Rapid water level rise drives unprecedented coastal habitat loss along the Great Lakes of North America

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Abstract

Lake Michigan rose to record high water levels in the 2010s; during this time, some coastal sites experienced habitat loss rates an order of magnitude higher than during previous high water periods throughout the 20th century. The high magnitude and rapid rate of rise observed during the 2012-2020 period in combination with a slight increase in the percentage of storm waves likely accelerated habitat loss rates beyond levels that were observed over the past century. Our data suggest that rapid and relatively large changes from low water levels to high water levels are the main driver of large erosional losses, as the coastal system shifts abruptly from one water-level regime to another. One likely impact of climate change on Great Lakes' water level is an increase in the variability of fluctuations, thus more scenarios of abrupt and rapid water-level rise and associated habitat loss are expected in the future. We propose that the unprecedented habitat loss observed during the 2012-2020 timeframe will become the new normal in the coming century as enhanced variability in water levels facilitates sustained coastal land loss.

Keywords:
Coastal erosion, lake level, habitat loss, Lake Michigan, hydrodynamics

Introduction

Water level is a primary driver of change in any coastal environment as it modulates the zone of influence for other physical drivers, such as waves. Along ocean and estuarine coasts, sea-level rise is the dominant water-level fluctuation that alters coastal evolution (Zhang et al., 2004; Nicholls and Cazenave, 2010); along large lacustrine shorelines, such as those in the Great Lakes region, water level fluctuates on the order of a meter approximately once a decade (Quinn, 2002; Argyilan and Forman, 2003; Sellinger et al., 2008). During low water-level phases, the shoreline and associated zone of erosion shifts basinward. Conversely, during high water levels, the zone of potential erosion shifts landward, resulting in obvious impacts to coastal habitat and infrastructure.

Erosion rates of beaches, bluffs, and other coastal habitats can be an order of magnitude higher during these periods of high water level than the average long-term rates (Meadows et al., 1997; Braun et al., 2019). The historical and geological records for the Great Lakes region document numerous such periods. For example, high water levels and associated increased coastal retreat rates occurred in the Lake Michigan-Huron basin in the 1970s, 1980s, and mid-1990s (Angel, 1995). Similarly, from 2014 to 2020, Lake Michigan rose to another high water phase after over a decade of low water levels that culminated in a record low in 2013 (Gronewold et al., 2016). High magnitude rates of erosion throughout the Lake Michigan basin have occurred during the rise to and at this recent high water phase. This study documents unprecedented vegetated coastal habitat loss and the associated driving physical processes at Illinois Beach State Park, the last remaining natural coastal area along the Illinois coastline, which is dominated by the Chicago Metropolitan region (Figure 1).

In 2019 and 2020, record high monthly water levels occurred in Lake Michigan; however, these water levels are only several centimeters higher than previous records set in the 1980s. At some sites, though, the rate and magnitude of coastal area and habitat loss experienced during the recent rise in water level is substantially higher than previous high water-level periods. This is particularly concerning for coastal landscapes that formed under specific conditions that occurred in the past as these relict landscapes will not recover once water level falls. For example, retreat of glacially-derived coastal bluffs results in permanent loss of coastal land (Buckler and Winters;1983; Jibson et al.; 1994). Similarly, erosion in response to storms and high lake levels at coastal strandplains that extend as promontories into the lake can result in habitat loss that is temporally imbalanced with the centuries to millennia the landscape took to form (Braun et al.; 2019). Loss in both of these landscapes is permanent as the processes that formed these landscapes cannot recover the losses in the relatively short windows of low water level, unlike sandy beaches, which are likely to recover at least partially after water level falls (Stockberger and Wood; 1991). Thus, it is particularly important to understand the dynamics of coastal retreat in locations where the loss is likely permanent in order to make science-based management decisions that can preserve the land.

This paper evaluates the probable drivers of increased coastal habitat loss over the last decade along Lake Michigan and uses these process-response relationships to explore how climate change may affect coastal habitat in the Great Lakes region, as well as in other large lacustrine systems that experience similar dynamics. Additionally, we examine the interplay between storms, water level, and geomorphology during this recent high water-level phase and suggest sustainable and proactive methods for conserving coastal habitat.

Methods

Study area

The three sites examined in this study are located in Illinois Beach State Park (IBSP) on the southwestern shore of Lake Michigan. IBSP is a 4,160 acre (1,664 ha) state park in Northeastern Illinois situated on the Zion Beach Ridge Plain, a ~3,700 year old curvilinear beach ridge complex (Larsen, 1985). The shoreline along the northern two-thirds of IBSP, where the three study sites are located, has historically migrated landward via coastal erosion, while the shoreline along the southern third of the park has migrated lakeward through accretion. Littoral drift along this shore is predominantly north to south, and thus the alongshore boundary between the northern erosion zone and the southern accretion zone has migrated south over the past several centuries (Chrzastowski et al., 1994). Shoreline erosion has destroyed 0.74 km^2 of vegetated coastal habitat in the northern two-thirds of the park since 1939 while shoreline aggradation has built 0.34 km^2 of habitat in the southern third of the park in that time.

Habitats within each study site vary with the ridge and swale topography of the plain (see Braun and Theuerkauf, 2021 for an in-depth discussion of these coastal habitats). Shoreline erosion has truncated ridges and exposed a variety of habitat types along the shoreface, such as wet, mesic, and dry sand prairies, freshwater marsh, and panne (Figure 1; Braun and Theuerkauf, 2021). Anthropogenic modification of the shoreline (e.g., rock revetments, breakwaters, and sheet pile walls) exist outside of the three study sites. Site 1 is located immediately south of breakwaters from North Point Marina and north of a shoreline armored with sheet pile walls. Site 2 is immediately south of a water intake structure, which is armored by a rock revetment. Site 3 is located immediately south of Site 2, though habitat type, shoreline geometry, and less anthropogenic influence at Site 3 differentiate the two sites. In the 1960s-1970s, Site 2 contained a subdivision that was abandoned due to extensive shoreline erosion and subsequently converted to prairie and savanna habitat. Site 3 also contained some development in the 20th century, though less than at Site 2. At both sites, the developed land eroded significantly in the 1970s and was completely removed by 1993. This exposed intact, high-quality habitats at these sites to shoreline processes.

