/yr, the second highest among WECLC watersheds. This sand+ sediment is sufficiently coarse to remain primarily in the littoral stream and is the material used to build and replenish a large component of the beach volumes in the WECLC and in the Presque Isle littoral cell immediately downdrift.

Walnut Creek Watershed

Coastal Geography

https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

The Walnut Creek watershed comprises 2.8 km of bluff coast located downdrift (NE) of the Trout Run watershed (Fig. 4.2). It extends eastwards from Eaton Road to just east of the Walnut Creek floodplain at Old Mill Road and includes the western part of Site 6LSCC used in Bayesian modeling (Chapter 3). Approximately 44% (1250 m) of the watershed lakefront consists of bluffs located updrift (SW) of the Walnut Creek floodplain (Fig. 4.20). Approximately 22% (620 m) consists of the Walnut Creek floodplain where the shore comprises natural beach and some engineering structures (low seawalls west of the Walnut Creek west jetty). About 22% (615 m) of the shoreline fronts the Walnut Creek boat-launch, parking, and facility areas between the Walnut Creek east jetty and Beechwood Drive. Approximately 12% (350 m) of the watershed lakefront is located east of the floodplain and includes the Site 6LSCC bluffs.

The Walnut Creek HUC-12 watershed comprises seven Lake Erie sub-watersheds (Fig. 4.20). Two of these sub-watersheds, at Lakeland Road and Fair Oaks Circle, respectively, do not have well developed surface drainage systems. This indicates that a relatively large percentage of the precipitation landing on these two watersheds is directed to groundwater recharge and ultimately to discharge at the lakefront bluff or bank face. The other watersheds are well drained by surface streams, particularly the Walnut Creek watershed. Short ravines, with a maximum inland extent of ~250 m, occur in both the western and the eastern bluff reaches (Fig. 4.21).

Frequent concave-to-lake bluff-crest indentations with along-coast extents ranging from several meters to 50 m characterize the bluff crest in this watershed. These visually sharp (both on lidar and aerial imagery) embayments are indicative of continuing erosion associated with rotational slumps in particular. A precipitous drop onto the bluff face, of 1-4 m based on observations across the study area, is the result of a steep (>70^0) slump headwall cut into the lacustrine sand strata that define the uppermost few meters of the bluff. This near-crest sandy horizon characteristically has steep slopes that may exceed 90^0.

Shoreline Engineering

Thirty-five engineering structures occur along this coast (two jetties at Walnut Creek; twenty-seven groynes; and six seawall sections totaling ~330 m in length (Table 4.4). Twelve groynes occur west of the Walnut Creek Marina, of which nine occur in a single groyne field near Eaton Road with typical lengths of 20 m and spacings of ~50 m. Four seawalls west of Walnut Creek are set back from the shoreline by as much as 55 m and individually range in length from 17 m to 115 m. Nine groynes and two jetties occur at Walnut Creek Marina, with lengths ranging from 8 m to 20 m with variable spacings. Six groynes are located east of the Manchester Beach property, with two seawalls totaling 110 m in length being located on the backshore at the bluff face. In general, sand and cobble fillets updrift (southwest or northwest) of most groynes are 50-75% full.

Watershed Bluff Stratigraphy

The coastal stratigraphy for the Walnut Creek watershed comprises Devonian shale bedrock in the nearshore and beneath the beach sediment prism; sands, gravels, and shale slabs located in the beach prism between the shoreline and the bluff toe; and very-stiff till, stiff till, and lacustrine strata on the bluff face. Shale bedrock begins to appear locally above lake level where the beach prism is small as the Walnut Creek watershed transitions to the Mill Creek (Mill Creek-West of this study) watershed downdrift. Beach-ridge sands and gravels found at the top of the bluffs in the Crooked Creek and Trout Run watersheds are absent from the lower-elevation bluffs in this watershed.

Bluffs increase in elevation slightly across the watershed, from ~199 m near on the western edge to ~201 m on the eastern edge. Lakefront bluffs comprise ~56% of the lakefront, with the remainder being floodplain.

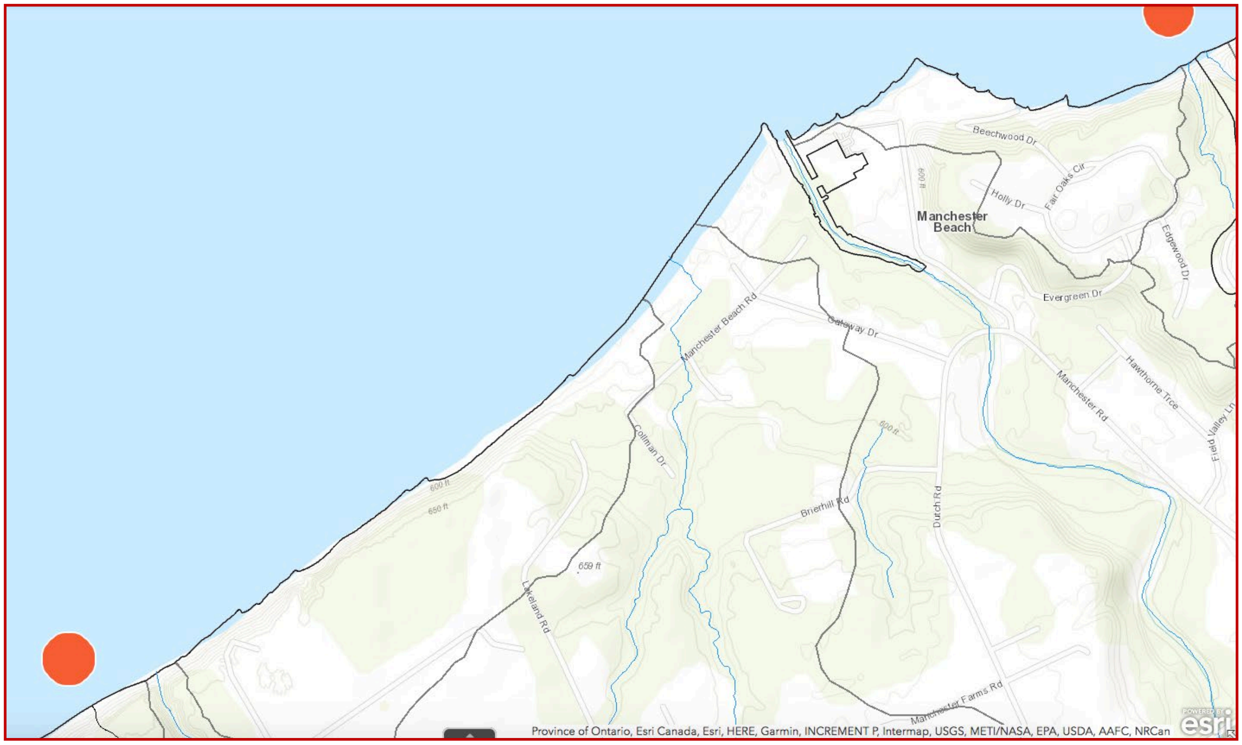


Figure 4.20*: Map showing the 2.8 km lakefront edge of the Walnut Creek watershed (delimited by orange markers). Seven Lake Erie sub-watersheds are also shown (grey line features). Approximate map scale is 1:14,800. (source: pawalter.psu.edu)*

Shale bedrock is present just below lake level, in the surf zone and nearshore along the entire watershed. Immediately updrift of Walnut Creek, an ~70 m wide beach and surfzone sediment prism becomes progressively narrower to the southwest when the bluffs redevelop near the west edge of the watershed. Downdrift of Walnut Creek, the beach prism is much narrower except at groynes which tend to be ~75% (symmetrically) filled.

Within the watershed immediately west of the Walnut Creek floodplain, bedrock locally lies ~0.25 m above April 2015 lake level of 174.25 m, then declines in elevation to below the beach prism at Collman Drive near the west limit of the floodplain (Fig. 4.20). Shale bedrock is then absent along the floodplain and the entire Walnut Creek access-area property. To the east of Walnut creek, bedrock does not extend above the beach backshore, primarily being hidden by the beach prism and by stretches of seawall. At the eastern edge of the watershed, bedrock reappears and extends ~0.4 m above the beach.

Watershed Bluff-Face Change Trends

The entire ~1600 m of lakefront bluff in this watershed are erosional (Fig. 4.22; online map). Over 60% of the bluff-face area shows 0.3-0.9 m of elevation change during the 2007-2015 time period, while <10% of the bluff face shows >0.9 m of elevation change. The remaining areas show less than 0.3 m of elevation change. Patches of more-significant erosion are most commonly located on the top half of the bluff face, indicating sediment removal from the upper till and lacustrine-sand strata.

Some of this erosion is located very near the bluff crest within rotational-slump features and indicates retreat of the bluff crest. An example of this can be seen in the western part of the watershed, north of the Lakeland Road. The most-erosional bluff areas lie northwest of Lakeland Road in the western half of the watershed, while the least-erosional bluff areas are sheltered from wave attack by the eastern end of the Walnut Creek floodplain/strandplain near Beechwood Drive.

Large-change areas on the lower on the bluff face are rare, occurring in the Lakeland Road area only. While not necessarily associated with crest retreat during 2007-2015, they indicate bluff-face steepening which leads to greater slope instability and a propensity for future crest retreat. There is no evidence of large translational slides (i.e., vertical displacement along hundreds of meters of bluff) during the 2007-2015 time period (Fig. 4.22; online map), nor from the pre-2007 period as shown on the 2007 lidar image (Fig. 4.21). The small number (<3) and size of slump failures during the 2007-2015 period (Figs. 4.21, 4.22) affected individual properties, rather than impacting many adjacent properties with lesser crest retreat that is more characteristic of translational slides (as seen in the western Trout Run watershed). A 70 m linear swath of as much as 0.9 m of sediment gain occurs on the mid-bluff face near the western edge of the watershed (Pinegate Road). An adjacent up-slope erosional swath of 0.3-0.9 m indicates that the elevation gain reflects sediment storage along the toe of a slump whose headwall is located near the bluff crest (online map).

