Rapid lake Michigan shoreline changes revealed by UAV LiDAR surveys

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ABSTRACT

The recent record-breaking Laurentian Great Lakes water levels have led to severe erosion along many shorelines, but quantification of this erosion has not yet been widely reported. In this paper, novel shoreline measurements of Lake Michigan erosion, using a LiDAR-equipped unmanned aerial vehicle (UAV). The vehicle surveyed two beaches, Dune Acres and Beverly Shores, along the Indiana shoreline of southern Lake Michigan over the period 2018–2019, which are compared to existing aircraft-based LiDAR surveys. The UAV surveys reveal extensive shoreline erosion and recession at both beaches since the low water conditions of 2012–2013, with both beaches losing 70.7 and 64.8 m²/m of dry beach volume. Shoreline recession over this period was nearly 35 m for both beaches. In the period 2018–2019, the UAV measurements reveal continued beach erosion and the transition of beach topography to a steep, actively eroding foredune. Storm erosion resolved by short-interval surveys highlights the episodic nature of shoreline erosion, with 8 m³/m of material lost over a stormy two-week period at Dune Acres. While large, the erosion and recession observed at both beaches is in keeping with limited historical observations of shoreline change during high water episodes. However, the observed overall shoreline recession slopes of 1:29 (water level rise : recession) are much less than historical slopes, suggesting that the beaches are not yet in equilibrium with the high water levels and that erosion will continue in the foreseeable future while lake levels remain high.

1. Introduction

After a prolonged period of lower-than-average water levels, the Laurentian Great Lakes recently experienced record high water levels due to excess basin precipitation, and these high water levels are causing rapid coastal erosion that is causing extensive shoreline damage in coastal communities. Lake levels are particularly high in Lake Michigan after a period of rapid increase (Fig. 1). Lake Michigan-Huron monthly water levels, which are tracked together because of the lakes’ connection, rose nearly 2 m from an all-time record low monthly value of 175.57 m (IGLD datum) in January 2013 to a near record high monthly value of 177.46 m in July 2020. In seven years, the lake has risen 1.89 m, essentially experiencing the full range of water levels that have been recorded since 1918 (1.93 m; United States Army Corps of Engineers, 2020). For reference, the average annual lake level fluctuation in monthly-averaged water levels for Lake Michigan-Huron is 30 cm.

With lake levels now persistently high even through the fall and winter, storms have had much more potential to erode shorelines as storm wave energy is allowed to reach erodible dunes and bluffs. Communities in the states of Wisconsin, Indiana, and Michigan have all reported extensive shoreline erosion that has damaged beaches, homes, and coastal infrastructure (Fig. 2). Media reports on this recent shoreline erosion are numerous, but only limited direct measurement and quantification of the erosion has been reported, due to the traditional challenges in carrying out coastal surveys, particularly to obtain morphodynamic changes on the annual and even shorter time scales over which the coastal change is now occurring.

Large-scale coastline surveys are often carried out with remote sensing tools. The best current remote sensing technology available for coastline surveys is aircraft-based topo-bathymetric LiDAR, which maps both land topography and underwater bathymetry. In the United States, the Army Corps of Engineers (USACE) utilizes the Coastal Zone Mapping and Imaging LiDAR System (CZMIL) to map coastal zone bathymetry, topography, and other properties (Feygels et al., 2013; Reif et al., 2013). This system provides O(0.1 m) scale accuracy in vertical elevations, at horizontal resolutions of O(1 m), covering entire stretches of coastline (∼1500 m cross-shore width) (Klemas, 2011). Coastal LiDAR data enables the quantification of shoreline change with a variety of feature and volumetric change metrics (Hardin et al., 2014).

However, due to cost, aircraft-based coastal LiDAR surveys can only...
be carried out infrequently for a particular location. For example, topobathymetric USACE LiDAR data is available for the Indiana coastline of southern Lake Michigan for the years of 2008 and 2012. This long time interval between flights does not allow for the quantification of the coastal response to individual storms and interannual water level fluctuations. Importantly, the largest shoreline changes often happen on episodic timescales, when wave energy is large; this is particularly true for fetch-limited water bodies such as large lakes, for which wave energy is highly variable in time. The lack of shoreline change data on fine timescales poses a severe bottleneck to the development and refinement of higher temporal resolution sediment transport models and budgets that can be used to guide coastline management practices that ensure coastal resiliency.

