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# Mapping Michigan's Historic Coastlines

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MAPPING MICHIGAN'S HISTORIC COASTLINES

By

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A REPORT

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# Acknowledgements

# Abstract

This five-year project, sponsored by the Michigan Department of Environment, Great Lakes, and Energy, is working to map how Michigan's Great Lakes shorelines have changed over the past 80+ years. Products of this project include publicly available digital, georeferenced, historic aerial photography datasets, as well as map layers depicting the locations of historic shorelines and bluff lines from 1938, 1980, 2009, 2016, 2018, and 2020. Additional products include bluff retreat risk areas, shoreline rate of change map layers, and tools to assist in the development of future Coastal Vulnerability Index projects for the Great Lakes. All products are available as publicly accessible maps, apps, and feature services at

https://portal1-geo.sabu.mtu.edu/mtuarcgis/apps/sites/#/czmp

# 1   Introduction

The State of Michigan has the longest freshwater coastline in the United States (USACE 2003). That coastline is ever changing, due to changes in water level, erosion by wind and waves, transport of sediment along beaches, and changes to the shoreline by people. Changing Shorelines (Joan Pope 1999).

Long term monitoring of the Great Lakes water levels by the US Army Corps of Engineers depict water level changes in Lakes Michigan & Huron of up to 2 meters within a 10-year period, and fluctuations of a half meter between summer and winter are not uncommon (Fig. 1.1) (USACE 2021).
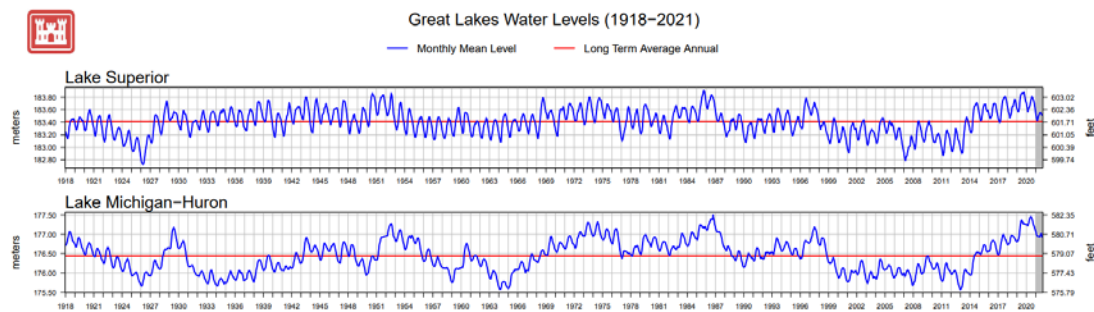


Figure 1.1: Monthly mean lake-wide average water levels. See A.3 for the figure in its entirety. Image source: https://lre-wm.usace.army.mil/ForecastData/GLBasinConditions/LTA-GLWL-Graph.pdf.  See B for full attribution and copyright licensing information.

On a typical gently sloping beach, a rise in water level will result in the shoreline - the line delineating water from dry land – moving more landward, with the beach appearing to shrink. Conversely, a drop in water level will result in the shoreline moving further away from land, and the beach will appear to grow (USACE 2003). These changes are often noticeable when observing a beach in person across several months or years, and can be easily observed when comparing historic aerial imagery for the same location from different years. These changes in shoreline do not necessarily indicate erosion or accretion of the shoreline, but may simply indicate that more or less of the beach is submerged beneath the water than it was in a previous year. Identifying actual shoreline erosion or accretion requires the comparison of the shoreline at two times having the same water level (Joan Pope 1999).

## 1.1 Changing Bluff Lines

Michigan's Great Lakes coastal bluffs, defined in this project as 'the lakeward-most edge of relatively level ground that breaks or drops off abruptly' (City of San Diego 2000), are also changing. Coastal bluffs along Michigan's sandy beaches are typically located beyond the area of normally wetted beach, and are prone to erosion due to rising water levels and the erosive action of waves. In fact, research has found that, historically,

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periods of higher great lakes water levels are also associated with more severe storms and larger, more energetic waves (Meadows, Meadows et al. 1997). This combination of higher water levels and higher wave energy can lead to increased erosion and dramatic changes to coastal bluffs (Fig 1.2).



Figure 1.2 Damage due to coastal bluff erosion of a large landscape-scale bluff along southern Lake Michigan coastline. Image source: Cory Morse, mLive.com, https://arc-anglerfish-arc2-prod-advancelocal.s3.amazonaws.com/public/MUKCTBK5RBFUBKUJ6O664EOBJQ.JPG See B for full attribution and copyright licensing information.

While fluctuations in the location of the shoreline may be relatively ephemeral, often changing throughout the year, changes to the bluff line are often more long-term. Small-scale bluffs (Fig 1.3) may erode and accrete over several years, but in situations where bluffs are large landscape-scale features (Fig 1.2), erosion of the bluff and bluff recession – the movement of the edge of the bluff more inland – may represent a permanent change within the human time scale.

This change does have a positive aspect though, in that the eroded material provides sediment that is moved toward the lake and along the shoreline, replenishing the beach and neighboring beaches. In this sense, the erosion of the bluff actually 'feeds' the beaches in a sediment transport cycle (USACE 2003).

Figure 1.3: Coastal bluff erosion of a small scale bluff along the southern Lake Michigan coastline. Image source: Cory Morse, mLive.com, https://arc-anglerfish-arc2-prod-advancelocal.s3.amazonaws.com/public/EHH3YOXNSRCPNARBLTL55TYHAQ.jpg

## 1.2 Impacts of Change

The impact of changing coastlines on property and infrastructure can be great. Bluff recession in particular can lead to severe impacts in areas located near the bluff edge. High water levels and strong waves in the fall of 2019 and spring of 2020 led to dramatic erosion along Michigan's southern Lake Michigan coastline, resulting in severe damage to roads and utilities (Fig. 1.4), risks to health and safety, and loss of property including entire homes (Fig. 1.2). In a survey of Michigan coastal communities, the Michigan Municipal League reported an estimated cost of $63 million to repair damages to public infrastructure incurred during the winter of 2019 and spring of 2020 (Gardner 2020). This does not include the costs related to losses of private property.

Figure 1.4   Cory Morse, mLive.com, arc-anglerfish-arc2-prod-advancelocal.s3.amazonaws.com/public/OHCHV4RFBRG3JNNA5HN6JZAK5M.jpeg

## 1.3  Responding to Change

Just as the changing coastline results in costs and consequences, responding to these changes also have associated costs and consequences. While there are numerous ways to respond to changes in a coastline, including not responding at all, two common responses are managed retreat and shoreline armoring (Joan Pope 1999).

Managed retreat involves moving infrastructure and buildings away from the risk, often away from a receding bluff line. Examples of this were exhibited in 2020 at McLean State Park in Houghton County, Michigan, and at a private residence in Berrien County, Michigan (Fig. 1.5). At McLean State Park, the majority of a large campground including underground utilities, roads, and buildings were relocated further inland, and the entrance to the park was completely reconfigured. In Berrien County, MI, a 6,000 square foot house was raised on rails and relocated 100' back from the rising shoreline (Wolfe-House-Movers 2015). Managed retreat can be effective, but it is time consuming, costly, and not always feasible.

Figure 1.5  An example of managed retreat being executed near St. Joe, MI. Image source: Wolfe house and building movers, https://www.wolfehousebuildingmovers.com/wp-content/uploads/2019/11/Lake-Michigan-Shift-2-1024x684.jpg

Shoreline armoring involves constructing a wall or placing rock along the shoreline (Fig. 1.6), with the goal of stopping erosion behind the armoring. While this does often stop the immediate erosion behind the armoring, it also often results in the loss of beach in front of the armoring. Shoreline armoring also typically fails over time, and, importantly, it results in a lack of sediment to 'feed' neighboring beaches (USACE 2003). Because the sediment transport cycle is cut off, neighboring beach material lost to erosion is not replenished, resulting in increased erosion of neighboring beaches.



Figure 1.6: Shoreline armoring along the southern Lake Michigan coastline. Image source: Superior Watershed Partnership, https://www.greatlakesshoreviewer.org/img/obliques/great-lakes/lp/DSC_4290.jpg

## 1.4 Avoiding these Conflicts

During the particularly low water level years of the early 2000's, development along Michigan's coastline increased in many of Michigan's coastal communities. As water levels in the Great Lakes began to rise, some of these homes became imperiled, and conflicts between protecting natural beaches and protecting private property became frequent.

One option to avoid these conflicts is to avoid constructing infrastructure and homes in areas that are likely to experience shoreline change and bluff recession. While individual communities have residents and personnel with memories of how the shoreline changed over time in their communities, there existed no high- resolution long-term analysis of shoreline change for much of the coast of Michigan (Stauble 2004).

In 2017, Michigan Technological University began working in cooperation with the University of Michigan, the Michigan Association of Planners, and regional planning agencies throughout the State of Michigan, on a project funded by the Michigan Department of Environment, Great Lakes, and Energy, and the National Oceanic and Atmospheric Administration, with the goal of identifying where Michigan's coastlines are likely to change, and sharing this information with coastal communities through a series of workshops and planning documents.

# 2  Goals & Deliverables

The main goal of this project is to improve the understanding of how Michigan's Great Lakes shorelines have changed over the past 80 years, and provide publicly accessible data and tools to help increase the resiliency of Michigan's coastal communities.

The products developed towards this goal include:

- Georeferenced historic aerial imagery
- Shoreline and bluff line locations for each historic year
- A summary of shoreline rates of change over time in the form of rate of shoreline change maps and feature layers and bluff retreat risk area maps and feature layers
- A collection of data services and web-mapping applications to make all these products easily accessible by the public and reusable by other researchers and planning agencies

An additional product of this project is a workflow and GIS toolbox for collecting coastal bluff characteristics such as distance to bluff, bluff height, and bluff slope and combining them with shoreline rate of change calculations at transects along the coastline. These data are intended to serve as a ready to use dataset for coastal vulnerability modeling along the coastline.

# 3  Methods

The general methods employed in this project for measuring rates of shoreline change over time involved using GIS to digitize the precise location of shorelines over the top of georeferenced historical aerial photographs. These shorelines were then used as input to the United States Geologic Survey (USGS) Digital Shoreline Analysis System (DSAS) to produce shoreline rates of change at 100 meter intervals along the coastline. Bluff lines were also used as input to a similar tool developed at Michigan Tech to produce Bluff Retreat Risk Areas depicted as shaded regions on a map in areas near historically active bluff top recession.

While the map depicting shoreline rates of change is an important deliverable, the georeferenced historic imagery and historic shoreline location maps have already shown to be valuable on their own to other researchers, such as the U.S. Army Corps of Engineers. Since the first year of this project, these data have been made publicly accessible as web feature services and web map services, and via a web-based interactive mapping application.

## 3.1  Historic Aerial Imagery

Some of the earliest publicly-available aerial photography of Michigan and its coastline was collected by the U.S. Department of Agriculture, Farm Service Agency, in 1938. This black and white photography is generally available at 1:20,000 scale (1" = 1,600'). Digitized copies of this imagery for 1938, and many other years, are available for a fee from the Michigan State University (MSU) Remote Sensing and GIS lab (RSGIS), and hard-copy archives are held at the offices of the Michigan Department of Environment, Great Lakes, and Energy (EGLE). This 1938 imagery is the source of the oldest shoreline digitized in this project.

Digital images of aerial photography for 1938 and 1980 were obtained from RSGIS for Michigan's Lake Michigan coastline south of the Leelanau Peninsula. Images for these same or similar years for most other areas were obtained directly from the EGLE historic imagery archives, and digitized by EGLE and Michigan Tech personnel. Because imagery for 1980 was not available for Lake Huron, 1978 imagery from EGLE was used as a substitute, producing a 1978 shoreline in those areas.

Imagery for modern years are available digitally from the USDA National Aerial Imagery Program (NAIP), online, and already precisely georeferenced. For this project, imagery for 2009, 2016, 2018, and 2020 were downloaded from the USGS EarthExplorer website and used as-is. NAIP imagery is specified to have a 1-meter resolution, and a true horizontal accuracy of 6 meters or better when compared to ground control points identifiable in the imagery. Relative accuracy is the measure of difference in location between features identifiable on two or more years of imagery, and is an important metric to understand when performing change analysis using imagery from different time periods. Relative accuracy is not reported for the NAIP imagery, but was observed to be 3 meters or better, on average, for areas of interest for this project by comparing locations

of major features such as break walls and piers visible on multiple years of imagery and unlikely to physically change location. A listing of historic imagery sources used in this project is included in Table 3.1.

