An analysis of bluff change along the Pennsylvania Lake Erie coast: 2007-15 and 2012-15

Sean Rafferty[1] and Mike Naber[2]

[1]Pennsylvania Sea Grant - Penn State Behrend, Tom Ridge Environmental Center, 301 Peninsula Dr., Suite 3, Erie, PA 16505; PH (814) 898-7082; srafferty@psu.edu

[2]Penn State Behrend, 1 Prishak Building, Erie, PA 16563; PH: (814) 898-6298; mdn10@psu.edu

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1.0 Abstract

Pennsylvania possesses approximately 123 kilometers (76.6 miles) of Lake Erie shoreline, dominated by unconsolidated bluffs ranging in height from 1.5 to 55 meters (five to 180 feet) above lake level. The Pennsylvania Coastal Resources Management (PA CRM) Program and municipalities along the Lake Erie shoreline currently rely on periodic physical monitoring of approximately 130 established control-point sites in the field to determine the position of the coastal bluff crest and any changes in crest position over time due to erosion. While a valuable resource, and an excellent ground-check on more recent digital methods of mapping coastal change, the control-point methodology is becoming antiquated. The purpose of the current project was to analyze bluff crest change over time using remote sensing techniques and the Digital Shoreline Analysis System (DSAS), an ArcGIS extension available from the United States Geological Survey (USGS). Bluff crest rates of change were calculated by comparing bluff crestlines delineated from LiDAR and orthoimagery collected in 2007, 2012, and 2015. From 2012 to 2015, the mean rate of bluff change at transects (n = 1,753) along the Pennsylvania Lake Erie coast was determined to be 0.3076 meters/year (1.009 feet/year). This was higher than the mean rate of change observed from 2007 to 2015, and by PA CRM at varying timescales between 1975 and 2019. The mean rate of bluff change at transects (n = 2,232) along the Pennsylvania Lake Erie coast from 2007 to 2015 was 0.2149 meters/year (0.705 feet/year). This eight-year timeframe, with more transects, likely gives a better picture of bluff movement over time along the Pennsylvania Lake Erie coast than the three-year timeframe, with fewer transects. Using remote sensing data techniques and DSAS provides a viable method for assessing bluff movement over time and will likely improve over time with better LiDAR resolution and longer time scales to assess.

2.0 Introduction

The Pennsylvania portion of the Lake Erie watershed drains an area of 1,316 square kilometers (508 square miles), including all or portions of 33 municipalities in Erie and Crawford counties. There are 52 streams totaling a length of 1,806 kilometers (1,122 mile within the watershed. Water resources within the watershed and along the coast supply drinking water to its residents, support economic growth primarily through recreational boating and fishing opportunities, provide spawning habitat for Lake Erie fishes, and supply habitat for aquatic-dependent plant and animal species. The Pennsylvania Lake Erie region provides one million jobs for its three million residents (GLC, 2013). Lake Erie provides drinking water for 11 million coastal residents living in the United States and Canada. Coastal communities across Lake Erie rely on the lake and its watershed to support their economies. The United States Fish and Wildlife Service (USFWS, 2006) estimates 1.4 million anglers spent $1.5 billion on sport fishing (trips and equipment) in the Great Lakes in 2006, including tributaries. Lake Erie was the most popular lake, attracting 37% of all Great Lakes Anglers. This translates to 518,000 anglers spending $555 million on sport fishing in Lake Erie. Murray and Shields (2004) suggest that anglers attracted to the Erie County, Pennsylvania stream and shoreline steelhead fishery alone spent nearly $9.5 million on trip-related expenditures in 2003. The steelhead fishery generated $5.71 million in new value-added activity in Erie County, supporting 219 jobs in the economy through direct and indirect effects. Graefe et al. (2018), estimated the total economic significance of the Pennsylvania section of Lake Erie recreational angling industry upon Erie County, Pennsylvania to be $49.5 million for the 2016 season. The National Marine Manufacturers Association (NMMA, 2013) estimates that for Pennsylvania Congressional District 3, which includes the Lake Erie watershed, there are 28,721 registered boats, 72 recreational boating-related businesses that support 2,301 jobs, $123.4 million being spent annually on recreational boating-related activities, and a total economic impact of recreational boating of $291.1 million.

Stress from urbanization, industrialization, and agriculture pose a threat to Lake Erie's recreation and tourism-based economy, ecosystem, and the health of its residents and visitors. Current pressures impacting Lake Erie's economy and ecosystem include land use, input of excess nutrients, natural resource over-use and disturbance, inputs of chemical and biological contaminants, and increasing populations of non-native invasive species (LaMP Work Group, 2008). In addition, bluff recession also poses a threat to the Pennsylvania Lake Erie economy, environment, and safety of its residents. The Pennsylvania Coastal Resources Management Program (PA CRM) identifies shoreline erosion and bluff recession as the most significant problems associated with the Pennsylvania Lake Erie shoreline. Bluff recession, as defined in Chapter 85 of the Pennsylvania Code, is the loss of material along the bluff face caused by the direct or indirect action by one or a combination of groundwater seepage, water currents, wind generated water waves, or high-water levels. Bluff recession is a normal process; however, human influenced factors such as stormwater runoff, wastewater management, and land development practices may significantly increase the rate of recession (Cross et al., 2007). Areas along the bluff where the rate of progressive bluff recession creates a substantial threat to the safety or stability of nearby existing or future structures or utility facilities are known as Bluff Recession Hazard Areas (BRHA) (DEP, 2013).

Pennsylvania possesses approximately 123 kilometers (76.6 miles) of Lake Erie shoreline, dominated by unconsolidated bluffs ranging in height from 1.5 to 55 meters (five to 180 feet) above lake level, including a large sand spit (at Presque Isle State Park) and an economically and historically significant bay (Presque Isle Bay) at Erie. The Lake Erie shoreline also includes over 52 stream mouths and associated floodplain lowlands; recreational, commercial, and industrial waterfront; public-access points; private and community properties along the nine municipalities that possess lakefront. Nearly all the shoreline is designated as BRHA (DEP, 2013). Physical losses associated with bluff recession, including the loss of land at the top of the bluff face by mass wasting, threaten Pennsylvania's coastal economy. Economic losses associated with bluff recession include loss of property, loss of tax base, loss of coastal agricultural land, loss of recreational opportunity, structural losses, and mitigation costs. While natural bluff processes are essential for the ecological health of Lake Erie, accelerated recession associated with human activities pose a threat to the Lake Erie ecosystem. Foyle and Naber (2012), suggest that because of their high clay and silt content, pulses of bluff-supplied sediments along the Pennsylvania shore degrade nearshore water quality. Given the economic and potential environmental impacts associated with accelerated bluff recession, there is a need for updated Pennsylvania Lake Erie bluff recession rate data

PA CRM and municipalities along the Lake Erie shoreline currently rely on periodic physical monitoring of approximately 130 established control-point sites in the field to determine the position of the coastal bluff crest and any changes in crest position over time due to erosion (Foyle, 2018). A control point is a fixed marker, such as a buried steel pin or existing utility pole, from which a direct measurement to the bluff crest is made. The control points are located approximately every one-half kilometer along the bluff crest from the Ohio to the New York borders. Direct measurements from the control points to the bluff crest are taken every four to five years, with the assistance of Global Positioning System technology.

Records of the measured distances from the fixed control points to bluff crest are maintained by PA CRM. At locations where the bluff line is actively receding, that measured distance gradually decreases from year to year. Over time, an average rate of bluff recession at that location emerges from the collected data. While a valuable resource, and an excellent ground-check on more recent digital methods of mapping coastal change, the control-point methodology is becoming antiquated. It is a labor-intensive, weather-dependent method of bluff-crest mapping, and it does not provide sufficient spatial resolution on bluff recession due to a typical transect spacing of 500-meters that is not closely scaled to the dimensions of stable-bluff and bluff-failure zones (10-100 meters). This will increasingly limit its utility as a means of providing the quality of coastal-erosion data that are necessary for any future revisions to, and active management of, BRHA.

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

3.0 Methods

3.1 Study Area

The study area comprises the entire 123-kilometer Pennsylvania Lake Erie bluff coast, which includes nine coastal municipalities in Erie County, Pennsylvania including Springfield Township, Girard Township, Lake City Borough, Fairview Township, Millcreek Township, the City of Erie, Lawrence Park Township, Harborcreek Township, and North East Township (Figure 1). The coast is characterized by unconsolidated bluffs and banks ranging in elevation from 1.5 to 55.0 meters above lake level. Depending on location, the unconsolidated bluff sediments may rest upon as much as 7.0 meters of Devonian bedrock that often forms a resistant bedrock toe (Foyle, 2018). The bluffs are intersected by numerous stream mouths, many of which are incised into Devonian bedrock. Small ephemeral springs drain modern actively eroding rotational slumps and ravines while perennial springs drain larger, well-vegetated Holocene bowls. In Harborcreek Township and North East Township, Pennsylvania, narrow beaches are present along 65-70% of the coast. They have a maximum width of 34.0 meters (updrift of marinas), a median width of 4.0 meters, and a modal width of 1.0 meters (Foyle and Naber, 2012).