Habitat maps

We mapped habitat extent over the past 80 years using two datasets: historical aerial imagery and orthomosaics and digital elevation models generated from imagery collected with a small unoccupied aerial system (sUAS, aka: drone). The historical aerial imagery was sourced from the Lake County, Illinois Planning, Building, and Development Department. These georectified images provided a decadal record of habitat change at IBSP. We used a DJI Phantom 4 Pro quadcopter with a 1-inch, 20-megapixel RGB camera to acquire orthomosaics and topography data. Surveys were flown with predetermined flight paths using the iPad application DJI Ground Control Station. The sUAS was flown nadir at 70-80 m altitude, capturing JPEG files with resolutions of 0.021 m per pixel. Image overlap was >80%. sUAS data were processed in Agisoft Metashape Professional using 10-15 ground control points surveyed with a Trimble Geo7X Centimeter Edition RTK-GPS, producing orthomosaics and digital elevation models with <5 cm vertical and horizontal accuracy. The sUAS surveys were only flown when the shoreface and habitat line were clearly visible, i.e., no shore ice or snow, as well as during low wave conditions, <0.5 m, to ensure the full shoreface was visible.

The boundaries between habitat types were sourced from the Illinois Natural Areas Inventory (INAI), a survey of natural habitats conducted by the Illinois Department of Natural Resources, Illinois Nature Preserves Commission, Illinois Endangered Species Protection Board, and the Natural Heritage Database. The most recent survey for the sites was conducted in 1976. For each historical image, we checked the INAI boundaries against the imagery to correct for obvious deviations in habitat boundaries and types. For example, the dry-mesic sand prairie/savanna along the shoreline at Site 1 converted to foredune following extensive erosion during the 1960s and 1970s. Prairie habitat at Site 2 and Site 3 was developed in the mid-1900s into a subdivision that was subsequently abandoned and reconverted to prairie. The habitat boundaries in the northern quarter of Site 1 were hand digitized following vegetation characteristics derived from aerial imagery as the INAI data did not include this portion of the site.

A base set of habitat area polygons were created for each site with a set northern, western, and southern border that was derived from the INAI data. The eastern border – the portion of the site exposed to coastal processes – was digitized for each available aerial image (Electronic Supplementary Material (ESM) Table S2) using the habitat line, which we define as the contact between bare beach (backshore or foreshore) or washover sand and vegetated coastal habitat (defined as an area with >75% vegetation cover). Since the northern, western, and southern borders were fixed, the habitat line was the only boundary that could move through time. Therefore, movement of this habitat line dictated changes in habitat area. From the habitat areas, we calculated the rate of habitat change between each survey, normalized by the alongshore length of the habitat line. We examined the record of habitat change on two scales: historical and modern. The historical scale, 1939-2020, was based primarily on the historical aerial imagery and had time-steps between surveys of 7-19 years. The modern scale, 2018-2020, was based on the sUAS data and had approximately monthly time-steps.

sUAS-derived elevation models

We used the sUAS-derived digital elevation models (DEMs) to determine the average elevation of coastal habitats immediately landward of the sandy beach at our three study sites. Shoreface habitat elevation was determined within a 3 m buffer landward of the habitat line. The average elevation of each habitat type within that buffer was calculated for the duration of the sUAS dataset, July 2018 – March 2020. We examined this elevation data through time to track how shoreface habitat elevation interacts with coastal processes to drive habitat loss.

Hydrodynamic data

Water levels and wave heights over the 81-year record (1939-2020) were evaluated to determine what hydrodynamic processes were associated with coastal habitat loss. Both datasets were generated using publicly available data from the National Oceanic and Atmospheric Administration (NOAA) and the United States Army Corp of Engineers (USACE). Data were compiled into spreadsheets and then summary statistics were generated for time bins that correspond with the change analyses.

Water-level data from Calumet Harbor IL (Station ID 9087044), the closest long-term station to IBSP, were downloaded from the NOAA Tides and Currents database. Monthly water-level data were downloaded from August 1939 through March 2020. These data were originally vertically referenced to IGLD85, but were converted to NAVD88 to align with the topography data. To convert the data from IGLD85 to NAVD88 0.1609 m was added to each measurement based on a conversion factor provided by the National Geodetic Survey.

A variety of analyses were performed on the water-level data to evaluate conditions during the time bins. First, percentages of monthly water-level observations above the long-term Lake Michigan average (176.606 m NAVD88) were determined for each long-term time step. This metric gives a general sense of whether water level was high or low during this period, but does not provide any detail on the nature of the water-level change. The other metrics that were calculated aim to describe the character of the rise to the maximum water level for a specific time step. Because we are examining large time periods for the long-term record (between available aerial image sets), we have to make assumptions about when any habitat change occurred. In this study, we assume any habitat changes associated with water level change will be related to the peak water level during a given time step. Therefore, we only generate metrics related to the rise to the maximum because presumably this would be the point of greatest coastal impacts (i.e., shoreline is moving towards its most landward position). Any water-level positions lower than that peak should generate less impacts or could potentially even stabilize the shoreline. The metrics used to characterize the rise to the maximum water level during a given time step include: (1) the water-level difference between the peak water level and the minimum level prior to the peak**;** (2) the length of time to achieve this rise; and (3) rate of this rise (see Figure 2; ESM Table S1).

A record of onshore storm wave events (i.e., wave heights greater than 2 m with an east directional component) was created from 1960 to 2020 using a combination of data sources. The USACE Wave Information Studies (WIS) hindcast data (Station 94033) were used to document storm events from 1960 through 2018. From 1960 to 2014, storm event details (duration above 2 m, peak wave height, and peak wave direction) were downloaded from the WIS database. For the period from 2014-2018 storm event details were generated using the complete wave hindcast record provided to the researchers by the USACE. A combination of wave buoy data and model data from the Great Lakes Environmental Research Laboratory (GLERL) were used to document the storm events during the period from January 2019 through March 2020 when there were no WIS hindcast data available. Data from the Waukegan Harbor wave buoy (NDBC Station ID 45186) were downloaded for the period from April 18, 2019 through November 13, 2019. GLERL Nowcast model data were used for the rest of this time period (January 1, 2019-April 18, 2019 and November 13, 2019-March 11, 2020). Using the complete storm event data generated for the period from 1960 through 2020, the percent of time in each long-term time step where wave observations were above 2 m was calculated. Additionally, the average peak wave height for the storms during each time step was calculated.

Basin-wide analysis

We analyzed elevation data and imagery from the Lake Michigan basin to test whether the coastal habitat vulnerability characteristics we identified at IBSP could be applied to the entire region. The NOAA CUSP shoreline was used to clip the 2012 USACE Great Lakes Topobathy LIDAR data to the Lake Michigan shoreline with a 50 m wide inland buffer. The majority of the NOAA CUSP shoreline was digitized in 2010-2011 (86%), nearly concurrent with the USACE LIDAR survey in 2012, which is the only available LIDAR survey for the entire basin. Half of the remaining shoreline (7%) was digitized in 2017, though this section of the shoreline in southeastern Wisconsin is primarily bluff and visual inspection of the 2017 shoreline on 2010-2012 imagery shows little divergence. The other remaining shoreline was digitized in the early 1990s (3%) and in 2008 (4%) in northwestern Michigan; visual inspection again shows little divergence in shoreline location.

