MAPPING ANNUAL TO DECADAL GEOMORPHIC CHANGES OF A RIVER MOUTH BAR TO EVALUATE THE ROLE OF THESE LANDFORMS IN ALTERING LITTORAL SEDIMENT BUDGETS

By

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ABSTRACT

River mouth bars, such as those of the Pinnebog River along Lake Huron's Saginaw Bay, are dynamic landforms shaped by both fluvial and coastal processes. Although they are prominent features in coastal settings, their influence on coastal geomorphology is poorly understood. These river mouth bars are ecologically important barriers that thwart storm waves from impacting upstream habitats. Given the frequent changes, studying these features and their impacts requires high temporal resolution geomorphic and hydrodynamic data sets. Using high-temporal resolution satellite imagery from Planet Labs, we documented the geomorphic evolution of the river mouth bar and adjacent shoreline over an 8-year period (2016-2023) including the effects of the rise and fall of Lake Huron water level. Wave data USACE hindcast were integrated with NOAA lake level and precipitation data to document the hydrodynamic processes driving the geomorphic behaviors at the river mouth. These satellite and hydrodynamic data indicated river mouth bars are highly responsive to fluctuating lake levels, river discharge and wave events, which alter location of the bar within the nearshore. Former mouths of the Pinnebog River, suggesting over annual periods these river mouth processes exert a measurable influence on nearshore depositional patterns. High temporal satellite images combined with a series of data reveal a highly mobile and dynamic bar affected by lake level, wave conditions and river discharge.

This thesis is dedicated to my parents, Tom and Sloane Stimpfel. You worked to give me the opportunities that you never had, ensuring that I was always supported by your unconditional love and encouragement. Your belief in me always reminded me of what was possible, and I can never thank you enough.

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TABLE OF CONTENTS

INTRODUCTION

River mouth bars are critical geomorphic and cultural features given their position at the interface between river system and the nearshore (e.g., lake, estuary, sea). They are pivotal components of both coastal and fluvial sediment budgets as they convey sediment flowing down the river into the body of water they enter (Nienhuis et al., 2016). Despite their apparent importance for both fluvial and coastal geomorphic evolution, they remain largely understudied, resulting in open questions about their specific role in shaping these environments and how they respond to changing hydrodynamic and hydrologic conditions. This is particularly true in the Great Lakes region where hundreds of rivers flow into the lakes, yet no previous research in the region has explored river mouth bars. In Lakes Michigan-Huron, 47% of the inflow results from stream flow (Wilcox et al., 2007) and water levels fluctuate dramatically on seasonal, annual, and decadal cycles. These conditions suggest that river mouth bars in this region are highly dynamic and need to be better understood from the standpoint of process geomorphology to better predict future changes to both coastal and fluvial systems.

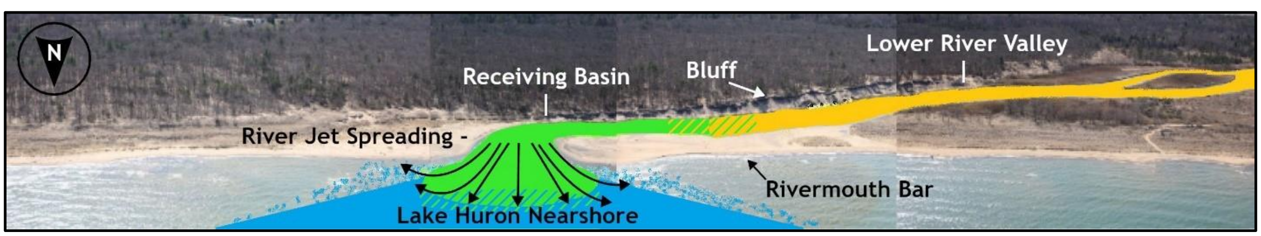

Figure 1. Oblique photo (2012) of the Pinnebog river where it debouches into Lake Huron. The lower river valley enters the receiving basin where the river jet spreads laterally depositing sediment as it enters the nearshore, producing the river mouth bar. Sediment is provided by fluvial sediments, eroded bluff material and coastal sediments.

River mouth bars (See Figure 1.) are generally described as sand bodies that form at the confluence of rivers and larger bodies of water (Fagherazzi et al., 2015). The presence of sediments from fluvial and lacustrine systems supply the bar with building material to maintain their presence (Fagherazzi et al., 2015). Yet even with the right conditions, a river mouth bar may never form due to human impacts such as dredging and harbor construction (Fagherazzi et al., 2015). These practices and structures alter natural sediment budgets and do not allow the conditions required to form river mouth bars to persist. Many of the largest river systems in the Great Lakes region have cities established at the mouth surrounding ports (Larson et al., 2013), which makes the occurrence of these river mouth bar features important where they do occur. These river mouth bars fill an ecological role as protective barriers that thwart and reduce storm waves. As waves approach the lakeward side of the bar, they can be thwarted completely or reduced as their energy is lost traveling up and over the bar (Albert et al, 2005). Without such a barrier, waves could travel upstream disrupting and damaging endemic wetlands and the species that reside within them (Albert et al, 2005).

Fluvial and coastal systems both have a unique mix of forces resulting in distinct physiographic conditions (Larson et al., 2013; Wilcox, 2002). At the confluence of these two systems river mouth bars form when there is high availability of sediment (Fagherazzi et al., 2015). The three main zones of river mouth systems are the lower river valley, receiving basin, and nearshore (Figure 1.) (Larson et al., 2013; Wilcox, 2002). All zones are characterized by the site's geological history, which affects the slope as well as sediment type and availability. The lower river valley generally has a gentler slope and is dominated by fluvial energy, with the potential for infrequent seiches to force lake water upstream during storms (Larson et al., 2013; Wilcox, 2002). The most mixing occurs in the receiving basin which is where the lake and river water meet resulting in substantial mixing and transport of water and associated sediment (Herdendorf, 1990). The nearshore zone is dominated by lacustrine energy with sediment plumes from river discharge extending into the zone occasionally (Larson et al., 2013; Wilcox, 2002).

Our knowledge of how river mouth bars form is derived from research in deltaic environments, providing vital insight into less studied regions such as the Great Lakes (Larson et al., 2013; Gao et al, 2018, Zhang et al, 2020). River mouth bars can form naturally without the presence of waves. Settings where coastal processes (e.g. waves & currents) are minimal, the effects of river energy are unimpeded fully relying on river jet deposition entering the nearshore. A “river jet” refers to a river’s main flow where turbulent mixing and transport of water and sediment occur (Nardin & Fagherazzi, 2012). The river jet holds momentum due to both flow velocity and its confinement by the riverbanks. Once the jet exits the channel and meets the open sea or lake it spreads laterally and the velocity slows substantially (Figure 1.) (Leonardi et al., 2013; Nardin et al., 2013). This reduction in velocity forces sediments to fall out of suspension and accumulate at the river mouth, leading to nearshore slope changes as well as bedform formation and evolution (Edmonds & Slingerland, 2007; Nardin et al., 2013).

As the slope increases a ridge will begin to form and prograde underwater due to the jet eroding the landward side of the adjusted slope and depositing sediment on the lakeward side (Edmonds & Slingerland, 2007). This process stops when bar height reaches approximately 40% of the jet's flow depth, forcing the jet to reroute around the margins or distal end a process known as stagnation (Edmonds & Slingerland, 2007; Nardin et al., 2013). The final location of the bar within the nearshore zone is also affected by sediment size and jet velocity, with larger sediments and low velocity leading to bar formation closer to the mouth while smaller sediments and high velocity leads to formation further from the mouth (Edmonds & Slingerland, 2007; Nardin et al., 2013; Nardin & Fagherazzi, 2012). Sediment size and jet velocity are both site specific and are affected by episodic events such as floods (Nardin et al., 2013).

The occurrence of varying wave direction, speed, and height results in changes to the bar's morphology (Nardin et al., 2013). Waves interacting with the river jet force spreading and associated sediment deposition to occur closer to the mouth. Increased wave conditions enhance coastal energy, counteracting energy from the river jet, forcing the jet spreading to occur closer to the river and changing the location of bar formation (Nardin et al., 2013). Bars will form closer to the mouth as wave velocity counters jet velocity (Leonardi et al., 2013; Nardin et al., 2013). The direction of the waves can also affect bar formation and evolution. Waves approaching perpendicular to the river cause jet destabilization forcing river mouth bars to form closer to the river mouth than other wave trajectories while oblique-approaching waves (45 to 60 degrees to the river mouth) result in jet deflection, producing a deflected river mouth bar. A deflected river mouth bar forms in the direction of the approaching waves and ultimately reorients the jet trajectory. Large waves have been found to be least conducive for bar formation and force bar retrogradation through overwash (Nardin & Fagherazzi, 2012). River mouth bars become wave dominated when wave energy overtakes stream energy forcing the bar to evolve primarily by wave conditions (Nardin & Fagherazzi, 2012).

Most of what is known about river mouth bars is derived from previous studies that focus on marine deltaic systems (Nardin & Fagherazzi, 2012). In these systems, tidal forcing plays a major role in the geomorphic evolution of river mouth bars. This shaping mechanism is not an important hydrodynamic force in the Laurentian Great Lakes because tides do not occur (e.g., Mattheus et al., 2016). Instead, water levels in the Great Lakes fluctuate over hourly events, days, seasons years and centuries /millennia (e.g., As-Salek & Schwab, 2004; Fry et al., 2020; Gronewold et al., 2016, 2019; Gharib et al., 2021; Wilcox et al., 2007). Short fluctuations are related to storm surges and seiches, which can affect local water levels up to 2 m (Gharib et al., 2021; Quinn, 2002 Wilcox et al., 2007). Seasonal fluctuations cause 0.2 m to 0.4 m of change and are driven by patterns of precipitation, snowmelt and evapotranspiration with annual highs in the spring and summer and lows in the fall and winter (Fry et al., 2014; Gronewold et al., 2016, 2019; Gharib et al., 2021; Quinn, 2002 Wilcox et al., 2007). Inter-annual variability over years and decades are controlled by long term precipitation and evapotranspiration ratios (Gharib et al., 2021; Quinn, 2002). Higher long term lake levels expose coastal features to larger storm waves, overwash and flooding, which can result in erosion and geomorphic changes (Gharib et al., 2021; Meadows et al., 1997; Theuerkauf & Braun, 2021; Wilcox, 2002).