Unmanned Aerial Vehicles (UAVs) provide an alternative option for timely coastal surveying (Klemas, 2015). Several past studies have shown that UAV-based shoreline change detection can achieve the same degree of accuracy compared to existing coastal survey techniques including total station, Real-Time Kinematic Global Navigation Satellite Systems (RTK-GNSS), Terrestrial Laser Scanner (TLS) and RTK-GNSS mounted on an all-terrain vehicle (Moloney et al., 2017; Turner et al., 2016; Westoby et al., 2018). They also demonstrated that UAV surveys are capable of collecting higher spatial and temporal resolution data more rapidly and efficiently, making the technique ideal for small spatial or temporal scale coastal monitoring, albeit over a smaller spatial scale than traditional aircraft-based systems.

However, UAV usage for shoreline mapping to date has been mainly restricted to image-based systems using Structure from Motion (SfM) analysis. For homogeneous surfaces, e.g., sandy beaches, SfM would have difficulty in identifying conjugate features among overlapping images. Moreover, in areas with some canopy cover, image-based analysis would be limited by not having any data below the canopy. For LiDAR-based monitoring, both limitations are mitigated. Namely, LiDAR directly derives point clouds without the need for identifying conjugate features in overlapping scans. Moreover, LiDAR systems can provide point cloud data below canopy due to the ability of the emitted radiation by the laser ranging unit in going through small gaps among the leaves to capture points below the canopy.

This paper details the development and application of a UAV, equipped with high-resolution topographic LiDAR and red-green-blue (RGB) imaging systems to quantify rapid (seasonal- and event-scale) coastal changes caused by elevated water levels and storms in Lake Michigan (Fig. 3). Extensive details of the system were provided in a recent paper (Lin et al., 2019), and the focus here is on the application of the vehicle to provide preliminary Lake Michigan terrestrial erosion estimates for two beaches. During 2018 and 2019, the UAV LiDAR system was applied to perform high-resolution topographic shoreline surveys at two coastal sites along the southern Lake Michigan shoreline: Dune Acres, IN and Beverly Shores, IN. The UAV surveys were successful in quantifying coastal erosion both over seasonal and episodic timescales, showing that coastal erosion at these locations is occurring at greatly elevated rates. Comparison with historical NOAA coastal LiDAR data shows that the present erosion is occurring with magnitudes that should cause concern for coastal managers and communities.

2. Methods

2.1. Study sites

Two sandy beaches along the Indiana shoreline of Lake Michigan were surveyed repeatedly with the UAV LiDAR system (Fig. 4). The highly-modified Indiana shoreline of Lake Michigan, approximately 65 km long, is comprised of several small residential communities, numerous industrial plants, cargo ports, marinas, and public lands and beaches. Sediment transport along this coastline has been significantly altered by human modifications to the shoreline (NPS, 2014).

The beaches surveyed are located in the towns of Dune Acres and Beverly Shores, which are small residential communities that are situated along a stretch of coastline bounded by the Michigan City harbor entrance to the northeast and Burns Harbor Port of Indiana to the southwest. The Dune Acres beach is backed by a steep, 3–5 m tall, actively eroding foredune that is topped with vegetation, whereas the Beverly Shores beach is backed by a more rounded, vegetated foredune of similar height, with an actively eroding base. Portions of the foredune at Beverly Shores have rock protection at the lakeward toe of the dune. At Dune Acres, a sheet pile retaining wall protecting a house forms the eastern boundary of the beach. Beach widths are approximately 10–20 m, and the duration of aerial surveys were about two days each. The times between flights were selected based on the season, wave energy, and wave model estimation of the wave energy. The flight dates were determined by the availability of the flight vehicle and the daylight available for the flight. The flight dates of the aerial surveys are shown in Fig. 3.