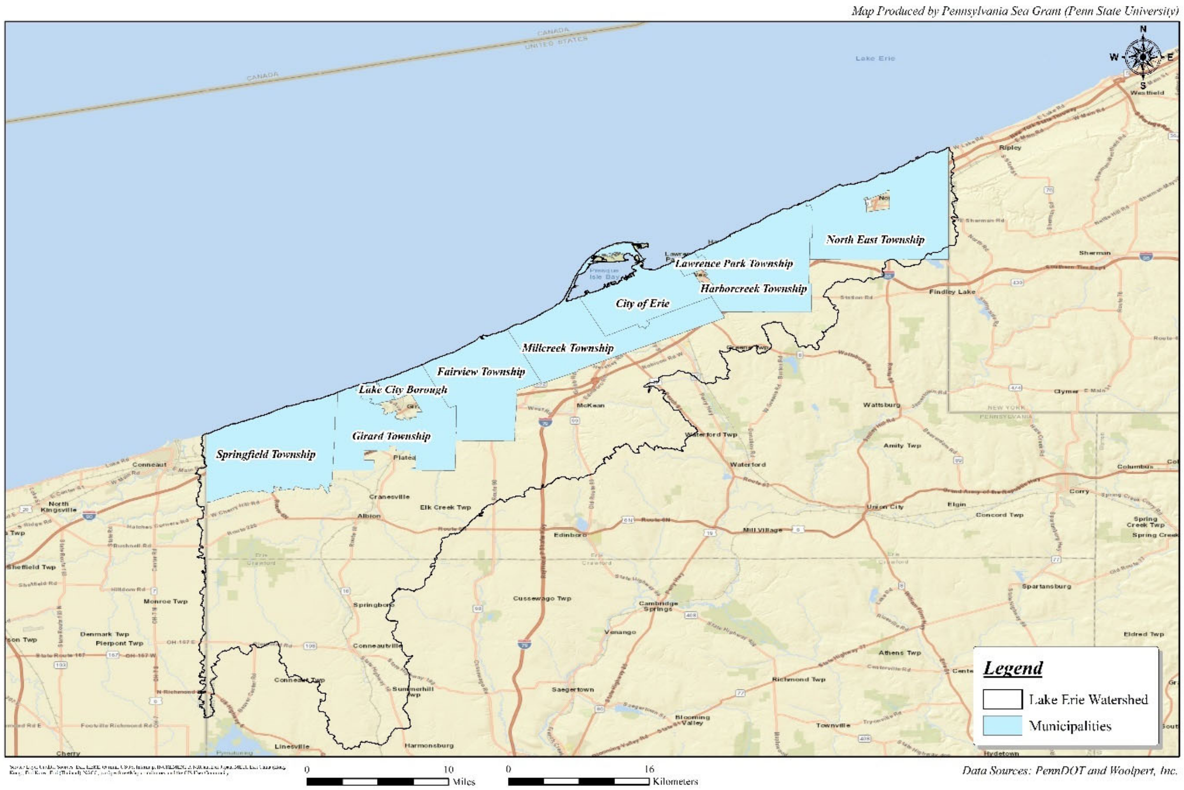

Figure 1. The study area comprising the entire 123-kilometer Pennsylvania Lake Erie bluff coast.

3.2 LiDAR Acquisition

The 2007 LiDAR dataset, available online from Pennsylvania Spatial Data Access (PASDA), was collected by the Pennsylvania Department of Conservation and Natural Resources (DCNR). The LiDAR was acquired at a flying height capable of producing an average 1.4-meter point density, a horizontal accuracy of 1.5 meters, and vertical accuracy of 0.27 meters (*Table 1*). The 2012 LiDAR dataset, available online from PASDA, was collected in November 2012 (leaf-off) and processed by Woolpert, Inc. The aerial LiDAR was acquired at a flying height capable of producing an average 1.0-meter point density, a horizontal accuracy of 0.43-meters, and vertical accuracy of 0.05-meters. The 2015 LiDAR dataset, available online from PASDA, was collected in April-May 2015 (leaf-off) and processed by Woolpert, Inc. The aerial LiDAR was acquired at a flying height capable of producing an average 0.7-meter point density, a horizontal accuracy of 0.36-meters, and vertical accuracy of 0.18-meters.

Table 1. Horizontal and vertical accuracy, and density of 2007, 2012, and 2015 LiDAR.

Metric	**2007 LiDAR**	**2012 LiDAR**	**2015 LiDAR**	**Bluff Crests**
Horizontal Accuracy	5-ft (1.5-m)	1.42-ft (0.43-m)	1.18-ft (0.36-m)	1.67-ft (0.51-m)
Vertical Accuracy	0.9-ft (0.27-m)	0.16-ft (0.05-m)	0.59-ft (0.18-m)	0.08-ft (0.02-m)
Density	4.59-ft (1.4-m)	3.28-ft (1.0-m)	2.3-ft (0.7-m)	N/A
Source	DCNR	Woolpert, Inc.	Woolpert, Inc.	Woolpert, Inc

3.3 Orthoimagery Acquisition

The 2012 4-band, 8-bit imagery orthoimagery, available online from PASDA, was collected in November 2012 (leaf-off) and processed by Woolpert, Inc. The aerial imagery was acquired at a flying height capable of producing 1" = 100' scale orthoimagery with a 0.5-foot pixel resolution. The 2015 4-band, 8-bit imagery orthoimagery, available online from PASDA, was collected in April 2015 (leaf-off) and processed by Woolpert, Inc. The aerial imagery was acquired at a flying height capable of producing 1" = 100' scale orthoimagery with a 0.5-foot pixel resolution.

3.4 Bluff Crest Delineation

The 2007, 2012, and 2015 Pennsylvania Lake Erie bluff crest shapefiles were created by Woolpert, Inc. using a multi-step feature extraction method, including: ground filtering, digital terrain model (DTM) preparation, hillshading, slope calculation, feature extraction, and quality control and quality assurance (QC/QA) and manual edits. GPS Real Time Kinematic waypoints were used to ground truth the crestlines at different points, which were captured on various public lands that intersected or were located on or near the crestlines.

3.4.1 Ground Filtering:

Airborne lidar systems collect information not only from land surface but also from every object between the sensor and the terrain that can reflect the laser beam. The bluff crest is a geomorphological feature of the terrain. Lake Erie shoreline is mostly covered by vegetation. It was therefore necessary to remove vegetation points from the point cloud. This was accomplished through filtering. Filtering out non ground points from raw point clouds was the first and most important step in bluff crest line delineation. Without these non-ground points, the ground could be modelled more accurately. The objective of this task phase was to remove the non-ground point and preserve terrain features. This was accomplished through the following steps: 1) create a 1ft-by-1ft grid; 2) filter out the lowest points in each grid square; 3) successively increase the size of the grid by 25%; 4) compare the elevation difference in the larger grid with the previous smaller grid; and 5) if the elevation difference between each point and the lowest point was smaller than a set threshold, the point was classified as a terrain point. The threshold was determined by the slope of the terrain. The slope was calculated iteratively by comparing the filtered and non-filtered points. This process increased the accuracy of ground filtering and resulted in a more densified point cloud representation of the ground

3.4.2 Digital Terrain Model (DTM) Preparation:

DTM creation was the next step in bluff crest delineation. To identify the location of the bluff crest line, terrain needed modeled using an interpolation technique that smoothed out insignificant breaklines and exaggerate the bluff crest. A mathematical function that minimized the overall surface curvature was utilized, resulting in a smooth surface that passed exactly through all the input ground points.

3.4.3 Hillshading:

The next step in crest line delineation was terrain enhancement. In this step, the goal was to capture local variations to show areas of rapid change in slope and/or aspect (i.e. bluff face). Hillshading is the hypothetical illuminating of a surface. It is accomplished by calculating the illumination values of each cell in relation to neighboring cells. By default, shadow and light are shades of gray associated with integers from 0 to 255 (increasing from black to white). The primary factor when creating a hillshade map for any particular location is the location of the sun in the sky. The azimuth is the angular direction of the sun, measured from north in clockwise degrees from 0 to 360. An azimuth of 90 degrees is east. The azimuth value used in this project was 315 degrees (NW). The altitude is the slope or angle of the illumination source above the horizon. The units are in degrees, from 0 (on the horizon) to 90 (overhead). The altitude value used in this project was 45 degrees.

3.4.4 Slope Calculation:

The maximum rate of change in value from every cell to their neighbors was calculated. Basically, the maximum change in elevation over the distance between the cell and it's eight neighbors identifies the steepest downhill descent from the cell (i.e. slope). The Curvature function displays the shape or curvature of the slope. A part of a surface can be concave or convex; you can tell that by looking at the curvature value. The curvature is calculated by computing the second derivative of the surface, the first is represented by slope. Three curvatures were calculated: 1) profile; 2) planform; and 3) standard (Woolpert, 2016).

3.4.5 Feature Extraction: The next step in the crest line delineation process was to carry out feature extraction through pattern matching and object recognition. The simplest approach to object-based image analysis (OBIA) is called thresholding. This was performed using a OBIA platform called eCognition, a Trimble ruleset creation software. The key to the success of this method was the selection of threshold values (or values when multiple levels are selected). In Woolpert's implementation of OBIA for bluff crest line delineation, the following threshold values were used: 1) Slope: > 38 degrees; 2) Hillshade: > 184; 3) Curvature: > 74; and Profile: < -3. To utilize these threshold values, Woolpert developed rulesets. Rulesets are a collection of logic-based queries that are created to group homogenous pixels or cells into objects. The ruleset development process also included the preliminary analysis of the input datasets to evaluate the efficacy of the rulesets.

3.4.6 QC/QA and Manual Edits:

Manual QC and edits were carried out in ArcMap, which enables mapping, compilation, and analysis of geographic information. The following steps were performed in ArcMap:

- After the crest bluff line were automatically extracted, the cartography team received these data in the form of shapefiles. The shapefiles are first imported into a geodatabase and processed to eliminate errors and ensure file continuity.
- Using cartographic workstations, Woolpert technicians then verified that the raw data meets or exceeds the applicable accuracy standards.
- Any voids in the data, over-runs, and dangling line work were edited.

- Tie edges between tile sheets were verified to ensure that the transition between all maps meet exactly.
- Exception reports were generated to flag any data that does not meet feature parameters.
- Where the data does not meet the target goal, it was manually edited and then reviewed.
- The resulting crest bluff lines were viewed and inspected while overlaid on top of the imagery to verify its completeness and to ensure that the vector data meets or exceeds the required accuracy standards.
- The final bluff crest lines were then subjected to a QC procedure to verify that all data is translated properly and that the final products meet all cartographic, aesthetic, and other applicable standards.
- The lines were then attributed accordingly.