The average elevation within 1 km square grids intersecting the shoreline was determined. Only portions of shoreline denoted as ‘natural’ in the CUSP data were included in analysis (i.e., harbors, revetments, hardened shorelines etc. were excluded). Then, grids were binned according to average elevation. Vulnerable grids were defined as having an average elevation less than 178 m NAVD88. This threshold was chosen to include all elevations susceptible to non-storm waves (<2 m) relative to the water level at the time of LIDAR collection (176.09 m). Mid-elevation grids were defined as 178-180 m NAVD88, with the highest bin including all grids with >180 m average elevation.

We used these 1 km shoreline grids to test whether nearshore elevation predicts habitat vulnerability across the Lake Michigan basin. Thirty sites were randomly chosen. Though CUSP data denoted these sites as 'natural,' all sites were visually inspected to ensure that <20% of the shoreline was hardened. Sites with >20% visible shoreline hardening or nearshore roads controlling shoreline geometry were discarded and replacement sites were randomly selected. Georectified imagery was sourced from the NOAA Data Access Viewer from 2010-2011 and 2018-2019 (ESM Table S2). The habitat line at each site was digitized and used to determine the amount of habitat change at each site during the most recent rise in water level (2011-2019). All land inland of the habitat line within the grid cell was defined as coastal habitat, and the habitat change rate was calculated from the change in area, the alongshore length of the habitat line, and the time-step.

Results and interpretations

Between 1939 and 2020, 0.4 square kilometers of habitat were lost from three study sites covering in total 2.3 km of shoreline at IBSP along southwestern Lake Michigan (Figure 1). The greatest long-term habitat change rate over the past 81 years was documented during the period from 2012-2020 (Figure 2c). Around 8.8 m of coastal habitat was lost per year per meter of alongshore length during this timeframe at all of the IBSP sites combined. This resulted in 0.15 km^2 of habitat lost to erosion and burial by overwash between 2012 and 2020. Overwash is the process where sand is transported landward from the beach and deposited. Sometimes this washover deposit can result in the loss of coastal vegetated habitat via burial as described here, but if the washover is thin it can promote vegetation growth and elevation gain. The habitat loss documented between 2012 and 2020 is 1.6 times greater than the period with the second greatest loss, 1961-1974, despite the 2012-2020 period being 5.5 years shorter. The second largest change rate during the study period was -2.4 m/yr, which occurred during the period from 1961-1974. During the period 1974-1993, which contained a period of elevated water level during the late 1980s and the all-time record high monthly water level in October 1986, the change rate was -1.6 m/yr. The change rates for the periods 1946-1961, 1939-1946, and 2000-2012 were -1.3 m/yr, -0.8 m/yr, and -0.7 m/yr, respectively. The lowest habitat change rate was recorded from 1993-2000 and was -0.004 m/yr, which should be considered no change. It is important to note that these data are for all of the sites at IBSP combined together and suggest only coastal habitat loss during the last 81 years. When individual sites are examined, there are specific time periods and sites where gain of coastal habitat occurs; for example, habitat grew lakeward in the northern end of IBSP when water level was low from 2000-2012 (ESM Table S1). Alternatively, there are sites and periods where the rate of habitat change was substantially higher than the all-sites combined rate, such as the loss at Site 2 during the period from 2012-2020. Given the spatial variability, the all-sites combined data give the best representation of the regional coastal habitat response to hydrodynamic forcing.

A variety of metrics were used to capture the dynamics of water-level variability over the period of record (ESM Table S1). The most basic metric is the percent of water-level observations (monthly averages) above the all-time Lake Michigan average (176.606 m NAVD88). Eighty-seven percent of the water-level observations during the period of 1974-1993 were above average. The periods of 2012-2020 and 1993-2000 both had around 73% of observations above average. The years 1939-1946, 1946-1961, and 1961-1974 all had nearly equal above- and below-average observations (43%, 48%, and 46% respectively). The lowest percentage of water-level observations above average was 2000-2012, which was ~3%.

The next several metrics used to capture water-level variability focus on the rise in water level to the maximum of each observation period. These metrics include: (1) the water-level difference between the maximum and the minimum just before maximum; (2) the length of time to achieve this rise; and (3) the rate of this rise (Figure 2a). The greatest differences between minimum and maximum water levels occurred from 2012-2020 (1.867 m) and 1961-1974 (1.731 m). The periods of 1946-1961 (1.387 m) and 1974-1993 (1.141 m) had the next highest differences. 1939-1946 (0.866 m), 1993-2000 (0.821 m), and 2000-2012 (0.8 m) all had differences less than 1 m. The length of time to achieve the measured rise varied over the different periods. Generally, the most rapid rises were associated with the lower magnitude rises, with the exception of 1946-1961. The rises during the periods 1939-1946, 1993-2000, and 2000-2012 all took less than 2 years (1.9 yrs, 1.5 yrs, and 1.4 years, respectively). The rise during the period from 1946-1961 took slightly more time (2.67 years) but was associated with a higher difference between maximum and minimum. The longest rise (10.4 years) was associated with the 1961-1974 period. The next longest rise was 9.7 years and was associated with the 1974-1993 period. The rise associated with the period of greatest magnitude difference between minimum and maximum, 2012-2020, was 6.5 years. Consequently, this rise resulted in the highest rise rate for the three periods with the greatest habitat change rates (2012-2020, 1961-1974, and 1974-1993). The rate of rise for the 2012-2020 period was 0.29 m/yr, which was double the rate for the other two large habitat loss periods (Figure 2a). Rise rates for the second (1961-1974) and third (1974-

1993) highest habitat change rate periods were 0.17 m/yr and 0.11m/yr, respectively (Figure 2a). Other periods in this study all had similar rates of water-level rise, which were around 0.5 m/yr (Figure 2a).