Imagery from 1938 and 1980 required georeferencing so the historic imagery aligned precisely with the modern imagery. Using the 2016 NAIP imagery as a target, project team members in the Geospatial Research Facility at Michigan Tech precisely georeferenced these historic images, using a spline transformation and up to 40 control points each, using ESRI's ArcGIS Desktop application. Special care was taken to include multiple control points close to the shoreline as well as in upland areas, to accurately capture coastal slopes and bluff areas near the shoreline. This was, by far, the largest labor portion of this project.
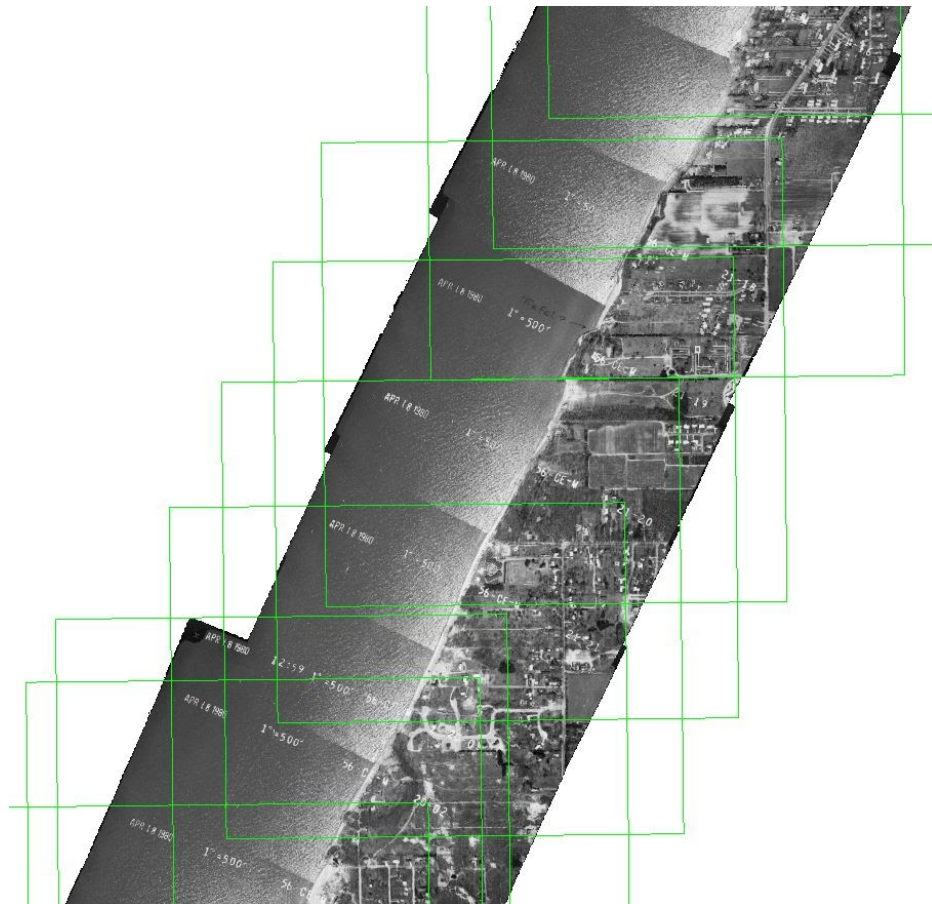


Figure 3.1: ESRI Image Mosaic of 1938 imagery along the southern coastline of Lake Michigan. Image source: MSU Historic Aerial Imagery Archive & Michigan Tech

NAIP Imagery from 2016 was selected as a base map for digitizing because it was the most recent imagery available at the beginning of this project, metadata documented that it was already precisely georeferenced, and comparison with static objects on NOAA navigational charts, such as piers and breakwaters, showed a very close correlation.

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Georeferenced images were then compiled into an image mosaic dataset for each year, allowing them to be treated as a single map layer (Fig. 3.1). The Create Image Mosaic Dataset tool within the ESRI ArcGIS Desktop Application was utilized to produce these mosaics, using an overlap rule of 'nearest to nadir' to control which image is displayed to the user in areas of image overlap. Using this overlap rule ensures that the user is provided with the image having the least distortion at the center of their map view, as they interact with the image by panning and zooming.

Table 3.1.  Imagery Sources.  Description of Imagery used in this project

| Year | Location | Source |
|------|----------|--------|
| 1938 | Lower Peninsula, Lake Michigan coastline South of Frankfort, MI to Indiana Border | MSU |
| 1938 | Lower Peninsula, Lake Michigan coastline North of Frankfort, MI to the Mackinaw Bridge | EGLE |
| 1980 | Berrien County, MI | Meadows |
| 1980 | Lower Peninsula, Lake Michigan coastline South of Frankfort, MI to Indiana Border | MSU |
| 1980 | Lower Peninsula, Lake Michigan coastline North of Frankfort, MI to the Mackinaw Bridge | EGLE |
| 1978 | Lake Huron | EGLE |
| 2009 | All of Michigan coastlines of Lakes Huron, Michigan, and Superior | USDA NAIP |
| 2016 | All of Michigan coastlines of Lakes Huron, Michigan, and Superior | USDA NAIP |
| 2018 | All of Michigan coastlines of Lakes Huron, Michigan, and Superior | USDA NAIP |
| 2020 | All of Michigan coastlines of Lakes Huron, Michigan, and Superior | USDA NAIP |

## 3.2 Shoreline and Bluff Line Creation

For this project, the shoreline is defined as the 'Landward-most extent of wetted beach', and is essentially where the water meets the land at the time of the photo. Shorelines were digitized in ArcGIS Desktop and ArcGIS Pro in a 'heads up' fashion, where analysts draw lines on top of a georeferenced natural color or black and white image. Shorelines were digitized for each year of historic imagery, generally at a 1:1,000 scale for modern imagery (Fig. 3.2), and less precisely for the 1938 imagery, due to the lower resolution of that photography.



Figure 3.2: Historic shorelines mapped for two of this project's years depicted on a 2016 aerial image. Image source: Michigan Tech, USDA NAIP

Modern imagery from NAIP (2009 – 2020) provided 4-band images: Red, Green, Blue, and Near Infrared (NIR). This NIR band was used periodically by analysts to provide more definition of the shoreline in areas of heavy shade or bright glare from the water surface.

Bluff lines, defined as 'the lakeward-most edge of relatively level ground that breaks or drops off abruptly' were also digitized in a similar heads-up fashion using the same historic imagery used for shorelines (Fig. 3.3). Analysts used oblique aerial photography from the US Army Corps of Engineers (photo) to help locate bluffs on the nadir aerial photography. Starting in 2016, LIDAR based digital elevation models (DEMs) of much of Michigan's coastline became available, and analysts used these as well to help identify areas where bluffs were present and visible in the historic aerial photography. Hillshade and contour products of these DEMs were used to help identify hidden bluffs, but the primary source of bluff location digitized is always the aerial photography.
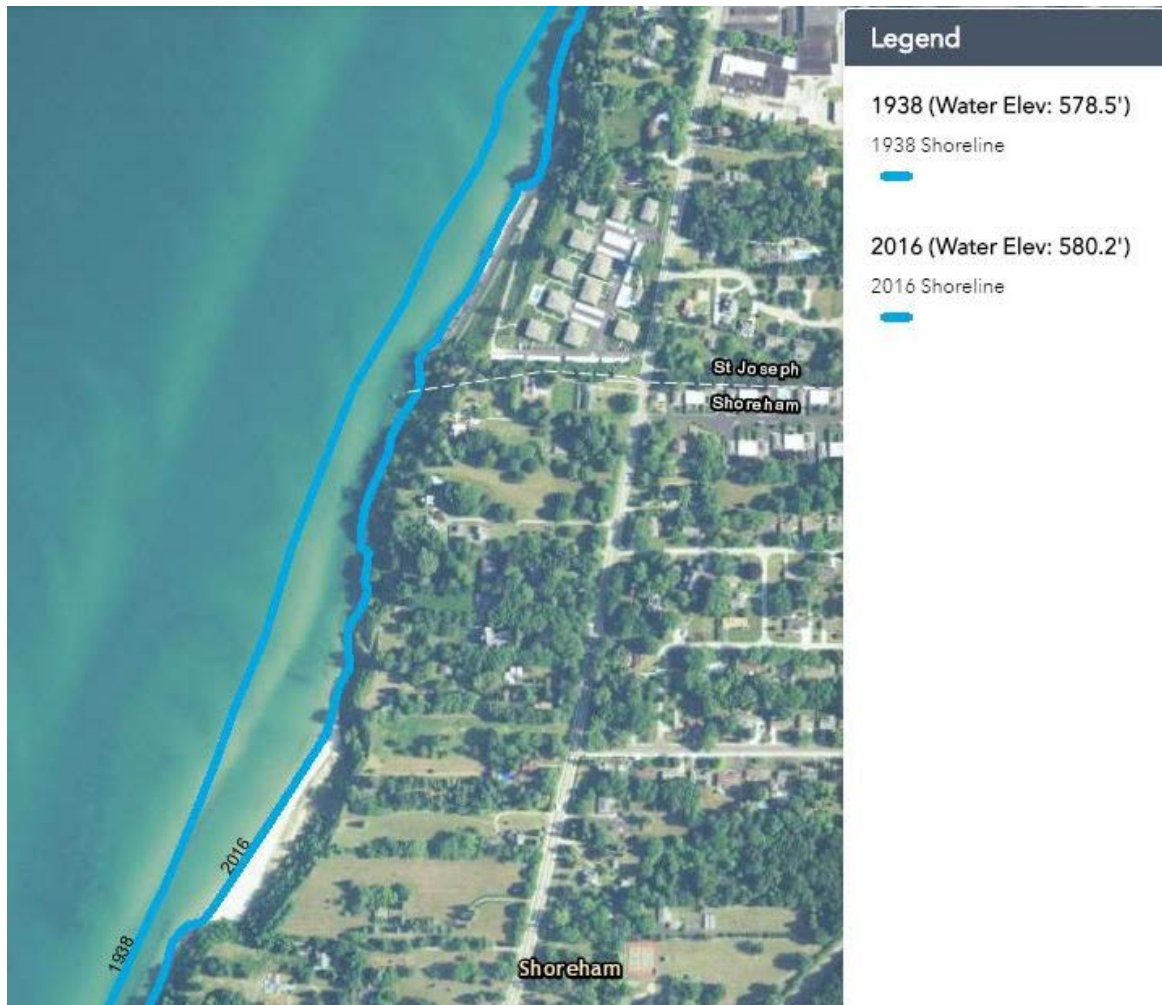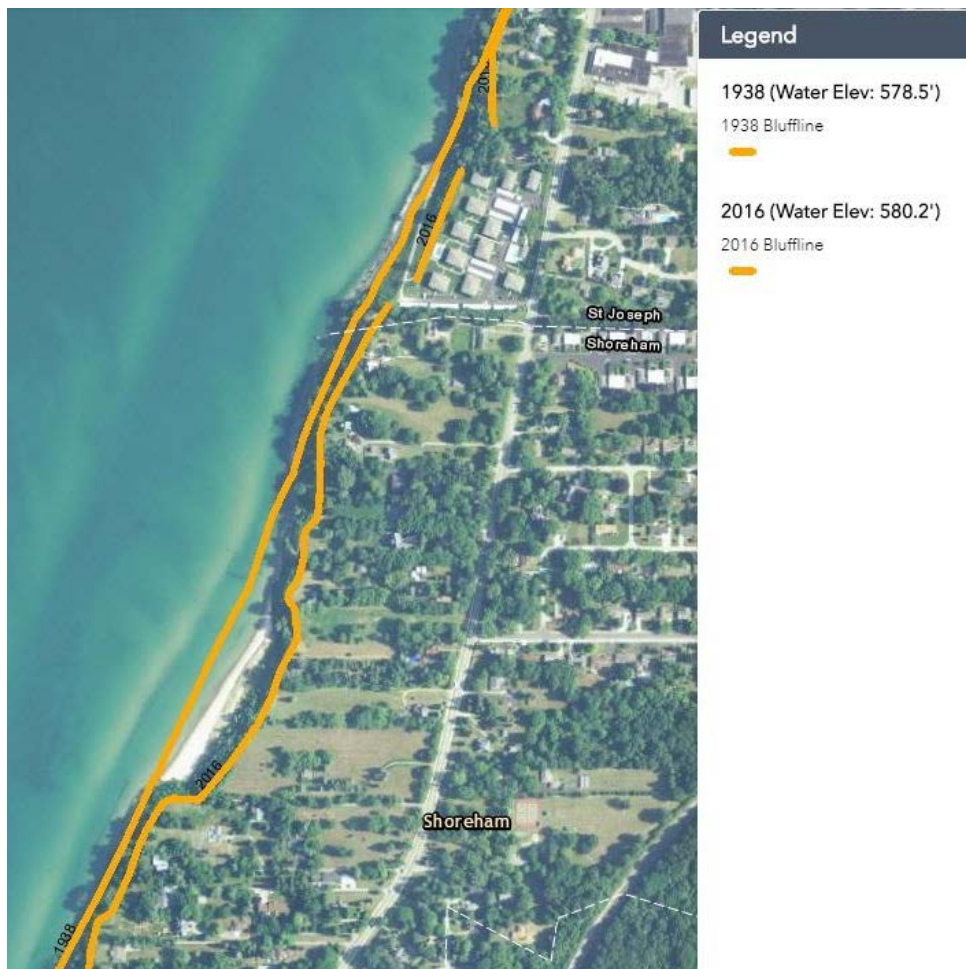


Figure 3.3: Historic bluff lines mapped for two of this project's years depicted on a 2016 aerial image. Image source: Michigan Tech, USDA NAIP

While initially hosted within an Enterprise Geodatabase (EGDB), Shorelines and bluff line features are now stored within a hosted feature service on the ArcGIS Enterprise hosted at Michigan Tech (https://portal1-geo.sabu.mtu.edu/mtuarcgis/apps/sites/#/czmp). Hosting on the Enterprise instead of the EGDB enables a more efficient remote editing experience and faster response for map viewers.