Previous studies have documented the geomorphic response of coastal features such as beaches, bluffs, and dunes to fluctuating lake levels, but no work has been done to explore how river mouth bars evolve with respect to changing lake levels. Studies have shown that lake level is a major driver that shifts the focal point of wave energy on coastal features enhancing erosion and deposition (Mattheus et al., 2016, 2021). In Lakes Michigan and Huron (which are connected hydraulically through the Straits of Mackinac and considered one lake basin for monitoring and forecasting purposes) lake level has fluctuated dramatically over the past few decades with a rapid switch from low levels from 2000-2013 to rapidly rising lake levels from 2014-2020 (Gronewold et al., 2016). Since 2020, lake level has fallen to near long-term average levels (as of 2024). During the low water period, emergency dredging of harbors and channels had to occur throughout the region, which had important economic and recreational impacts (Knight & Clark, 2014). This period was followed by one of the most rapid lake level rises over the past century caused by the polar vortex, which reduced evapotranspiration due to enhanced ice cover. Subsequently, an interval of higher precipitation than normal occurred (Gronewold et al., 2016). Rapidly rising lake level resulted in extensive coastal erosion and habitat loss (e.g., Theuerkauf & Braun, 2021). However, the impact this rapid rise in lake level has had on river mouth bars is unclear. Prior studies have shown that as lake level rises coastal features migrate landward in response to overwash, which moves sediments from the lakeward side of a coastal feature to the landward side (Theuerkauf, et al., 2019; Theuerkauf et al., 2021; Gharib et al., 2021). Overwash also occurs at higher rates as the coastal feature narrows in width due to erosion induced by rising lake level (Gharib et al., 2021). As lake level recedes and stabilizes, recovery of coastal features such as beaches and foredunes can occur increasing their width and height (Bajorunas & Duane, 1967; Gharib et al., 2021; Houser, 2009 Mattheus, 2023).

The overarching fundamental question of how these river mouth bars are altered by high and low lake level, differing wave condition, and river discharge are addressed. This thesis aims to fill the knowledge gap related to river mouth bar morphodynamics in lacustrine environments. Previous studies of river mouth bar geomorphic change (Gao et al., 2019; Nardin & Fagherazzi, 2012) have exclusively focused on marine coastal environments, but these landforms are also present along large lacustrine coasts with different hydrodynamic forcing mechanisms. To address this gap three research questions were perused in this study:

1) To what degree does shifting lake level effect bar location and area during both high and low stands?

2) How do wave direction and size alter river mouth bars during varying times of the year?

3) How does river discharge alter river mouth bar location and interact with coastal forces on the bar?

To investigate this study's specific goals, are to document how the morphology of river mouth bars evolve in response to wave events, fluctuating lake level, and variable river discharge. This analysis was conducted by tracking decadal, annual, and daily bar morphology change at the mouth of the Pinnebog River in Saginaw Bay, Lake Huron with satellite and aerial imagery. These geomorphic changes were related to hydrodynamic and fluvial processes through time series analysis and then used to develop a conceptual understanding of how these systems evolve. This work has important management implications as these systems are prone to rapid adjustments in response to changing environmental conditions, which can alter ecological functions in adjacent ecosystems. These results are then put into context with broader scale coastal processes to infer management, which is needed because of river mouth bars ecological importance.

STUDY SITE

Of the Great Lakes, Lake Huron is the third largest, holding 16% of the total volume of Great Lakes water (Herdendorf, 2004). Lake Huron has an expansive 2,973 km coastline extending along Canada and the United States (Herdendorf, 1990). Saginaw Bay is in the southern portion of the Huron Lake basin within the United States. The bay opens to the rest of Lake Huron in the northeast allowing for high fetch, which can transport water and sediment into the bay. “Fetch” is the term referring to the distance wind can travel over a lake to produce waves, larger distances increase the possibility of larger waves (Gahirb et al, 2021; Meadows et al., 1997). In our site wind traveling from a northeastern direction allow winds to travel across Lake Huron from Canadian shorelines. This distance can vary but at its furthest length fetch limits reach 200 km for our site. A total of 12 watersheds empty into Saginaw Bay (Stroud Water Research Center, 2023). Based upon satellite imagery the Pinnebog is the only river to have a river mouth bar. The Pinnebog’s location is prime for river mouth bar evolution due to the access to large volumes of sediment. This sediment is derived from the sedimentary rock that makes up the Lake Huron basin, combined with glacial till (Wilcox, 2002).

The voluminous amounts of sediment have historically been common in this region creating another coastal feature known as a ridge and swale complex (Comer & Albert, 1993). These coastal features developed after the historic Lake Nipissing water level receded, forming these complexes in areas rich in sediment that allowed for dune building (Comer & Albert, 1993). It is essential for river mouth bar formation that the river mouth is uninhibited by anthropogenic change. Historically humans have built along river mouths as they are ideal sites for the establishment of port cities. Infrastructure such as piers, harbors, and marinas are used within these cities to keep river channels stationary and open to the lake, which alters natural sediment transport (Larson et al, 2013). This is demonstrated exemplified by ports near the study site such as Caseville and Port Austin (Figure 2B) whose rivers have access to similar sediment supply but do not have river mouth bars due to human infrastructure.

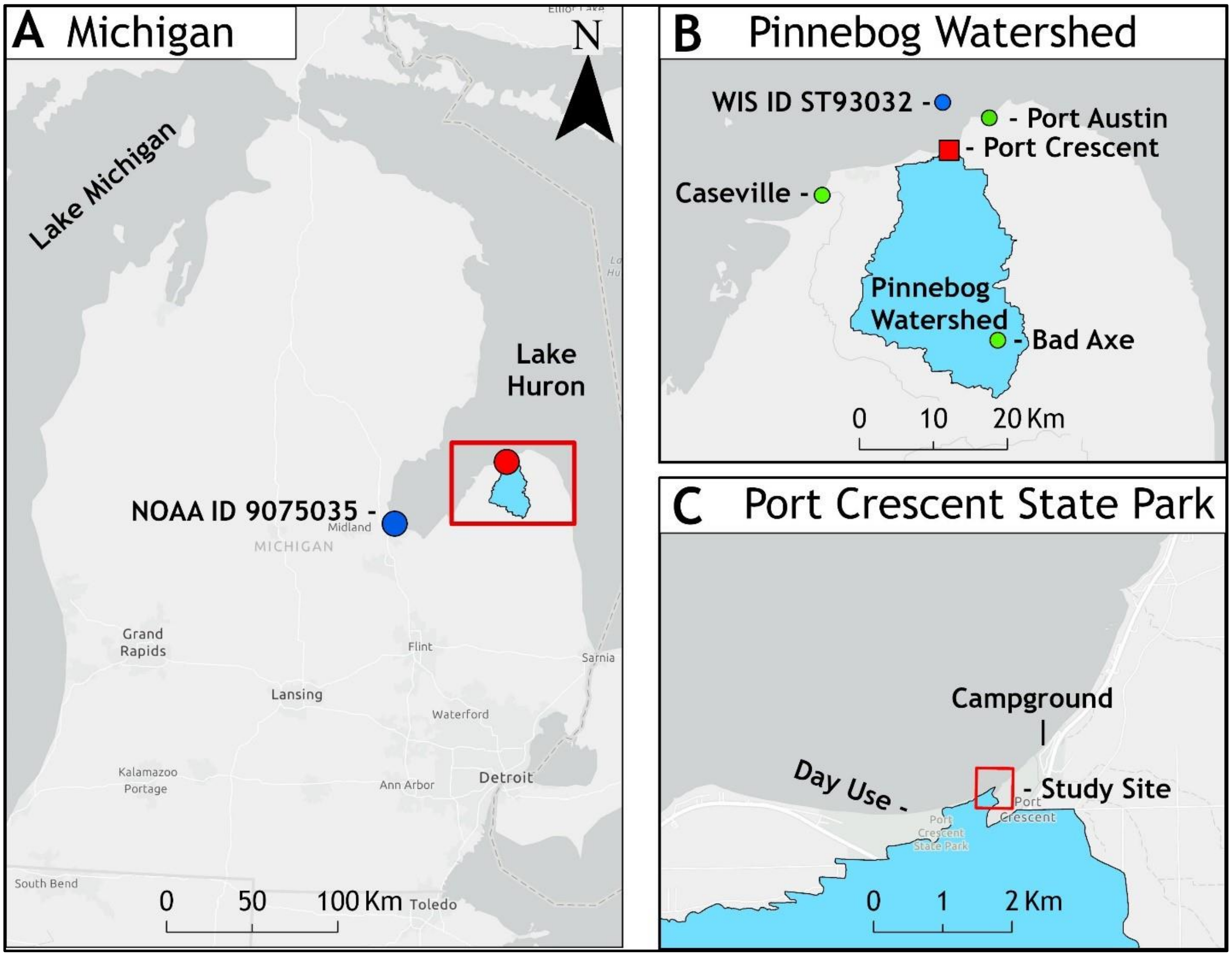

Figure 2. Location of the Pinnebog river mouth (Study site) in Michigan. A) Lake level data was obtained from NOAA ID: 9075035 located in Essexville. The red box denotes image B (Pinnebog watershed), and the red dot denotes image C (Port Crescent State Park). B) Pinnebog watershed contains the location of wave data (WIS station ID ST93032) and referenced cities (Caseville, Port Austin, and Bad Axe). C) Port Crescent State Park shows the extent of all satellite imagery and the river mouth's location in relation to day use and campground.

Port Crescent State Park is along the eastern Saginaw Bay shoreline in Huron County (Figure 2B). The Pinnebog River divides the park with the western side containing the day use area and the eastern side the site of the campground (Figure 2C). The focus of this study is on the middle of the park where the river enters Lake Huron. At this confluence, a sandy bar forms from both fluvial and coastal sediments. Along the river is a sandy bluff/ foredune on the eastern banks and a dune field on the western side. The bluff and foredune span eastward until it meets an old tributary of the Pinnebog river. Access to the site is provided through Port Crescent State Parks railroad bridge just south of the site along M-25. The study area covers 0.275km^2 with the bar occupying a varying length of 300 m and width of 40 m. This location is optimal for studying river mouth bar dynamics as it is exposed to river discharge, varying wave conditions, and fluctuating lake levels on seasonal, annual, and decadal time frames.