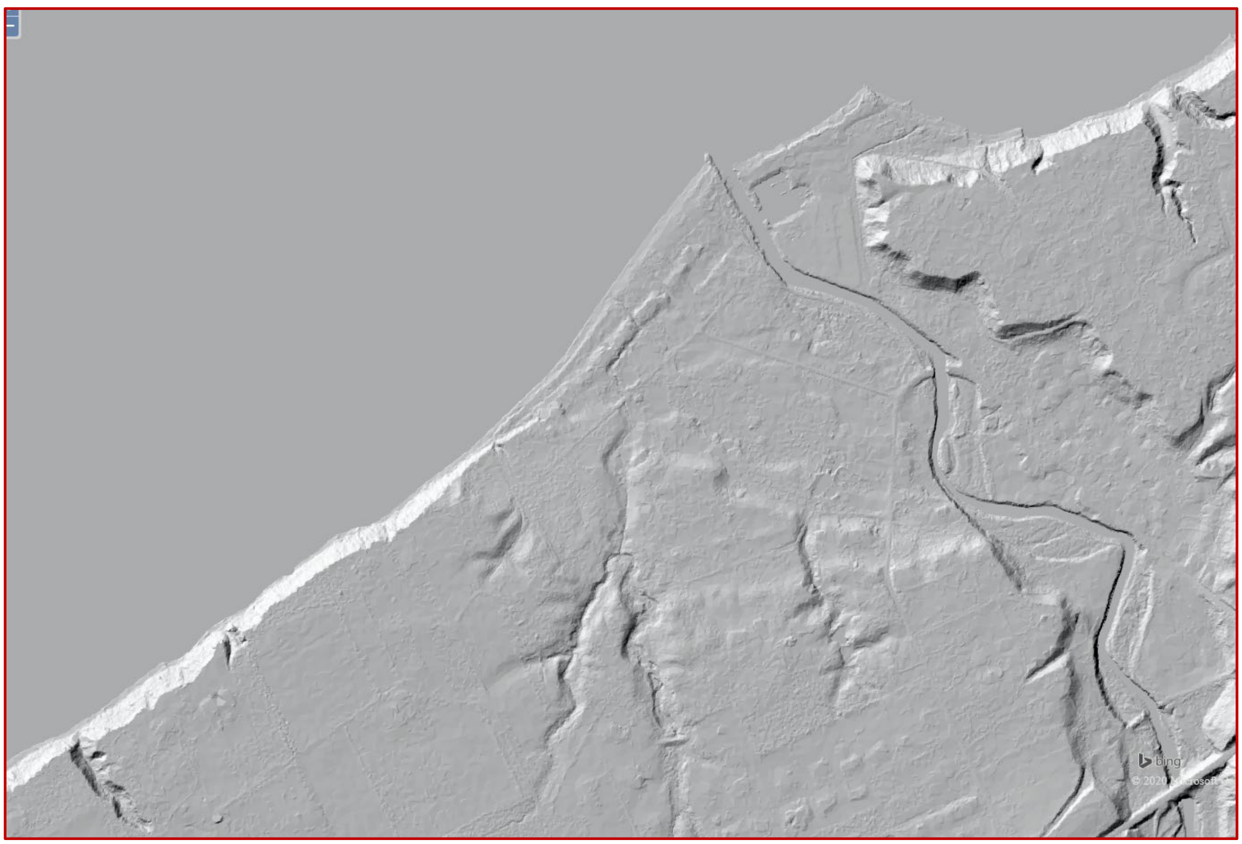


Figure 4.21*: Section of 2007 DEM hillshade for the Walnut Creek watershed. Walnut Creek traverses the landscape along the right side of the image and has generated a wide (~1 km) floodplain where lakefront bluffs are absent. Lakeward-facing bluffs appear as lighter-toned curvilinear features due to "apparent sun" low-angle illumination from the north-northwest. The lake surface is represented by a simple flat, constant-elevation, surface at an elevation of ~174.5 m. Approximate map scale is 1:14,800.*
(map: pasda.psu.edu/uci/DataSummary.aspx?dataset=1247)

Minor apparent aggradation occurs along descending-elevation ridge lines that form where the sides of ravines transect the lakefront bluff face. These aggradation anomalies result from a lower density of lidar ground strikes in one or both lidar datasets, the geometry of the lidar-survey flight paths, and TIN-interpolation artifacts along these knife-edge ridge features: these anomalies are consequently excluded from sediment volume calculations.

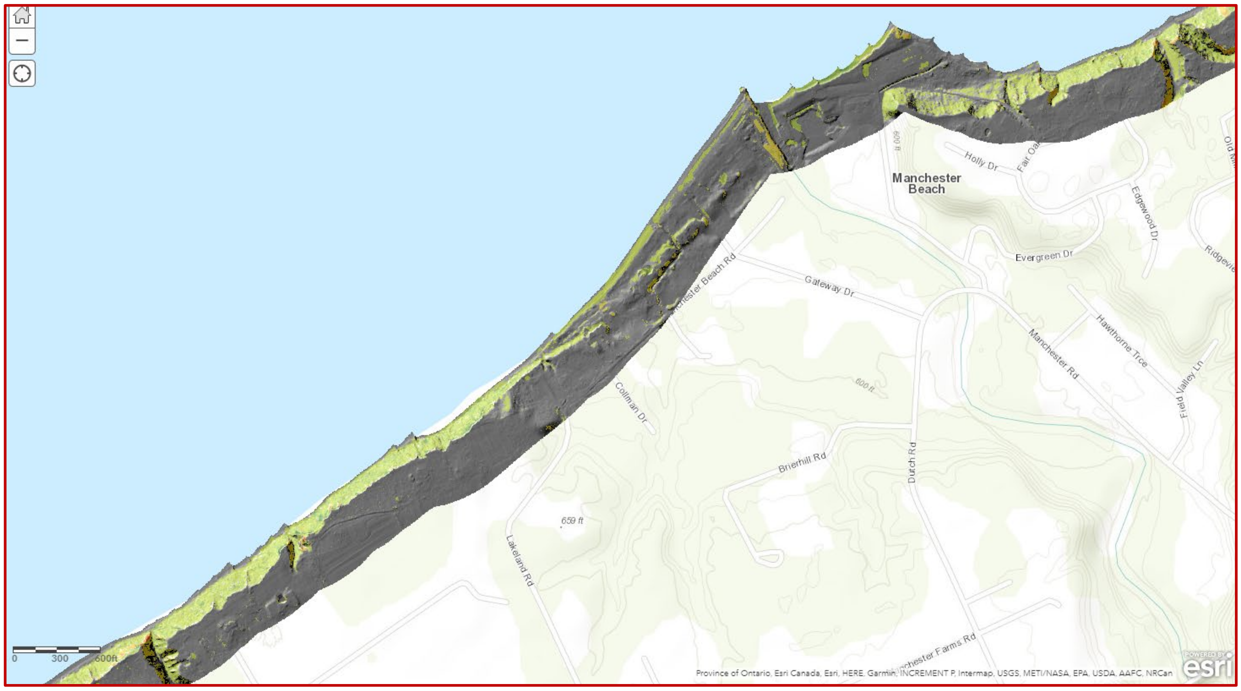


Figure 4.22: *Lidar surface-difference raster map (2007-2015) for the 2.8 km Walnut Creek watershed's bluff face overlain on a 150 m-wide DEM hillshade strip. On the bluff-face (narrow colored strip), cool shading denotes sediment losses while warm shading denotes sediment gains. Beach areas lakeward of the bluff toe, and ravines and creeks traversing the bluff crest, are excluded from sediment volume calculations. Refer to online map for greater detail and legend. Scale bar is ~183 m (600 ft) in length.*

Watershed Sediment Gains and Losses from the Bluff Face

Based on comparison of lidar-derived DEMs (Fig. 4.22; online map), the Walnut Creek watershed shows ~690 m^3 of total-sediment gain, ~15,420 m^3 of sediment loss, and a net change of almost –14,730 m^3 over the 2007-2015 time period (Table 4.1). Annualized, the net change is a loss of ~1840 m^3 of total sediment from this stretch of bluff face per year, or ~1,150 m^3/bluff km/yr. This total-sediment material ranges in grain size from clay particles to shale pebbles and cobbles, to igneous boulders formerly encased within the glacial till.

Integrating this total-sediment volume with watershed stratigraphy and typical grain-size compositions of WECLC bluffs (Table 4.3), lakefront bluff retreat in the Walnut Creek watershed yielded an average of ~570 m^3/yr of sand+ material to the littoral zone per year (Tables 4.2 and 4.3; 14,727 m^3 total sediment x 30.7% sand+ content x 0.125). Normalized to volume of littoral sediment supply per kilometer of lakefront bluff, the sand+ sediment yield is just over 350 m^3/bluff km/yr. This sand+ sediment is sufficiently coarse to remain primarily in the littoral stream and is the material used to build and replenish a large component of the beach volumes in the WECLC and in the Presque Isle littoral cell immediately downdrift.

Mill Creek-West Watershed

Coastal Geography

https://www.arcgis.com/home/webmap/viewer.html?webmap=562d1062e45844b9bcea7a85a9692933&extent=-80.5252,41.9597,-80.1496,42.1274

The western part of the Mill Creek watershed (i.e., Mill Creek-West watershed in this report) comprises 6.8 km of bluff coast without any significant floodplains. It is located downdrift (NE) of the Walnut Creek watershed (Fig. 4.2). It extends from just east of the Walnut Creek floodplain at Old Mill Road to Waldameer Park at East Kelso Drive where Presque Isle joins the mainland (Fig. 4.23). It includes the eastern part of Site 6LSCC and the entire Site 7BMDR used in Bayesian modeling (Chapter 3). The watershed marks the downdrift end of the WECLC where it adjoins the updrift end of the Presque Isle littoral cell. At Waldameer Park, the bluff is fronted by a large beach strandplain (~150 m wide) with an historic beach community along ~500 m of Lake Front Drive that is protected by a seven-unit groyne field.

The shore comprises natural beach areas, beach-free areas where lake waters are in contact with a bedrock bluff toe, and engineering structures (groynes, seawalls, rip-rap slopes). Lakefront land use is primarily low-density residential development. The Mill Creek-West HUC-12 watershed comprises thirty-two Lake Erie sub-watersheds (Fig. 4.23(a)). Fifteen of these sub-watersheds have poorly developed surface drainage systems and alternate with sub-watersheds containing creeks that transect the bluffs via ravines. A total of twenty-two ravines transect the bluffs in this watershed. Ravines are generally less than ~200 m in length, with the largest (2200 m) being associated with Wolf Run, near Wilkins Road, the only large creek exiting the watershed (Figs. 4.23(b), 4.24). The fifteen sub-watersheds without well-developed surface drainage direct a large percentage of their precipitation to groundwater recharge and ultimately to discharge at the bluff.