Historic shorelines and bluff lines were generated for much of Michigan's Lake Michigan, Lake Huron, and Lake Superior coastlines.

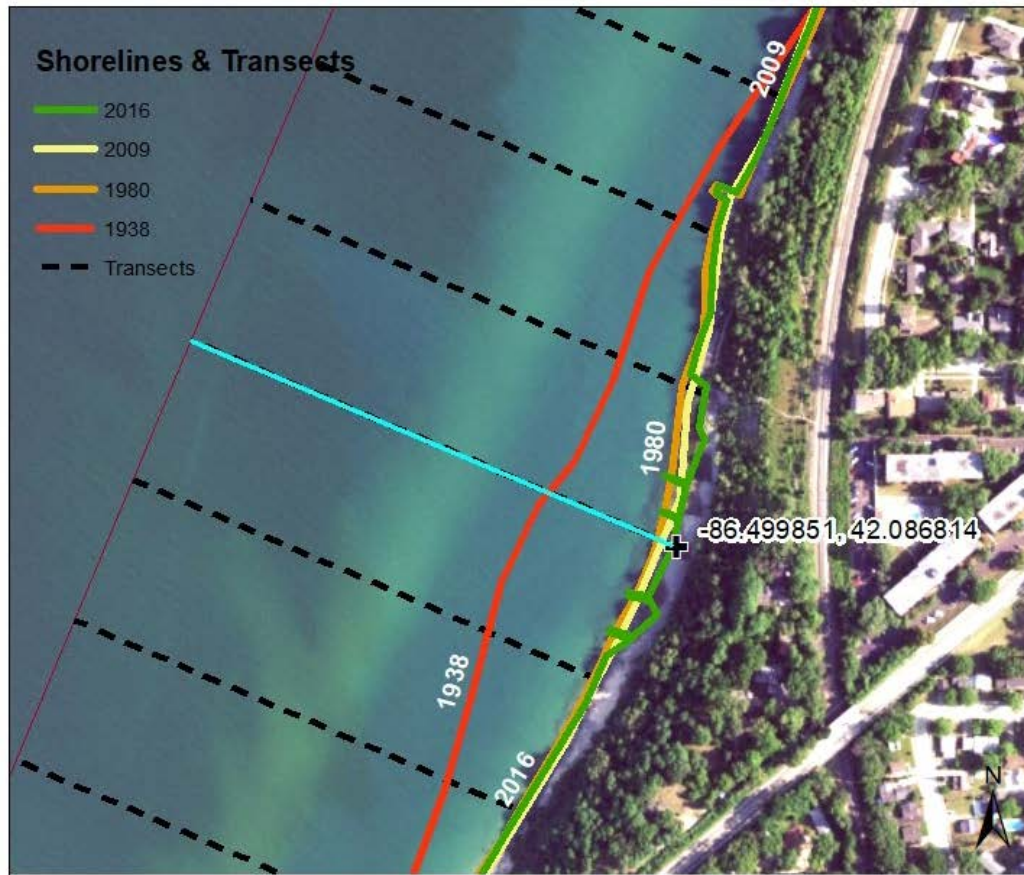## 3.3 Shoreline Rate of Change Analysis

Shoreline rate of change analysis was performed using the USGS Digital Shoreline Analysis System (DSAS) (Thieler 2009). A baseline was digitized offshore of all historic shorelines, and transects were cast perpendicularly away from the baseline towards land, across all historic shorelines, at 100 meter intervals (Fig 3.4). Baselines and transects were produced for much of Michigan's coastline along Lake Michigan, Lake Huron, and Lake Superior.

The analysis is performed by locating the intersection of each historic shoreline along each transect, and measuring the distance between these intersections. This distance is normalized by the time difference between each shoreline. Rate of change analysis was performed along each transect, on shorelines from 1938 – 2016, with analysis from 1938 – 2020 pending at the time of writing. Outputs of the DSAS analysis are transect line features, attributed with calculated rate of change over time statistics including the shoreline change envelope (SCE) representing the largest distance between shorelines of all years, the Linear Regression Rate (LRR) including change between consecutive years, and more (Thieler 2009).

Additionally, a copy of the baseline was segmented at 500 meter intervals and used to summarize rates of change from the 100 meter intervals. Each 500-meter segment is intersected with the perpendicular transects, with the rate of change attributes of all transects summarized as min, max, and average values. This produces a simplified view of the rates of change along the shoreline, and is a more cartographically appropriate layer for summary maps of the coastal regions. This layer is also more comparable to other coastal datasets such as Humphry's shoreline classifications.

A separate analysis of years 2009 – 2020 is planned to serve as a near-term change analysis during a period of historically high water levels in the great lakes.

**Berrien County, St. Joseph**

Shorelines & Transects
- 2016
- 2009
- 1980
- 1938
- - - Transects

-86.499851, 42.086814

1980

1938

2016

2009

Transect End @ -86.499851, 42.086814

| 0 | 65 | 130 | 260 Meters |

**Geomorphology (a):** Wetted beach sand, some fine gravel at water line; dry beach sand with gravel and small cobbles
**Coastal Slope (b):** Wetted beach 10%; Dry beach 5%
**Elevation Change (c):** 4ft
**Shoreline Change Rate (d):** -1.09 m/yr (Linear regression between all years)
-1.13 m/yr (rate between 1938 to 2016 only)
**Wave Runup (e):** 5.1 ft
**Total Surge (f):** 9.1 ft
Sources: a, b Humphry's shoreline classifications ca: 1950
c, e, f  Wave Runup modeling, Meadows 2018
d MTU EGLE sponsored historic shoreline mapping pronect 2017 - 2020

Figure 3.4: Example of  baselines, transects, and historic shorelines used in the DSAS. Additional attributes depicted below map are examples of attributes acquired using the CVI data collection script tool in development at Michigan Tech. Image credit: Michigan Tech, USDA NAIP.

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## 3.4 Bluff Retreat Risk Area Creation

Bluff retreat risk areas were created using an ArcGIS Script tool developed at Michigan Tech. This tool functions similarly to DSAS, except a baseline is not used. Bluff lines for two historic years are compared and transects are cast inland from the earliest bluff line to the more recent bluff line. The distance between these two bluff lines is measured, and a line of equal length is cast inland from the most recent bluff line. This produces a 'comb shaped' series of transect radiating inland from the most recent bluff line. A closing line is generated across the inland ends of all transects, resulting in a series of features in a layer that appears as a hashed area (Fig 4.1). This layer can then be overlaid on modern imagery to depict areas potentially at risk of bluff recession

## 3.5 Coastal Vulnerability Index Development

A Coastal Vulnerability Index (CVI) is intended to succinctly characterize the vulnerability of a coastal region to change, using multiple inputs including geomorphology, water levels, beach slope, bluff characteristics, historical rates of shoreline change, and other factors such as infrastructure proximity and sometimes social parameters (Pendelton, Barras et al. 2010). While a Coastal Vulnerability Index (CVI) exists for the ocean coasts of the United States a similar index does not exist for the great lakes.

A portion of this project is devoted to supporting the development of a CVI for the Great Lakes. While more research is needed to identify which attributes of a coastal region are most effective at characterizing coastal vulnerability, this project did work to develop a coastal vulnerability index data collection tool for ArcGIS that combines data from DSAS rate of change transects with nearby coastal bluff characteristics including distance to bluff toe, bluff height, and bluff slope.

The CVI data collection tool is under development as a Python script for ArcGIS. This tool utilizes rate of change transects generated using DSAS and performs a stack-profile analysis across a digital elevation model (DEM) raster dataset and derivatives, and summarizes the attributes of the first bluff identified, moving inland from the most recent shoreline.

Within the Python script, bluff locations are identified using the Minnesota Department of Resources Bluff Mapping ArcGIS Toolbox (MNDNR 2018), a 1-meter resolution DEM, and user defined parameters, to generate a bluff raster. This output raster is reclassified using the raster reclassification tool to reclassify unknown pixels to a value of 0, while pixels identified as a bluff remain a value of 1.

Additionally, the same DEM used in bluff identification is also used to identify bluff height and to generate a slope raster. The Stack Profile tool is then executed using the rate of change transects generated in DSAS, the reclassified bluff raster, the slope raster, and the source DEM, to generate pixel values along each transect at a 1-meter interval.

The stack profile output for the bluff raster analysis is analyzed using the Python Pandas module to identify the first occurrence of a bluff, moving inland from the baseline. The indexes for each location along the transect within this first bluff are captured and used to extract the slope and elevation data from the stack profile analyses for these data layers. Attributes for this first bluff are then summarized for each transect to product a distance to bluff toe, distance to bluff top, bluff height, bluff slope, and append these to the shoreline rates of change calculated using DSAS. This tool was run for select study areas along Lake Michigan.

## 3.6  Web Based Mapping Applications & Service Creation

All data including historic shorelines and bluff lines, georeferenced historic aerial imagery, and bluff retreat risk areas are hosted as web-map and web-features services on an ArcGIS Enterprise hosted at Michigan Tech (https://portal1-geo.sabu.mtu.edu/mtuarcgis/apps/sites/#/czmp).

An ArcGIS Enterprise Site was developed by the project team to organize all project feature services, web maps, apps, and other associated products.

Historic shorelines and bluff lines are stored as Hosted Feature Services within ArcGIS Enterprise, and edits are made to these data within ArcGIS Pro or via a web mapping application with editing capabilities.

The interactive web mapping applications include shoreline and bluff line layers for each historic shoreline year, a user selectable basemap gallery including historic aerial imagery for each year, oblique aerial photography where available, as well as additional layers including shoreline classifications from Humphry's and the Great Lakes Aquatic Habitat Framework (GLAHF) (Fig. 3.6). Web Maps and Web Mapping Applications were all developed within ArcGIS Enterprise.



Figure 3.5: Screenshot of interactive web mapping application depicting historic shorelines along Lake Michigan.

# 4  Discussion & Products

## 4.1 Bluff Retreat Risk Areas

Bluff retreat risk areas were developed for Michigan's coastal areas of Lakes Michigan and Huron, having bluffs identified in 2016 and 1938. While the methods used to produce these areas was simplistic, calculating the rate of change between 1938 and 2016 and projecting inland at that same rate for 30 years, they did accurately depict many areas that experienced bluff retreat and property loss along Michigan's Lake Michigan coastline in 2019 and 2020 (Fig 4.1). These risk areas are a simplistic, easy to understand method of communicating the findings of this project, and similar, more robust methods might be employed to produce shoreline change risk areas as well.



Figure 4.1: The Gancer Family home in Muskegon, MI was lost in early 2020 (Left). This property was located well within the predicted Bluff Retreat Risk Area produced by this project prior to 2019. Image credit: Michigan Tech, USDA NAIP, Cory Morse, mLive.com, See B for full attribution and copyright licensing information.