Although feature extraction methodologies were primarily utilized for the delineation of the bluff crests, it was determined that in some instances supplemental use of stereo compilation methodologies were required to accurately define the bluff. Variables that led to the use of stereo compilation included the existing LiDAR density, water features, heavy vegetation, and abrupt terrain features made use of this supplemental methodology essential in some areas. The steepness of the bluff edge and heavy vegetation (where the LiDAR was not effective at delineating the ground surface) required that the bluff crests also be collected using manual techniques.

The bluff crest lines were mapped with a horizontal accuracy consistent with 100 scale mapping. Supplementary mapping techniques were applied to improve the limiting RMS error from +/- 1 meters (consistent with 100 scale mapping) to +/- 0.5 meters or +/- ~20 inches. The overall vertical accuracy has a limiting error of +/- 0.1 meters. Vertical map accuracy is defined as the RMS error in evaluation in terms of the datum for well-defined points. The height values for the crest line were defined directly from lidar dataset which was deemed to have limiting rms error of +/- 0.025 meters or +/- ~1 inch. This height accuracy is relevant where lidar pulse reflected off the top of the bluff. In the event the lidar pulse was not coincident with the top of the bluff, the height was interpolated.

3.5 Determining Crestline Change using DSAS

DSAS v5.0 is a freely available ESRI® ArcGIS desktop add-in developed to calculate rate-of-change statistics from multiple shoreline positions (Himmelstoss et al., 2018). In the current study, DSAS was used to assess bluff change along the Pennsylvania Lake Erie Coast from 2007-2015 and 2012-2015. DSAS allows for an automated method for establishing measurement locations and performing change calculations.

3.5.1 DSAS Inputs

DSAS has strict data requirements. To run properly, the correct file format must be used, a personal geodatabase, which serves as a repository for the data. DSAS includes three required inputs: Geodatabase, Shoreline (Crestline), and Baseline.

3.5.1.1 Geodatabase

All DSAS data must be stored in a personal geodatabase. DSAS also requires that all data be in metric units and the projected coordinate system is metric, such as the Universal Transverse Mercator projection or State Plane projection. In ArcCatalog, a new Personal Geodatabase was created by locating where it would be stored in the file tree and right clicking. All data was created here, but data can also be imported to this location from other places by right clicking on the created geodatabase and importing. Version 5.0 of DSAS allows for the updating/upgrading of older existing geodatabases.

3.5.1.2 Crestlines

All crestline data must be in a single feature class within the appropriate personal geodatabase. Often, crestlines are created as shapefiles. This does not present an issue as shapefiles can be imported into a geodatabase using ArcCatalog. DSAS requires that all feature classes be in metric units in a projected coordinate system, and they must meet specific field requirements. Crestlines can vary greatly, differing from shorelines primarily in that they vacillate in elevation, where a shoreline is normally static in elevation when taken at one point in time. Crestlines can be digitized in conjunction with spatial data like orthophotos, historical survey maps, and LiDAR data. Here, a stacking method proprietary to Woolpert, Inc., which in most basic terms employs many types of spatial data to delineate the feature was used to create the crestline shapefiles (see *Section 3.4*).

Each crestline vector in the current study represents a specific time and date in the crestline attribute table. Transects cast by the DSAS program from the baseline intersect the crestline vector line file. These points of intersection were used to compute the rate of change between years. It is important to note that calculated rate of change in DSAS is only as reliable as the crestline data. Many methods are available to compute rates and sampling errors in shorelines (Anders and Byrnes, 1991; Crowell and others, 1991; Thieler and Danforth 1994; Moore 2000). In the current study, the DSAS suggested option of using the default uncertainty value was used. Crestline data must be formatted with the appropriate attributes for use with DSAS. *Table 2* identifies the field names and data types. *Table 3* provides a description of these attributes.

Table 2. Shoreline attribute field requirements for Digital Shoreline Analysis System (DSAS) version 5.0. (modified from Himmelstoss et al., 2018).

Field Name	Data Type	Attribute Addition	DSAS Requirement
OBJECTID	Object identifier	Autogenerated	Required
SHAPE	Geometery	Autogenerated	Required
SHAPE_Length	Double	Autogenerated	Required
DATE_(DSAS_date)	Text (length = 10 or 20)	User-created	Required
UNCERTAINTY (DSAS_uncy)	Any numeric field	User-created	Required
SHORELINE_TYPE (DSAS_type)	Text	User-created	Optional

Table 3. Descriptions of shoreline attribute fields for Digital Shoreline Analysis System (DSAS) version 5.0. (modified from Himmelstoss et al., 2018).

Attribute Field	Description
DATE_	The date field is required but not name specific, meaning it can be named DATE_, DSAS_date or any other user-defined name. A character length of 10 is required for shoreline change spanning days, months or years, where dates are required to be formatted as mm/dd/yyyy. A character length of 20 is required for shoreline data spanning different hours within the same day, where dates are formatted as mm/dd/yyyy hh:mm:ss (using either 24-hour time or AM/PM). *Note: The computer's date format must be set to English (USA) mm/dd/yyyy.*
UNCERTAINTY	The uncertainty field is required but not name specific, meaning it can be named UNCERTAINTY, DSAS_uncy, or any other user-defined name.
SHORELINE_TYPE	The shoreline type field is used to specify the datum the shoreline is referenced to. It is a required field as part of the proxy-datum bias (PDB) correction when proxy-based and datum-based shorelines are combined to compute shoreline change rates. It is not name specific. *Note: If no PDB data are used, this field is optional.*

3.5.1.3 Baseline

DSAS uses a baseline measurement method developed by Leatherman and Clow, 1983 in its calculation of rate-of-change statistics. This baseline method is user constructed and serves as the beginning point for all transects used in the DSAS application. Transects intersect with the crestline to create a measurement point that was used to calculate crestline change rates. Baseline requirements include: the baseline must be a feature class within a personal geodatabase, it must have a projected coordinate system in metric units, it can be one single feature or multiple segments, and it must meet the baseline attribute field requirements described in *Table 4* and *Table 5*.

Table 4. Baseline attribute field requirements in the Digital Shoreline Analysis System (DSAS) version 5.0. (modified from Himmelstoss et al., 2018).

Field Name	Data Type	Attribute Addition	DSAS Requirement
OBJECTID	Object identifier	Autogenerated	Required
SHAPE	Geometery	Autogenerated	Required
SHAPE_Length	Double	Autogenerated	Required
ID	Long Integer	User-created	Required
GROUP (DSAS_group)	Long Integer	User-created	Optional
Search_Distance (DSAS_search)	Double	User-created	Optional

Table 5. Descriptions of baseline attribute fields in the Digital Shoreline Analysis System (DSAS) version 5.0. (modified from Himmelstoss et al., 2018).

Attribute Field	Description
ID	The baseline identifier (ID) field is required field that is not name specific. DSAS uses this value to determine the ordering sequence of transects when the baseline feature class contains multiple segments. If this attribute field is created prior to drawing baseline segments, the ID value defaults to zero. The attribute table must be edited, and a unique ID value designated for each segment of the baseline. It is best to have baseline segment IDs in order alongshore. DSAS will not cast transects along baseline segments where the ID value is zero.
GROUP	The group field is an optional field that is not name specific, meaning it can be named GROUP, DSAS_group or any other user-defined name. This field is to be used for data management purposes only. Providing a group attribute will not affect any of the change statistics provided within DSAS or returned in the rate feature class. New to DSAS version 5.0, the summary report text file that is generated each time rate calculations are run will use the group attribute field to provide rate averages for each group.
SEARCH DISTANCE	The search distance field is an optional field that is not name specific. It provides users with an option to set a search distance, in meters, that DSAS will use to search for shorelines, extending out from either side of the baseline. The distance value can be unique for each baseline segment depending on the organization of shorelines with respect to the baseline. In some shoreline configurations, it will be necessary to specify different search distances for each baseline segment. For example, islands and barrier islands or areas with recurved shorelines could be assigned a small distance value to prevent shorelines on the opposite side of the island from being included. Values populated in this field will override the maximum search distance value entered in Cast Transects settings.

Three methods can be used to create a baseline in DSAS, 1) create new feature class, 2) buffer/smooth an existing shoreline, or 3) update an existing shoreline. Here, an existing shoreline of Lake Erie was used to create a buffer for the baseline. To create a baseline from an existing crestline, a suitable crestline that best represents the trend of either the single crestline or of the complete crestline segments must be used. Here, a smoothed buffer of the existing crestline presented the best facsimile of the crestline feature. The smoothed and buffered crestline offset toward Lake Erie provided the necessary coverage and accuracy.

DSAS supports baselines to be located where the user desires, whether that be offshore, inland, or between crestline. DSAS searches by default out from either side of the baseline for crestline data extended to a distance set by the user, that intersects all crestline data within that range. Here, it was determined that offshore would provide the most flexibility. Transects that are cast can be truncated by distance, but they can also be truncated to crestline extent by selecting Cast Transects and checking the box for “Clip transects to shoreline extent.” Using search distance allows one to deal specifically with the polylines in question and not allowing the transects to overreach in areas where there are more crestline features.

3.5.2 DSAS Workflow/Methodology

Following the creation of the required geodatabase and input feature classes and all necessary feature classes were added and properly attributed, DSAS was used within ArcMap to establish transect locations and calculate change statistics. *Figure 2* provides an overview of the DSAS workflow.