Percent of storm waves (defined as wave heights greater than 2 m; (Hubertz 1992)) varied slightly throughout the 81-year record, though the average peak wave height did not vary considerably (Figure 2b). The highest percentage of wave heights above 2 m occurred during the periods 2012-2020, 1974-1993, and 1993-2000 (Figure 2b). The highest percentage of waves above 2 m (0.99%) occurred during the period of 2012-2020; this period had the highest rate of habitat change, the highest rate of rise for all periods with high habitat change rates, and the second highest percentage of water-level observations above average (Figure 2). The next highest percentage of storm waves (0.79%) occurred during the period from 1974-1993. Percent of storm waves were actually lowest during the period with the second highest habitat change rate (1961-1974), which also had the second highest difference between minimum and maximum water level. The 3rd and 4th highest percentages of storm waves occurred during the periods 1993-2000 and 2000-2012, which were a period of higher water level and lower water level, respectively. During periods of elevated water level, the interplay between water level, storm waves, and geomorphology becomes critically important. High-resolution data from 18 months (July 2018 through March 2020) revealed the spatial and temporal dynamics of habitat loss under high water-level conditions (Figure 3).

In total, 0.06 km^2 of habitat were lost between July 24, 2018 and March 11, 2020. Half of this loss (0.03 km^2) occurred during a single time period, between January 6, 2020 and March 11,

2020. It is important to note that excluding this high-loss period from the long-term (decadal) record still results in the 2012-2020 period having an unprecedentedly high habitat change rate of -7.1 m/yr. The habitat area change rate for all three sites from 2018-2020 is -8.4 m/yr (Figure 3). The time-steps with greater than average habitat change rates are: August 31, 2018 to September 11, 2018 (-11.7 m/yr); October 24, 2018 to November 5, 2018 (-9.5 m/yr); November 5, 2018 to December 18, 2018 (-11.7 m/yr); March 28, 2019 to April 25, 2019 (-14.8 m/yr); October 7, 2019 to December 5, 2019 (-19.3 m/yr); and January 6, 2019 to March 11, 2020 (-42.0 m/yr). The habitat change rate was positive twice, both during the vegetation growing season: April 25, 2019 to June 16, 2019 (+1.3 m/yr) and July 10-26, 2019 (+1.1 m/yr).

The greatest negative rates of habitat change are associated with large wave events occurring when shoreface elevation is lower and closer to water level, thereby increasing the vulnerability of coastal habitats to erosion and burial by overwash (Figure 3). The range of average shoreface elevation between 2018 and 2020 was 0.86 m at Site 1, 0.41 m at Site 2, and 0.48 m at Site 3.

At Site 1, the average shoreface elevation decreased 0.61 m from an initial high in September 2018 to a low of 178.6 m NAVD88 in December 2018, which persisted through April 2019 (Figure 3). Average elevation then rose 0.65 m to a high in July 2019, then fell to a low of 178.4 m NAVD88 in March 2020. The increase in shoreface habitat elevation in the summer of 2019 corresponded with the only expansion in habitat area recorded at this site. The summer 2019 gain in elevation and habitat at Site 1 was lost at the onset of the fall storm season. The greatest habitat change rate at Site 1 occurred during the period with the lowest average shoreface elevation: January 6 to March 11, 2020.

The average shoreface elevation was highest at Site 2 on August 31, 2018 (178.7 m NAVD88) and on August 30, 2019 (178.75 m NAVD88); shoreface elevation was lowest on January 18, 2019 at 178.35 m NAVD88 (Figure 3). Elevation at this site had the smallest range and corresponded less to the habitat change rate. As shoreline erosion and overwash burial continued at this site, the habitat line approached an access road running parallel to shore in the spring and summer of 2019. The rise in average elevation between April and August 2019 is due to the habitat line moving landward towards the higher-elevation road. The peak in elevation in August 2019 coincides with a sand nourishment project at this site, conducted between August and October 2019. The introduction of nourishment sand contributed to the loss of habitat moving forward, as excess sand overwashed onto habitat landward of the access road and buried it. The habitat line after August 2019 continued migrating landward of the road into the lower elevation habitats behind it.

At Site 3, the average shoreface elevation peaked at 178.7 m NAVD88 on August 30, 2019 (Figure 3). The wetland (panne) elevation at Site 3 lowered in the winter of 2018/2019 and spring of 2019 as the habitat line migrated landward over the wetland. Then, the elevation rose in the summer of 2019 towards a peak elevation on August 30, 2019 as the wetland depression filled with washover sand and the habitat line approached the landward edge of this depression. This gain in elevation was accompanied by a small gain in habitat area as vegetation was able to colonize beach and washover sand. While the average elevation was increasing in the summer of 2019, the foredune elevation declined dramatically on July 26, 2019 as erosion began to scour the lakeward edge of the foredunes. The habitat line then moved several meters landward after

July 2019 as the foredune habitat continued to erode. The final remnant of foredune habitat was completely removed during the storm in January 2020. While the lowest average elevation was achieved on January 18, 2019 (178.24 m NAVD88), the greatest loss in habitat occurred between January and March 2020. During the January and March 2020 period, the average shoreface elevation was 178.51 m NAVD88. This elevation, however, was actually 0.15 m closer to water level than the elevation in January 2019 because water levels remained high during the winter of 2020.

The results from our study along southwestern Lake Michigan suggest that the elevation of coastal habitat in the Great Lakes strongly controls vulnerability to coastal habitat loss. Given this finding, we applied the elevation control concept to the entire Lake Michigan basin to (1) test whether the relationship between habitat elevation and loss is consistent throughout the basin and (2) identify habitats at high risk for erosional loss throughout the basin. This basin-wide analysis shows that habitat loss throughout Lake Michigan during the most recent rise in water level, measured with data from 2010-2011 and 2018-2019, is clearly linked to average coastal habitat elevation (Figure 4).

We determined that 30.5% of the natural shoreline of Lake Michigan is at high risk of habitat loss, defined as having an average elevation below 178 m NAVD88. These high-risk sites on average had a habitat change rate for the most recent rise in water level (2010-2019) that was 3.1 times higher than >178 m NAVD88 sites. The high-risk sites' habitat change rate averaged -4.6 m/yr, while >178 m NAVD88 sites averaged -1.5 m/yr. Based on these results, we classified the shorelines of Lake Michigan into low, mid, and high elevation bins of <178, 178-180, and >180 m NAVD88. While lower elevation sites experienced the greatest loss of habitat, higher elevation sites were not immune to habitat loss. Only 4 out of the 30 randomly selected sample sites gained habitat area; habitat gained at those four sites was an order of magnitude lower than habitat losses at the other 26 sites (Figure 4). The average habitat change rate for all sites was -2.7 m/yr.