## 4.2 Long-Term Shoreline Rates of Change (1938-2020)

Shoreline rates of change were calculated for more than 1,200 miles of Michigan's coastline, utilizing more than 15,000 transects, spaced at 100-meter intervals along the shoreline. Calculated rates of change varied greatly between different lakes and different regions of each lake, ranging from recession rates of more than 1 meter-per-year (mpy) in areas of Lakes Michigan and Superior, to areas of accretion along Lake Huron's coastline. An important consideration when evaluating the rates of change described in the following paragraphs is that they include changes due to high water levels and immersion of the beach, and may not represent actual long-term shoreline change and loss of land. Analysis of actual shoreline change quantifying accretion and erosion must utilize shorelines captured at similar water levels. This project has produced shorelines from different years having similar water levels, and future work should include calculating rates of shoreline change using only these shorelines having similar water level years.

The USGS DSAS tool used to calculate shoreline rates of change in this project produces multiple statistical outputs at each transect, and the Linear Regression Rate of change (LRR) is perhaps the most robust calculation. The LRR value is accompanied by an associated $R^2$ value, ultimately indicating the consistency of the observed rates of change between years. Areas having transects of low $R^2$ values represent irregular long-term rates of change, and it may be difficult to predict a rate of change for these areas with much precision. There is likely some value in studying areas of low $R^2$ in more detail to better understand the causes of these irregular rates of change.

### 4.2.1 Lake Michigan

Along the Lake Michigan coastline of Michigan's lower peninsula, long-term rates of change were calculated using shorelines between 1938 and 2020. This long-term analysis yielded a mean rate of recession of 0.25mpy, with several areas exhibiting a greater than 1.0mpy rate of recession along the southern Lake Michigan coastline.

Near the City of South Haven, MI, long-term rates of change exhibited variability north and south of the piers at the mouth of the Black River (Fig. 4.2). Transects north of the piers showed little to no long-term change and some accretion, while transects south of the piers showed generally high long-term rates of recession of more than 0.5mpy, with some isolated areas of greater than 1mpy recession. This pattern is repeated many times at similar areas along the Lake Michigan coastline, and potentially represents the impact of coastal structures on the long-shore sediment transport cycle.
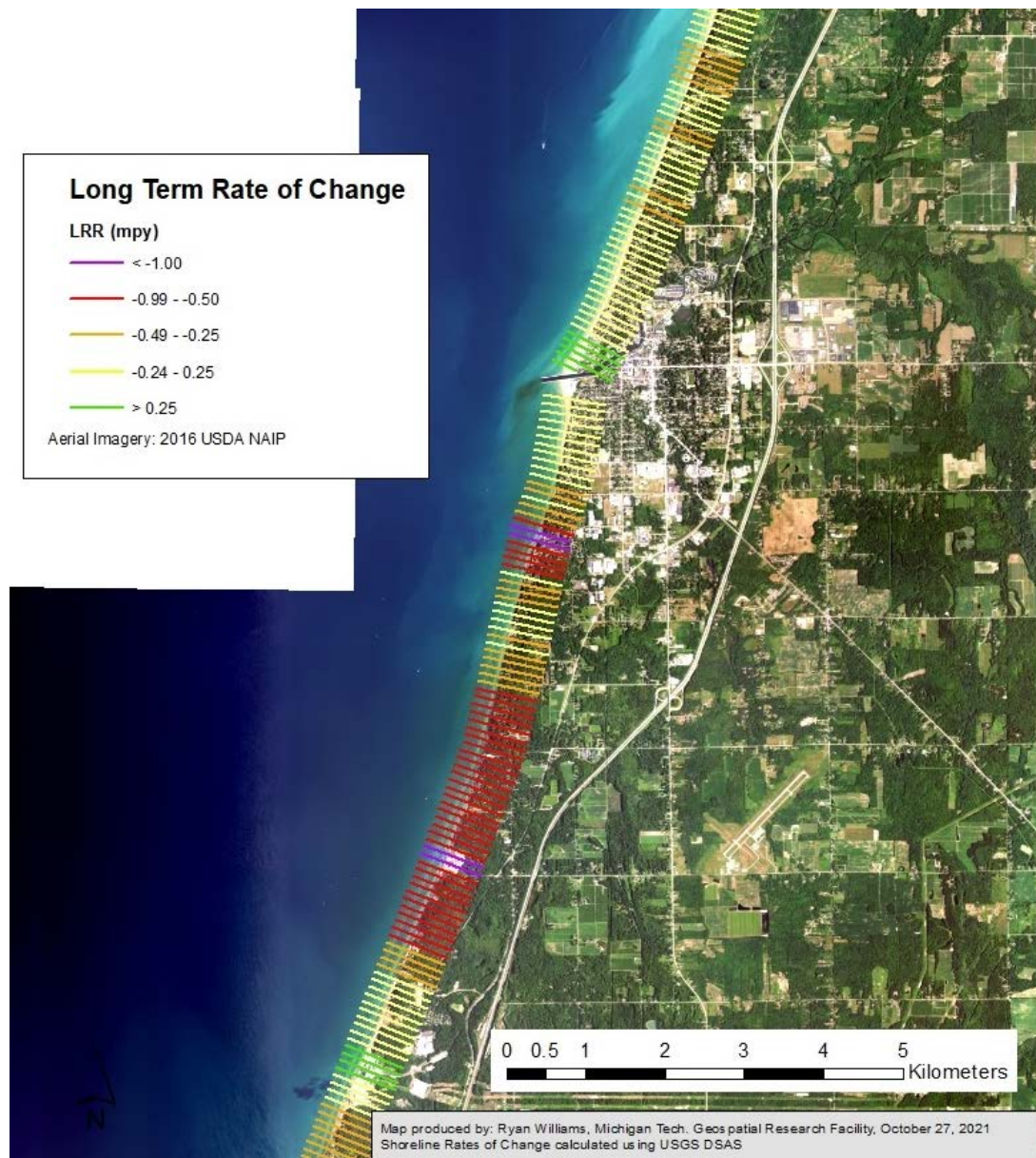
Figure 4.2: Long term rates of change (1938-2020) near the City of South Haven, MI varied from little to no change north of the piers at the Black River, to high rates of recession, greater than 0.5mpy, south of the piers.

## 4.2.2 Lake Huron

Along the Lake Huron coastline of Michigan's lower peninsula, long term rates of change showed general stability with a mean rate of recession of 0.05mpy, and several areas of accretion with very few areas exhibiting high rates of recession. In the region of the 'thumb' of Michigan's lower peninsula, near White Rock Township, MI, long term shoreline rates of changed showed a general trend of little to no long term erosion, with several large areas exhibiting shoreline accretion (Fig 4.3).

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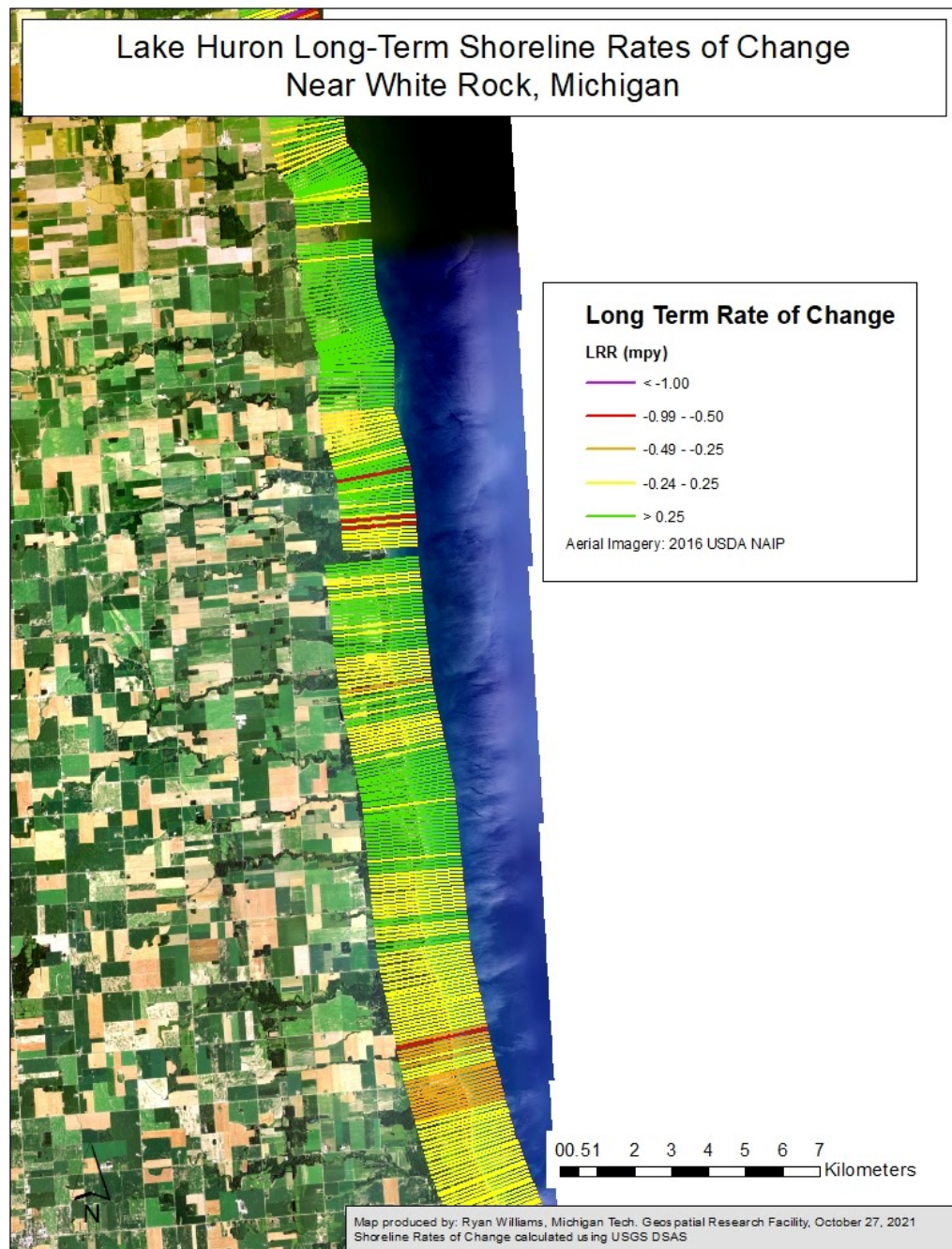
Figure 4.3: Long term rates of change (1938-2020) near the Township of White Rock, MI showed general stability, with some areas of accretion. Image Credit: MTU GRF, USDA

Many shoreline areas near the back of Saginaw Bay in Lake Huron are dominated by aquatic vegetation and wetlands. A precise, definitive shoreline is difficult to discern clearly in these conditions, and some areas of Saginaw Bay were omitted from long-term rate of change calculation.

## 4.2.3 Lake Superior

Analysis of Michigan's historic Lake Superior shoreline posed some challenges unique from the other Great Lakes. Within the historic aerial imagery archives at EGLE, historic 1938 and 1980 imagery were only available for a limited amount of areas along Lake Superior, and some areas of imagery were composed entirely of trees and water, making georeferencing of these images difficult or too imprecise for this project. Historic 1938 imagery was available near coastal communities such as Marquette, Baraga, and Ontonagon, and was georeferenced and utilized for analysis in these areas. Similarly, 1980 imagery was utilized only along the western shore of Michigan's Upper Peninsula and parts of the Keweenaw Peninsula. Because of this, long-term rate of change analysis could only be performed for a limited amount of Lake Superior's coastline.