Historical Background

Sand played a fundamental role in the Port Crescent area long before human development. The landscape is composed of a ridge and swale complex, a historical remnant of fluctuating lake levels and the changing coast. This was a desirable site for First Nations people due to the sand bluffs overlooking the bay providing a vantage point, and ability to utilize the river for water and travel. The area in and around the study site was used for hunting and fishing. It was during this time that the river was named Pinnepog, a Chippewa name meaning “partridge drum,” which would later be changed to Pinnebog (Mcdonald et al, 2009). With the arrival of European settlers, the Pinnebog river was used to power mills (Mcdonald et al, 2009). Port Crescent grew into a thriving port city with a grist mill, sawmill, and salt and sand mines. During the late 1800’s and early 1900s sand in the area between the old Pinnebog and Lake Huron was mined (Figure 3) by the Haskell mining company (Mcdonald et al., 2009). The sand was noted for its fine grains made of mostly silica. The quality of sand made it highly prized for glass production and metal works. The Sand Production Company bought the claim in the early 1900s and during the 1920’s used modern clam bucket technology to excavate more sand (Mcdonald et al., 2009). Innovative technology separated sand based on granule sizes allowing for diverse uses. Mining operations spanned 68,796.6 m2 from the Pinnebog's northern bank to Lake Hurons shores. Along the northern bank, a berm was left to thwart river overflow which failed and resulted in the modern channel (study site) (Figure3). Prior to 1941, the current extent of the study site was simply an excavated site and shoreline with no river mouth.

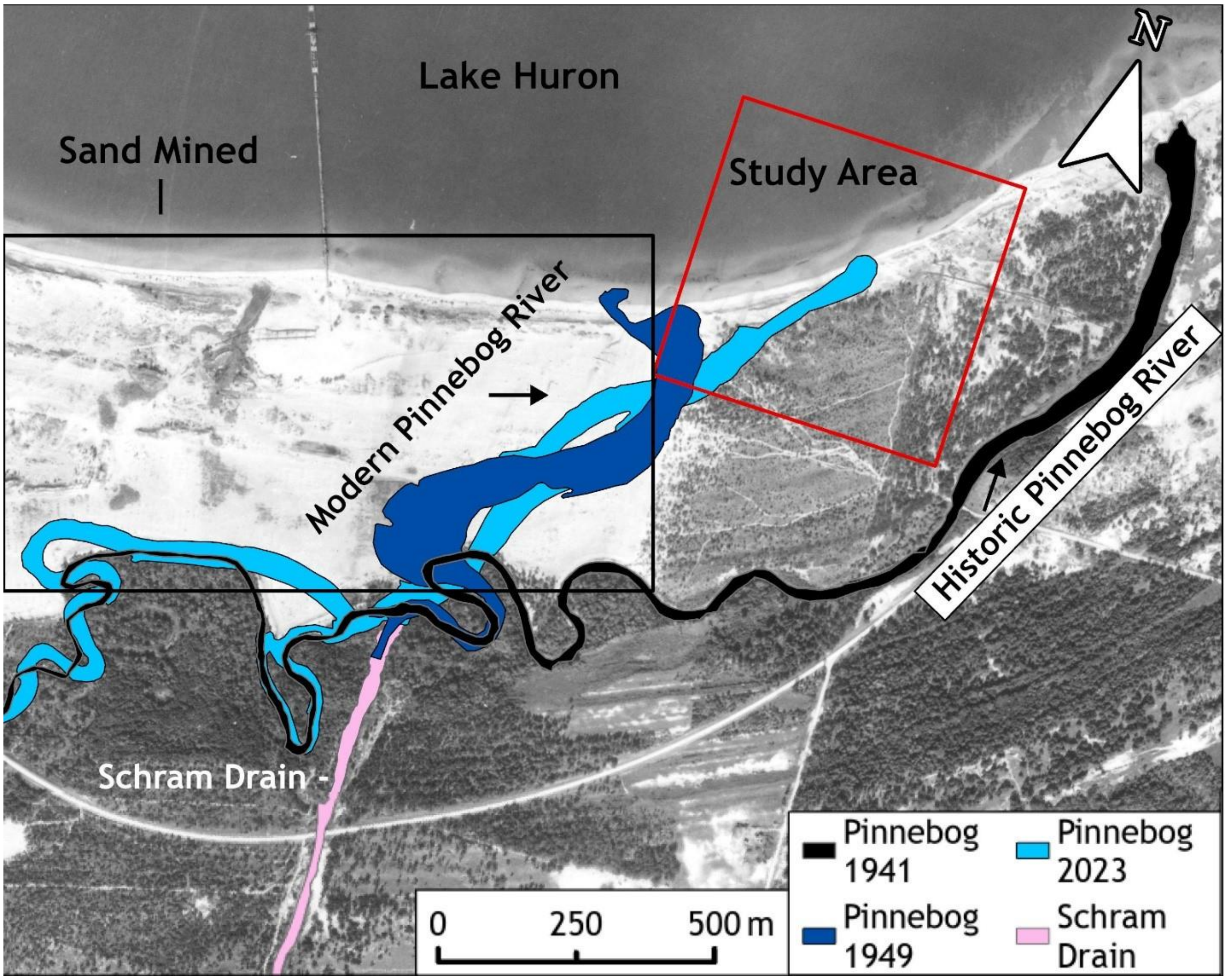

Figure 3. Migration of the Pinnebog River from 1941 to 2023 due to mining (black box) overlayed on 1941 imagery. The historic river channel from 1941 is altered by 1949 resulting in the modern river where our study area is located (red box).

DATA AND METHODS

Data Collection

Hydrodynamic Data

Hourly records of wave direction (θ) and significant wave height (Hs) were downloaded from the US Army Corps of Engineers Wave Information Study (U.S. Army Corps of Engineers, 2024a). Wave Information Study Station ID ST93032 (Figure 2B) provided data on wave characteristics for the study site from 6/29/2016 - 12/31/2022. This station was selected as it has the closest proximity at 9 km north of the study site. These data were the study's only resource of wave data, given that no wave buoys are near the study area.

Monthly lake averages obtained for Lake Huron from 1/1/1918 - 12/1/2023 were downloaded from U.S Army Corps of Engineers Great Lake Hydraulic and Hydrology (U.S. Army Corps of Engineers, 2024b). U.S Army Corps of Engineers obtained monthly lake average from a series of coordinated gages from multiple locations consisting of Mackinaw City MI, Harbor Beach MI, Ludington MI, Milwaukee WI, Thessalon WI, and Tobermory Ont. (U.S. Army Corps of Engineers, 2024b). Water level elevation was measured in IGLD 85 vertical datum. The second water level data were hourly water level averages for Lake Huron from 6/29/2016- 12/31/2023 that were downloaded from NOAA Tides and Currents for Station (ID: 9075035) (National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services, 2024). This station was the closest station to the study site at 75 km east in Essexville MI (Figure 2A). Hourly water level was also measured in IGLD85 vertical datum.

Daily precipitation data were collected for the Pinnebog River between 6/29/2016- 12/31/2023 and were downloaded from the National Oceanic and Atmospheric Administration

Climate Data station ID USC00206662 (Port Austin) (Figure 2B) and ID USC00200417 (Bad Axe) (Figure 2B) (National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services, 2024b, 2024c). Port Austin is located 8 km east of the study site along the coast while Bad Axe is located 23 km south of the site at the headland of the Pinnebog. Precipitation was measured in inches with Port Austin providing 89% area coverage and Bad Axe 97% area coverage. Precipitation was converted to cm once in the Excel spreadsheet.

Aerial Imagery (Satellite, Historical)

River mouth bar images were collected between 6/29/2016 - 12/31/2023 and were downloaded from Planet Labs for a square layout of 0.275 km^2 around the study site (Figure 2C) (Image ©2024 Planet Labs PBC). These images were downloaded in raster format with a 3 m pixel size and the horizontal datum set to NAD 1983 UTM Zone 17 N. Planet lab images were acquired through a constellation of PlanetScope satellites that are radiometrically, atmospherically, and geometrically corrected. Images are also unsharp masked, sun angle corrected, and georeferenced to less than a 10 m root mean square error (RMSE). Historical images were acquired from Michigan State University's Remote Sensing and GIS (RS&GIS) office for the time periods 9/27/1941, 10/13/1949, 6/7/1972 and 5/9/1993. Images were downloaded as raster format in 3.4 m pixels (1941 & 1949) and 7 m pixels (1972 & 1993) with horizontal datum set to NAD 1983 UTM Zone 17 N.

Unmanned Aircraft System Data

Higher resolution unmanned aircraft system (UAS) data were collected on July 18, 2023, and September 1, 2023. During these field research days, the DJI Phantom 4 Pro V2.0 Drone was flown over the site. Proper spatial display required the placing of 12 ground control points and 5 checkpoints each measured with the Trimble R10-2 RTK GPS antenna and the Trimble TSC7 controller. Trimble provides centimeter accuracy both horizontally and vertically which the drone imagery can be tied to. Data was placed in Agi Soft Metashape where both an ortho image and a digital elevation model were produced (AgiSoft PhotoScan Professional., 2021). The ortho images could be compared in ArcGIS where they were digitized. DEM's were used to create a subtraction map showing areas of accretion and erosion. The process to produce the map starts with digitizing the west and east sides of the bar. The digitized coordinates are used to mask the data to only display the river mouth bar excluding the water. The masked images can then be mosaiced together. With both July and September data mosaiced they were extracted based upon nodes. Nodes were added to the September data to match the July data. The final step was to subtract the September data from the July data producing a contour map of differing raster's, a visualization of accretion and erosion.

Data Processing

A record of river mouth bar adjustments was created by visually identifying bar morphology changes (e.g. erosion, overwash, migration, bar opening, etc.) in Planet Explorer. These events (187 in total for the period from 6/29/2016 to 12/29/2023) were tabulated in Microsoft Excel. When obvious measurable change was visualized, a beginning date and end date were established in Excel. All data were then organized to provide necessary information that included wave direction, wave height, precipitation totals, precipitation averages, lake level min/ max and bar area for that event. These data records enabled our study to track all conditions holistically, producing a clearer picture of how the river mouth bar was changing under differing conditions.