Discussion

The long-term habitat change record indicates that the period from 2012-2020 experienced an order of magnitude higher rate of habitat loss than any other period over the past 81 years. Monthly water levels during this period did not exceed the previous records set in the 1980s by a substantial amount nor did they break the all-time record high level set in October of 1986. Given this, one of the primary questions we aimed to evaluate with our dataset is why were habitat change rates so high during this period in comparison to the other periods? Anthropogenic causes, while certainly a factor in local habitat loss, were not likely a major driver of change across this study area as most of the area remains relatively natural. The interaction between water level and waves is ultimately responsible for driving coastal change as numerous studies throughout the Great Lakes and beyond have indicated (Davis, 1976; Meadows et al., 1997; Ruggiero et al., 1997; Theuerkauf et al., 2019). Thus, there must have been something different about this interaction during the period from 2012-2020 than the previous decades.

The hydrodynamic dataset revealed substantial variability in the metrics of water level and wave conditions across the observed periods from 1939-2020. Periods with increased storm wave duration were associated with the highest percentages of water-level observations above average (2012-2020, 1974-1993, and 1993-2000). This is similar to the pattern observed by Meadows et al. (1997), which documented an increase in wave energy associated with the 1980s high water levels. Despite wave energy being elevated during the period from 2012-2020, the increase alone is not likely to account for the 5.5 times greater habitat change rates during this period.

Given that the highest percentage of water-level observations above the long-term average was recorded during the 1974-1993 period, yet the greatest habitat change rate and greatest magnitude of habitat loss was observed from 2012-2020, the duration of high water alone also cannot explain the increased erosion. The 2012-2020 period had the greatest difference between minimum and maximum water levels and the greatest rate of rise for the three periods with the highest rates of habitat change (2012-2020, 1974-1993, and 1961-1974). In fact, the rate of water-level rise during this period was double the rate for the other two periods. The high magnitude and rapid rate of rise observed during the 2012-2020 period in combination with the increased percentage of storm waves likely accelerated habitat change rates beyond levels that have ever been observed over the past century. Previous research by Thompson and Baedke (1995) indicate that accelerated habitat loss during rapid water level rise should be expected given the balance between creation of new accommodation space and the existing sediment supply. Additionally, it is worth mentioning that the impacts of high-water level and storms accumulate through time, thus it is plausible that some portion of the enhanced habitat loss observed during the most recent high lake level phase could be related to changes to the coastal system initiated during previous high lake phases. However, the long-period of coastal recovery recorded during low lake levels of the 2000s suggest this is not as likely as the explanation provided by our data that the rate of lake level rise is responsible for unprecedented rates of vegetated coastal habitat loss.

The second highest habitat change rate period documented in this study was between 1961-1974, which had the second highest magnitude of difference between maximum water level and the prior minimum water level, but the longest rise to the maximum and therefore a lower rate of water-level rise. Interestingly, this period experienced a lower percentage of total water-level observations above the long-term average than the other periods with high habitat change rates and also had the lowest percentage of storm waves of all the periods in this study. The primary facilitator of the high rates of habitat change during this period was likely the high magnitude transition from low levels to high levels over the course of the decade. This differs from the 2012-2020 period in that the rate of rise was slower and the wave energy was lower, which likely explains the lower rate of habitat change. The 1961-1974 period also contrasts with the 1974-1993 period, which had the highest number of water-level observations above the long-term average. This indicates that the water levels were high throughout most of the period from 1974-1993 and that there was not a large change from low to high despite record high water levels being achieved. Our data suggest that rapid and high magnitude changes from low water levels to high water levels are the main driver of large habitat losses via erosion and overwash burial, as the coastal system is shifted abruptly from one water-level regime to another. The habitat loss occurs when the system is out of equilibrium, thus just merely having high water levels would not drive a major increase in erosion. The water-level change must be of high magnitude (1961-

1974 and 2012-2020) or associated with an increase in wave energy (1974-1993 and 2012-2020) to drive high rates of erosion and habitat loss.

Interestingly, we observed relatively low habitat change rates for the entire study region during the period from 1993-2000 despite water levels being high and an increased percentage of storm waves. This was driven by positive habitat change rates (i.e., habitat growth) at Site 1 during this period; the other two sites experienced habitat loss (Site 2) or neutral change (Site 3) during this time (ESM Figure S1). Habitat growth at Site 1 occurred in response to an influx of sediment from the construction of a marina just north of the site in the late 1980s (see marina on left of Figure 1b). That influx of sediment overwhelmed the erosional response and helped to stabilize the area, allowing for foredune vegetation to colonize the higher elevations of the coastal profile. This vegetation led to further foredune growth until the sand supply from the construction of the marina was likely exhausted in the early 2000s. At this time, the foredune habitat area began to decline even though water levels were low throughout this period.

The documented coastal responses to high magnitude and rapid fluctuations in water level also provides insight into how sandy ocean and estuarine shorelines might respond to abrupt sea-level rise. A period like 1974-1993 with a relatively slow rate of water-level rise would be more analogous to a slow and continuous rise in sea level, similar to what is predicted along most oceanic and estuarine coasts for the next 100 years (Douglas, 1991; Rahmstorf, 2007). During the period from 1974-1993, water-level rise in combination with storm waves were generating erosion and habitat loss, but at a slower rate relative to other periods with more rapid rates of water-level rise. This is presumably because the coastal system is able to continuously adjust to the lower magnitude water-level increases. This contrasts sharply to rates of water-level rise during periods such as 2012-2020, which were nearly double the rate of that in 1974-1993. The rapid and high magnitude change in water level overwhelms the coastal system and forces transgression. This would be analogous to a period of rapid sea-level rise and supports the notion that a given shoreline reach likely has a threshold rate and magnitude of water-level rise that it can keep pace with (Timmons et al., 2010; FitzGerald et al., 2018). Beyond this rate and magnitude, erosion and habitat loss will ensue in an effort to reach a new dynamic equilibrium with the conditions. This may be achieved in oceanic and estuarine settings as sea-level rise is continuous and is an order of magnitude smaller that water-level fluctuations in the Great Lakes (Cazenave et al., 2014; Chen et al., 2017), allowing for the coastal system to reach a quasi-equilibrium. However, in the Great Lakes region, water-level fluctuations are not continuous (Hanrahan et al., 2010), thus this dynamic equilibrium state is rarely achieved. A period of water-level rise is followed by a period of decline and then eventual rise again. Our results suggest that the variability in timing and magnitude of these fluctuations clearly drives erosion and habitat loss, which has important implications for future coastal evolution in the Great Lakes region in response to climate change.

In contrast to ocean and estuarine shorelines where climate change is driving sea-level rise, climate change in the Great Lakes will likely increase the variability of water-level fluctuations (Notaro et al., 2015; Gronewold and Rood, 2019). Climate change, therefore, is likely to generate more scenarios similar to what occurred during 2012-2020 where water levels fluctuate rapidly from low to high and vice versa. This in turn will drive high rates of coastal erosion and associated habitat loss as was observed in this study. We propose that the unprecedented habitat loss observed during the 2012-2020 timeframe will become the new normal in the coming century as enhanced variability in water levels facilitates sustained erosion and coastal land loss. Adding to the difficulty associated with rapid coastal change is the fact that the primary phenomenon driving the change, fluctuating water level, is inherently unpredictable beyond a year (Coulibaly, 2010). This uncertainty makes it difficult to plan for future coastal conditions beyond a range of probable scenarios.