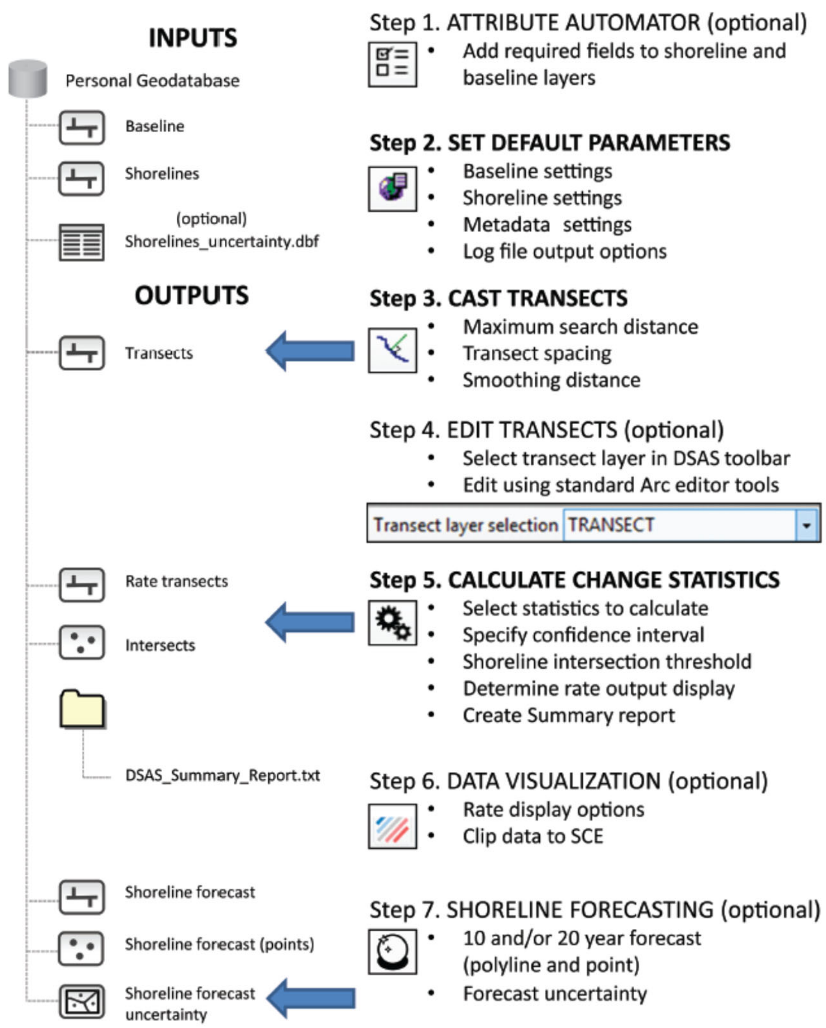

Figure 2. The Digital Shoreline Analysis System (DSAS) workflow with steps necessary to establish transects and compute change-rate statistics. SCE, shoreline change envelope. (modified from Himmelstoss et al., 2018).

3.5.2.1 Attribute Automator

The attribute automator interface allows the user to automatically add required fields to the crestline and/or baseline data layers. This feature was used to add a date field (DSAS_date), an uncertainty field

(DSAS_uncy), and a field indicating crestline type (DSAS_type). These fields were then populated from existing data by using the ArcMap field calculator.

3.5.2.2 Set Default Parameters

Transect generation was initiated by selecting preferred settings in the Set Default Parameters window. Default Parameters are accessed from the DSAS toolbar and has three main tabs, 1) Baseline settings, 2) Shoreline settings, and 3) Metadata settings. Though this information can be edited or changed at any time, the user needs to ensure it is entered correctly.

Baseline Settings

Baseline settings manages the fields associated with the baseline fields and location of the crestline to the baseline. The following options are available in the baseline settings tab: baseline layer, baseline group field, baseline search distance, show baseline orientation, and land location in relation to baseline. Baseline layer allows the selection of the baseline layer to be used, which must be a feature in the geodatabase. Baseline Group Field is optional, if there are groups or subregions that are needed to be calculated as locations of interest a value may be assigned to each segment. Baseline search distance is associated with transects that are cast from the baseline. Transects can be cast without a uniform distance and can be truncated to the crestline extent. The baseline search distance field allows different segments to have different search distances. Maximum search distance is set by the user to establish a single search distance while baseline search distance field allows the user to set a crestline search distance value for each baseline segment. If unused, the default will be until a crestline is encountered and then truncated to the crestline. Baseline orientation adds arrows to the baseline and indicates which direction each baseline is going. Right clicking in this environment allows the user to change to direction of flow. Land location in relation to baseline allows the user to indicate the location/direction of the land relative to the baseline to show negative or positive rates of crestline change. Choices are onshore, offshore, or mid-shore. Default searching includes looking for crestline on both sides of the baseline, this can be adjusted in Baseline Settings.

In the current study, the baseline used was offshore from the crestline and running from approximately southwest to northeast along the Pennsylvania coastline from Ohio to New York. The selection for land relative to baseline was to the right.

Crestline (Shoreline) Settings

The shoreline (crestline) settings tab allows the user to specify the crestline attribute fields for date and uncertainty values. Crestline parameters include crestline layer, crestline, crestline uncertainty. The crestline layer must reside as a single feature in the geodatabase. Crestline date is the field that stores the date information for the crestline data creation. Shoreline uncertainty is the field that stores the positional uncertainty values for the crestline feature.

If the crestline uncertainty field is not populated, DSAS defaults and uses the United States Geological Survey suggested default value of 10-meters, which is the approximate average of uncertainty of various crestline data types used in recent regional reports that USGS has published under the National Assessment of Shoreline Change project. If a transect crosses the same crestline more than once, the intersection parameter selects which intersection is used, either the seaward most one or the landward most intersection. This deals with the relationship of the baseline and whether it is inshore, offshore, or mid-shore. Seaward option selects the intersection that is farthest from the land when a transect crosses a crestline more than once, selecting landward tells DSAS to use the intersection most landwards. In the current study, the default uncertainty value 10-meters was used. When working with intersection parameters, the most seaward intersections of linear features was selected.

Metadata Settings

Metadata generated by the DSAS program meet the Federal Geographic Data Committee Content Standard for Digital Geospatial Metadata version 2.0. The metadata record contains basic data elements as well as a description of the phases performed by DSAS to generate the transect feature class, compute change-rate statistics, and run the beta shoreline forecasting. Metadata in DSAS v5 is in three different categories

1) General Information (data about update and access information, and contact information). General information includes information on the originator such as the individual(s) and organization responsible for creation of the dataset. Abstract information provides information on the project and study area. Purpose information provides a general description of the shoreline dataset and its possible uses.
2) Data Update and Access Information includes information on the frequency of data updating, this simply states how often transects will be updated. Progress information basically is a status of the transect dataset. Constraints on access information describes any restrictions or legal prerequisites for using the data.
3) Contact information includes information on the name of the organization responsible for the data. Person information identifies the individual within the organization who is using DSAS to cast transects. Last is Address information for the organization and/or individual.

In the current study, all fields in the metadata settings were completed. Otherwise, DSAS would prompt the user that rates cannot be calculated until this section is complete.

Log File Output

At the bottom the tab for Default Parameters, the user is given the option of creating a log file. When DSAS is used to make a transect file or a calculate change statistics there is information on what is being done. This information includes, 1) Regular information - information about each process step; 2) Extended information - more detailed information of each step in the process; 3) None - unselected and nothing of the process will be saved for future use. In the current study, the Log File Output was set to "Extended" in case of the need for trouble shooting.

3.5.2.3 Cast Transects

DSAS generates transects that are cast perpendicular to the reference baseline at a user-specified spacing alongshore (*Figure 3*). There are no restrictions on where the reference baseline is drawn, it may be positioned completely to one side of the shoreline data or be placed between the historical shoreline positions. In DSAS v5.0, the cast transect action and calculation action are two different processes, allowing the user to adjust/edit transects prior to running shoreline change calculations. Once an appropriate baseline is chosen, the next step is to cast transects. In the current study, two methods of baseline creation, one inland of the crestline and one where the baseline was situated offshore, were explored. It was determined that the offshore option was more efficient and objective as it presented less issues with the complex nature of the varied terrain and peculiarities of the crestline that were present with the inland baseline and casting transects.

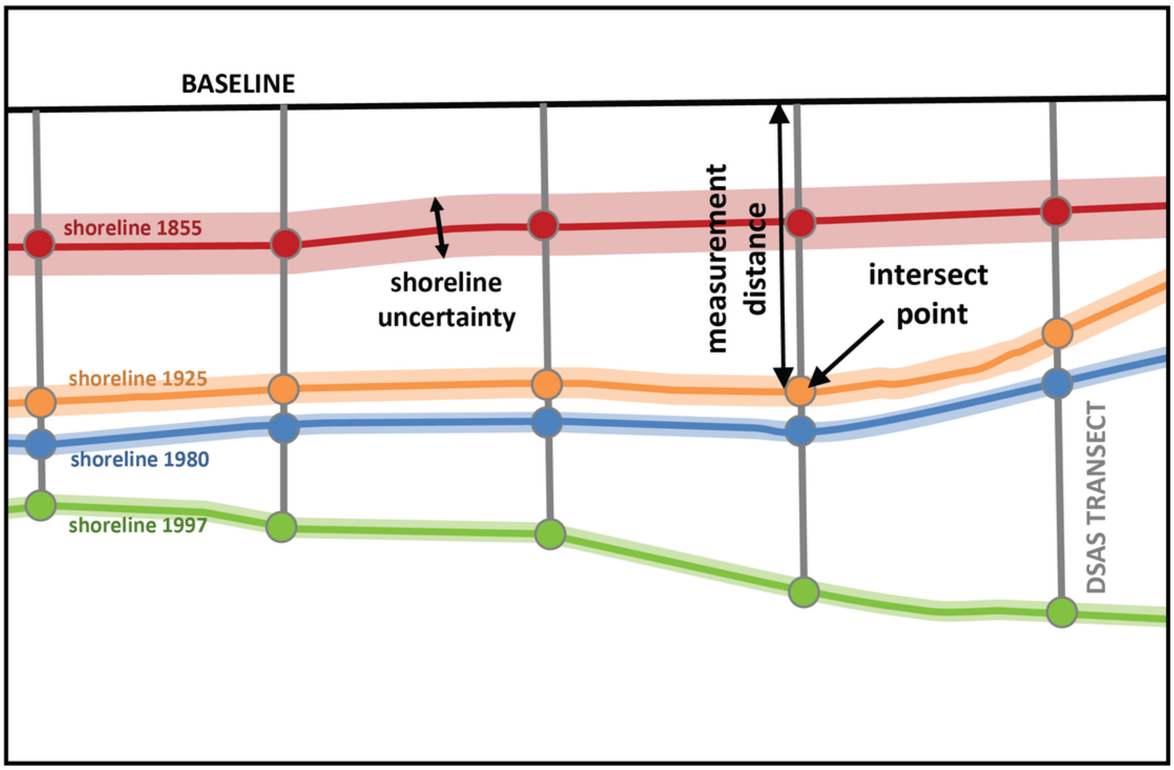

Figure 3. The measurement distance along a transect from the baseline to each intersect point; this distance is used in conjunction with the corresponding shoreline date to compute the change-rate statistics. (modified from Himmelstoss et al., 2018).