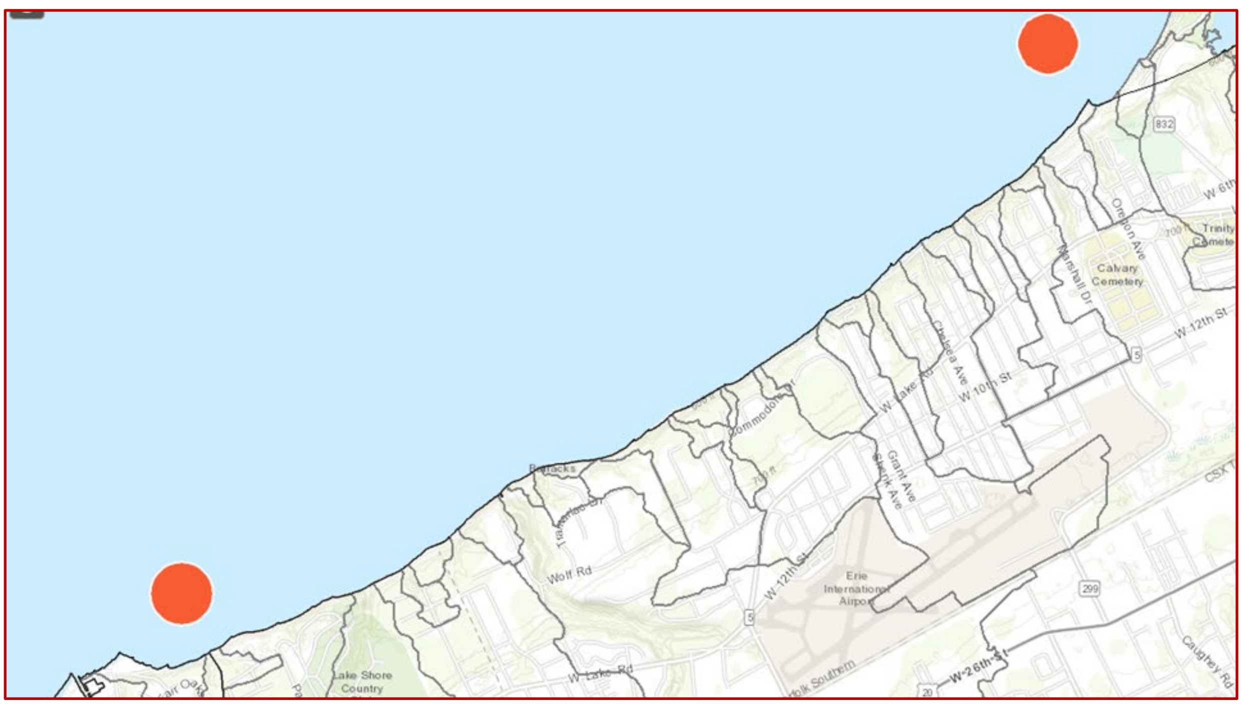


***Figure 4.23(a)**: Map showing the 6.8 km long lakefront edge of the Mill Creek-West watershed (extent delimited by orange markers). It extends from just east of Walnut Creek to a groyne at Waldameer Park where Presque Isle joins the mainland. Thirty-two Lake Erie sub-watersheds (grey line features) define this stretch of coast located at the downdrift end of the WECLC. Approximate map scale is 1:48,700. (source: pawalter.psu.edu)*

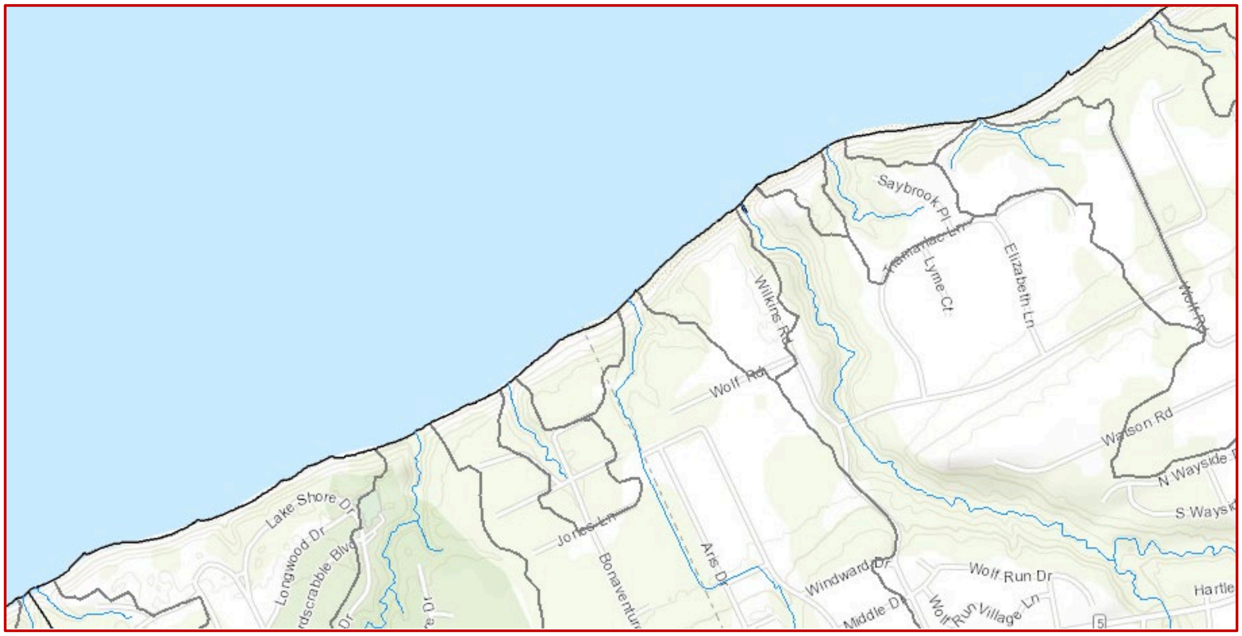


***Figure 4.23(b)**: Western 3.4 km of the Mill Creek-West watershed. Approximate map scale is 1:19,800. (source: pawalter.psu.edu)*

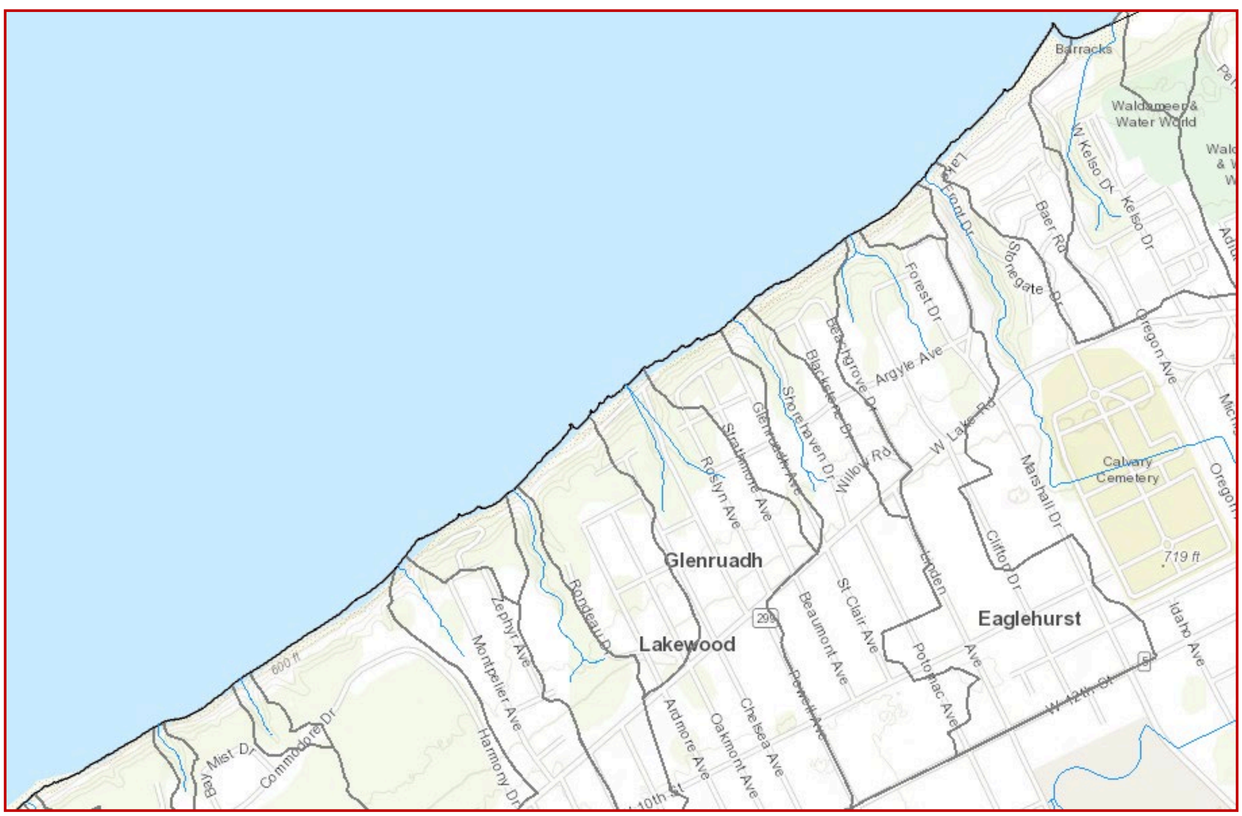


***Figure 4.23(c)**: Eastern 3.4 km of the Mill Creek-West watershed. Approximate map scale is 1:17,600. (source: pawalter.psu.edu)*

Concave-to-lake bluff-crest indentations with along-coast extents commonly ranging from 10-120 m characterize the bluff crest in this watershed. These visually sharp (on lidar and aerial imagery) concave embayments are indicative of continuing erosion associated with rotational slumps. A precipitous drop onto the bluff face, of 1-4 m based on observations across the study area, is the result of a steep (>70^0) slump headwall cut into lacustrine strata on the uppermost part of the bluff. This near-crest sandy horizon is less cohesive than underlying glacial tills and may develop slopes exceeding 90^0 (~2 kg/cm^2 vs ~4 kg/cm^2; Dawson and Evans, 2001). The larger slumps with along-coast extents of up to ~375 m, such as in the Bonaventure Drive-East Bonaventure Drive and Commodore Drive areas, contain stepped benches and scarps due to the presence of more than one curvilinear slip plane within larger translational slide features. Typically, the lakeward edges of the benches appear on surface-difference maps as narrow elongate swaths showing either no elevation change or a net gain in elevation of as much as ~1 m.