As habitat loss comparable to the 2012-2020 period may become more frequent in coming decades, it is vital to understand the interactions between different processes and factors controlling habitat loss over short time-scales relevant to coastal management. Our high-resolution sUAS data from 2018-2020 reveal that local habitat elevation plays a critical role in the ultimate vulnerability of a site. Loss is most likely to occur during storm events when the elevation of habitat along the shoreface is low relative to water level, such as during the most destructive stormy period of the record, from January 6 to March 11, 2020. Subtle increases in coastal habitat elevation, resulting from both cross-shore and alongshore sediment transport, can protect the landscape from further loss, as exemplified by the submeter gain in elevation and associated habitat growth during the summer of 2019 at Site 1. This accumulation of sediment resulted from vegetation colonizing recently deposited beach and washover sand, which trapped sand and raised the average habitat elevation. The higher elevation habitat buffered the site from further erosion during the seasonal high water level of 2019, which contrasts with Site 2, where no gain in elevation occurred resulting in sustained habitat loss. The sensitivity of coastal habitat to alongshore and cross-shore variations in elevation, which are a function of sediment transport and supply, suggests that management actions that conserve or restore high elevation coastal features such as ridges or berms are critical for protecting low-elevation habitats such as wetlands.

Based on these results, we identified an elevation threshold for coastal habitat vulnerability throughout the Lake Michigan basin: sites with average shoreface elevations below 178 m NAVD88 were at the greatest risk for coastal habitat loss between 2010 and 2019 (Figure 4). This threshold elevation includes all sites that would be inundated under non-storm waves (<2 m) relative to water level at the beginning of the study period (~176 m NAVD88). Our detailed examination of 30 study sites throughout the entire Lake Michigan basin, spanning a range of landform types from sandy beaches to bluffs to dunes, confirmed that low elevation sites have experienced the highest magnitude habitat loss over the most recent rise in water level. Sites with higher average elevations, however, are not guaranteed protection from habitat loss, as the steady rates of loss for higher elevation sites shows. Higher elevation sites are still at risk as elevated wave base during periods of water-level rise facilitates erosion at the base of higher elevation landforms, such as dunes and bluffs.

Coastal habitat vulnerability is clearly a function of the difference between habitat elevation and water level. The vulnerability threshold will thus fluctuate through time as water levels rise and fall. For the Lake Michigan region, we propose a 2 m window of risk, set relative to the most recent decadal water-level low. This window of risk identifies probable sites where habitat loss is most likely to occur in response to rapid or high magnitude shifts in water level. Our approach of defining a simple elevation threshold and associated risk window where coastal habitat is vulnerable can be updated easily with new coastal elevation and water level data as it becomes available and can be easily extrapolated to other coastal sites. While this method does not take into account more complicated variables that mediate coastal response, such as the rate of sediment supply, it does provide a framework for land managers and stakeholders to identify vulnerable coastal areas through time, particularly in settings like the Great Lakes where predictions of future water levels are difficult.

Conclusion

Over the past century, the greatest losses of coastal habitat along the shores of Lake Michigan occurred when water level rapidly rises over a prolonged period in concert with greater storm wave energy. From 2018-2020, a period of record high water level, the bulk of habitat loss was associated with storm events. Coastal habitat was most vulnerable to erosion from these storms when habitat elevation was low relative to water level. Our results indicate that coastal habitat loss could be combatted by ensuring that coastal elevation is at least 2 m higher than projected water levels. Coastal managers can leverage this elevation control on habitat loss to identify areas at risk of erosion and put in place targeted management strategies in response to specific events such as storms or seasonal water-level rises to reduce a site’s vulnerability to coastal erosion and habitat loss.

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Author contributions

E.T. procured the funding, designed the study, conducted hydrodynamic data processing and analysis, and supervised all other data processing and analyses. K.B. created habitat maps and conducted basin-wide habitat change analysis. E.T. and K.B. jointly performed field work, analyzed data, and wrote the manuscript.

Figure Captions

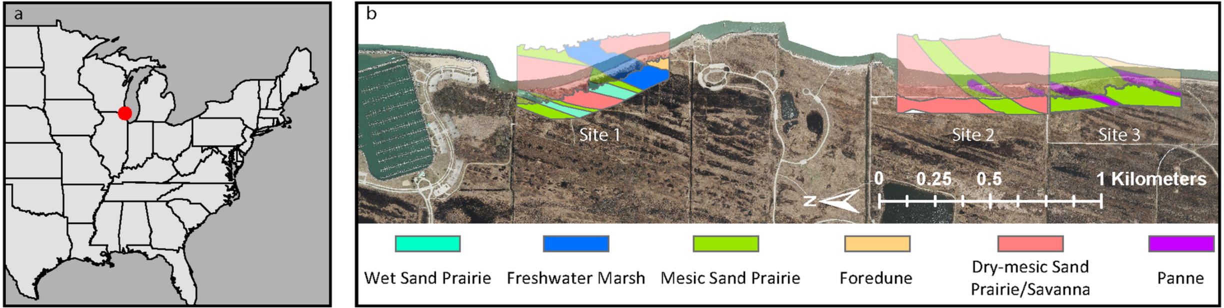
Figure 1 a: Study-area map denoting location of Illinois Beach State Park with a red dot on the southwestern shore of Lake Michigan, USA. Base map sourced from ESRI. b: Aerial photograph from 2018 of the three study sites at Illinois Beach State Park. Transparent habitat areas indicate the extent of coastal habitat in 1939, aerial image (sourced from the Lake County, Illinois Planning, Building, and Development Department) shows habitat in 2017, opaque habitat areas are extent on March 11, 2020.