Satellite Data

Satellite images in raster format were uploaded into ESRI's ArcGIS Pro software (Environmental Systems Research Institute, 2024). Imagery allowed for tracking of bar area change and bar migration. River mouth bar area change required the digitization of features in 137 Planet Lab images. From each image two feature classes were created, one for the river mouth bar and the other for the adjacent bluff and foredune. Each river mouth bar and bluff/foredune was digitized into polygons (Environmental Systems Research Institute, 2024). The area that overlapped between the two separate feature class polygons were clipped, leaving all river mouth bar extents with the same shoreline extent. Then using the polygon measure tool each of the river mouth bar polygon areas could be calculated and placed into Excel. River mouth bar migration required polyline digitization of the river mouth bar in eight images. The dates selected were 10/14/2016, 9/30/2017, 9/29/2018, 9/24/19, 10/5/2020, 9/30/2021, 9/30/2022, and 10/3/2023. Utilizing images during the same time of year reduces additional influences. The fall was specifically chosen due to the natural stability of the bar during that period. Data of cross shore profile change were acquired by using ArcGIS's measure (length) tool to measure from one polyline's lakeward side to the lakeward side of consecutive years' polyline (Environmental Systems Research Institute, 2024). Measuring occurred on the N – S direction along the trajectory of the river for all consecutive years. Lake level could then be paired with each year's change.

Historical Data

Given the inherent misalignment of imagery, it was necessary to georeferenced them in ArcGIS. For all images a 1st order polynomial transformation was performed as it has a minimum requirement of 3 ground control points (Environmental Systems Research Institute, 2024). For 1949 and 1993 4 GCPs were used and 5 GCP's for 1941 and 1972. The common set of GCPs were M-25's Schram bridge, Pinnebog bridge, day use entrance, Kennedy Rd/M-25intersection and Port Crecent Rd/M-25 intersection. After georeferencing the forward root mean square error (RMSE) for each image were as follows 1941 (2.20 m), 1949 (0.82 m), 1972 (3.74 m), and 1993 (0.32 m). Once georeferencing measurements of the mouth of the river channel between years and full river channel extent could be digitized.

Wave Information Study Data

Wave data had to be transposed so that average wave direction could be determined Average wave direction required a series of Excel code:

Wave =MOD((360+(ATAN2(Wx,Wy) *180/PI())),360)

Wx is the north to south vector, Wy is the east to west vector and Wd the WIS wave direction in degrees (0-359):

Wx =SIN(Wd (PI()/180))

Wy =COS(Wd (PI()/180))

These data could then be tabulated in Excel for each event along with wave Hs average and maximum wave height for each event identified in the satellite imagery.

Data Analysis

Hydrodynamic Data

To understand how wave and precipitations conditions affect the river mouth bar, comparisons of tabulated data in Excel with satellite imagery were used. To separate each factor a series of conditional formatting rules were set in Excel. Precipitation rules focused on events where 2.5 cm of rain occurred for a single day and events where totals averaged 1 cm per day. This allowed for multi-day and single day precipitation events to be studies in relation to bar morphodynamic changes seen in satellite imagery. For wave conditions rules focused on single day events with >2 m wave hs and for multi day events a wave hs average >1.5 m, once established bar morphodynamic changes could then be analyzed in satellite imagery. The measure of 2 m wave hs (significant wave height) was selected as they are considered storm waves, while an average of 1.5 m wave hs requires multiple hours of larger waves. During each event wave direction was also focused on mainly onshore waves. Wave direction was broken into two categories: “all waves” and “onshore waves.” All waves include waves that are not directly interacting with the bar but support littoral drift (90 – 270). In contrast onshore waves (270 - 90) approach the bar from a northernly direction and interact directly with the bar.

Bar Area Validation

Since the satellite data used for prior data accumulation was 3m/ pixel and proved difficult to extract the exact waterline of the bar an accuracy analysis was designed to establish the precision of the digitized satellite data. The July 18th drone data’s area was calculated to be 17,812.62 m^2. The closest satellite image (July 19th) was digitized, and the area of the digitized polygon was calculated to be 18,945.23 m^2. A total difference of 1,134.41 m^2 roughly 6%, providing confidence in prior digitized data.

RESULTS AND INTERPRETATIONS

Lake Level

Seasonal lows for Lake Huron occur in January and February and seasonal highs occur during July and August (Wilcox et al., 2002, 2007). Long-term lake level provides a deeper understanding of historical lake conditions that previously affected this site. Historical data compares recent events such as the rapid rise in lake level from 2014 to 2020 to previous lake level rises, a period where lake level rose 0.29 m / year until July 2020 (Theuerkauf & Braun, 2021). This rise occurred at a rate not previously experienced by the Great Lakes for such a long duration. Lake level peaked in 2020 at 177.5 m, which is higher than the previous high in 1986 where levels reached 177.48 m. The study period also captured the drop in lake level after 2020 when lake level lowered by 1.059 m to 176.441 m in January of 2024. A decrease of 0.43 m /yr over the 2-year and 5-month period. This rate aligns with lake level conditions after peaks in both 1986 and 1997. For the 2 years and 5 months after 1986, lake level decreased at 0.477 m /yr and after 1997 a rate of 0.52 m /yr. Over the study period, lake level was lower than the long-term average in 2016, 2022, and 2023. All conditions experienced by the bar occurred during a temporal period of high-water level even during lake level drop. (Figure 4B). Exemplifies seasonal shifts in water level with highs occurring during July an important factor affecting bar change.

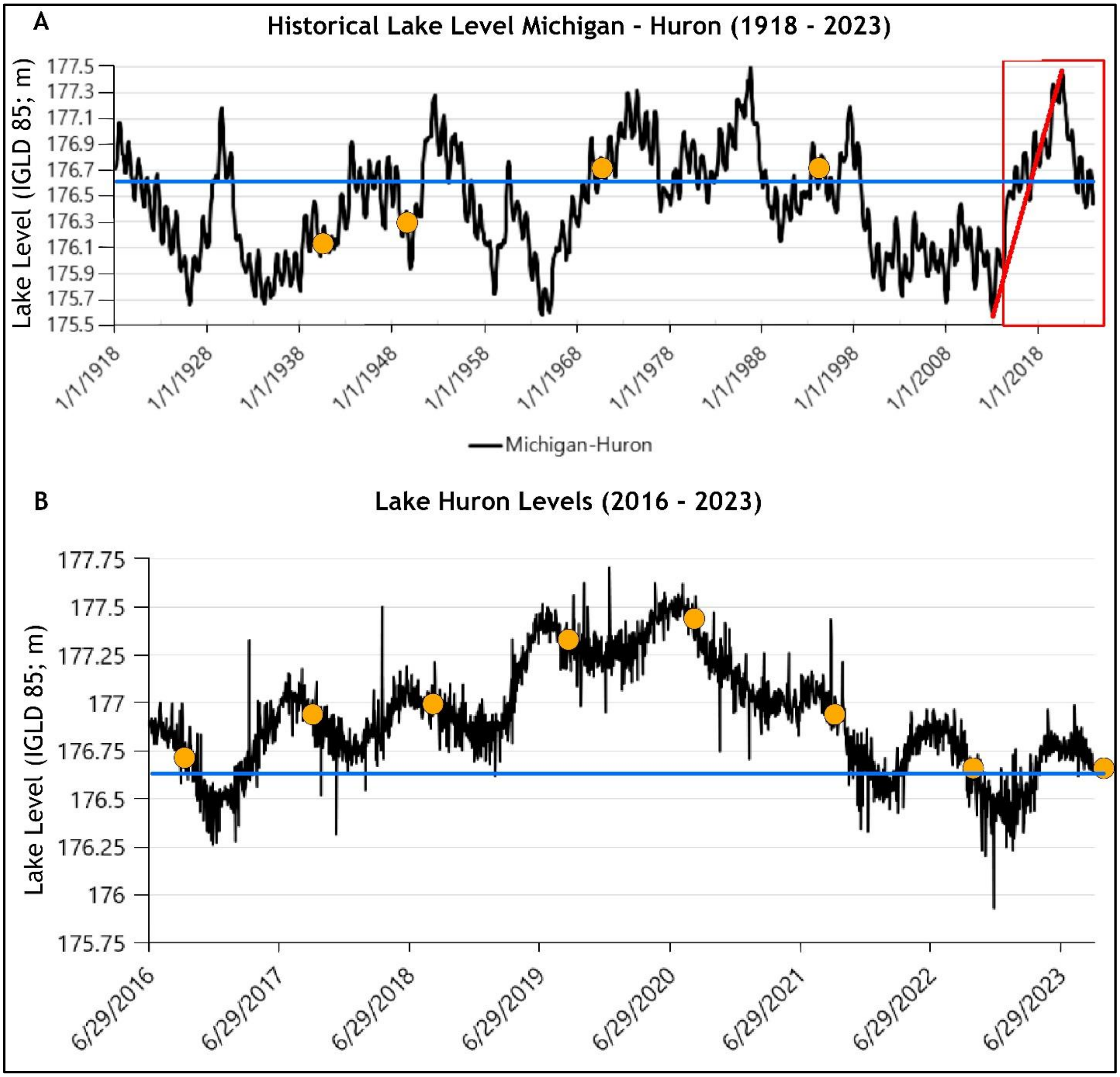

Figure 4. Lake level curves for Lake Michigan and Lake Huron. A) Lake level fluctuations of Lake Michigan and Lake Huron from 1918 to 2023 (IGLD 1985 meters) from U.S Army Corps of Engineers Great Lake water level data (U.S Army Corps of Engineers, 2024b). Historical images (from Figure 5.) represented by orange dots. B) Record of Saginaw Bay water level (i.e., Lake Huron water level) data (IGLD 1985 meters) from 2016 to 2023 acquired from the NOAA station in Essexville, MI (ID: 9075035) (Figure 2A). Graph B, Orange dots represent the chronology of satellite images in (Figure 6.)