Shoreline Engineering

Approximately eighty-five engineering structures occur along the lakeward edge of the Mill Creek-West watershed (at least sixty-six groynes; nineteen seawall sections totaling ~1770m in length; Table 4.4). Many groynes are part of short groyne fields within a property or along a number of adjacent properties. Groynes show a large variation in spacing (~7 m where a short-groyne field buttresses a seawall, to ~250 m when several are present along adjacent properties). Groynes in this watershed have lengths in the 4-20 m range with a maximum length of ~80 m. The updrift fillets of most groynes are near-filled (2015 aerial-photo imagery; pawalter.psu.edu), primarily by littoral drift from the southwest. At the east end of the WECLC at Waldameer Park and West Kelso Drive (Fig. 4.23(c)), the bluff toe is separated from the lake by as much as 170 m of historical beach accretion on the updrift side of the WECLC's largest (80 m) groyne.

The ~19 individual seawalls range in length from 12-235 m and have a total combined length of ~1770 m. Most are back-filled to protect property, and one comprises a 50 m length of riprap to protect a gazebo. The variation in construction/design of seawalls in this watershed is greater than in the other WECLC watersheds. The greatest concentration of both groynes and seawalls occurs along the downdrift end of the watershed where beach-cottage communities have historically been built at the base of the bluff.

Watershed Bluff Stratigraphy

The bluff stratigraphy in the Mill Creek-West watershed comprises Devonian shale bedrock in the nearshore, while sands, gravels, and shale slabs define the beach prism between the shoreline and the toe of the bluff. When the beach prism is thin or patchy, shale is visible just beneath the beach sediments. When the beach prism is absent, shale bedrock locally "defines" the beach as a smooth, stepped wave-cut platform. Along ~75% of the shore, shale bedrock extends from 0.2-2.3 m above lake level, reaching its highest elevation at Site 7BMDR (177.2 m), which is the highest bedrock-toe elevation in the WECLC. At the west and east edges of the watershed, shale-top elevations decline so that bedrock is absent from the bluff face and lies buried beneath the beach sediment prism. Above the shale toe, the typical stratigraphy of very-stiff till, stiff till, and lacustrine sand strata make up the bluff face. Beach-ridge sands and pea gravels found at the top of the bluffs in the Crooked Creek and Trout Run watersheds to the west are absent from the bluffs in this watershed. The Mill Creek-West watershed has shale bedrock occurring at higher elevations over a greater length of shore than any of the other five WECLC watersheds.

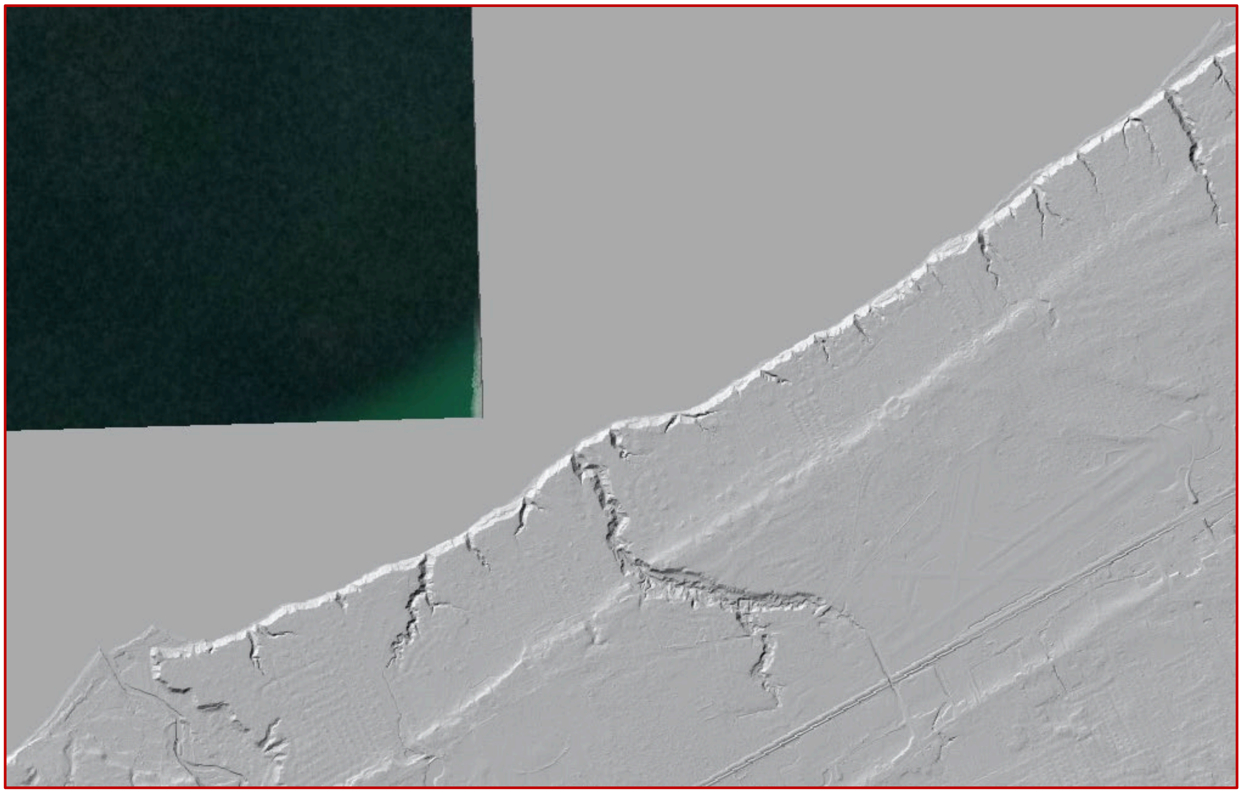


***Figure 4.24**: Section of 2007 DEM hillshade for the Mill Creek-West watershed. Walnut Creek is on the lower left, Wolf Run traverses the center of the image, and the root of the Presque Isle isthmus is on the upper-right edge. Lakeward-facing bluffs appear as lighter-toned curvilinear features due to "apparent sun" low-angle illumination from the north-northwest. The lake is represented by a featureless surface at an elevation of ~174.5 m. The approximate scale of the image is 1:25,300. (map: pasda.psu.edu/uci/DataSummary.aspx?dataset=1247)*

Like all watersheds in the WECLC, shale bedrock is present just below lake level, in the surf zone and nearshore along the entire watershed. East of Walnut Creek, shale appears on the lower 0.75 m of the bluff face north of Fernwood Drive, increasing to 2.1m above lake level (176.4 m elevation) along a beach-free stretch of shore at Lake Shore Country Club near Lake Shore Drive (Fig. 4.23(b)). The absence of significant beach in this area results in a pronounced ~2 m tall shale bedrock toe at the shoreline that extends alongshore for ~650 m. These are the second-highest bedrock-toe elevations observed in the WECLC. Between Bonaventure Drive and Elizabeth Lane (Fig 4.23(b)), numerous groynes and seawalls and an associated beach prism mask the shale with the exception of short (<5 m) shore stretches. East of Elizabeth Lane, the 2 m tall bedrock toe resumes, occasionally masked by localized beach accumulation updrift of groynes. The 2 m shale toe continues at Wolf Point Drive (east of a six-element groyne field and seawall) where the beach is absent, then declines in elevation eastward to occupy the lowermost 0.25 m of the bluff face by east Harmony Drive as the beach prism redevelops (Fig. 4.23(c)). East of Montpelier Avenue, beach-cottage development at the base of the bluff, with numerous seawalls, groynes, and stretches of beach, hides any evidence of shale bedrock at the bluff toe.

In general, the western ~75% of the Mill Creek–West watershed's shore, including Site 7BMDR, has a relatively continuous presence of shale bedrock at the bluff toe. This provides protection from wave attack for the overlying unconsolidated glacial and lacustrine sediments on the bluff face.

Along the eastern ~25% of the watershed, the absence of bedrock protection is compensated-for by an abundance of groynes and seawalls that protect the historical beach-cottage communities.

Watershed Bluff-Face Change Trends

In common with the other watersheds in the WECLC, the 6.8 km of bluff in this watershed are primarily erosional. Accretion occurs on ~4% of the bluff (Table 4.1). For the 2007-2015 comparison period, about 50% of the bluff face shows less than 0.3 m of elevation change, about 40% shows 0.3-0.6 m of elevation change, and about 10% of the bluff face shows more than 0.6 m of change. Elevation change of >0.9 m occurs in small localized swaths on ~5% of the bluff (online map). The majority of the more erosional swaths are located on the top half of the bluff face, indicating sediment removal from the upper till and lacustrine-sand stratigraphic horizons. This pattern also indicates bluff steepening over the observation period. Areas where erosion is located close to the bluff crest are largely within cuspate rotational-slump features and indicate retreat of the bluff crest (Fig. 4.25). Examples of this can be seen near Lake Shore Drive/Longwood Drive near the western edge of the watershed (Fig. 4.25(b)), and along Baer Beach Road near the eastern edge of the watershed (Fig. 4.25(c)). Vertical erosion in excess of 0.9 m is rare and most often associated with the headwalls of <20 m-wide rotational slumps. Linear swaths showing over 0.9 m of elevation change occur along ~400m of lower bluff near Voyageur Drive (Fig. 4.25 (c)) where groundwater drives retreat of glacial tills across bedrock producing a step in the bluff profile.

***Figure 4.25(a)**: Lidar surface-difference raster map (2007-2015) for the 6.8 km Mill Creek-West watershed's bluff face overlain on a 150 m-wide DEM hillshade strip. On the bluff-face (narrow colored strip), cool shading denotes sediment losses while warm shading denotes sediment gains. Beach areas lakeward of the bluff toe, and ravines and creeks traversing the bluff crest, while shown here, are excluded from sediment volume calculations. Refer to online map for greater detail. Scale bar is ~644 m (0.4 miles) in length.*

***Figure 4.25(b)**: Lidar surface-difference raster map (2007-2015) for the western 3.4 km of the Mill Creek-West watershed's bluff face. Refer to online map for greater detail. Scale bar is ~322 m (0.2 miles) in length.*

In general, elevation change at the toe of the bluff in excess of 0.3 m is rare, suggesting that subaerial processes, including groundwater discharge, are a greater driver of sediment loss higher on the bluff than wave attack for this watershed where shale bedrock is often present at the toe of the bluff. West of Wolf Road, sediment loss of over 0.6 m occurs along ~300 m of shore (Fig. 4.24(b)). This area has an ~2 m shale bedrock cliff at the base of the bluff but also has large wetland areas just inland (north of West Lake Road) with poor surface drainage. During the wet season, these wetlands overflow to flood Commodore Drive (Fig. 4.25(c)) as runoff moves downslope towards the coast. It is likely that these wetlands provide significant recharge to the groundwater system such that groundwater discharge rates at the shortened sediment column of the bluff face (due to the bedrock toe) may become high.