When the cast transects tab is chosen, the user is presented with options on maximum distance, transect spacing, and what smoothing distance will be chosen. DSAS casts transects without a uniform default length. By default, transects are cast by using a search distance and transects are truncated to the crestline extent. This default can be changed in the Cast Transects window by unchecking the "Clip transects to shoreline extent" option. The transect spacing option allows the user to specify distance (in meters) between transects along the baseline. Spacing depends on the scale of the data and the intended scale of the output rate information. A user-specified smoothing distance value can facilitate an orthogonal transect/crestlines intersect by creating a supplemental baseline (not visible to the user) at the provided smoothing length, with the transect location at the midpoint. In the current study, a maximum search distance of 100-meters, transect spacing of 20 meters, and a smoothing distance of 20-meters were used.

DSAS generates a new set of measurement transects based on the settings specified by the user in the Set Default Parameters window. Before casting transects, DSAS checks the default parameter settings to ensure that the user has specified all required elements and that selected files or attribute fields (*Table 6*) will not result in a program error.

Table 6. Description of DSAS-generated transect attribute fields. (Himmelstoss et al., 2018).

Field Name	**Data Type**	**Field purpose**
OBJECT IDENTIFIER	Object ID	The object identification field is automatically created and maintained by ArcGIS. It establishes a unique identifier (ID) for each row in the attribute table. This number is used by DSAS to relate all shoreline change results to transects. The field name may be called “ObjectIdentifier,” “ObjectID,” “OID,” or “FID.”
Geometry	Geometry	The geometry field is automatically created and maintained by ArcGIS. It provides a definition of the feature type (point, line, polygon). The field name may also be called “Shape.”
BaselineID	Long Integer	Values in this field correlate to the baseline attribute field “ID” and are assigned by DSAS to identify the baseline segment used to generate the measurement transect. Baseline segments assigned an ID=0 are ignored by DSAS, and no transects will be cast along those line segments.
GroupID	Long Integer	Values in this field correlate to the optional baseline attribute field “DSAS_group” (Group_) and are assigned by DSAS if selected by user. This field is used to aggregate sections of the coast into groups. All transects within a group will have average summary statistics in the DSAS summary report. Refer to the baseline field requirements in section 5.3.3 and a description of the summary report in section 9 for more information.
TransOrder	Long Integer	Assigned by DSAS on the basis of transect order along the baseline or baselines. If the user manually adds transects to the file in an edit session, they will be added to the end of the transect attribute table and given a new TransID (ObjectID). However, TransOrder will be updated to reflect the position of the new transect with respect to the other transects along the baseline. This field provides the user with a method to sort transect attribute data from the start of the baseline segment with an ID=1 and increment by one alongshore to the end of the final baseline segment.
TransEdit	Text	Indicates whether a transect was automatically created by DSAS (0=transect was autogenerated by DSAS; 1=transect was added or edited by user).
Azimuth	Double	Used to record the azimuth of the transect measured in degrees clockwise from north.
SHAPE_Length	Double	Length of transect in meter units, assuming data were properly projected in a meter-based coordinate system. This field is automatically generated when data are within a geodatabase.

Transect Storage

By default, DSAS stores transects into the geodatabase where the base feature classes are stored (baseline and crestline). Though the user may choose to store them elsewhere, the baseline and crestline must be stored in the same place, we chose the default method to keep data in one location.

Editing Transects

To edit a transect layer in DSAS, the layer must be selected in the DSAS toolbar. This will ensure all topological changes and relationships with the baseline and the crestline are saved and referenced within the DSAS program and as well within ArcGIS. In the current study, editing on the transects was performed. However, with the baseline located onshore, the more than 2,000 transects were corrupted and unusable within DSAS. This was likely due to the immense amount of editing needed along curved sections to keep orthogonality of the transects along the crestline, and although this was a tremendous amount of work, it did lead to using the baseline offshore, where the editing was much more manageable, efficient, and in the end as effective.

3.5.2.4 Calculating Change Statistics

When all transects updates, edits, and any modifications are saved and stored, the user can proceed to the Calculate Rates option. DSAS allows the user to choose from a list of statistical analyses that will be performed or select all. In the current study, there were only two timeframes to analyze, limiting the study to the following statistics: 1) shoreline change envelope (SCE), 2) net shore movement (NSM), and 3) end point rate (EPR). All other change statistics require three or more crestlines. This was not limiting factor, however, as only crestline change from 2007 to 2015 and 2012 to 2015 were of interest. To accomplish this, only the SCE value was needed. Once all parameters and outputs were specified and the "Calculate," was selected a new linear output feature file with a calculated length between the crestlines on the transects was casted. This feature provided the abiltiy to calculate, compare, and display crestline change along the Pennsylvania Lake Erie coast. SCE value represents the greatest distance (meters) among all the crestlines that intersect a given transect. NSM is the distance (meters) between the oldest and the youngest crestlines for each transect. EPR is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline.

3.6 Data Analysis

The rate of change (meters/year and feet/year) was calculated for each transect by dividing the SCE by the number of years between crestlines. Only transects with observed change were included in the analysis. For 2007 to 2015 rate of change, the SCE was divided by eight years. For the 2012 to 2015 rate of change, the SCE was divided by three years. The mean rate of change for each municipality was calculated by summing the rates of change and dividing by the total number of transects in the municipality. Standard deviation and 95% confidence intervals were calculated for the mean rate of change. All calculations were preformed using the formula function in Microsoft® Excel.

4.0 Results and Discussion

4.1 Rate of Bluff Change by Municipality (2007 to 2015)

The rate of bluff change was assessed at 2,232 transects along the Pennsylvania Lake Erie coast from 2007 to 2015. The mean rate of bluff change (95% CI) along the Pennsylvania Lake coast (n = 2,232) from 2007 to 2015 was 0.2149 meters/year (0.2068, 0.2229) or 0.705 feet/year (0.6786, 0.7314) (*Table 7* and *Table 8*; *Figure 4* and *Figure 5*). Northeast Township (n = 391) had the highest mean rate of bluff change (95% CI) from 2007 to 2015 at 0.2654 meters/year (0.2380, 0.2929) or 0.8708 feet/year (0.7807, 0.9609). Lake City Borough (n = 6) had the lowest mean rate of bluff change (95% CI) from 2007 to 2015 at 0.1513 meters/year (0.0636, 0.2391) or 0.4965 feet/year (0.2086, 0.7844).

Table 7. Mean rate of bluff change (meters/year) along the Pennsylvania Lake Erie Coast (2007 to 2015) by municipality

Municipality	Number of Transects	Mean Rate of Change (m/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	427	0.1668	0.1128	(0.1561, 0.1775)
Girard Township	231	0.2165	0.1411	(0.1983, 0.2347)
Lake City Borough	6	0.1513	0.1097	(0.0636, 0.2391)
Fairview Township	267	0.2145	0.2020	(0.1903, 0.2387)
Millcreek Township	170	0.1651	0.1682	(0.1398, 0.1904)
City of Erie	235	0.2286	0.1763	(0.2060, 0.2511)
Lawrence Park Township	59	0.2098	0.1906	(0.1612, 0.2585)
Harborcreek Township	446	0.2292	0.1891	(0.2117, 0.2468)
North East Township	391	0.2654	0.2770	(0.2380, 0.2929)
All	2,232	0.2149	0.1938	(0.2068, 0.2229)