Within the areas of Michigan's Lake Superior coastline where historic imagery were available, long-term rates of change were observed to be 0.04mpy on average, with few isolated areas of higher rates of recession (Fig 4.4). One prominent area of accretion is located on the eastern side of the Keweenaw Peninsula, south the village of Gay, MI. In this location, a vast amount of the by-product of copper ore processing known as 'stamp sand' was deposited along the shoreline in the late 1800's and early 1900's. These stamp sands, commonly known as the 'Gay Stamp Sands', continue to migrate southward along Keweenaw Peninsula Shoreline and are currently accreting north of the piers protecting the mouth of the Big Traverse River.
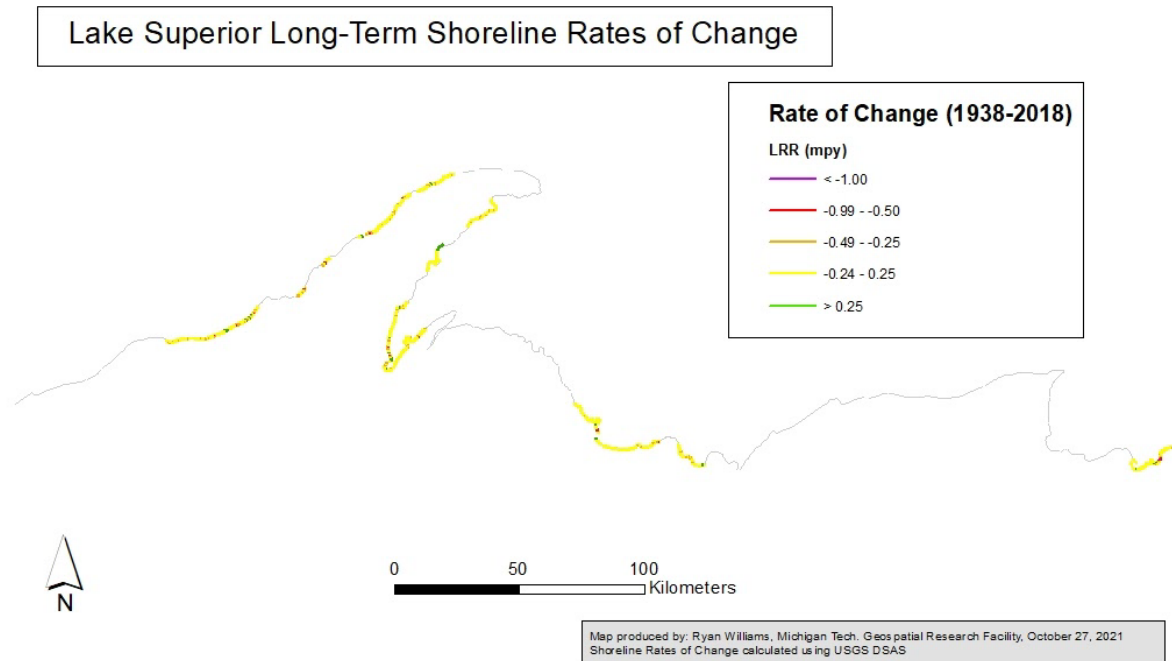


Figure 4.4: Lake Superior Long-term rates of change (1938-2018) for select areas with available long-term imagery. Credit: MTU

## 4.3 Short-Term Shoreline Rates of Change

Short-term shoreline rate of change analyses were performed for a select number of recent shoreline years, along Lake Michigan to capture and characterize the impact of historic water level changes between 2009 and 2020, and along Lake Superior between 2009 and 2018, in areas where historic 1938 and 1980 imagery were not available.

### 4.3.1 Lake Michigan (2009 – 2020)

Short-term analysis of Michigan's Lake Michigan coastlines between 2009 and 2020, showed an overall mean rate of recession of 2.2mpy, with many areas exhibiting rates of recession in excess of 5mpy. These high short-term rates of change were observed at many locations along the entire coastline, and correspond well with anecdotal evidence and well documented incidents of shoreline change and impacts to coastal property and infrastructure.

Near the City of South Haven, MI, short-term rates of change were considerably higher than observed long-term rates of change, with many areas with recession rates excess of 3mpy (Fig. 4.2).

These short-term rates of change for Lake Michigan are likely a strong indicator of areas at risk for future coastal change when a similar cycle of low-to-high water levels and powerful waves occurs again.
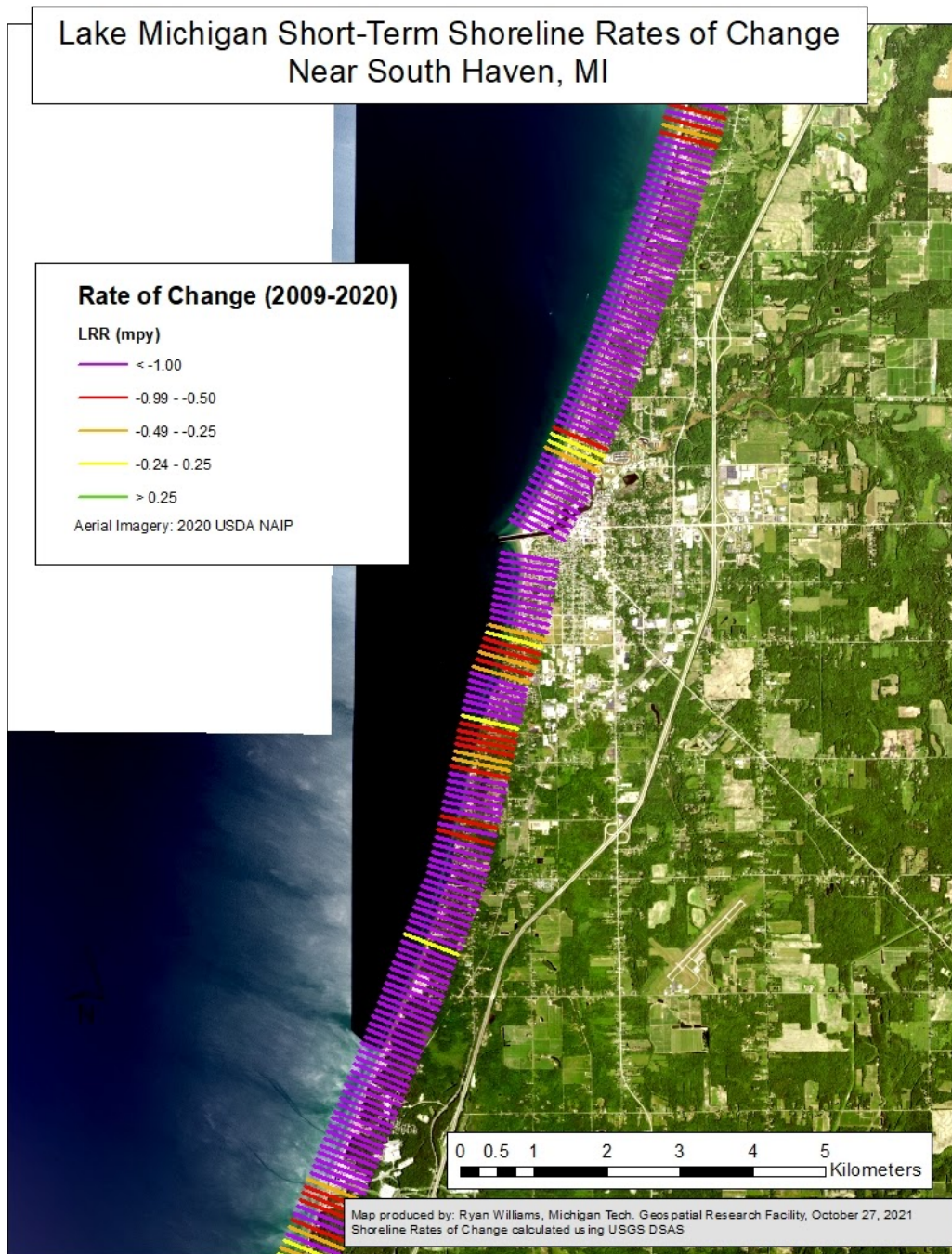
Figure 4.5: Short term rates of change (2009-2020) near the Township of White Rock, MI showed general stability, with some areas of accretion. Image Credit: MTU GRF, USDA

## 4.3.2 Lake Superior (2009 – 2018)

Short-term analysis of Michigan's Lake Superior coastlines between 2009 and 2018, showed an overall mean rate of recession of 0.6mpy (Fig. 4.6), with a wide variation between different regions of this coastline. Areas between Pictured Rocks National Lakeshore and Whitefish Bay experienced the highest rates of shoreline recession of 0.5mpy to more than 1mpy. Many other areas exhibited little to no change, especially in the protected areas of Keweenaw Bay, and areas characterized by rocky shorelines along the Keweenaw Peninsula and near Marquette, MI.
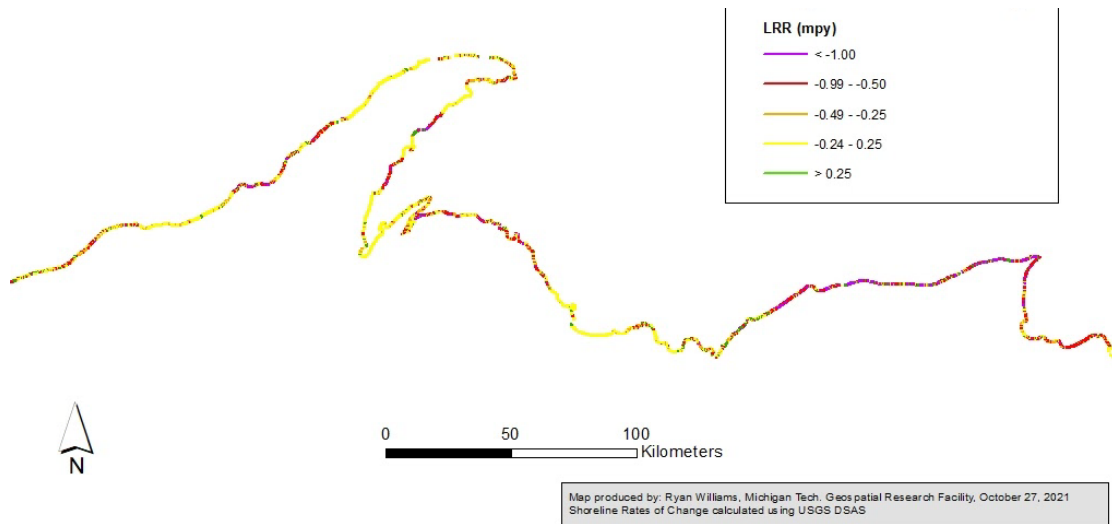


Figure 4.6: Lake Superior Short-term rates of change (2009-2018). Credit: MTU

# 4.4 Publicly Accessible Datasets and Applications

A concerted effort has been made to ensure that all datasets produced by this project are made publicly available following at least minimum suggestions of the FAIR data guidelines, where data are Findable, Accessible, Interoperable, and Reusable. Data are made findable via a project data and applications portal, accessible at https://geospatialresearch.mtu.edu/czmp. Accessibility is also supported via this data portal, where data services may be added to interactive web based or desktop mapping applications, or downloaded in multiple formats for use off-line. Interoperability is additionally supported by these capabilities to use data directly or download in another format. Additionally, the data are stored and hosted in a manner that allow for additional data to be added, for future years of shoreline and bluff line features for example, creating a reusable, commonly accessible 'Hub' for Michigan's historic coastlines data. Reusability is supported by providing data documentation, metadata, and source datasets such as historic aerial imagery, for each dataset. Also, all datasets and attributes necessary for the use of the well-known USGS Digital Shoreline Analysis System toolkit for ESRI's ArcGIS software are publicly accessible for reuse by others.

The importance of sharing this data in a reusable form, easily accessible to others, is great in that this is the most complete collection of historic shorelines and shoreline imagery for Michigan's Great Lakes coastlines. To date, there is no known effort to map the Great Lakes shorelines annually, and other existing shoreline data products for the Great Lakes are more than ten-years out of date (Fig. 4.7).
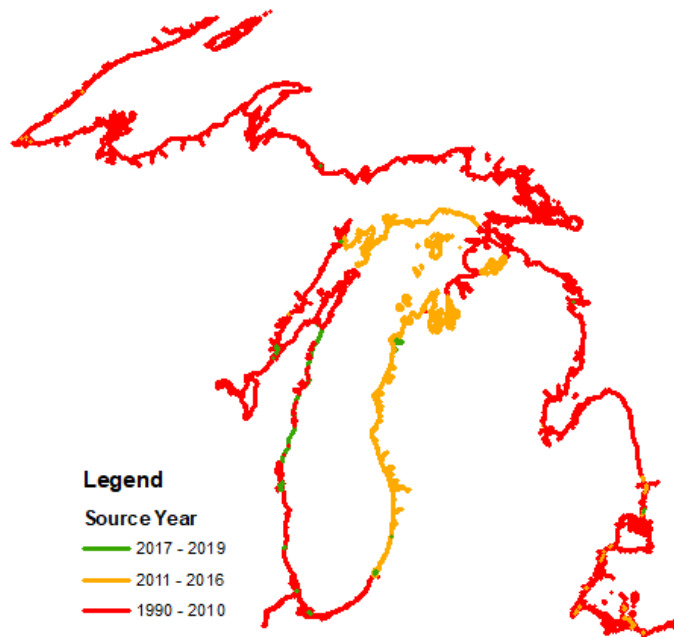


Figure 4.7: Source years of the USGS Continually Updated Shoreline Product (CUSP) Credit: MTU, USGS

# 5  Future Work

While funding for this project completed in 2021, additional work on this topic should continue. The historic shoreline and bluff line features, historic imagery, and shoreline rate of change analyses, are all datasets that may feed directly into further analyses to better understand why the Great Lakes coastlines change and how modifications at one area of the coastline can impact the future changes at another area of coastline. All of these data and future studies support a better understanding of the impact and risk of coastal development, and should continue to be regularly updated to provide Michigan's coastal communities with the timely information needed to increase their resiliency, and better plan their community's future.