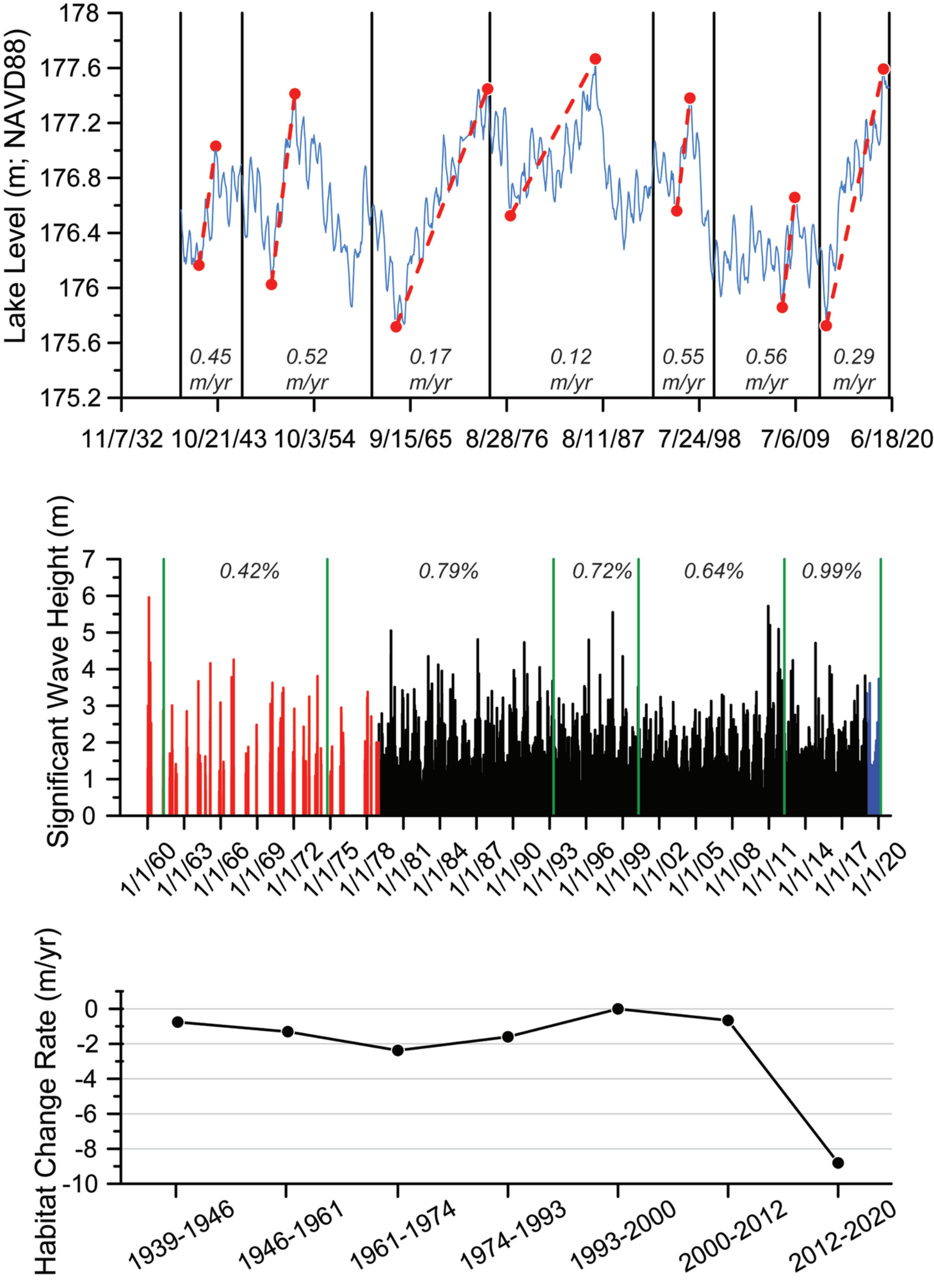
Figure 2 (top panel) Hydrograph of data from the NOAA Calumet Harbor station from 1939 to 2020 (solid blue line). Dashed red line denotes the rise to the maximum water level during each time period examined in this study. The rate of water-level rise is annotated in each time bin. The black lines indicate the time bins defined by habitat area data generated in this study. middle panel Plot of significant wave height data for the period from 1960 through 2020. Red line data are from the USACE WIS Hindcast Storms Only Database; Black line data are the entire WIS hindcast data available; Blue line data are a combination of NOAA buoy (Waukegan Harbor) and GLERL Nowcast data. Percentages of wave heights above the storm threshold (2 m) are denoted in italics. The green vertical bars indicate the time periods of habitat area data. (bottom panel) Line graph of long-term habitat loss rate data generated from the analyses conducted in this study.

Figure 3 a, b, c: Line graphs showing the elevation of shoreface habitat (dashed colored lines) and Lake Michigan water level (solid gray line), at Sites 1, 2 and 3 respectively. d, e, f: Trellis graphs of short-term habitat change rates for each habitat type and all habitats combined at Sites

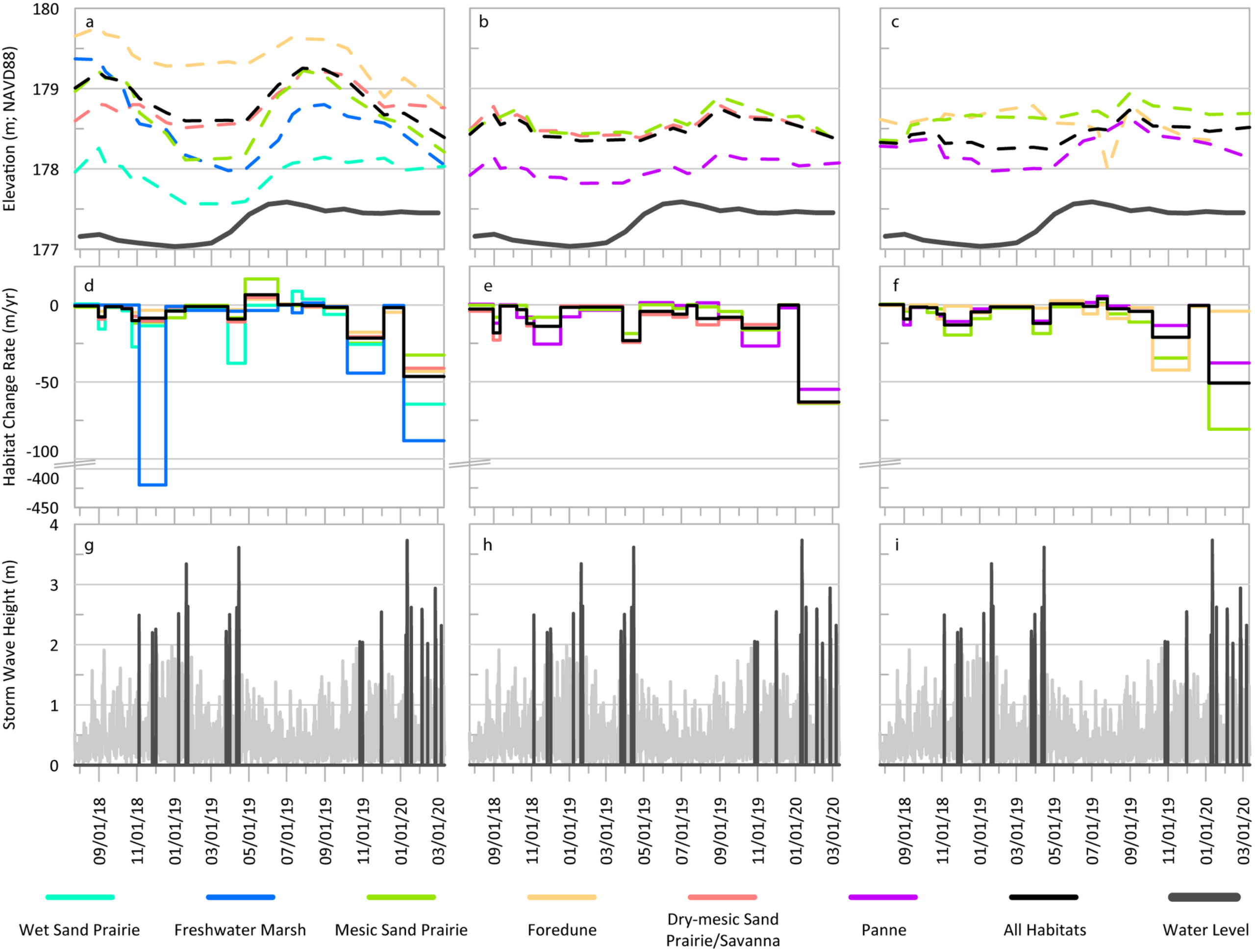
1, 2, and 3 respectively. g, h, i: Time series plot of wave data for the period of study (light gray bars), with storm waves (>2 m) highlighted with dark gray bars.