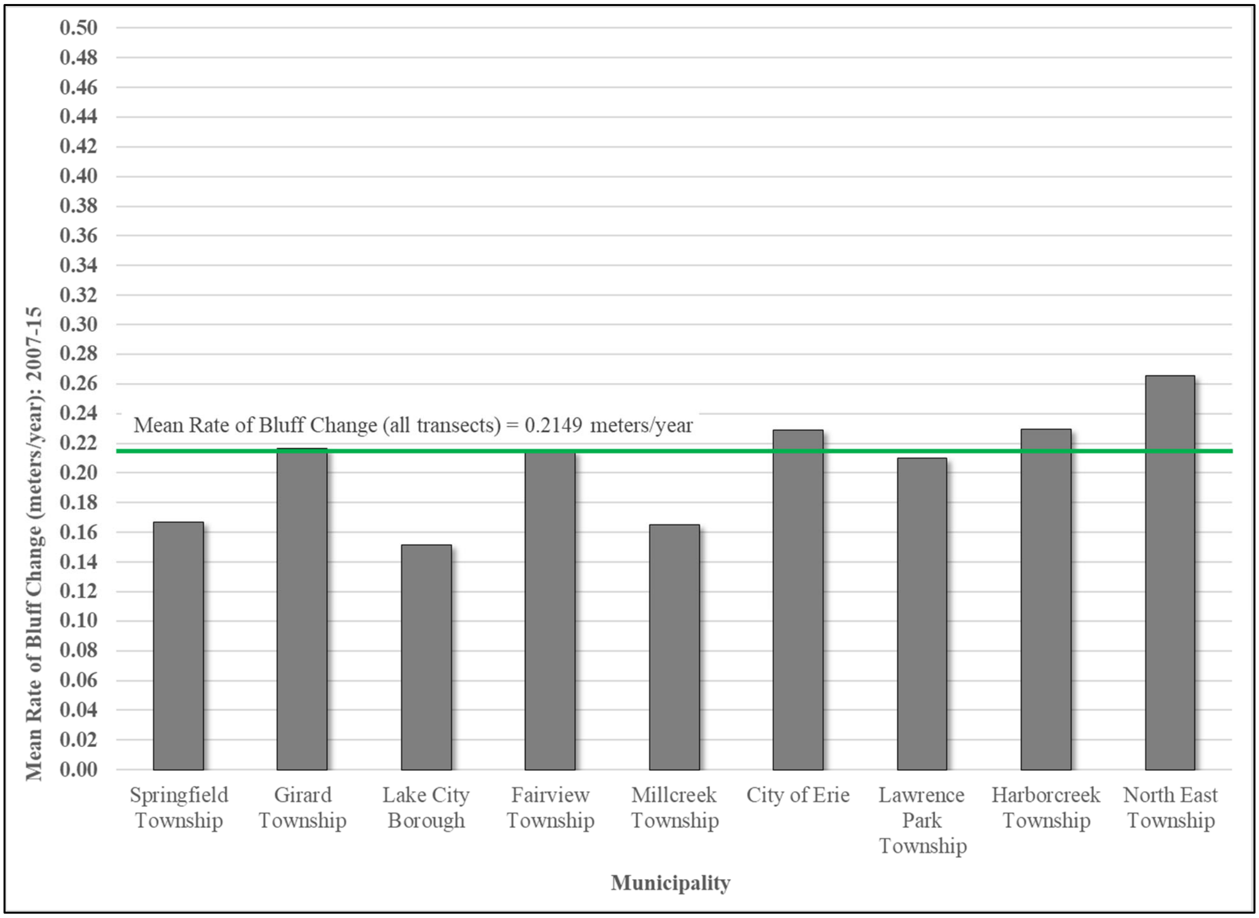

Figure 4. Mean rate of bluff change (meters/year) along the Pennsylvania Lake Erie Coast (2007 to 2015) by municipality

Table 8. Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2007 to 2015) by municipality

Municipality	Number of Transects	Mean Rate of Change (ft/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	427	0.5474	0.3701	(0.5123, 0.5825)
Girard Township	231	0.7104	0.4631	(0.6506, 0.7701)
Lake City Borough	6	0.4965	0.3598	(0.2086, 0.7844)
Fairview Township	267	0.7038	0.6628	(0.6242, 0.7833)
Millcreek Township	170	0.5416	0.5519	(0.4587, 0.6246)
City of Erie	235	0.7500	0.5784	(0.6760, 0.8239)
Lawrence Park Township	59	0.6884	0.6254	(0.5288, 0.8480)
Harborcreek Township	446	0.7521	0.6206	(0.6945, 0.8097)
North East Township	391	0.8708	0.9088	(0.7807, 0.9609)
All	2,232	0.7050	0.6357	(0.6786, 0.7314)

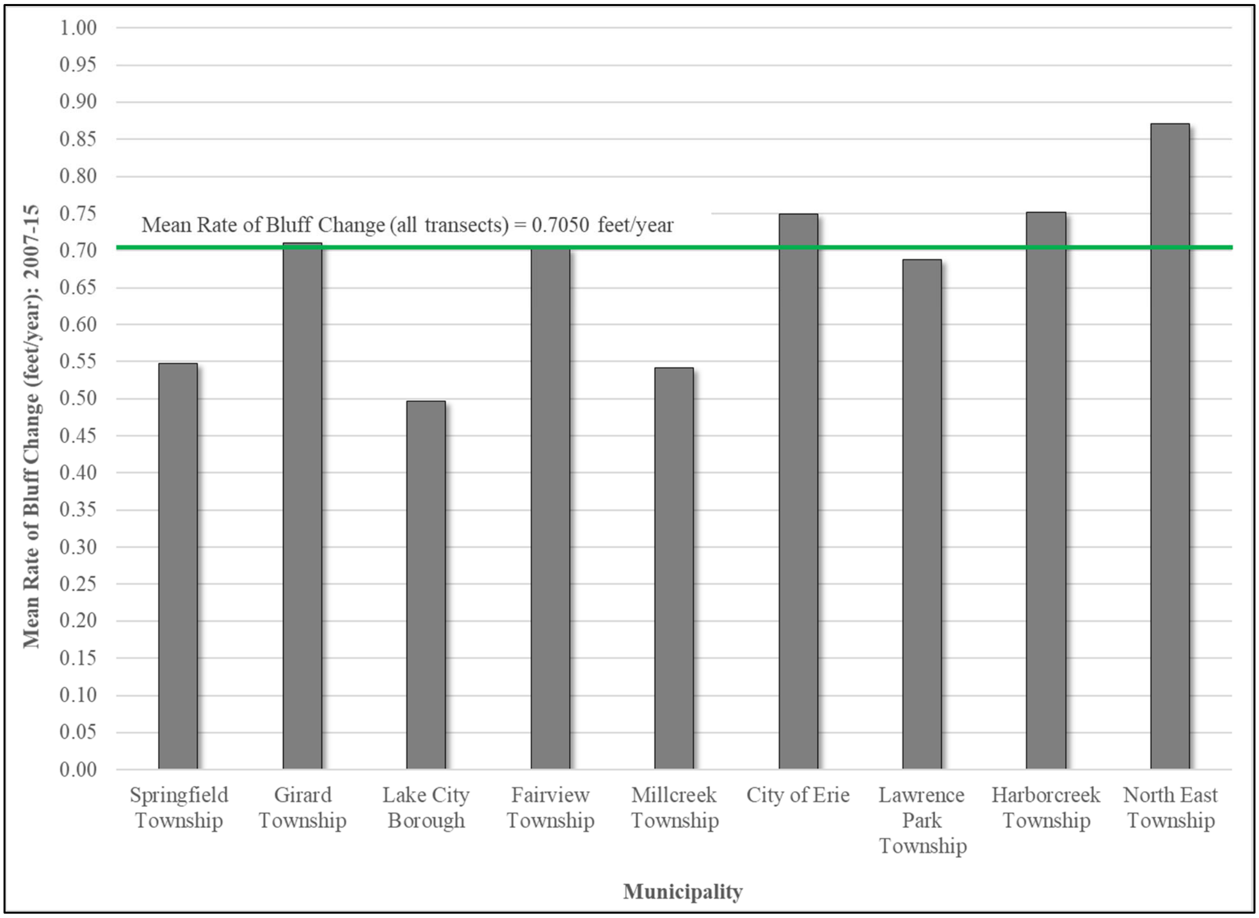

Figure 5. Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2007 to 2015) by municipality.

4.2 Rate of Bluff Change by Municipality (2012 to 2015)

The rate of bluff change was assessed at 1,753 transects along the Pennsylvania Lake Erie coast from 2012 to 2015. The mean rate of bluff change (95% CI) along the Pennsylvania Lake coast (n = 1,753) from 2012 to 2015 was 0.3076 meters/year (0.2930, 0.3221) or 1.009 feet/year (0.9613, 1.0568) (*Table 9* and *Table 10*; *Figure 6* and *Figure 7*). Northeast Township (n = 322) had the highest mean rate of bluff change (95% CI) from 2012 to 2015 at 0.4501 meters/year (0.4053, 0.4949) or 0.1.4768 feet/year (1.3298, 1.6238). Lake City Borough (n = 6) had the lowest mean rate of bluff change (95% CI) from 2012 to 2015 at 0.1535 meters/year (0.1097, 0.1973) or 0.5037 feet/year (0.3600, 0.6474).

Table 9. Mean rate of bluff change (meters/year) along the Pennsylvania Lake Erie Coast (2012 to 2015) by municipality.

Municipality	Number of Transects	Mean Rate of Change (m/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	354	0.2349	0.2190	(0.2121, 0.2577)
Girard Township	140	0.2627	0.2394	(0.2230, 0.3023)
Lake City Borough	6	0.1535	0.0547	(0.1097, 0.1973)
Fairview Township	200	0.2394	0.2758	(0.2012, 0.2777)
Millcreek Township	148	0.2167	0.2092	(0.1830, 0.2504)
City of Erie	194	0.2864	0.2605	(0.2498, 0.3231)
Lawrence Park Township	44	0.4250	0.4841	(0.2819, 0.5680)
Harborcreek Township	345	0.3454	0.3081	(0.3128, 0.3779)
North East Township	322	0.4501	0.4102	(0.4053, 0.4949)
All	1,753	0.3076	0.3108	(0.2930, 0.3221)