Several large historical slumps (pre-2007) remained active during the 2007-2015 comparison period, as indicated by narrow curvilinear patterns of elevation decline (sediment loss) or gain on the bluff face. These features are geomorphologically transitional between translational slides and rotational slumps. Examples near Bonaventure Drive in the western part of the watershed (Fig. 4.25(b)), and near Commodore Drive and Zephyr Avenue in the eastern half of the watershed (Fig. 4.25(c)), have notable internal benches and scarps that indicate the presence of more than one slip plane within the larger slump features. Narrow (<10 m wide) patches of sediment loss up to ~30 m in downslope distance occasionally occur on the upper two-thirds of the bluff face. These difference-map features indicate very localized, individual property-scale, slumps (chutes) with 2-3 m of elevation loss, locally reaching 3-6 m. Examples can be seen at Wolf Point Drive, Bay Mist Drive, and Baer Road in the eastern third of the watershed (Fig. 4.25(c)).

Figure 4.25(c)*: Lidar surface-difference raster map (2007-2015) for the eastern 3.4km of the Mill Creek-West watershed's bluff face. Refer to online map for greater detail. Scale bar is ~322 m (0.2 miles) in length.*

The most erosional sector of bluff in this watershed occurs near its eastern edge at Baer Road (Fig. 4.25(c); online map). Here the bluff shows an elongate swath of elevation loss on the top half of the bluff, predominantly in the 2-3 m range, with an along-coast extent of 250 m. Because the bluff toe is fronted by an historical community constructed on a wide strandplain, wave attack is not the driving process at this location: sediment supplied from this bluff sector is excluded from sediment volume calculations because it does not reach the littoral zone.

Large tracts of bluff-face steepening due to toe erosion did not occur between 2007 and 2015 (Figs. 4.25(b), 4.25(c)). The 2007 DEM surface does, however, indicate that historical translational slides, up to 300 m in length, occurred on the mid to lower bluff face prior to 2007. These occurred at the Longwood Drive, East Bonaventure Drive, and Saybrook Place areas of the watershed (Fig. 4.25(b); online map), and at the Commodore Drive, Zephyr Drive, and Baer Road areas in the eastern half of the watershed (Fig. 4.25(c); online map). These historical slides, now well-vegetated, resulted in slight progradation of the bluff toe as material moved downslope to accumulate on the beach backshore or at the shoreline to add sediment to the littoral system.

The largest amount of accretion in the Mill Creek-West watershed occurs just outside the WECLC in the Waldameer Park area. Bluff face accretion of 6-12 m appears to have an anthropogenic origin and is inferred to be due to slope reconstruction at that location (Fig. 4.25(c)). In common with other watersheds to the west, minor apparent aggradation also occurs along descending-elevation ridge lines that form where the sides of ravines transect the lakefront bluff face. Again, this type of aggradation anomaly results from a lower density of lidar ground strikes in one or both lidar datasets, the geometry of the lidar-survey flight paths, and TIN-interpolation artifacts along these knife-edge ridge features: these anomalies are consequently excluded from sediment volume calculations in this report.

Watershed Sediment Gains and Losses from the Bluff Face

Based on comparison of lidar-derived DEMs (Figs. 4.25(b), 4.25(c); online map), the Mill Creek-West watershed shows ~2,970 m^3 of total-sediment gain, ~64,590 m^3 of sediment loss, and a net change of over –61,620 m^3 for the 2007-2015 time period (Table 4.1). Annualized, the net change is a loss of ~7,700 m^3 of total-sediment from this stretch of bluff face per year, or ~1,220 m^3/bluff km/yr. This total-sediment material ranges in grain size from clay particles to shale pebbles and cobbles, to igneous boulders formerly encased within the glacial till.

Integrating this total-sediment volume with watershed stratigraphy and typical grain-size compositions of WECLC bluffs (Table 4.3), lakefront bluff retreat in the Mill Creek-West watershed yielded an average of ~2,720 m^3/yr of sand+ material to the littoral zone per year (Tables 4.2 and 4.3; 61623 m^3 total-sediment x 35.3% sand+ content x 0.125). Normalized to volume of littoral sediment supply per kilometer of lakefront bluff, the sand+ sediment yield is just over 430 m^3/bluff km/yr (Table 4.3). This sand+ sediment is sufficiently coarse to remain primarily in the littoral stream and is the material used to build and replenish a large component of the beach volumes in the WECLC and in the Presque Isle littoral cell immediately downdrift.

WECLC Watersheds Discussion and Analysis

Based on bluff-face topographic changes mapped in this study between 2007 and 2015, the net 8-year total-sediment and sand+ change for the bluffs were net losses of 318,400 m^3 and 105,850 m^3, respectively. Crooked Creek and Trout Run watersheds were the principal supply sources (Table 4.1, Table 4.2). Annualized, the bluffs in 2007-2015 supplied 39,800 m^3/yr of total-sediment (clay to boulders) and 13,250 m^3/yr of sand+ (sand to boulders) to the WECLC. The sand+ volume is 65% smaller than prior estimates for the 20th/21st Century era by Morang et al. (2011) and Cross et al. (2016). Total-sediment supply was 77% smaller. Estimated sand+ yields of ~430 m^3/bluff km/yr averaged across the six watersheds, however, are comparable to 475 m^3/km/yr turn-of-century (1990-2004) yields estimated for bluffs on the Ohio coast by Jones & Hanover (2014) and discussed in Chapter 2 (Table 4.2). Both of these yield estimates are only ~40% as large as the 1068 m^3/km/yr that can be derived from Morang et al. (2011) and Cross et al. (2016) for the Conneaut OH-Presque Isle coastal reach during the 1973/78-2006 (turn-of-century) era.

In their recent sediment budget analysis for the southern Lake Erie coast, Cross et al. (2016) used 1-km-long coastal reaches to generate sediment budget-related data. All reaches within the WECLC area used a single average crest-retreat rate based on ~50 DSAS transects per reach; an assumption that shale bedrock, lacustrine sands, and highstand gravels were absent; and treated the bluffs as a simple one-unit mass of cohesive glacial till. Glacial tills had an average sand+ content of 21% , ranging from an average of ~18% in the western half of the WECLC to ~23% for the eastern half. Sand+ content was as low as 7% along ~6 km of the Turkey Creek watershed. This 21% average sand+ content for the glacial till is somewhat less than the 22% and 29% sand+ averages for the stiff upper till and the very-stiff lower till, respectively, used in this study (Table 4.3). The 21% average is also lower than the entire-bluff average sand+ content we developed for each watershed within the WECLC. The HUC-12 watersheds ranged from ~28.9% sand+ (Turkey Creek) to 36.3% (Elk Creek) as shown in Table 4.3. The Cross et al. (2016) simple-stratigraphy assumption and lower sand contents assigned to the bluffs should have resulted in lower sand+ contribution estimates for their turn-of-century (1973/78-2006) period of high but falling lake levels (Fig. 4.26) compared to this study. However, using a parallel-retreat calculation method, which can overestimate sediment losses from multi-layered bluffs, partly explains why their turn-of-century volumes were about three times greater than those of this study (37,900 m^3/yr versus 13,250 m^3/yr). Also important, however, is that our study covered a weakly-transgressive, lower lake-level period, when less erosion would be expected than during the 1973/78-2006 period.

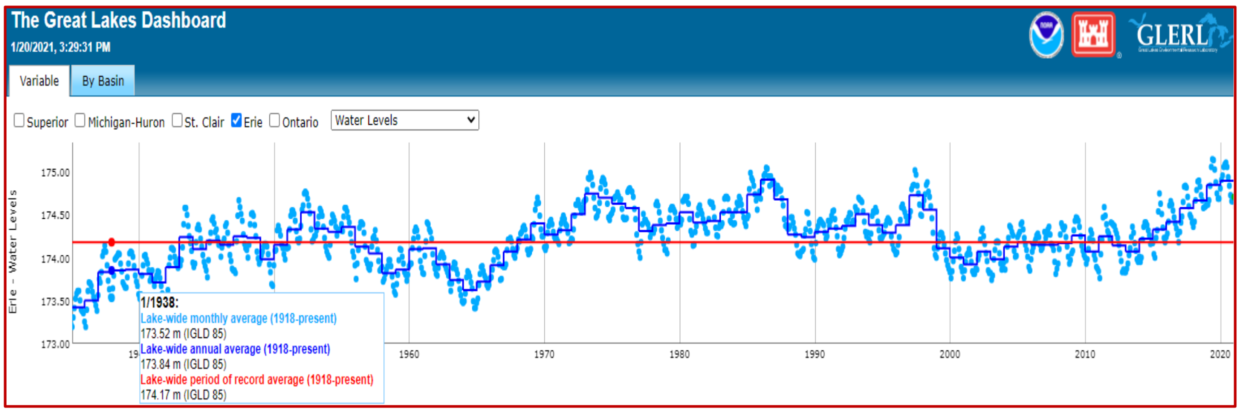


***Figure 4.26**: Water levels from 1936 to 2020 for Lake Erie encompassing the timeframe used in this study. Image modified from the NOAA Great Lakes Water Level Dashboard, 2020.*

Our new estimates of bluff sand+ input to the WECLC are lower than prior studies and contain some uncertainty (conservatively, ±50%). Estimates of individual HUC-12 watershed contributions of sand+ to the littoral system are quite variable and were previously unknown (Fig. 4.27). Our WECLC-wide estimate of bluff sediment losses is inferred to be more precise that prior studies because of (i) better, although still imperfect, resolution of stratigraphic complexity, (ii) a DEM-differencing approach that allows higher resolution mapping of topography and elevation changes across the bluff face at ~1 m point spacings, and (iii) better tracking of slump-supplied sediment accumulations (gains) on the bluff face that partially offset some (~5%) of the loss volumes (Table 4.1, Table 4.5). Our volumes are lower than similar-era prior studies for several reasons. The 8-year comparison may not have captured large but infrequent bluff sediment-supply events that would have a higher probability of being captured by analyses covering several decades. A likely decades-scale process-response time lag between lake level and bluff erosion means that much of the 2007-2015 bluff face may have been responding primarily to lower and more uniform lake levels during the 1999-2011 time period (Fig. 4.26). And lastly, our observation window occurred largely within a longer 12-year period of relatively low and stable, weakly-transgressive, lake levels between 1999 and 2011. In other words, the bluffs by 2007-2015 had not yet ramped up sediment supply to the littoral zone in response to a slow post-2001 rise in lake level that accelerated in 2012 and continued through 2020. Process-response lag times on the Great Lakes have been estimated to range from ten to fifty years (Knuth and Lindenberg, 1995; Baird, 2003).