Figure 4 a: Scatterplot showing habitat change rates at thirty study sites before and after the most recent water-level rise in the Lake Michigan basin (data from 2010-2011 and 2018-2019). Colors match elevation classification in b. b: Map of shoreline elevation classification for the entire basin. The thirty sites examined in detail for habitat area changes associated with water level rise are circled. Yellow colors denote sites that are currently vulnerable to high water levels, green denote sites that could become vulnerable if water level rises beyond 2020 levels, and blue denotes sites that are generally at a high elevation and not vulnerable to erosional loss. Base map sourced from ESRI.

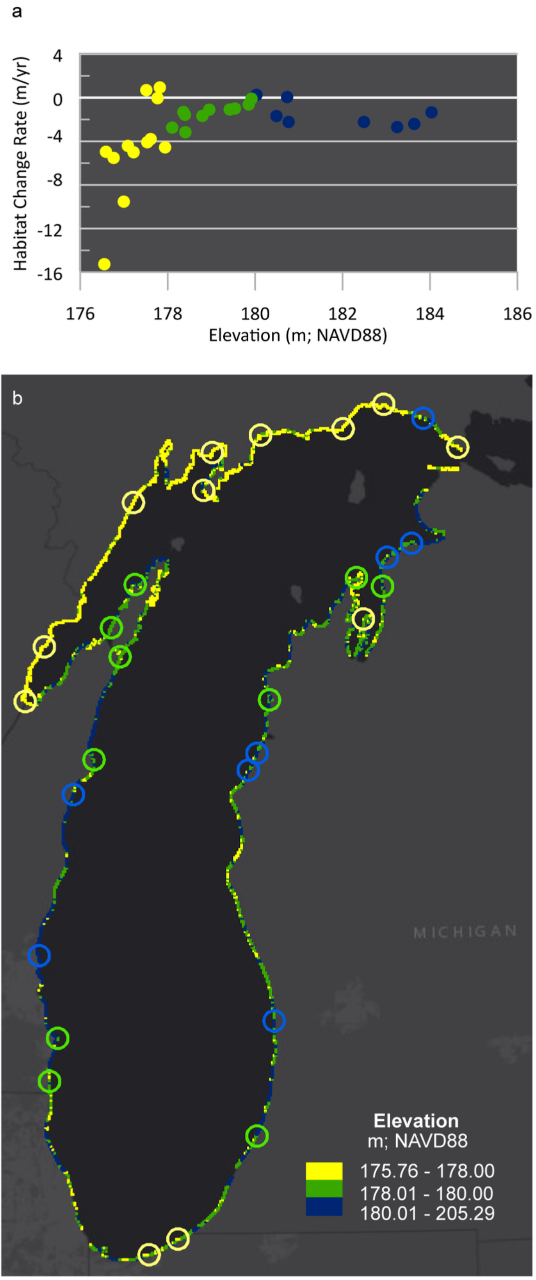

a
b
Site 1
Site 2
Site 3
0
0.25
0.5
1 Kilometers
N
Wet Sand Prairie
Freshwater Marsh
Mesic Sand Prairie
Foredune
Dry-mesic Sand Prairie/Savanna
Panne



Lake Level (m; NAVD88)
0.45 m/yr
0.52 m/yr
0.17 m/yr
0.12 m/yr
0.55 m/yr
0.56 m/yr
0.29 m/yr
11/7/32
10/21/43
10/3/54
9/15/65
8/28/76
8/11/87
7/24/98
7/6/09
6/18/20
Significant Wave Height (m)
0.42%
0.79%
0.72%
0.64%
0.99%
1/1/60
1/1/63
1/1/66
1/1/69
1/1/72
1/1/75
1/1/78
1/1/81
1/1/84
1/1/87
1/1/90
1/1/93
1/1/96
1/1/99
1/1/02
1/1/05
1/1/08
1/1/11
1/1/14
1/1/17
1/1/20
Habitat Change Rate (m/yr)
1939-1946
1946-1961
1961-1974
1974-1993
1993-2000
2000-2012
2012-2020



a
b
c
d
e
f
g
h
i
Elevation (m; NAVD88)
180
179
178
177
Habitat Change Rate (m/yr)
0
-50
-100
-400
-450
Storm Wave Height (m)
4
3
2
1
0
09/01/18
11/01/18
01/01/19
03/01/19
05/01/19
07/01/19
09/01/19
11/01/19
01/01/20
03/01/20
Wet Sand Prairie
Freshwater Marsh
Mesic Sand Prairie
Foredune
Dry-mesic Sand Prairie/Savanna
Panne
All Habitats
Water Level


a
Habitat Change Rate (m/yr)
4
0
-4
-8
-12
-16
176
178
180
182
184
186
Elevation (m; NAVD88)
b
MICHIGAN
Elevation
m; NAVD88
175.76 - 178.00
178.01 - 180.00
180.01 - 205.29