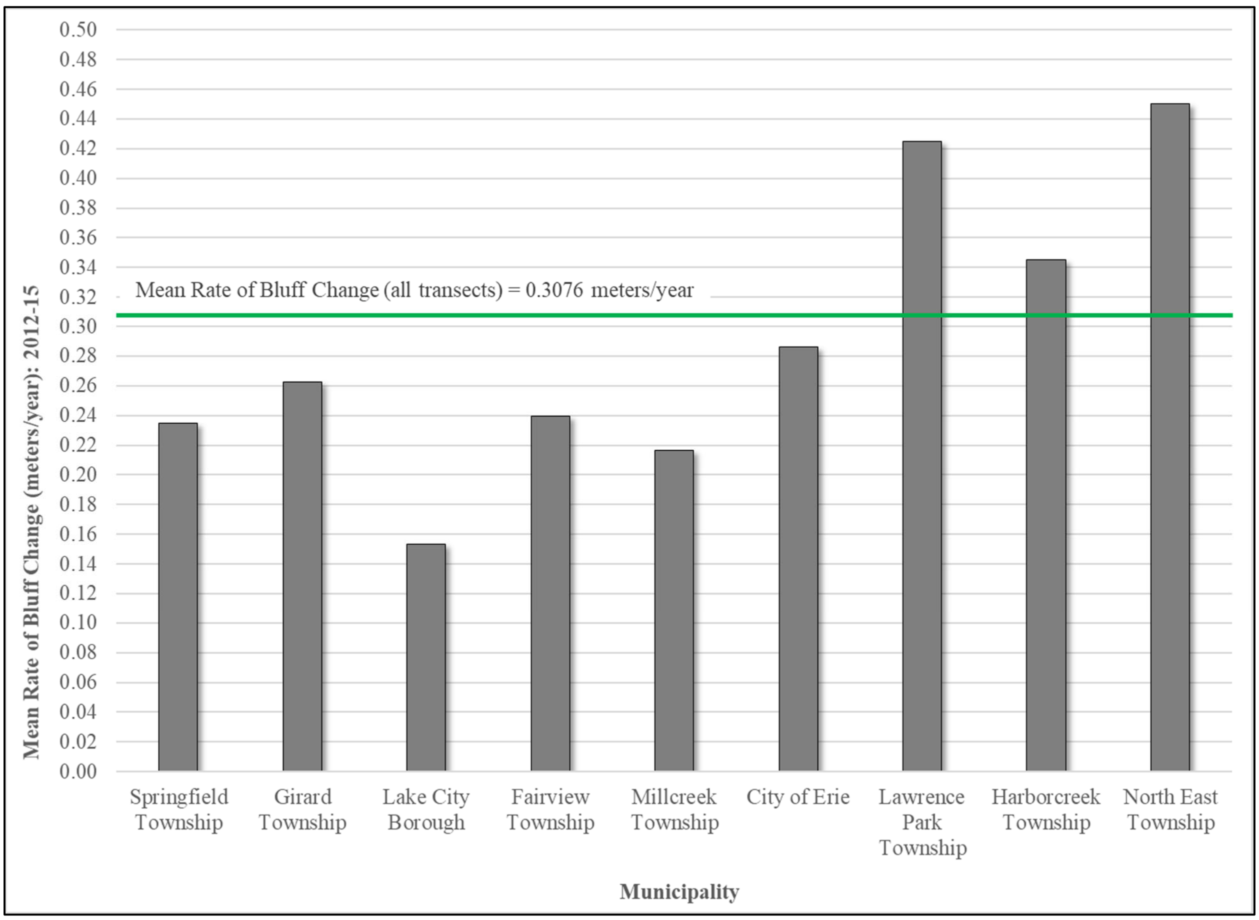

Figure 6. Mean rate of bluff change (meters/year) along the Pennsylvania Lake Erie Coast (2012 to 2015) by municipality.

Table 10. Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2012 to 2015) by municipality.

Municipality	Number of Transects	Mean Rate of Change (ft/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	354	0.7706	0.7184	(0.6957, 0.8454)
Girard Township	140	0.8618	0.7853	(0.7317, 0.9919)
Lake City Borough	6	0.5037	0.1796	(0.3600, 0.6474)
Fairview Township	200	0.7855	0.9048	(0.6601, 0.9109)
Millcreek Township	148	0.7109	0.6862	(0.6004, 0.8215)
City of Erie	194	0.9397	0.8546	(0.8194, 1.0600)
Lawrence Park Township	44	1.3943	1.5884	(0.9249, 1.8636)
Harborcreek Township	345	1.1331	1.0109	(1.0264, 1.2397)
North East Township	322	1.4768	1.3459	(1.3298, 1.6238)
All	1,753	1.0090	1.0196	(0.9613, 1.0568)

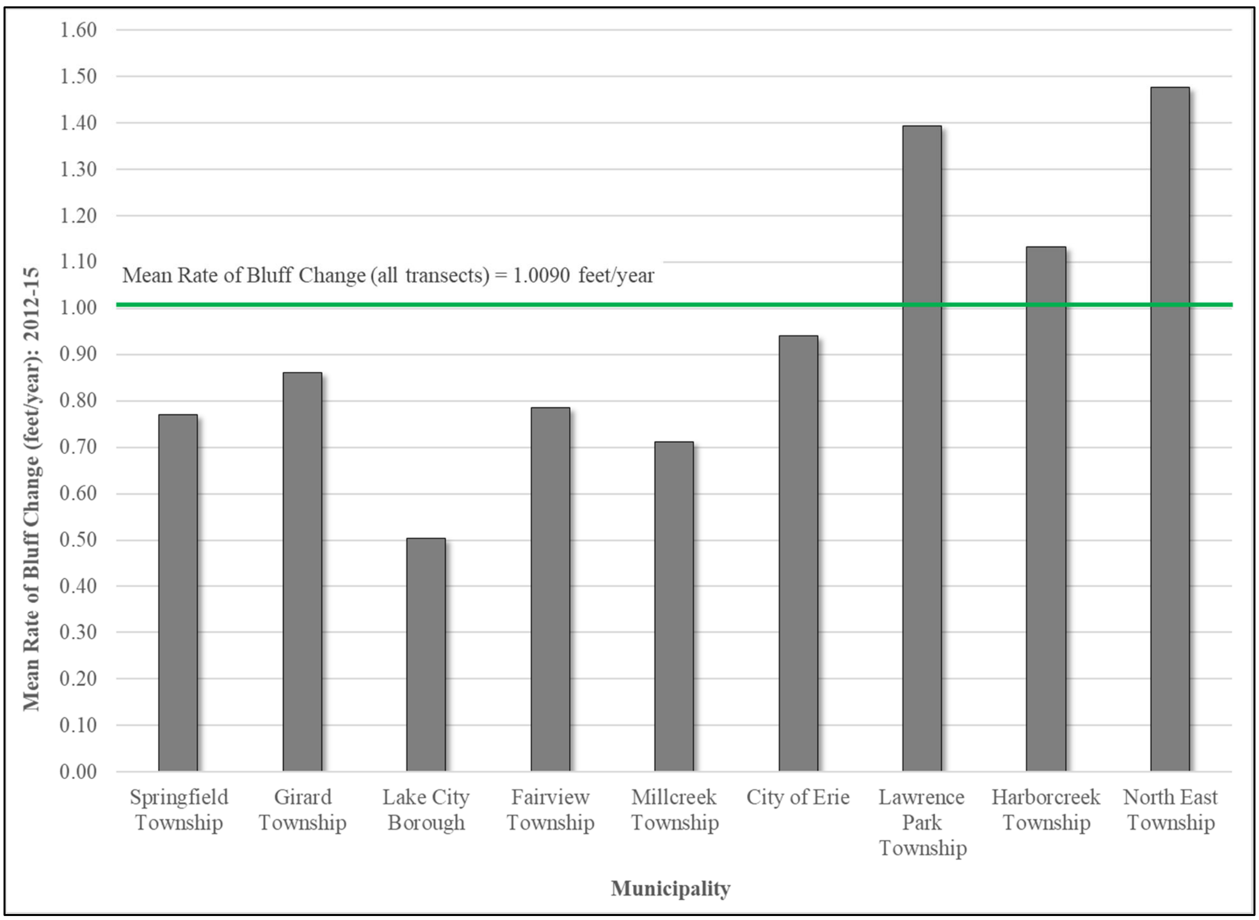

Figure 7. Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (2012 to 2015) by municipality.

4.3 PA CRM Bluff Rate of Change by Municipality

From 1975-2019, at varying time intervals, PA CRM monitored bluff recession at 129 control points along the Pennsylvania Lake Erie coast (Click here for more information on the PA CRM control point monitoring program). The mean rate of bluff change (95%) along the Pennsylvania Lake Erie coast (n = 129) during these varying time intervals was 0.1557 meters/year (0.1292, 0.1823) or 0.511 feet/year (0.4239, 0.5980) (*Table 11* and *Table 12*; *Figure 8* and *Figure 9*). Springfield Township (n = 25) had the highest mean rate of bluff change (95% CI) at 0.2714 meters/year (0.1967, 0.3462) or 0.8905 feet/year. Millcreek Township had the lowest mean rate of bluff change (95% CI) at 0.068 meters/year (0.0185, 0.1175) or 0.2231 feet/year (0.0609, 0.3854).

Table 11. Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (1975 to 2019) by municipality determined through the PA CRM control point monitoring program.

Municipality	Number of Transects	Mean Rate of Change (m/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	25	0.2714	0.1907	(0.1967, 0.3462)
Girard Township	17	0.2149	0.1305	(0.1529, 0.2769)
Lake City Borough	-	-	-	-
Fairview Township	16	0.1332	0.1091	(0.0797, 0.1866)
Millcreek Township	15	0.0680	0.0977	(0.0185, 0.1175)
City of Erie	3	0.1279	0.0987	(0.0162, 0.2396)
Lawrence Park Township	4	0.1054	0.0420	(0.0643, 0.1465)
Harborcreek Township	22	0.1073	0.1176	(0.0581, 0.1564)
North East Township	27	0.1236	0.1450	(0.0688, 0.1783)
All	129	0.1557	0.1538	(0.1292, 0.1823)

Table 12. Mean rate of bluff change (meters/year) along the Pennsylvania Lake Erie Coast (1975 to 2019) by municipality determined through the PA CRM control point monitoring program.