## 5.1  Continue Annual Shoreline Mapping and Incorporate New Remote Sensing Techniques

The products of this project provide evidence that there can be large differences between long-term rates of shoreline change and short-term rates of change. Some areas of Michigan's Lake Michigan coastline saw a short-term rate of shoreline recession that was 10-times greater than the same area's long-term rate of recession. This highlights the importance of timely, recent shoreline data to continually understand how and where coastlines are changing. Increased years of shoreline location data will also lead to more robust shoreline rate of change analyses and enable the comparison of shoreline locations at similar water level conditions. Because no other agency is currently producing an annual map of the Great Lakes shorelines, it is important that this work continue.

While historic shoreline mapping for this project was performed using aerial imagery and manual heads-up digitization, there are other options that may potentially be used with more modern imagery datasets. Remote sensing analysis tools and techniques exist that could allow for a more automated method of shoreline detection in the future. These methods include analysis of natural color or near-infrared band imagery (Toure, Diop et al. 2019), utilizing LIDAR datasets (Harris, Brock et al. 2006), and even utilizing data collected from space-based platforms including Synthetic Aperture Radar and Hyperspectral Imagery (Cordeiro 2020). These platforms have a temporal resolution, or 'revisit rate', much more frequent than practical with aerial photography, and imagery is captured at multiple times throughout the year, and even within months. Because of this higher temporal resolution, using these data sources would enable the targeting of imagery collected during a specific lake water levels or sea states.

Further research and development should be done to assess the precision and utility of existing space-based remote sensing datasets, such as synthetic aperture radar and hyperspectral imagery, for the detection of shoreline locations along the Great Lakes.

## 5.2 Perform Rate of Change Analysis Using Similar Water Level Years

The rate of change analyses performed thus far in this project included shoreline locations from multiple years, having a variety of differing water level heights. Because of this, some observed shoreline change is the result of beach immersion or exposure, and does not necessarily represent an actual loss of gain of land. To analyze actual loss or gain of land, all shorelines in the analysis must have been captured at similar water level heights. The data produced with this project currently includes at least two comparable years for two different water levels. Completing more annual shorelines using the methods described in the previous section will also enable the collection of more comparable water level years of shoreline data to increase the robustness of this analysis.

This analysis will provide a better understanding of areas where actual recession of the shoreline is occurring, isolating the effects of simple inundation.

## 5.3 Perform 'Sensitivity Analysis' Between Coastal Vulnerability Characteristics and Observed Shoreline Rates of Change

With the completion of the long-term and short-term rate of change datasets for Michigan's Great Lakes shorelines, one of the missing pieces of a Coastal Vulnerability Index (CVI) for the Great Lakes is being filled. Further research needs to be done to better understand what coastal characteristics correlate most with observed changes to coastlines.

Utilizing the rate of change datasets, and the CVI Data Collection Tool produced by this project, nearshore coastal characteristics may be compiled and their relationships assessed to better understand what coastal characteristics relate most with coastal change.

This work will lead towards further development of a CVI for the Great Lakes, and provide another tool to help planning agencies and communities not only understand historic trends in shoreline change, but also predict the impacts of modifications to the coastlines or changes in water level or storm strength.

# 6  Reference List

City of San Diego, C. (2000). Coastal Bluffs and Beaches Guidelines, Land Development Code, San Diego Municipal Code. C. o. S. Diego. San Diego, CA, City of San Diego, California.

Cordeiro, M. (2020) Water Detection in High Resolution Satellite Images using the waterdetect python package. Towards Data Science

Gardner, P. (2020). Numbers show impact of Michigan coastline flooding and erosion from high water. mlive, Advance Local Media LLC.

Harris, M., et al. (2006). Extracting shorelines from NASA airborne topographic lidar-derived digital elevation models.

Joan Pope, C. J. S., Robert Dolan, Judith Peatross, Charles L. Thompson (1999). The Great Lakes Shoreline Type, Erosion, and Accretion, U.S. Army Corps of Engineers.

Meadows, G. A., et al. (1997). "The Relationship between Great Lakes Water Levels, Wave Energies, and Shoreline Damage." Bulletin of the American Meteorological Society **78**(4): 675-684.

MNDNR (2018). MNDNR Bluff Mapping ArcGIS Toolbox Tool. Minnesota Geospatial Commons, Minnesota Department of Natural Resources.

Pendelton, E. A., et al. (2010). Coastal Vulnerability Assessment of the Northern Gulf of Mexico to Sea-Level Rise and Coastal Change, United States Geologic Survey.

Stauble, D. K. (2004). Development of a National-Scale Inventory of Shoreline Change Data for Identification of Erosion and Accretion - working draft, U.S. Army Corps of Engineers.

Thieler, E. R. G. S. (2009). The Digital Shoreline Analysis System (DSAS) version 4.0 : an ArcGIS extension for calculating shoreline change. [Reston, Va.], [U.S. Geological Survey].

Toure, S., et al. (2019). "Shoreline Detection using Optical Remote Sensing: A Review." ISPRS International Journal of Geo-Information **8**: 75.

USACE (2003). Living on the Coast: Protecting Investments in Shore Property on the Great Lakes. G. L. H. a. H. Office, U.S. Army Corps of Engineers and University of Wisconsin.

USACE (2021). Monthly mean lakewide average water levels. LTA-GLWL-Graph.pdf. USACE Website, U.S. Army Corps of Engineers.

Wolfe-House-Movers (2015). "Lake Michigan Home Relocation." Retrieved 10/27/2021, 2021, from https://www.wolfehousebuildingmovers.com/project/lake-michigan-home-relocation/.

# A      Output and Data

The majority of products for this project are publicly available at the ArcGIS Enterprise hosted at Michigan Tech at https://portal1-geo.sabu.mtu.edu/mtuarcgis/apps/sites/#/czmp

These include:

- Historic shoreline feature classes for 6 years along Lake Michigan, and 4 years elsewhere
- Historic bluff line feature classes for 6 years along Lake Michigan, and 4 years elsewhere
- Bluff Retreat Risk Areas for all areas with mapped bluffs
- Historic imagery for 4 years
- Rate of Change Analysis maps will be added to this dataset shortly
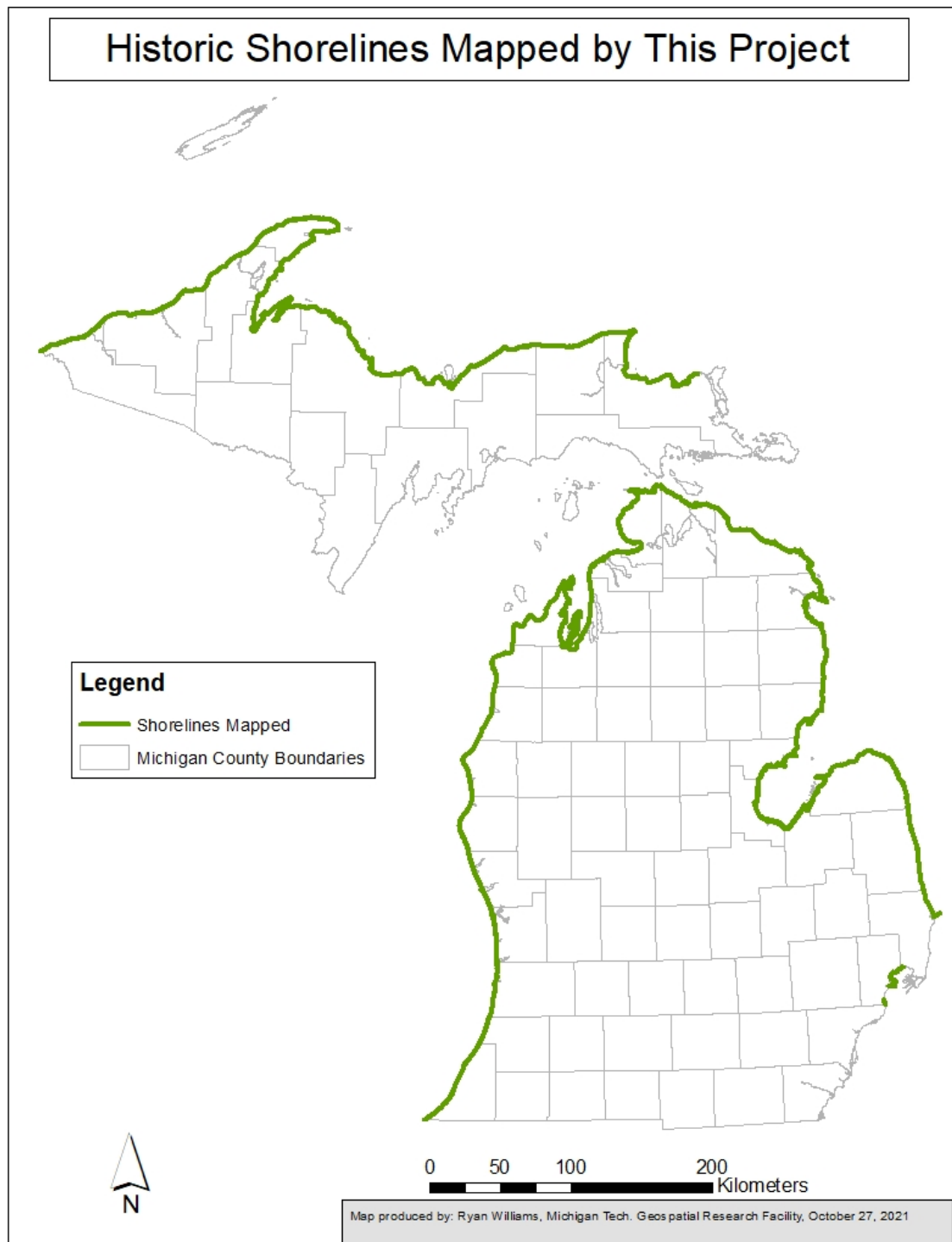
## A.1       Extents of Project Products



Figure 6.1: Locations of shorelines mapped during this project.

## A.2      Example Maps of Output Products

Some example maps of select areas are included on the following pages.