WECLC Watershed	Total Gain (Cu Ft)	Total Loss (Cu Ft)	Net Change (Cu M)	Bluff Area (Sq M)	Avg Elev Change (M)	Magnitude
Mill Creek	104,742	-2,281,296	-61,624	301,397	0.224	
Walnut Creek	24,512	-544,673	-14,727	65,289	0.247	
Trout Run	257,573	-4,063,688	-107,761	489,899	0.250	
Elk Creek	69	-21,825	-616	3,012	0.206	lowest
Crooked Creek	70,603	-3,344,903	-92,704	236,056	0.410	highest
Turkey Creek	107,233	-1,553,919	-40,959	134,962	0.348	
WECLC-Wide	**564,732**	**-11,810,304**	**-318,391**	**1,230,615**	**0.285**	

Table 4.5: *Total-sediment gain, loss, and net change volumes; bluff-face areas affected; and vertical elevation change and magnitude on the bluff face by WECLC watershed. Note mix of English and Metric units.*

Lake level is a principal factor that determines wave impact severity and frequency at the bluff face (Fig. 4.26). Lake level thus influences bluff sediment supply to the littoral zone, with larger sediment supplies associated with higher lake levels (and with stormier and wetter climate). The 37,900-39,500 m^3/yr of bluff-derived sand+ supplied to the littoral zone between Conneaut, OH and the Presque Isle peninsula during the 1973/78-2006 time period (Morang et al., 2011; Cross et al., 2016; Chapter 2) occurred during an initially high but punctuated fall in lake level of ~0.5 m (Fig. 4.26). This regression, expectedly, contributed less bluff sediment to the littoral zone when compared to a sand+ input of 61,000 m^3/yr during an earlier 1938-1973/78 transgression (Morang et al., 2011). The recent 1973/78-2006 regressive-era sand+ volume was also similar to an 1875-1938 regressive period when sand+ input was 47,000 m^3/yr (Morang et al., 2011; Chapter 2).

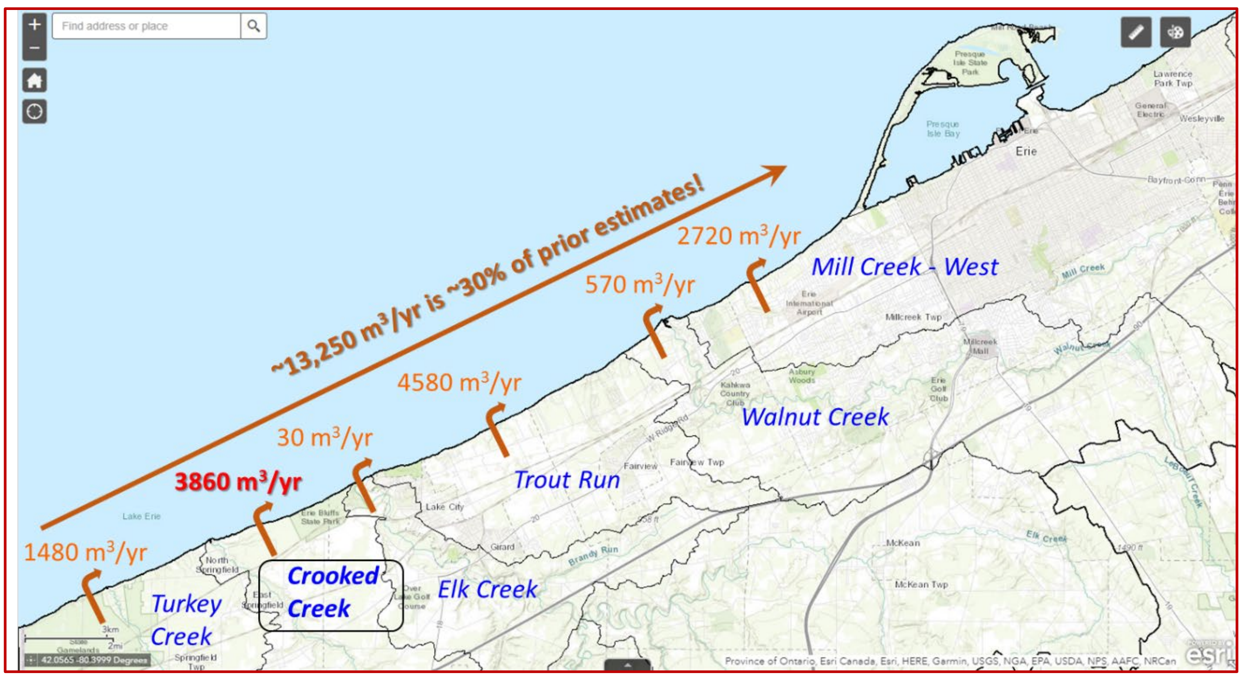


Figure 4.27*: Sand+ contributions to the WECLC by the six HUC-12 watersheds in western Erie County (2007-2015). Most or all of the combined volume exits the WECLC downdrift and enters the Presque Isle State Park littoral cell. The Crooked Creek watershed is the most productive sand+ supplier on a per-km basis.*

Because this study's 2007-2015 observation period was only weakly transgressive, bluff sediment supply to the littoral system would have been expected to be less than that of the 1938-1973/78 transgressive period. This was the case, because the smaller sand+ volumes supplied during 2007-

2015 were associated with both a lower magnitude transgression (lake level rose by just ~0.18 m) and with a relatively steady lake level hovering near long-term average during the first 6 years of that era (Fig. 4.26). The 2007-2015 period also supplied less sand to the littoral stream than occurred during the 1973/78-2006 regressive period because the bluff toe likely experienced more wave-impact hours and less protection from beaches during that higher lake-level era.

As discussed in Chapter 2, lower crest-retreat rates occurred along the WECLC during the 2007-2015 era relative to the 1938-2007 era used in this project's Bayesian analysis (Fig. 2.12). Because lower retreat rates are more likely to be associated with less sediment loss from the bluff face, it can be inferred that bluffs during the 1938-2007 period supplied more sand+ to the littoral zone than they did during 2007-2015. Lower retreat rates over the 2007-2015 period likely occurred because multiple transgressions between 1938 and 2007 resulted in periods of substantially higher lake levels than occurred during 2007-2015 (Fig. 4.26). Additionally, the longer-term 1938-2007 record would also have captured more of the large and infrequent failure events that cause major jumps in the position of the bluff crest.

Considering the physical processes involved in bluff retreat, retreat rates and sediment supply from bluffs should be lower when, individually, the following conditions are satisfied: the beach prism is larger (beach width is large and toe elevation is well above lake level), SPR resilience is high, the top of bedrock is well above lake or backshore level, groundwater flux is low, bluff-face slope is low, and wave impact hours are reduced. The majority of these attributes are most likely to occur during periods of lowered lake level. In natural systems, however, these attributes would rarely operate in isolation because interactions and feedbacks would occur. The Bayesian Network model in Chapter 3 examines how these individual attributes can interact, establish positive and negative feedbacks, and drive bluff-crest retreat rates.

The Crooked Creek watershed in the western WECLC lost the largest annualized sediment volume (both total and sand+) per kilometer of bluff coast among all six HUC-12 watersheds (Fig. 4.27; online map; Tables 4.1 and 4.2). It also experienced the largest amounts of watershed-averaged bluff-face elevation change, indicative of the high erosion rate (Table 4.5). In general, the top half of the bluff lost more sediment than the lower half, and cuspate patterns indicative of large deep rotational slumps are more prevalent than in other watersheds (Fig. 4.28). The 2007-2015 period of relatively high erosion may presage slower bluff retreat going forward. This is because bluff slopes were reduced in many areas during the observation period: the crest and upper slopes lost material with no obvious occurrences of comparable-magnitude steepening and toe retreat on the lower bluff (online map).

Overall, total-sediment and sand+ volume losses were greatest for the Trout Run watershed, which has the longest WECLC lakefront. When normalized to cubic meters of total-sediment and sand+ supplied to the littoral zone per kilometer of bluff, its significance declines relative to that of the Crooked Creek watershed. In fact, the Crooked Creek watershed supplied 53% more sand+ (relative to the Trout Run watershed) to 220% more sand+ (relative to the Turkey Creek watershed) to the littoral zone than any other WECLC watershed. The eastern half of the Crooked Creek watershed's lakefront bluffs are notable in that they are located within Erie Bluffs State Park where there is no coastal infrastructure at risk from bluff retreat.

The WECLC-average amount of vertical change on the bluff face is ~0.3 m when averaged across all six watersheds. The elevation change, representing sediment loss and gain on the bluff face, varies by watershed, being greatest for Crooked Creek (~0.41 m) and lowest for Elk Creek (~0.21 m). Scattered gains in elevation on the bluff face are a consequence of bluff-face deformation at slumps and of partial sediment storage lower on the bluff from upslope failures. As much as 6.5% of sediment moving from a given location on the bluff may be stored on the bluff downslope (see online map). Overall, the sediment-loss volumes from the bluff face are about 20 times larger in magnitude than the gain volumes (Table 4.1).