Historical Bar Change

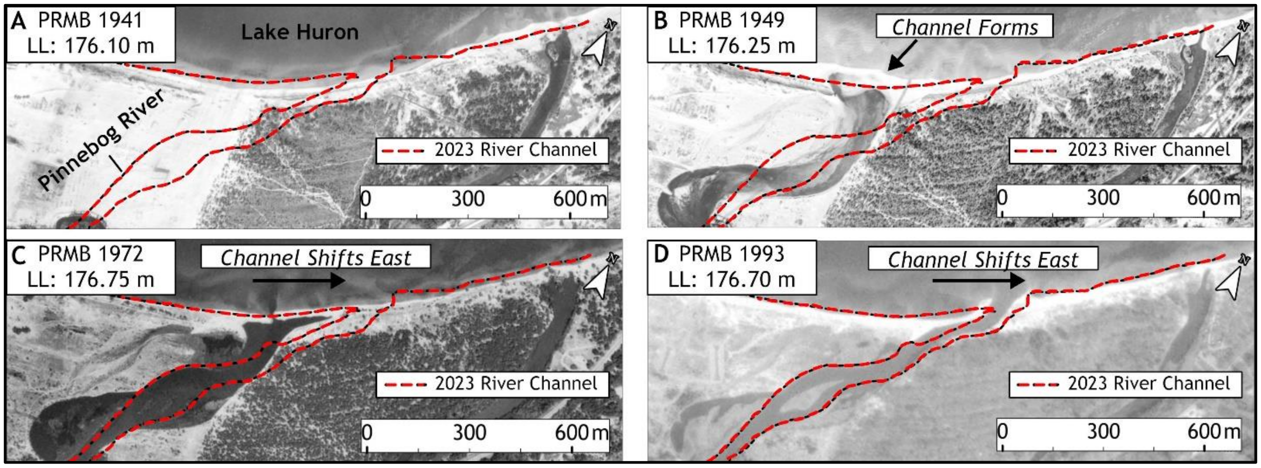

Figure 5. Location changes of the Pinnebog River Mouth Bar (PRMB) from 1941 to 1993. Channel formation can be observed from 1941 to 1949. Adjustment of the main river channel to the east can be observed from 1949 to 1993 as lake level (LL) rises and falls. A) Historic 1941 imagery prior to modern channel formation. B) 1949 image just after channel formation. C) 1972 image, river channel has shifted east compared to 1949 (B). D) 1993 image, river channel has shifted east compared to 1972(C). The overall trend after formation is an eastward migration of the river channel.

Historical images from 1941 to 1993 reveal the formation and evolution of the new position of the Pinnebog River (Figure 5). Imagery documenting river morphology changes all occur near the overall lake level average (176.06 m), in-between each images major rises and falls in lake level occur but are not captured. Observations over time indicate an eastward migration of the river mouth channel, which resulted in a loss of 20,234.3 m^2 of land on the river's eastern bank and area gain along its western bank. The earliest image from 1941(Figure 5A) revealed a region of sand dunes without the presence of the Pinnebog River. In 1941, the previous location of the Pinnebog River flowed further eastward and would not develop its modern channel within the study site until sometime around 1949 (Figure 5B). During the 8-years from 1941-1949 the channel formed and deposited sediment along the modern river mouth. Post 1949 lake level rose from 1950 until 1953 at a rate of 0.52 m /yr. The 1972 imagery (Figure 5C) captures the study site during a 0.17 m /yr. rise that started in 1965 and lasted until 1973 (rate from Theuerkauf & Braun, 2021). During this time, the river migrated 53 meters eastward and reduced excess sediment along the western bank. Lake level dropped until 1976 when it rose at a rate of 0.12 m /yr. until 1986 when it reached 177.5 m. The last historical image from 1993 (Figure 5D) was taken during lake level stabilization after the 1986 peak. The river mouth channel migrated another 32 meters eastward where it eroded the eastern bank. The 1993 river channel aligns with the 2023 channel (Figure 5) indicating that the river is no longer migrating.

River Mouth Bar Migration

A correlation between lake level rise and fall revealed the migration of the river mouth bar. Using 2016 as the starting point the bar migrated landward at a rate of ~ 36 m /yr. until 2019. Migrations per year are as follows, 2016 (Figure 6A) to 2017 (Figure 6B) the bar migrated ~ 21 m, ~ 50 m in 2018 (Figure 6C) and ~ 36 m in 2019 (Figure 6D). The only year that the bar did not migrate landward during lake level rise was 2020 (Figure 6E) where it migrated lakeward ~ 45 m. Bar migration lakeward after 2020 continued until the end of the study in 2023. From 2020 until 2023, the bar shifted lakeward at an average rate of ~ 34 m /yr., including ~ 45 m in 2020, ~ 37 m in 2021(Figure 6F), ~ 40 m in 2022 (Figure 6G) and ~ 15 m in 2023 (Figure 6H).

As the bar migrated landward the area along the banks from 2016 to 2018 was pushed against the foredune and bluff. The sediment cannot be placed upon the banks as they are too steep, forcing the sediment to inundate in place as lake level rose. The 2019 river mouth bar (Figure 6D) no longer exists along the banks and was only present within the river channel as the channel provided an area where the coastal processes could push the sediment further inland as there was no bluff of foredune acting as a barrier. The river mouth bar within the channel has been squeezed upstream 15-meters from the western foredune. During this time, previously protected foredune and bluff on each bank is exposed to coastal conditions. The most apparent change occurred on the western banks vegetated foredune which had a 28 m reduction and was partially submerged in 2019. As lake level receded the submerged land was free of vegetation. Similar occurrences can be seen along the eastern bank but are not as drastic.

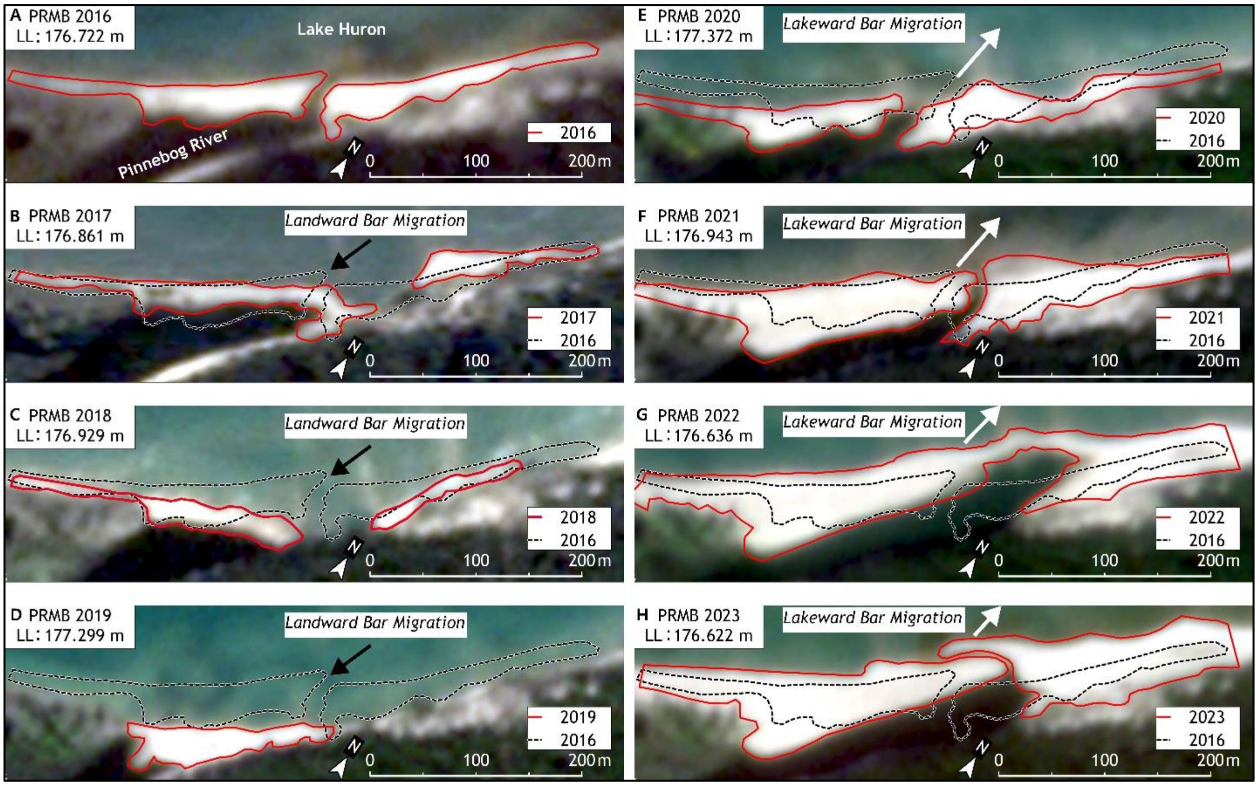

Figure 6. Pinnebog River Mouth Bar (PRMB) migration over the study period 2016 to 2023. Patterns of bar migration and area can be observed in response to fluctuation in Lake Huron water level (LL). Rising lake level from 2016 to 2020 and fall lake level from 2021 to 2023. A) 2016 river mouth bar is used in the following images as a reference point. B) 2017 river mouth bar shifts landward ~ 22 m from 2016(A). C) 2018 river mouth bar shifts landward ~ 50 m from 2017(B). D) 2019 the river mouth bar shifts landward ~ 36 m from 2018(C). E) 2020 the river mouth bar shifts lakeward ~ 45 m from 2019(D). F) 2021 the river mouth bar shifts lakeward ~ 37 m from 2020(E). G) 2022 the river mouth bar shifts lakeward ~ 40 m from 2021(F). H) 2023 the river mouth bar shifts lakeward ~ 15 m from 2022(G). Overall, from 2016 to 2019 the river mouth bar shifted landward at an average rate of ~ 36 m /yr. and from 2020 to 2023 at a lakeward rate of ~ 34 m /yr.

River Mouth Bar Area

The response of the river mouth bar area was inversely related to lake level. Bar area was smaller during 2016 to 2020, which corresponds to the period of lake level rise. As lake level subsequently fell. From June 2016 until July 2020 the bar area fluctuated from 3,500 m^2 up to 10,000 m^2 (Figure 7). After July 2020 bar area increased at a rate of 6,010 m /yr. until March 2023 where bar area peaked at 23,846 m^2 (Figure 7). During this study, the bar area was the smallest from May to July and largest from October to January from 2019 to 2023. Bar area progressively decreased from 2016 until the end of 2018. In 2019 and 2020 despite peak water levels, the bar area increased.