Figure 6.2: Shoreline rates of change calculated along DSAS transects at 100 m spacing along the shoreline near St. Joseph, MI. Linear Reference Rate calculated using 1938, 1980, 1985, 2009, 2016 shorelines. Small scale view.
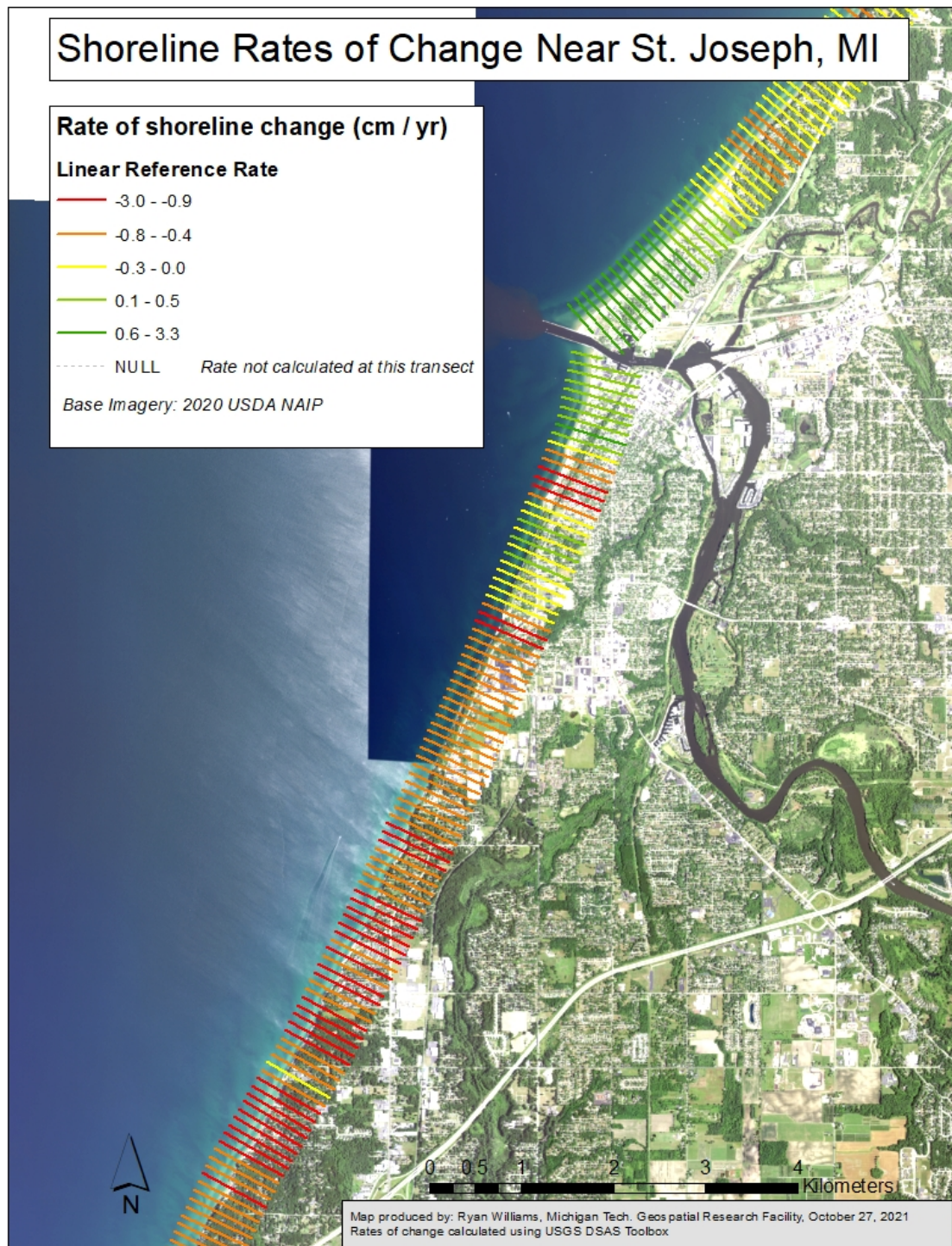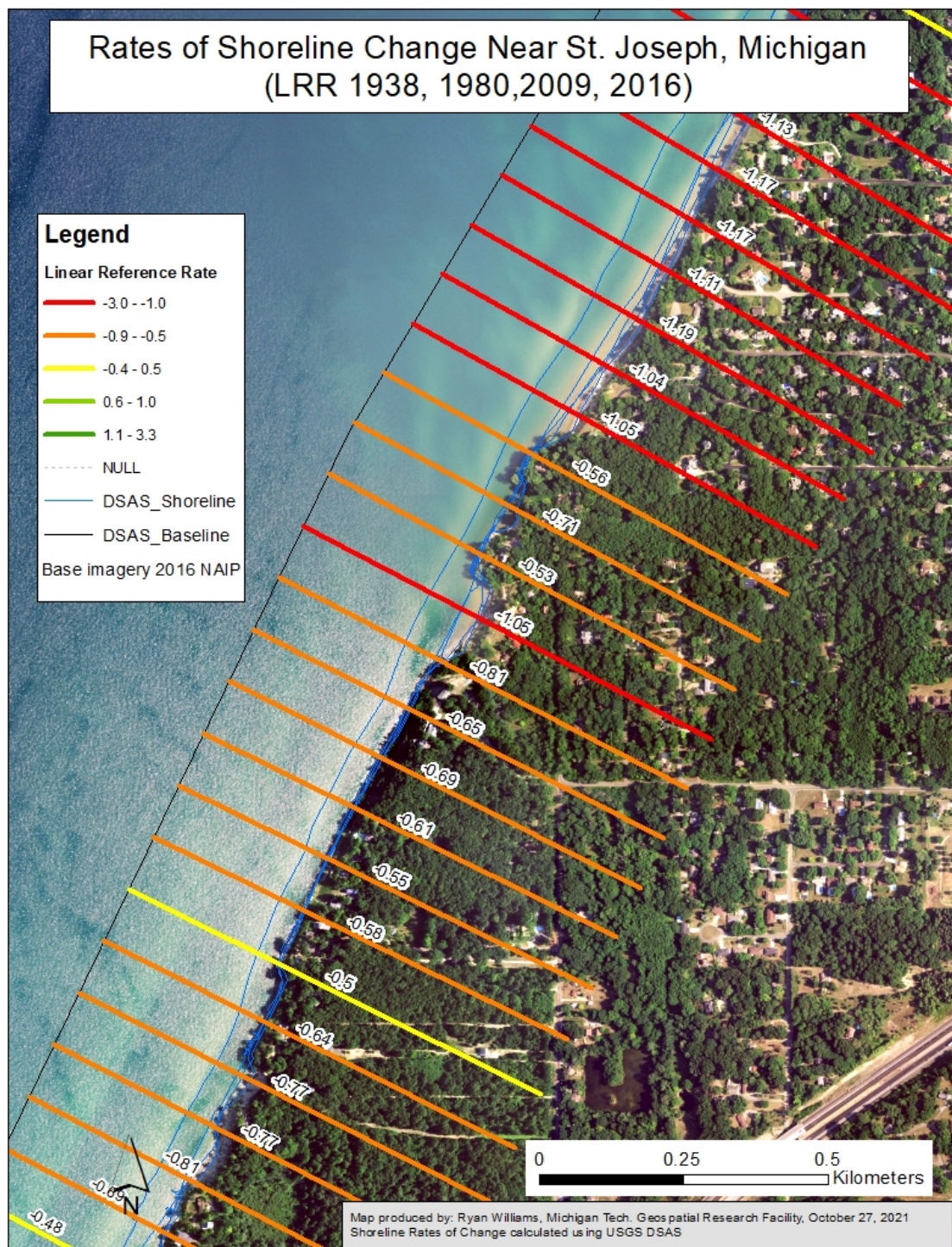
Figure 6.3: Shoreline rates of change calculated along DSAS transects at 100 m spacing along the shoreline near St. Joseph, MI. Linear Reference Rate calculated using 1938, 1980, 1985, 2009, 2016 shorelines. Large scale view.

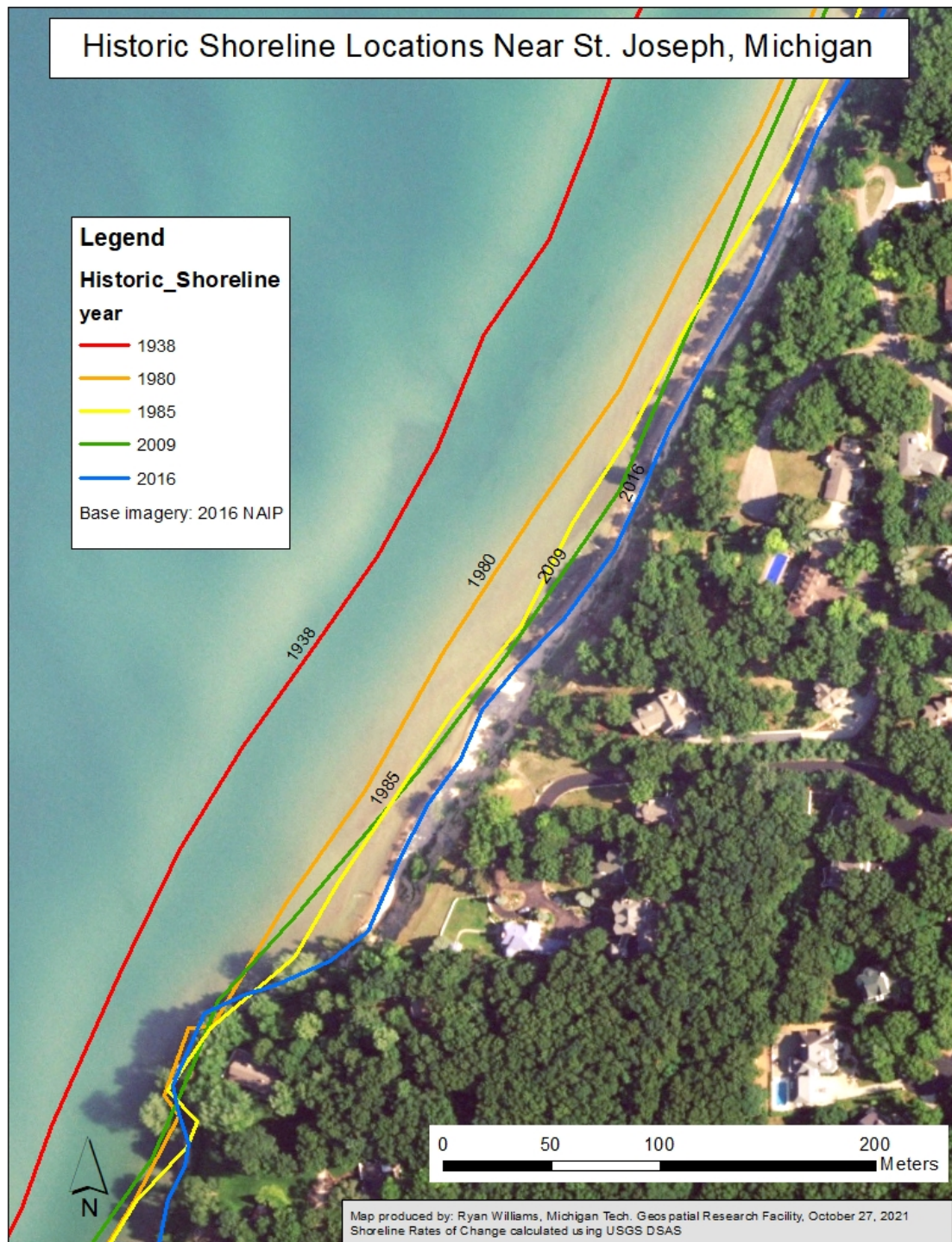Figure 6.4: Historic shoreline locations along the Lake Michigan Coastline near St. Joseph, MI.