***Figure 4.28**: Sand+ contribution to the WECLC by erosion on the bluff face of the Crooked Creek watershed amounted to 3860 m³/yr between 2007 and 2015. Darker brown shading on this map indicates that greater sediment losses are generally more prevalent on the top half of the bluff face. See online map for greater detail.*

There are several coastal-management related implications of our findings. Estimates of bluff contributions to littoral sand+ transport along the WECLC, based on the surface-differencing methodology, are lower than previously estimated both for the recent 20th/21st Century era and for the mid-20th Century era. This suggests that sediment budget assumptions currently being used for coastal sand management and erosion mitigation downdrift at the Presque Isle State Park littoral cell may benefit from revision to account for the smaller, 2007-2015 era, sand+ input to that cell from the WECLC. The small 2007-2015 volumes are interpreted to be representative of sand contributions to the littoral system during periods when lake level is near long-term average and a weak-transgressive trend is present (such as 1999-2015). Sediment supply associated with this lake-level scenario has not been quantified before for the Pennsylvania coast and is valuable because such average lake level/weak-transgressive periods do occur in the record (e.g., 1944-1956) and will likely recur (Fig. 4.26). Incorporating such a sediment-supply revision for the Presque Isle littoral cell would influence estimates of sand nourishment quantities required to mitigate beach erosion at Presque Isle over the coming decades. Such average lake-level scenarios may also be opportune periods for artificial sand bypassing at large coastal structures such as Conneaut Harbor, OH. During such periods, littoral sediment transport volumes along the WECLC would be low and would thus benefit more from artificial-bypass inputs. Additionally, the logistics of artificial bypassing may be easier when lake levels are near or below their long-term mean. Cross et al. (2016) estimated that 10,300 m³/yr of sand naturally bypassed Conneaut Harbor prior to 1938 and that the bypass rate has been zero through 2006.

While the 13,250 m^3/yr of sand+ supplied to the WECLC by bluff retreat is small relative to estimates of turn-of-century rates by the US Army Corps of Engineers (Morang et al., 2011; Cross et al., 2016), the volume is interpreted to be representative of lake-level conditions leading up to and during the 2007-2015 period. The volume is also smaller than a Nummedal et al. (1984) estimate of 30,000 m^3/yr of potential littoral sediment transport at the Presque Isle isthmus immediately downdrift. That study of the late 20th Century period used hindcast wave power estimates at Presque Isle State Park to determine how much sandy material could potentially be carried along-coast in the littoral system given the wave climate. Conceptually, if the rate of potential littoral sediment transport is not matched by actual sediment input, erosion will occur in a littoral cell; if sediment supply is greater than potential littoral sediment transport, coastal accretion (beach growth) can be expected. Given that the southern Lake Erie coast is in general sand-starved along its eastern Ohio to western NY sector, it is understandable that sand+ volumes in the WECLC could be less than the potential transport volumes calculated by Nummedal et al. (1984) at Presque Isle. If they were greater, erosion along the Presque Isle isthmus would be significantly less than it has historically been, and the need for hard stabilization to address a littoral sediment deficit would also have been less.

The most important source of sand+ material to the WECLC, and to Presque Isle State Park that depends on sediment output from the WECLC, is the Crooked Creek watershed. It represents ~18% (6 km) of the WECLC's total length but supplies ~30% of the sand+ sediment entering the WECLC from bluff retreat that subsequently moves downdrift to the Presque Isle littoral cell (Table 4.2). Three kilometers of the Crooked Creek lakefront are located within Erie Bluffs State Park, a stretch of aesthetically pleasing, natural, tall-bluff coast that supplies ~50% of the Crooked Creek watershed's sand+ output to the WECLC. Because of this, Erie Bluffs State Park is worth consideration as a bluff conservation/feeder bluff zone (Shipman et al., 2014) because it supplies a critical percentage of the sand+ provided to the littoral system by bluff retreat. Given that only ~1,000 m^3/yr of sand+ may be entering the WECLC from the Ohio coast (Jones and Hanover, 2014), this local sediment source becomes even more important. The Crooked Creek watershed also has the lowest spatial density of coastal-engineering structures among all watersheds with the exception of Elk Creek (Table 4.4). The three kilometers of watershed within Erie Bluffs State Park do not have any coastal-engineering structures influencing littoral sediment transport, and there is no upland infrastructure at risk from bluff retreat. The sand+ provided to the WECLC from the Crooked Creek watershed amounts to almost 700 m^3/bluff km/yr, which is 53-220% greater than any other WECLC watershed (Table 4.3). Maintaining the park bluffs in their aesthetically pleasing, naturally eroding state would be beneficial to the Pennsylvania littoral system as a whole, and particularly to that part of the system updrift of the Erie entrance channel.

5 Summary and Conclusions

***Figure 5.1**: The Western Erie County littoral cell (WECLC) located between the OH-PA state line (lower left) and Presque Isle State Park (top right). Approximate map scale is 1:190,000. (Image: google.com/maps)*

This project completed high-resolution continuous mapping of the lakefront bluffs along the northwestern Pennsylvania coast of Lake Erie. Crest elevations were obtained at <1 m intervals, and bluff-face topographic changes were mapped every ~1 m^2, along the 33.5 km WECLC coast. Such data represent a valuable addition to the regional geo-environmental knowledge base and allow improved understanding of bluff behavior. The project used Bayesian Network modeling to explain past bluff-retreat patterns and to simulate future bluff-crest retreat through 2065. The importance of bluff retreat as a contributor of sediment to the littoral transport system during average lake-level conditions was established using GIS change-detection analysis on a watershed by watershed basis.

Causes of Bluff Retreat

The Bayesian Model was developed for seven 1-2 km long study sites representative of coastal conditions and the six HUC-12 watersheds within the WECLC. The overall modeling goal was to improve understanding of coastal processes driving bluff retreat and associated hazards on the Pennsylvania coast. Bayesian models can explain and predict the location and magnitude of geohazards by defining joint-probability density functions that relate forcing variables and initial conditions to geologic events such as bluff retreat. Bluff retreat on the Erie County coast is suited to Bayesian analysis because bluff failure may be related to identifiable pre-existing conditions, there are a reasonable number of constrainable environmental processes, and long- and short-term bluff-retreat rate data are available.

In this bluff-retreat application, geodata were compiled from coarse-scale environmental data sources and shore-normal DSAS transects spaced at 20 m intervals along each of seven WECLC sites. The model-input data were binned so that discrete probability distributions were created to examine how input variables and retreat rates were causally related. The Bayesian Network model was built using the R statistical programming language and a *bnlearn* package.

The network model was built to explain historical change in coastal bluff-crest location (1938-2007) and then evaluated on its ability to predict "future" change over a recent (2007-2015) validation window. The model was then used to simulate future crest retreat for each of the seven WECLC sites (Sites 1STGL through 7BMDR). The simulations looked out into the future for 10, 25, and 50 years (through 2025, 2040, and 2065, respectively). These time windows approximated (i) the average duration of individual-home ownership in the United States, (ii) a typical mortgage duration, and (iii) a time duration used in defining construction setbacks on the Pennsylvania coast. The Bayesian Network model initially relied on nine data inputs and one dependent-variable dataset (2007-2015 bluff-retreat rate). Only transects in which all input variables and a 2007-2015 retreat rate were present were used during the model fitting process, resulting in 414 transects with usable data (88% of the entire 470-transect dataset). In total, 511 models were examined and included one model with all nine inputs, nine models each with one or eight inputs, 26 models each with two or seven inputs, 84 models each with three or six inputs, and 126 models each with four or five inputs. The initial runs of the model used:

(i) A long-term historical bluff retreat rate (1938-2007) as the *prior-behavior* parameter.
(ii) Six *initial-state* parameters of bluff height, bluff slope, bluff stratigraphy (expressed as geotechnical resilience), beach prism width, bluff toe elevation (expressed as beach thickness), and top-of-bedrock elevation.
(iii) Groundwater flux at the bluff face and wave energy (expressed as wave-impact hours) at the bluff toe. These were the two expected dominant *forcing agents* in the WECLC.

Using k-fold cross-validation, the optimal model was one in which eight of the nine possible inputs were used. These inputs included SPR resiliency, long-term retreat rate, bluff face slope, beach prism width, toe elevation, top-shale elevation, bluff height, and wave impact hours. Fitting the final model with all 414 transects, it correctly predicted the 2007-2015 retreat-rate bin 395 times, or for 95.4% of the transects (a *correct-classification rate* of 395 out of 414). This is a measure of the percentage of times the observed 2007-2015 retreat rate bin matched the bin with the highest predicted posterior probability. The predicted value was assumed to correctly match if the observed 2007-2015 retreat rate matched the bin with the largest predicted posterior probability. The prediction was also considered to be correct if the largest predicted posterior probability was tied among multiple bins (two bins in 80 cases, three bins in 9 cases) and the observed 2007-2015 retreat rate was among those bins. If ties were excluded, the model predicted 71.5% of the binned short-term rates correctly.

A method to assess model fit that considers the uncertainty in the model predictions is to average the predicted probability of being in the observed 2007-2015 retreat rate bin for each transect. This approach takes into account the confidence in predicting the correct short-term retreat rate, not just the percentage of times the correct short-term retreat rate is correctly predicted. When using the final model with all 414 transects, the *mean predicted posterior probability* of the observed 2007-2015 retreat rate was 84.1%. This value was used as a baseline to determine the importance of each input in the model. For the final 8-element model, the two most important inputs were long-term retreat rate (caused a 14.3% reduction in prediction probability if removed) and bluff face slope (caused a 13.8% reduction in prediction probability if removed). The third most important variable was toe elevation/beach height, which was also determined to be the best model via k-fold cross validation when only one input was used. This means that when building a

1-element model using any one of the nine geodata inputs, toe elevation/beach height was the best-performing input of the nine as a predictor of crest retreat.

The Bayesian Network model suggests that, in fundamental terms for property owners, long-term retreat rate, bluff face slope, toe elevation and beach prism volume together explain most of the predicted 2007-2015 crest-retreat rates. Groundwater flux within the model appears to have only a minor influence because the model skill degrades when it is included (Table 3.3). The reason for this is uncertain and may be due to imperfect quantification of the groundwater flux through WECLC watersheds.

The 8-element Bayesian Network model was used to simulate future positions of the bluff crest at each of the seven WECLC sites for the years 2025, 2040, and 2065 (using 2015 as the starting year). The plots for all three simulation periods show that, as has been true historically, simulated future retreat is spatially very variable between nearby transects and between field sites. Over the next 50 years, bluff-crest retreat at the seven WECLC sites may be expected to range from 1 to 15 m depending on location, using a 10-transect moving average. That represents a range of crest retreat rates of 0.02 to 0.3 m/yr, within the range of values for historical bluff retreat. However, an implicit assumption here is that environmental conditions going forward do not vary any more than they have during the 1938-2015 timeframe used to build the Bayesian Network.