An added effect that increases bar area is river mouth closures, an event when the bar welds to the eastern shore cutting the river off from the lake, an example can be seen in (Figure 6G) PRMB 2022. During these closures, sediment from the river can no longer travel into the nearshore zone and builds up on the landward (river) side of the bar, ultimately increasing the bar area. Channel closures occurred during the fall months as follows: 39 days in 2017, 9 days in 2018, 108 days in 2019, 2 days in 2020, 10 days in 2021 and 1 day of closure in 2022. During 2019, the channel was closed from July 13th to October 28th (108 days), resulting in river sediments accumulating on the bar's inside. Sediment accumulated from the river for much longer during 2019 allowing for the bar area to increase 1,228 m^2.

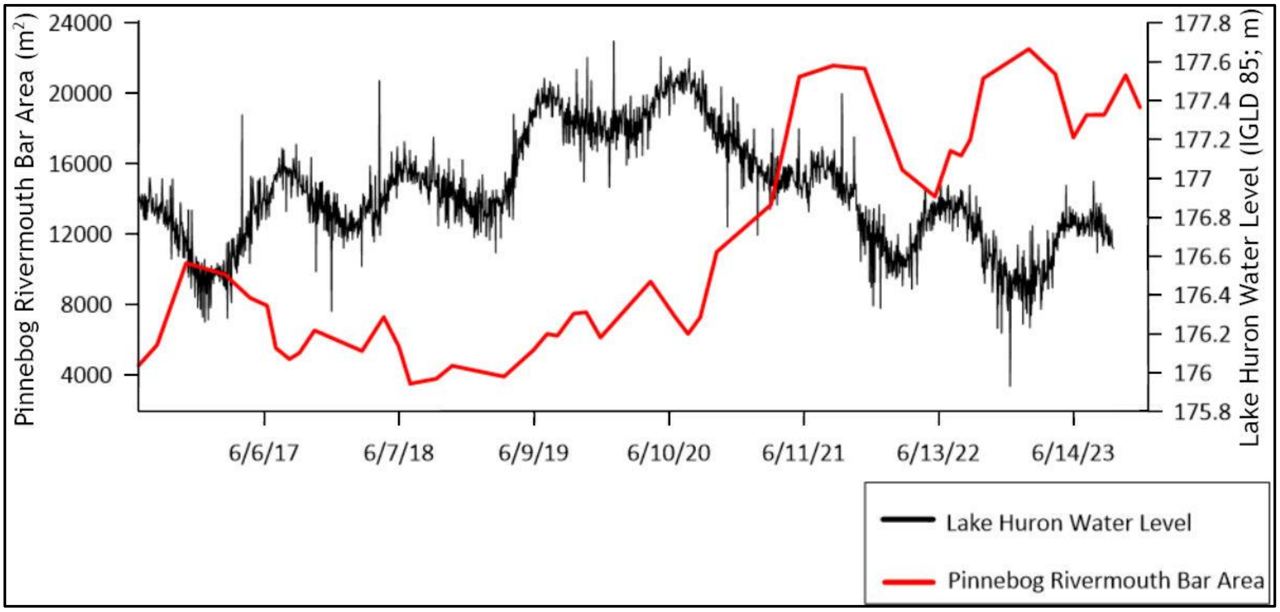

Figure 7. Record of river mouth bar area (m^2) from 2016 to 2023 acquired through delineation of satellite images. Overlayed with Lake Huron lake levels (Figure 4B) during the same period. A stark rise in bar area and fall in lake level can be observed after 2020.

Bar Geomorphic Changes Resulting from Discharge

Precipitation data were collected from 2016 to 2023 tracking seasonal and yearly cycles. It is well documented that a seasonal pattern of precipitation occurs in the area, with increased amounts during spring and summer and lower rates in the late summer through fall (Meadows et al., 1997, Wilcox., 2002, 2007). Examination of Figure 8A reveals yearly precipitation had a higher average between 2017 to 2020, with 2017 documenting a high of 70.51 cm and 2018 with a low of 58.5 cm. During 2021 and 2022 totals were lowest for the study period at 49.23 cm and 54.10 cm.

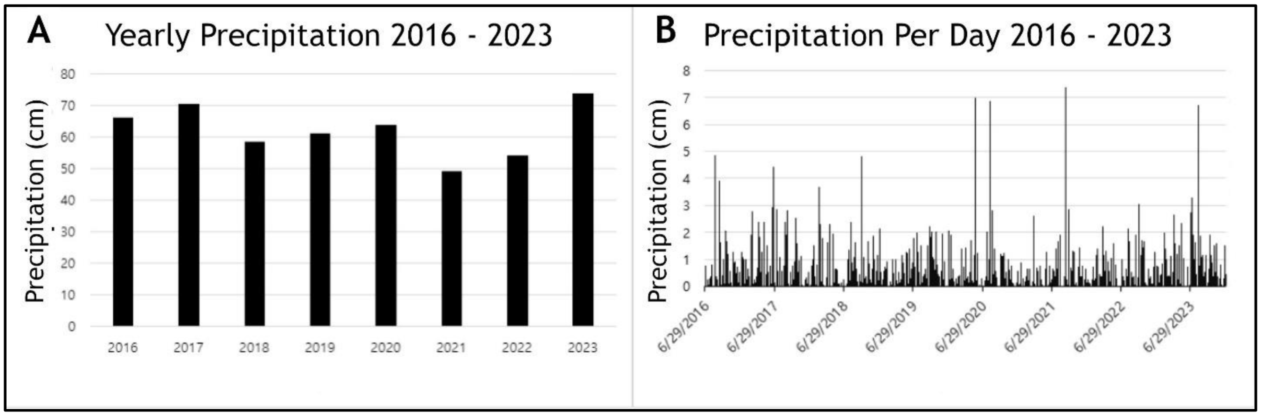

Figure 8. Precipitation totals in centimeters over the study period. A) Yearly totals 2016 to 2023 note higher yearly precipitation for 2016 to 2020. B) Precipitation per day over the study period, higher day totals during the summer months (Station USC00206662 Port Austin, MI (Figure 2B).

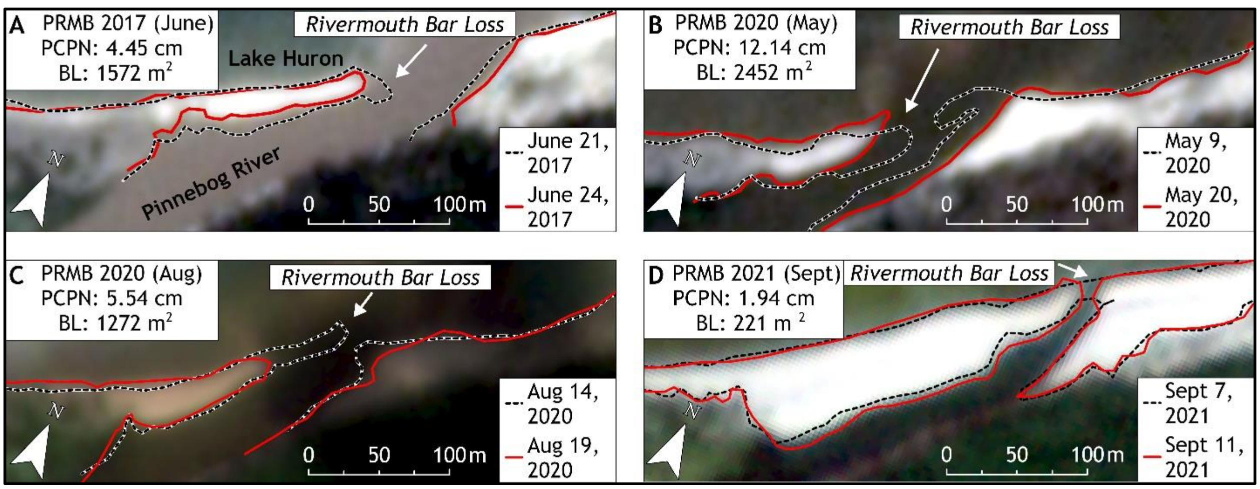

Figure 9. Observations from 2016 to 2023 of various precipitation events resulting in river discharge. Precipitation (PCPN) events affecting the Pinnebog River Mouth Bar (PRMB) resulting in river mouth bar loss (BL). A) Three-day event in June 2017 during which 4.45 cm of rain occurred and a bar loss of 1572 m^2 followed, much of which is from the distal end. B) 11-day event in May 2020 during which 12.14 cm of rain occurred and a bar loss of 2452m^2 followed, loss was from both the bar and eastern channel edge. C) A five-day event in August 2020 during which 5.54 cm of rain occurred followed by 1272m^2 of bar loss on both the distal end of the bar and eastern bank. D) A four-day event in September 2021 during which 1.94 cm of rain occurred followed by 221 m^2 of bar loss and channel opening. Overall, precipitation events preceded bar loss.

Precipitation events over multiple days, and single large rain events resulted in bar loss and erosion of the channels eastern bank. Precipitation is not causing the bar loss in Figure 9, but the discharge resulting from precipitation (Figure 12). In June 2017 (Figure 9A), precipitation occurred over a one-day period receiving 4.45 cm on June 23rd. Accordingly, the bar area decreased by 1572 m^2, a 20-meter reduction in length. A similar event of bar loss occurred during May 2020 (Figure 9B). May 9th was the last available image prior to the rain with totals of 1.14 cm on the 15th and 0.66 cm on the 16th while most of the rain occurred on the 18th and 19th with totals of 3.23 cm and 6.99 cm respectively. Changes included bar area reduction of 2452 m^2, a 30-meter loss in bar length, and a 15-meter reduction of the eastern bank. August 2020 (Figure 9C) received 5.52 cm on the 16th and bar area was reduced by 1272m^2. The September event (Figure 9D) is during early fall when the bar area is stabilizing and increasing in area. On September 7th the river channel was closed, the next day on the 8th there was a 1.8 cm precipitation event the channel then opened in the September 11th imagery and the bar area was reduced by 221 m^2. Precipitation was lower than other events and there was less bar change. In all events, the bar's sediment was removed by the river's enhanced jet and distributed into the nearshore zone. From the satellite imagery it is possible to infer that the displaced sediment aligns with the river trajectory (northeast) in which the river empties into Lake Huron.