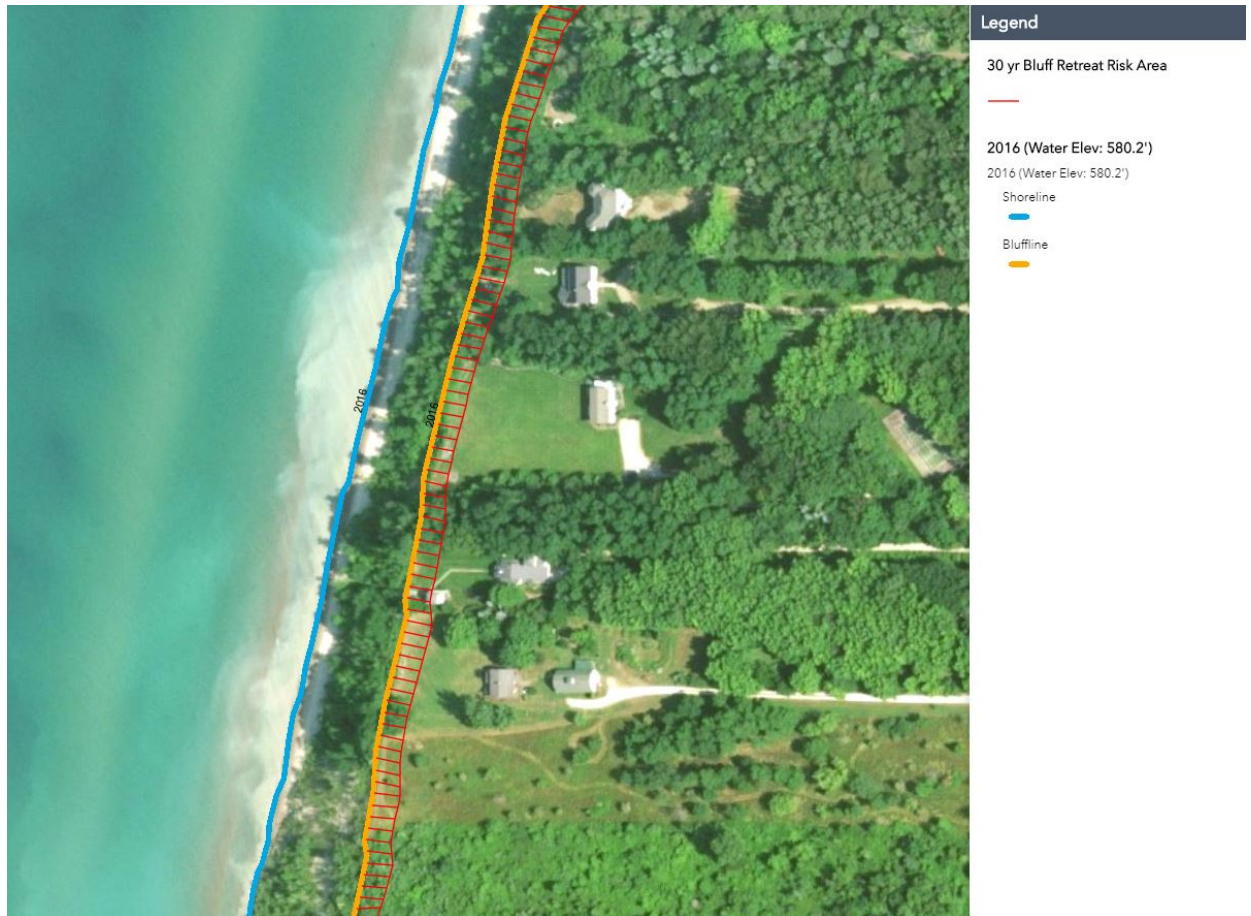Figure 6.5: Example of Bluff Retreat Risk Area along the Lake Michigan Coastline, using an average bluff line rate of change including historic bluff lines for 1938, 1980, 2009, and 2016. Image credit: Ryan Williams, Michigan Tech, basemap imagery 2016 USDA NAIP.
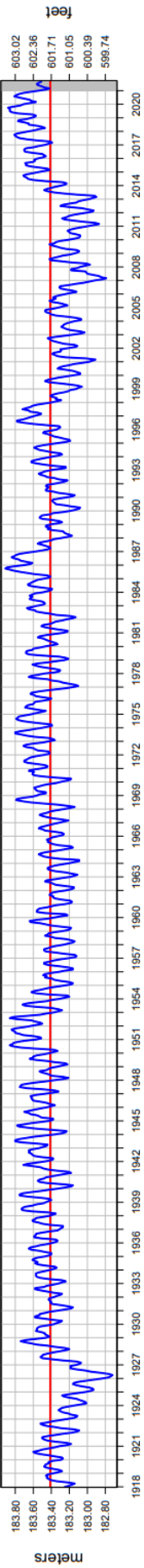
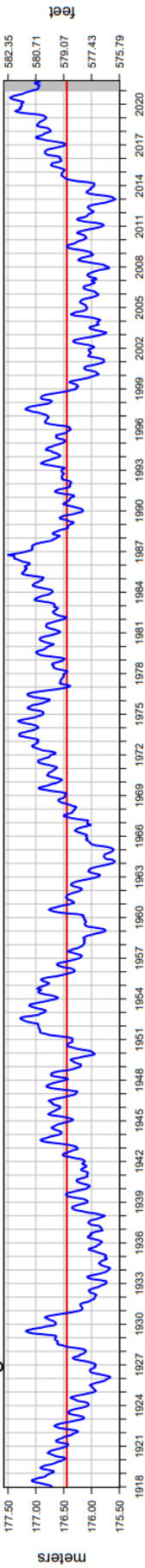## A.3    Great Lakes Water Levels (1918 – 2021)

Great Lakes Water Levels (1918–2021)

Lake Superior

Lake Michigan–Huron

— Monthly Mean Level
— Long Term Average Annual

# B      Copyright documentation

Figure 1.2, 1.3, 1.4: Cory Morse, mLive.com  Each available publicly at the website listed in each image caption and at https://www.mlive.com/news/2020/03/numbers-show-impact-of-michigan-coastline-flooding-and-erosion-from-high-water.html.  Accessed October 2021.

Figure 1.5: 'Lake Michigan Home Relocation" Wolfe house and building movers, https://www.wolfehousebuildingmovers.com/wp-content/uploads/2019/11/Lake-Michigan-Shift-2-1024x684.jpg accessed October 2021

Figure 1.6: Imagery as part of a publicly available imagery dataset located at http://www.greatlakesshoreviewer.org/#/great-lakes Superior Watershed Partnership, https://www.greatlakesshoreviewer.org/img/obliques/great-lakes/lp/DSC_4290.jpg

No other images are known to be copyrighted

# C Python Code for CVI Attribute Collection Tool

```
1  # This calculates the distance from the beginning of a transect to the toe and top of
2  # the FIRST bluff identified using the MNDNR Bluff Finder Tool
3  # using 'stack profile' output of a transect laid over a bluff map.
4  # output eventually gets appended to the transect
5  # Author: Ryan Williams, Michigan Technological University, rywillia@mtu.edu
6
7  import arcpy
8  import numpy as np
9  import pandas as pd
10
11 mode = 'dev' #dev or prod
12 print('configuring in ' + mode + ' mode')
13 # input stack profile output of bluff measurements along transects
14 if mode == 'dev':
15     #input Digital Elevation Model
16     indem = r'E:\cvi_pilot\USGS_one_meter_x51y463_MI_13Co_BerrienCO_2015.tif'
17     # input transects to measure and sample along, generated previously by DSAS
18     intransx = "Berri_noclip3_rates_20210917_142737"
19     # output GDB
20     outgdb = r'E:\cvi_pilot\cvi\CVI_working.gdb'
21     # outtable is the table created containing the summary of first bluff features
22     outtable = 'berri_2016b_test16'
23
24 else:
25     indem = arcpy.GetParameterAsText (0)
26     intransx = arcpy.GetParameterAsText (1)
27     outgdb = arcpy.GetParameterAsText (2)
28     outtable = arcpy.GetParameterAsText (3)
29
30 #parameters for ephermeral output used during processing...
31 # Output from MNDNR Bluff Finder tool.
32 bluffras = "Berrien_lmx51y463_Ber_2015B3"
33 # Reclassified bluff raster
34 bluffrasrc = bluffras + "_rc"
35 # elevation source
36 elevsrc = indem
37 # table to hold bluff location data from stack profile analysis
38 bluff_stack_tbl = "berrien_bluffs3"
39 # table to hold elevation data from stack profile analysis
40 elev_stack_tbl = "berrien_elev3"
41 # table to hold slope data from stack profile analysis
42 slope_stack_tbl = "berrien_slope"
43
44 arcpy.env.workspace = outgdb
45 arcpy.env.overwriteOutput = True
46
47 # ===================================================
48 # Run the bluff finder...
49 print('Running the bluff finder...')
50 arcpy.ImportToolbox("C:/czmp/cvi/bluff_mapping_tool/bluff_mapping_tool/bluff_finder.tbx")
```

```
51  tempTb = arcpy.gp.toolbox
52  arcpy.gp.toolbox = "C:/czmp/cvi/bluff_mapping_tool/bluff_mapping_tool/bluff_finder.tbx"
53  # parameters for bluff identification listed here in slope = 30 deg, depth = 10, height = 20
54  arcpy.gp.BluffIdentifierFourParamBeta(indem, bluffras, "30", "10", "20", "Meter", "FOUR")
55
56  #====================================================
57  # done with bluf finder, restore TB and reclassify output raster....
58  print('Reclassifying bluff finder output')
59  arcpy.gp.toolbox = tempTb
60  # reclassify bluff raster...
61  arcpy.gp.Reclassify_sa(bluffras, "Value", "1 1; NODATA 0", bluffrasrc, "DATA")
62
63  #====================================================
64  # run slope analysis and generate a slope raster
65  print('running slope analysis')
66  arcpy.CheckOutExtension('3D')
67  arcpy.Slope_3d(indem, sloperas, "PERCENT_RISE", "", "GEODESIC", "METER")
68
69  # ====================================================
70  # Run the stack profiler....
71  print('Running the stack profiler on the bluffs...')
72  # run profile against bluff identity raster
73  arcpy.ddd.StackProfile(outgdb + "\\" + intransx, bluffrasrc, bluff_stack_tbl)
74  # run profile on elevation
75  arcpy.ddd.StackProfile(outgdb + "\\" + intransx, elevsrc, elev_stack_tbl)
76  # run profile on slope
77  arcpy.ddd.StackProfile(outgdb + "\\" + intransx, sloperas, slope_stack_tbl)
78
79  arcpy.CheckInExtension('3D')
80
81
82  # ================= get transect data to pandas data frames, name fields more meaningfully,
83  # for each profile stack output
84  bluff_trans = arcpy.da.TableToNumPyArray(bluff_stack_tbl, ("FIRST_DIST","FIRST_Z","LINE_ID"))
85  bluff_trans.dtype.names = ['bluffdist','bluffbool','lineid']
86  bluff_df = pd.DataFrame(bluff_trans)
87
88  elev_trans = arcpy.da.TableToNumPyArray(elev_stack_tbl, ("FIRST_DIST","FIRST_Z","LINE_ID"))
89  elev_trans.dtype.names = ['elevdist','elev','lineid2']
90  elev_df = pd.DataFrame(elev_trans)
91
92  slope_trans = arcpy.da.TableToNumPyArray(slope_stack_tbl, ("FIRST_DIST","FIRST_Z","LINE_ID"))
93  slope_trans.dtype.names = ['slopedist','slope','lineid3']
94  slope_df = pd.DataFrame(slope_trans)
95
96  # Concatenate data frames together by merging across data frames to yield one row for each
97  # transect with attributes from multiple profile analyses
98  trans_data = pd.concat([bluff_df, elev_df, slope_df], axis=1)
99
100 #Prepare results DF to put analysis results into in the following bit
```

```
101  outdf = pd.DataFrame([])
102
103  print('starting first bluff feature locating')
104  # for each lineid (transectID) do the following...
105
106  for lineid in range (1,len(trans_data)):
107      # get rows for this line id
108      linedata = trans_data[trans_data['lineid'] == lineid]
109      # get just the rows that have a bluff value > 0
110      linedata_bluffs = linedata[linedata['bluffbool'] != 0.0]
111
112      # get the first bluff segment. Find the first identified bluff pixel that has a measurement
113      # diff > 1. Get bluff > 0 rows below this measurement.
114      if(len(linedata_bluffs[linedata_bluffs.diff()['bluffdist'] > 1.1]) > 0):
115          #identify the first break....
116          first_break = ([linedata_bluffs[linedata_bluffs.diff()['bluffdist'] > 1.1].iloc[0]['bluffdist'] ])
117          # get rows that fall within the bluff toe and top, inclusive
118          linedata_firstbluff = linedata_bluffs[[x < first_break[0] for x in linedata_bluffs.bluffdist]]
119      else:
120          #if there are no breaks, everything along the transect is a bluff, take all rows
121          linedata_firstbluff = linedata_bluffs
122
123      #calculate meaningful summary attributes for THIS transect...
124      toedist = linedata_firstbluff['bluffdist'].min()
125      topdist = linedata_firstbluff['bluffdist'].max()
126      toeelev = linedata_firstbluff['elev'].min()
127      topelev = linedata_firstbluff['elev'].max()
128      depth = (topdist - toedist) if topdist > toedist else 0
129      height = (topelev - toeelev) if topelev > toeelev else 0
130      mslope = linedata_firstbluff['slope'].mean()
131
132      #Output the attributes for this transect into a series, then append that to the output
133      # from all previous transects...
134      lineout = pd.Series([lineid, toedist, topdist, toeelev, topelev, depth, height, mslope])
135      outdf = outdf.append(lineout, ignore_index = True)
136
137      #print out some feedback to the user. This only outputs in standalone mode.
138      print(lineid)
139      print(toedist)
140      print(topdist)
141      print(toeelev)
142      print(topelev)
143      print(depth)
144      print(height)
145      print(mslope)
146
147  #Prep to output the dataframe to a table, setting column names here..
148  outdf.columns = (['lineid', 'toedist', 'topdist', 'toeelev', 'topelev', 'depth', 'height', 'mslope'])
149  #Further prep to dump to a table; Converting the Pandas data frames into Numpys, because that's what ArcPy lets us use right now...
150  outnp = np.array(outdf)

151  #Transposing rows so we get data formatted properly for this ESRI tool to work as expected... Also setting names and types.
152  struct_array = np.core.records.fromarrays(outnp.transpose(), np.dtype([('lineid', 'f4'), ('toedist', 'f4'), ('topdist', 'f4'), ('toeelev', 'f4'), ('topelev', 'f4'), ('depth', 'f4'), ('height', 'f4'), ('mslope', 'f4')]))
153  # actually dump the output from the summarizing of transects and bluff attributes to the output table. Currently
154  arcpy.da.NumPyArrayToTable(struct_array, outtable)
155  print('completed!')
156
157
158
```