The 50-year simulation shows relatively consistent but greater future retreat for Site 1STGL, and for Sites 4LECP and 5YMCA (in the Trout Run watershed) compared to other sites. Simulated retreat averages ~8 m by 2065. Four sites (2RACK, 3EBSP, 6LSCC, 7BMDR) tend to show more within-site variability in amounts of simulated retreat by transect. Simulated retreat is, on average, generally similar across all sites, with the lowest simulated retreat occurring at Sites 2RACK, 3EBSP, 6LSCC, and 7BMDR. This is significant because the long-term historical record shows major retreat for Sites 1STGL and 2RACK in the Turkey Creek watershed (rates ~2X those of other WECLC sites): this trend weakens in the future simulations. The reason for this future (simulated) erosion reduction at historically high-erosion locations is unknown.

While the Bayesian Network model has certain limitations as a forward-predictor of bluff-crest location, it is nevertheless valuable because it highlights the relative roles of the multiple environmental drivers involved in bluff retreat. It also highlights the most important variables that would be valuable for stakeholders to informally monitor as they consider moving to, or remaining on, a lakefront lot on the bluff top: (i) long-term retreat rate, inversely correlated with bluff stability; (ii) bluff-face slope, inversely correlated with bluff stability; (iii) toe elevation, positively correlated with bluff stability; and (iv) beach volume, positively correlated with bluff stability.

Bluff Sediment Supply

Based on bluff-face topographic changes mapped using lidar data from 2007 and 2015, the 8-year total-sediment and sand+ changes for the WECLC bluffs were net losses of 318,400 m^3 and 105,850 m^3, respectively. Lakefront bluffs in the Crooked Creek and Trout Run watersheds were the principal sediment-supply sources (Table 4.1, Table 4.2). Annualized, the bluffs supplied 39,800 m^3/yr of total-sediment (clay to boulders) and 13,250 m^3/yr of sand+ (sand to boulders) to the WECLC. The sand+ volume was 65% smaller than prior estimates for the 20th/21st Century era. Total-sediment supply was 77% smaller. Estimated sand+ yields of ~430 m^3/bluff km/yr averaged across the six WECLC watersheds are comparable to turn-of-century (1990-2004) yields estimated by others for bluffs on the Ohio coast. The 13,250 m^3/yr sand+ supply results in a small littoral-sediment transport rate by both ocean coast and Great Lakes standards, given that sediment input from WECLC streams and from bluff erosion on the Ohio coast is minor. The sand+ supply reflects change within a longer ~12-year period when lake levels hovered about the mean level for Lake Erie (174.17 m) just prior to a rising lake-level era that began in 2011/2012.

The WECLC-average elevation change on the bluff face is ~0.3 m across all six watersheds. The elevation change, representing sediment loss and gain on the bluff face, varies by watershed (Table 4.5), being greatest for Crooked Creek (~0.41 m) and lowest for Elk Creek (~0.21 m). Scattered gains in elevation on the bluff face are a consequence of bluff-face deformation at slumps and of sediment storage lower on the bluff from upslope failures. As much as 6.5% of sediment moving from a given location on the bluff may be stored on the bluff downslope. Overall, the sediment-loss (erosion) volumes from the bluff face are about 20 times larger than the gain (accretion) volumes. Each of the six HUC-12 watersheds fronting the WECLC supplies a significantly different quantity of bluff-derived sediment to the Pennsylvania sector of the larger Lake Erie littoral system. This variability was previously unknown and was revealed by GIS change-detection analysis techniques applied to the bluff face. Rates and patterns of bluff retreat, total-sediment supply, and sand+ supply are regulated by several geo-environmental variables reviewed in Chapter 2, modeled using a Bayesian Network in Chapter 3, and quantified using change-detection analysis in Chapter 4.

Crooked Creek is the most important of the six WECLC watersheds in terms of bluff sediment supply normalized to cubic meters per kilometer of bluff per year. The Crooked Creek watershed supplied 53% more (relative to the Trout Run watershed) to 220% more (relative to the Turkey Creek watershed) sand+ to the littoral zone than any other WECLC watershed. Given the undeveloped, unarmored and natural state of its lakefront bluffs, Erie Bluffs State Park in the eastern half of the Crooked Creek watershed is the best watershed-scale candidate in western Erie County for bluff conservation measures such as designation as a feeder bluff zone. Its sediment supply role is also important because it is responsible for providing material to the protective baymouth bar at Elk Creek in the next-downdrift watershed. Without this bar, which is supplied with coarse sediment by littoral drift along both the Turkey Creek and Crooked Creek watersheds, fishing aesthetics, a sheltered shallow-water fish nursery at the mouth of the creek, and other ecosystem services would be compromised.

The bluff-retreat sand+ volumes derived in this study provide a unique opportunity to understand sediment contributions from bluffs to the littoral zone during near-average and relatively stable lake levels. Opportunity for such high-resolution analysis was not possible before because time windows capturing such infrequent average lake-level periods did not align with high-resolution lidar data sets and recent developments in geospatial analysis. The data from this study thus allow estimation of bluff retreat rates and sediment losses for long-term average/stable lake-level scenarios that have occurred in the past (1944-1956; 1999-2011) and are likely to return in the future. Implicit in this observation is that bluff change during 2007-2015 was responding, with some process-response time lag, to environmental conditions beginning at least in 1999 and continuing through 2015 at the end of the data/observation window.

A significant 0.76 m (~95 mm/yr) rise in lake levels that began in ~2012 and continued through 2020 may not be reflected in greater rates of bluff change for potentially another decade because of suspected time lags of at least a decade in the response of bluffs to lake-level change. It is expected that change rates, when ultimately determined for the 2012-2020+ period, will be greater than those reported for this study of the 2007-2015 era. They may approach or exceed rates determined for prior transgressive periods when sediment supply was ~five times larger than our 2007-2015 rates.

There are several coastal-management implications of our findings. Estimates of bluff contributions to littoral sand+ transport along the WECLC, based on the surface-differencing methodology, are 65-80% lower than previously estimated for the recent 20th/21st Century and earlier mid-20th Century eras. However, the small 2007-2015 volumes are interpreted to be representative of sand contributions to the littoral system during periods when lake level is near long-term average and a weak-transgressive trend is present (such as during 1999-2015). Because of this, sediment budget assumptions used for coastal sand management and erosion mitigation at the next-downdrift littoral cell at Presque Isle State Park may need to be revised to account for the smaller, 2007-2015 era, sand+ input to that cell from the WECLC. Incorporating such a sediment-supply revision for the Presque Isle littoral cell would influence estimates of sand nourishment quantities required to mitigate beach erosion at Presque Isle over the coming decades.

Average and relatively stable lake-level periods, such as occurred during 1999-2015, may be opportune periods for artificial sand bypassing at large coastal structures such as Conneaut Harbor, OH, that are known to block net-eastward littoral sediment transport. During such periods, littoral sediment transport volumes along the WECLC would be low and thus the littoral sediment stream would benefit more from artificial-bypass inputs. Additionally, the logistics of artificial bypassing may be easier when lake levels are near or below their long-term mean. Prior research shows that approximately 10,300 m^3/yr of sand naturally bypassed Conneaut Harbor prior to 1938 and may have been zero through at least 2006. This 10,300 m^3/yr is a relatively large littoral transport volume for the sand-starved Pennsylvania coast compared to the 13,200 m^3/yr supplied to the littoral zone by bluffs during the 2007-2015 era and the 39,500 to 61,000 m^3/yr supplied during prior eras.

Erosion on the WECLC bluffs is pervasive, occurring across the entire bluff face in most watersheds. This supports the general model that bluff retreat is not necessarily driven by either wave attack or groundwater discharge. While in localized areas retreat may be driven by one or other forcing agent, in most cases it is driven by a combination of both forcing agents. This is indicated by the occurrence of erosion swaths near both the base and crest of the bluffs along much of the WECLC. Consequently, when lower lake levels result in less erosion and steepening at the toe of the bluff, groundwater-driven failure may remain active higher on the bluff, and vice versa during high lake levels.

Our estimates of bluff sand+ input to the WECLC are lower than prior studies and contain some uncertainty (conservatively, ±50%). However, our estimates are inferred to be more precise than those of prior studies because of (i) better, although still imperfect, resolution of stratigraphic complexity, (ii) a DEM-differencing approach that allows higher-resolution mapping of topographic changes across the bluff face at ~1 m point spacings, and (iii) better tracking of slump-supplied sediment accumulations (gains) on the bluff face that partially offset some (~5%) of the loss volumes. Our estimates are significantly lower than recent-era prior studies, and there are several possible reasons for this. The 8-year comparison may not have captured large but infrequent bluff sediment-supply events that would have a higher probability of being captured by analyses covering several decades. A likely decades-scale process-response time lag between lake level and bluff erosion means that the 2007-2015 bluff face may have been responding primarily to lower and more uniform lake levels during the 1999-2011 period. And lastly, our observation window largely occurred within a longer 12-year period of relatively low and stable, weakly-transgressive, lake levels (1999-2011) that had not previously occurred for over half a century.

Considering the physical processes involved in bluff retreat, retreat rates and sediment supply from bluffs should be lower when, individually, the following conditions are satisfied: the beach prism is larger (beach width is large; toe elevation is well above lake level), SPR resilience is high, the top of bedrock is well above lake or backshore level, groundwater flux is low, bluff-face slope is low, and wave impact hours are reduced. Many of these attributes are most likely to occur during periods of lowered lake level. In natural systems, however, these attributes rarely operate in isolation because interactions and feedbacks occur, making predictions more challenging.

This project used a high-resolution sediment-loss mapping approach for Pennsylvania coastal bluffs. Surface-differencing (change-detection analysis) of lidar-derived DEMs over an almost decade-long observation window allowed higher-resolution mapping of change across the entire bluff face with a sampling density of ~1 data point per square meter. In comparison, prior research was resolution-limited because it relied on transect-based change mapping where large 100-1000 m transect spacings necessitated significant spatial averaging, stratigraphy was not well-constrained, and it was assumed that bluffs retreated in a simple parallel-retreat manner based on change measurements at the bluff crest only. Application of change-detection analysis to beach change at Presque Isle State Park and to the bluff coast of eastern Erie County would be beneficial to sand-resource management efforts by Pennsylvania DCNR, Pennsylvania DEP-CRMP, and the US Army Corps of Engineers. It would complete a state-of-the-art, up-to-date, high-resolution sediment-input analysis for the entire Pennsylvania coast of Lake Erie.

Finally, this study reveals that there is a degree of positional uncertainty in bluff-crest location mapping, and volumetric uncertainty in bluff-face change estimations, when conducting GIS-based analysis of lidar data. To minimize the significance of these potential errors, long-term tracking of bluff retreat and sediment losses on the Erie County coast may not require lidar mapping any more frequently than once per decade.

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