Wave Data

Wave energy interacts with both newly deposited sediment from the river jet and the mouth bar. For this study, available wave data were analyzed during the study period from 2016 to 2022, with a focus on average wave direction and large wave events (>2m). Due to the geometry of the coast at this site, only waves approaching from the north were considered as directly onshore waves (wave angle normal to the bar). Waves that approach with a westerly component are still important as they move sediment towards the bar in the littoral zone, while onshore waves impact the bar directly in the form of bar alteration such as overwash. At our site the average wave trajectory toward the bar is 335 degrees, but the average onshore waves are 11 degrees with 49% of all waves approaching the bar in a northernly direction. Based on satellite imagery, sediments displaced into the nearshore are reworked by waves depositing the sediments back onto the bar during periods of low precipitation.

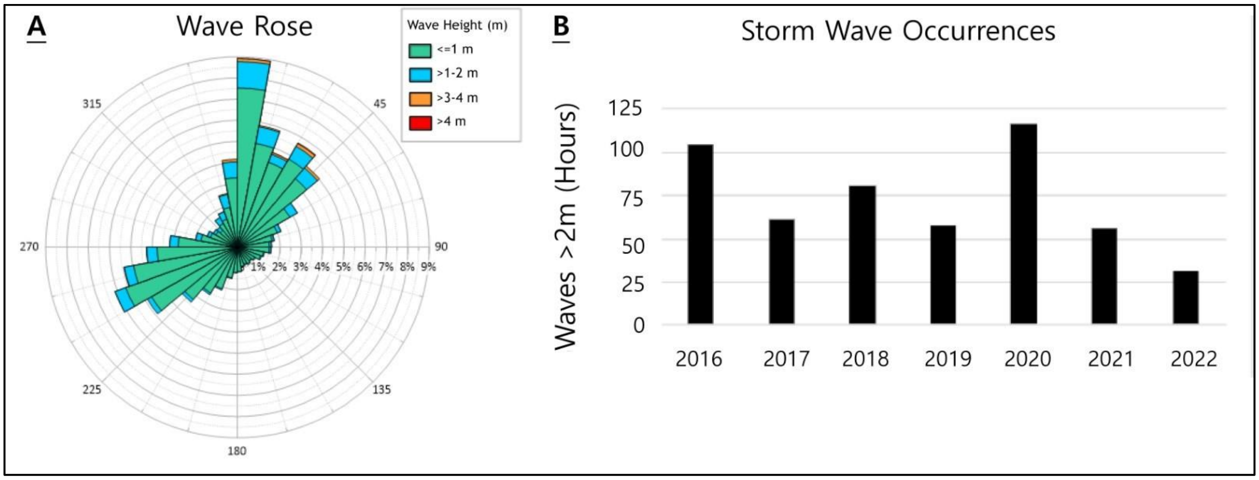

Figure 10. Wave characteristics for the study area from 2016 to 2022. A) Percents of wave angle from 2016 to 2022 with wave height and number of hours of waves over 2 meters in height (storm waves) per study year. (Note 2023 has no data as buoy data was unavailable, WIS Station ID ST93032 MI (Figure 2B). Wind Rose of all waves even those not directly interacting with the bar (90 –270). Onshore waves (270- 360 and 0 –90) impact the bar directly and during the study period occur with larger waves. B) Storm wave occurrences greater than 2 meters reveal large wave interaction during the study years, note these waves are only onshore waves (270- 360 and 0 –90).

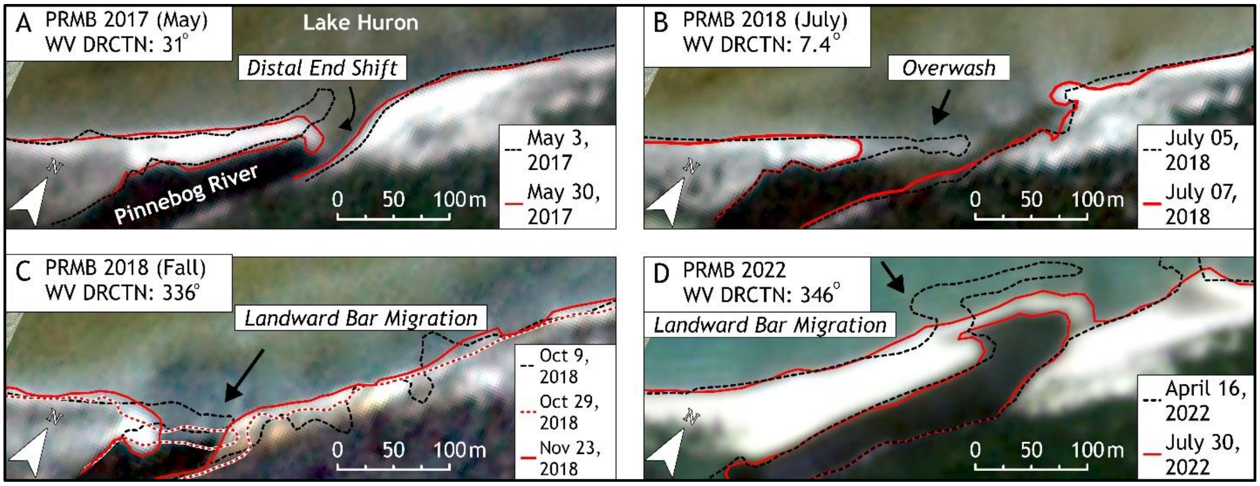

Figure 11. Wave event changes on the Pinnebog River Mouth Bar (PRMB) from 2016 to 2023 that shifted river mouth bar location and resulted in bar loss due to wave direction (WV DRCTN) and height. A) Wave event that alters the distal end by 31-degree waves impacting the bar. B) Wave event where waves were large enough and the elevation of the bar was low enough to remove the bar. C) Fall wave activity that migrated the bar 15 m landward before eroding the bar. D) Wave events during the spring which forced migration of sediments within the nearshore zone landward. Overall, wave activity can cause landward bar migration and alter the distal end.

During periods of low precipitation (< 0.2 cm per day average), the reworking of the river mouth's bar is common. An example of such behavior was observed in May 2017 (Figure 11A) when waves with an average trajectory of 31 degrees altered the distal end. Shifted the distal end direction from a northward position to an eastern position placing the bar in the river channel. Precipitation was minimal with 3.4 cm total and maximum one-day rain event of 0.43 cm over the 27-day period. This event had low fluvial energy allowing coastal processes to evolve the bar location. In early April of 2022 (Figure 11D), discharge from snowmelt and precipitation (3.4 cm) eroded sediment into the nearshore, where waves reworked them into a bar. A smaller bar is visible much higher relative to the distal end of the main river mouth bar. Over time, the attached bar migrated 25 meters south and rewelded to the eastern shoreline. Wave angle averaged 346 degrees as the bar migrated south toward the river. Precipitation was high with 11 cm of rain occurring, but because the bar was attached to the shoreline much further north the river does not interfere with its evolution. The attachment of the bar away from fluvial forces allows for coastal processes to dominate the evolutionary trajectory. In the fall of 2018 (Figure 11C), the jet was enhanced by increasing river discharge, allowing sediment to be easily swept away, resulting in the river mouth bar shifting south 15 meters from October 9th - 29th. During this period wave angle averaged 351 degrees with 19% of waves greater than 1 meter. In the second phase from October 29th - November 23rd the bar area was reduced by 939 m2 and length by 70 meters. The wave angle shifted to 318 degrees, forcing the bar into the jet where it was eroded and settled along the eastern bank. The river had an overall low discharge with 7.04 cm of precipitation. On occasions when waves where large enough (> 1.5 m), overwash would result in the reset of the bar. An example of this behavior occurred in July of 2018 (Figure 11B). A 13-hour wave event with an average wave height of 1.55 meters occurred on July 6th, 2018, which reduced bar length by 97 meters and bar area by 1,298 m^2.

DISCUSSION

We discovered changes in river mouth bar geomorphology in the study area are directly related to fluvial and coastal processes, particularly those associated with fluctuating lake level. River mouth bar geomorphic changes within the Great Lakes have not been well studied, creating a knowledge gap on how these landforms evolve that must be addressed to inform ecosystem management. To fill this gap, this study utilized satellite imagery to generate a time series of river mouth bar geomorphic changes across decadal, annual, seasonal, and event time scales. These changes were then linked to the driving coastal and fluvial processes to evaluate the dynamics associated with river mouth bars and to infer the potential impacts these dynamics have on nearshore sediment budgets. With a goal of answering a series of questions 1) To what degree does shifting lake level effect bar location and area during both high and low stands? 2) How do wave direction and size alter river mouth bars during varying times of the year? And 3) How does river discharge alter river mouth bar location and interact with coastal forces on the bar?

This study yielded a better understanding of how major water level fluctuations affect these coastal systems. The geomorphic response of river mouth bars includes landward and lakeward migration, bar area changes, and shifting sediments into the nearshore. The bar migrated landward during lake-level increases due to overwash transferring sediments from the lakeward side of the bar to the river side. A discrepancy between lake rise and bar migration occurred in 2020, when the bar began to migrate lakeward. Following the previous years the bar should have continued to migrate landward but did not and migrated lakeward. This phenomenon suggests river bluff erosion during the high lake level of 2019 added sediment to the system and counteracted landward migration. Previous research has documented enhanced erosion and sediment delivery to the nearshore zone during periods of high lake level, which aligns with our results (e.g., Meadows et al., 1997; Theuerkauf et al., 2022; Mattheus et al., 2024; Meadows et al., 1997).

During 2019, the bar area grew for the first time over the study period (2016 - 2023). Lake level migrated the bar 15 meters upriver from the western beach. Due to the bar being constrained within the river channel it closed in July of 2019 and remained closed for 108 days. Sediment can be seen in the satellite imagery accumulating on the landward side of the river mouth bar as fluvial conditions deposit sediment. Unlike in previous years, river sediment was not pushed into the nearshore zone until late October. This trapped sediment combined with the eroded sediment from the bluff resulting in the bar migrating lakeward in 2020. As lake level dropped after the peak in 2020, the bar continued to migrate lakeward, a function of the mixing zone shifting lakeward forming the bar further north. This trend continued through the end of the study. Lake level was similar in 2016 and 2023 but the bar area in 2023 was 11,132 m^2 larger, which exemplifies the nuanced role lake level plays in controlling river mouth bar morphodynamics. Lake level alone appears to not be the primary control on bar area. Rather, fluctuating lake level facilitates landward and lakeward shifts in erosion and sediment transport that are ultimately expressed in bar morphodynamics. For example, in this study, rising lake level led to enhanced river bluff erosion, which liberated sediment and forced the bar area to grow and migrate lakeward, even during a high stand.