Municipality	Number of Transects	Mean Rate of Change (ft/yr)	Standard Deviation	95% Confidence Interval
Springfield Township	25	0.8905	0.6257	(0.6453, 1.1358)
Girard Township	17	0.7051	0.4281	(0.5015, 0.9086)
Lake City Borough	-	-	-	-
Fairview Township	16	0.4369	0.3580	(0.2615, 0.6123)
Millcreek Township	15	0.2231	0.3206	(0.0609, 0.3854)
City of Erie	3	0.4196	0.3238	(0.0532, 0.7860)
Lawrence Park Township	4	0.3457	0.1377	(0.2108, 0.4807)
Harborcreek Township	22	0.3519	0.3859	(0.1907, 0.5131)
North East Township	27	0.4054	0.4759	(0.2259, 0.5848)
All	129	0.5110	0.5046	(0.4239, 0.5980)

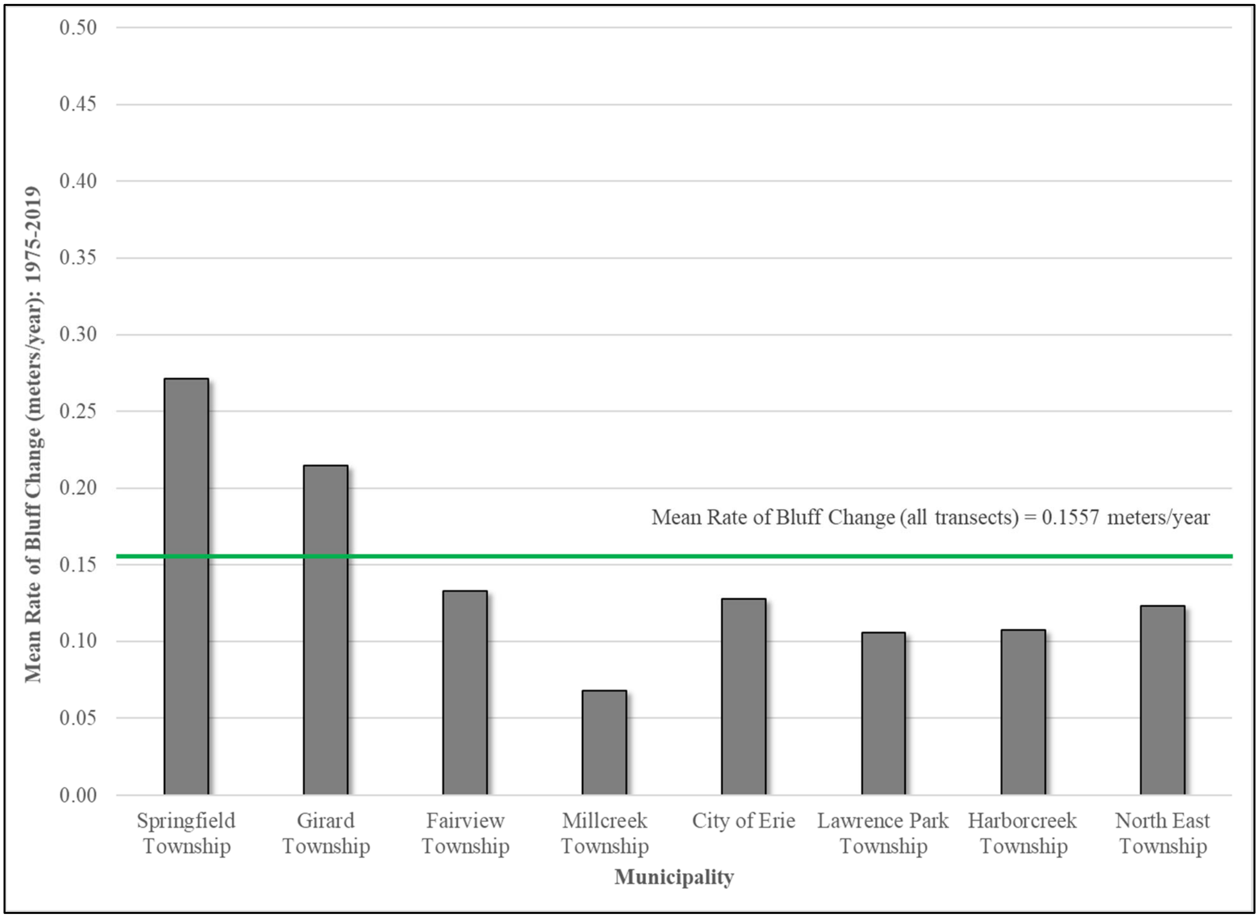

Figure 8. Mean rate of bluff change (meters/year) along the Pennsylvania Lake Erie Coast (1975 to 2019) by municipality determined through the PA CRM control point monitoring program.

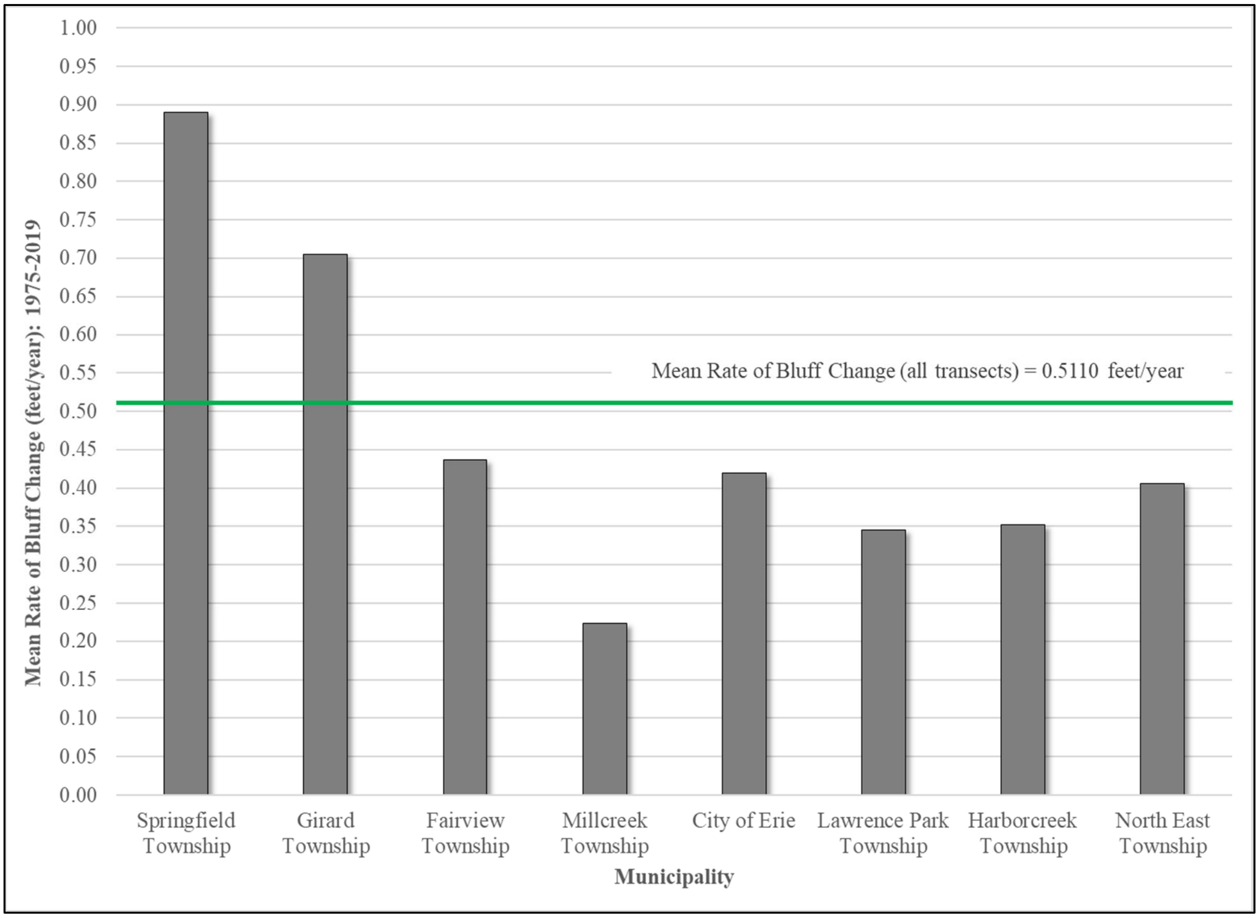

Figure 9. Mean rate of bluff change (feet/year) along the Pennsylvania Lake Erie Coast (1975 to 2019) by municipality determined through the PA CRM control point monitoring program.

4.4 Discussion

While a valuable resource, and an excellent ground-check on more recent digital methods of mapping coastal change, the PA CRM control-point methodology is becoming antiquated. It is a labor-intensive, weather-dependent method of bluff-crest mapping, and it does not provide sufficient spatial resolution on bluff recession due to a typical transect spacing of 500-meters that is not closely scaled to the dimensions of stable-bluff and bluff-failure zones. In response, the current project sought to evaluate the feasibility of using remote sensing techniques and DSAS to assess the bluff change over time at a tighter spatial resolution (20-meters).

From 2012 to 2015, the mean rate of bluff change at transects (n = 1,753) along the Pennsylvania Lake Erie coast was determined to be 0.3076 meters/year (1.009 feet/year). This was higher than the mean rate of change observed from 2007 to 2015, and by PA CRM at varying timescales between 1975 and 2019. The mean rate of bluff change at transects (n = 2,232) along the Pennsylvania Lake Erie coast from 2007 to 2015 was 0.2149 meters/year (0.705 feet/year). This eight-year timeframe, with more transects, likely gives a better picture of bluff movement over time along the Pennsylvania Lake Erie coast than the three-year timeframe, with fewer transects. Using remote sensing data techniques and DSAS provides a viable method for assessing bluff movement over time and will likely improve over time with improved LiDAR resolution and longer time scales to assess. The strength of the PA CRM data is the longer time scales in which bluff movement is assessed. However, the lack of spatial scale (129 control points versus 2,232 transects) of the PA CRM data may result in over/underestimating the true bluff recession rate along the Pennsylvania Lake Erie coast.

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