Based on previous research and the findings of this study, lake level affects coastal features during fluctuating phases (rising - falling) (Gharib et al., 2021). During high lake levels, the small bar area results in more sediment being removed by river discharge. Low bar area enhances the likelihood of overwash, which facilitates bar migration. With higher water levels, the bar naturally forms closer to the river in response to the more proximal reduction in river jet speed due to the closer presence of wave conditions. This is exemplified in 2019 when the bar formed within the main river channel further inland than the adjacent beaches. In low lake level phases bar area is much greater requiring more energy from river discharge to displace sediment into the nearshore. During low lake level, greater wave energy is required to impact the bar as the greater width thwarts most overwash events resulting in the lakeward end being the most vulnerable to change. In general, the results from this study suggest that the Pinnebog river mouth bar is river-dominated during precipitation events and wave-dominated when precipitation is not present. The magnitude of dominance depends on the time of year and the lake level phase. As previously stated, during high lake levels the bar is easily manipulated by both fluvial and coastal processes, but as lake levels lowers the effects are reduced. Seasonally, fluvial processes dominate in the spring and summer with coastal processes dominating in fall and winter.

Fluctuation in bar area is inversely related to lake level. As lake level rose from 2016 to 2019, the bar decreased in area and fluctuated with seasonal water level changes. The bar area was the smallest during seasonal high-water levels (June-August) and increased as lake level dropped towards the annual minimum in the winter. From 2016 until 2019 the bar area was decreasing following the trend of increasing lake level. Previous studies have found that when water level rises a mix of transgression and drowning will occur (Mellett & Plater, 2018). In this study the loss of bar area exemplifies the bar drowning in response to a rapid rise in lake level. At peak lake level, the bar area began to grow and approached the magnitude of the 2016 area, despite lake level being high. This behavior is out of phase with the area response of the bar to rising lake level, but can be explained by the influx of sediment in response to river bluff erosion. After the 2020 peak lake level, the bar area grew threefold during 2021 and generally maintained this area through 2023 though there was a sharp reduction in area observed in spring of 2022 due to high discharge. As lake level lowered, the bar already contained the excess river bluff sediment, which caused the increase in 2020 but then gained access to nearshore sediments inundated during rising lake level. This process exemplifies a natural river mouth bar recovery response to rising lake level which produces a larger bar for protection of riverine ecosystems.

River bar configuration is a function of precipitation (fluvial) and wave conditions (coastal), which caused shifts in sediment position through erosion and deposition. Precipitation was highest during 2016 to 2020, which was a primary driver of rising lake level (Wilcox et al., 2002, 2007). Precipitation was found to erode the distal end of the bar and transfer sediment into the nearshore zone. This occurrence has likely become increasingly powerful due to the river becoming flashier; a result of poorly draining soils in the watershed and the construction of drains for agriculture (Miller & Simons, 1919). The Pinnebog watershed's main land use is agriculture with cultivated crops accounting for 78% of all land cover. The soil that the crops are in is 79% slow infiltration (Stroud Water Research Center, 2023). To promote increased infiltration and runoff ditches and tiling have been implemented (Miller & Simons, 1919). Studies have found that these drainage methods result in flashier streams as water travels from the fields to the streams faster (Miller & Lyon, 2021, Adelsperger et al., 2023). During multi-day or large single day rain events the rivers discharge meets the bar overtaking coastal forces and pushes bar sediment further into the nearshore, causing the bar to migrate lakeward. The river also reshapes the distal end from usually a round bulbous end to a tapered lakeward pointing end. Once sediment is within the nearshore zone, waves transport it landward and reweld it back to the bar. The angle at which the sediments are moved is based upon the trajectory of the waves. During the rainy season, a cycle of river discharge and rewelding occurs repeatedly. As fall approaches both precipitation drops, and lake level decreases allowing for bar stabilization and growth. It is during this season that wave presence overtakes river presence and welds the bar closed. Naturally with a larger more stable bar, precipitation events have a lower effect on the bar and require more energy to reopen and move sediments off the bar.

While this study advances our understanding of river mouth bar morphodynamics in large lacustrine environments, there are several important limitations to discuss. Satellite imagery can have temporal gaps due to weather conditions which can result in missing imagery associated with a precipitation or wave event. This temporal gap could introduce error in documenting bar areal changes as bar evolution may have already begun between the event and the first available image. Another limitation of the study is the reliance on hindcast and buoy wave data from offshore stations as opposed to real-time information from an in-situ sensor. No wave instruments are located at the site, so the best available data are from the hindcast record and offshore buoys. As waves approach the shore, coastal features such as headlands and nearshore bars reflect and refract wave energy. There are likely more dynamic linkages between nearshore waves and river mouth bar geomorphic behavior than what could be resolved in this study, though the primary connections between large wave events and bar migration and reworking were still captured. Another element that could not be well-constrained with satellite imagery is anthropogenic influence, as this location is highly trafficked by recreational users who can alter bar morphology. During one of the field missions for this study, recreational users of the beach were observed digging a trench of the river mouth bars eastern side, which resulted in an ephemeral breach. Situations such as this one are nearly impossible to interpret from satellite data and if visible could be misinterpreted as a natural breach. Finally, all satellite imagery has a 3m pixel size resulting in a limit to the accuracy of bar area digitization and calculation.

However, area changes documented in this study were large enough to remove user digitization discrepancy as the reason for change, but this could be a source of error for future studies that might be interested in using these methods to document smaller spatial scale variability in bar morphodynamics.

CONCLUSION

This analysis used a series of historic and recent imagery of the Pinnebog River mouth and its bars. Along with lake level, precipitation, and wave data, to characterize river mouth bar dynamics in a characteristic Great Lakes environment. It found that lake level rise results in river mouth bar migration landward while lake level fall migrated the bar lakeward. Alteration in this process is influenced by an influx of sediment into the system seen in 2019 enabling lakeward migration. During rising lake level, the bar area was reduced while falling lake level increased bar area dramatically. The general trend of precipitation induced river discharge moved the bar lakeward over short temporal periods (i.e. Days). Wave activity influence distal end trajectory and moves the bar landward over days and weeks. Overall, this study improves our understanding of how river mouth bars change during fluvial events, coastal events, seasonal lake levels and interannual lake levels. Satellite imagery provided detailed documentation of geomorphic changes to this system that could be translated into quantitative and qualitative data. The findings of this study are important for understanding river mouth bar behavior and the effect they have on sediment transport during fluctuating lake levels. Identifying the reactive nature of river mouth bars provides insight into the migration capability of these coastal features. The bar ultimately changes location in response to lake level shifting the erosive power of wave conditions, facilitating overwash and driving geomorphic change. River energy and wave energy work in tandem with lake level shifts and alter the distal end of the bar during shorter time periods The findings from this study are important for management of river mouth bars as they are very vulnerable to shifts in sediment availability. This research is a gateway to a greater understanding of river mouth bars and provides a framework that can be used in studying river mouth bars outside of the Great Lakes region.

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APPENDIX A: PRECIPITATION AND RIVER DISCHARGE GRAPH

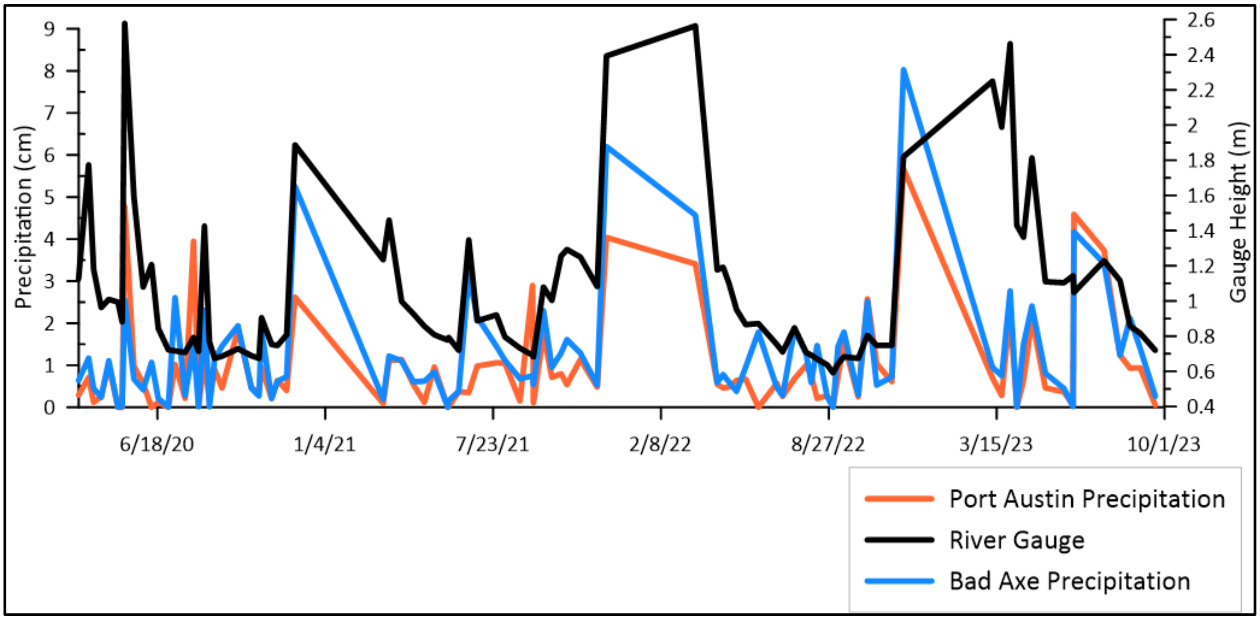

Figure 12. Precipitation data compared with river gauge data. Precipitation data from climate stations ID USC00206662 (Port Austin) (Figure 2B) and ID USC00200417 (Bad Axe) (Figure 2B) graphed with river gauge from USGS Willow Creek Station ID 041590774. Willow Creek resides in the adjacent watershed (Elk Creek watershed) to the Pinnebog watershed (Stroud Water Research Center, 2023). The graph reveals a relationship of increased precipitation causing increased river discharge. The same relationship is inferred to occur in the Pinnebog watershed.