Fig. 1. Lake Michigan water levels and LiDAR flight dates. Lake Michigan water surface elevation (WSE), from Calumet Harbor, IL, NOAA Station ID 9087044, from (a) 1903–2020 and (b) 2008–2020, relative to the long-term monthly mean water surface elevation for the station (176.4 m, IGLD85 datum). LiDAR flight dates are shown as vertical lines on the graph (airborne: before 2014; UAV: 2018–2019).
m at both beaches, and the composition of the sand is similar (Simon et al., 2016).

The harbors of Michigan City and Burns Harbor that bound the stretch of Indiana coastline containing these beaches serve as littoral barriers to sediment movement (Fig. 4). As such, this reach of coastline is a closed littoral cell, with the dominant sediment drift towards the southwest, which is dictated by the dominant wave direction (Wood et al., 1988; Morang et al., 2012). The long-term sediment transport pattern associated with this closed cell is historical erosion at Mt. Baldy, a large dune near Michigan City, and historical accretion immediately updrift of Burns Harbor (Kilibarda and Shillinglaw, 2015). The shoreline in this reach is generally either sandy beach backed by dunes or armored with sheetpile or rocks (Wood et al., 1988). The portion of the reach that includes Dune Acres and Beverly shores has been classified as “dynamically stable”, meaning that the shore is generally not eroding or accreting over many decades, but does adjust to fluctuations in the lake level (NPS 2014; Appendix C). From the 1960s through the 1980s, Wood et al. (1988) noted that both of these beaches were erosional in response to elevated water levels (see Discussion section).

2.2. Purdue UAV-based mobile mapping system

To quantify terrestrial coastline changes, repeated beach surveys were carried out with a topographic LiDAR-equipped unmanned aerial vehicle (UAV; Fig. 3, Table 1). Full details of the system, which was developed at Purdue using off-the-shelf components, and its application to coastal surveying can be obtained from Lin et al. (2019) but some of the basic details are presented here. The UAV-based Mobile Mapping System (MMS) used in this study consists of a DJI M600 Pro as the vehicle, which carries a laser scanner, a camera (Sony Alpha ILCE-7R), and an integrated Global Navigation Satellite Systems and Inertial Navigation Systems (GNSS/INS) unit (APX-15 V2) for direct georeferencing.

As flown, the average point density of the UAV LiDAR datasets ranges from 383.3 pt/m² to 890.1 pt/m² (Fig. 5(c)), which is much higher than the average point density of the NOAA LiDAR data to which results are compared later (which ranges from 0.4 pt/m² to 3.9 pt/m²). A Raspberry Pi module is used to store the LiDAR data in the form of *.pcap files. The Sony Alpha ILCE-7R is a 36.4 MP off-the-shelf camera.

To quantify the elevation and volume change of the shoreline, the LiDAR-based raster Digital Surface Model (DSM) was generated, with 4 cm resolution. Despite the spatial irregularity of a raw LiDAR point cloud, LiDAR-based DSM presents a uniform gridded terrain surface from which spatial subtraction and integration can be performed directly and computationally efficiently. The vertical accuracy of the DSM is estimated as in the ± 5–6 cm range.

Finally, the orthophoto mosaic (shown in Fig. 5(b)) was generated using the UAV imagery, following methods in He et al. (2018). The orthophoto mosaic is geometrically corrected and can be utilized as a map. Combining the RGB information in the orthophoto mosaic and the elevation in LiDAR-based DSM, the color-coded DSM is obtained. The color-coded DSM provided a large-scale overview of the ground surface (water, bare ground, vegetation, etc.) from which the location and elevation of the shoreline was determined for each date of the survey.

To assess the compatibility between the UAV LiDAR data and the NOAA LiDAR data, a portion of the point cloud capturing a building (a structure that presumably remained unchanged in term of its location and height throughout the years) was manually picked and extracted and checked for alignment.

Plane fitting was performed over a planar segment on the roof of a house using the UAV May 2019 dataset, calculated the normal distance between each NOAA LiDAR point to the best-fitted plane, and reported the root-mean-square error for the absolute positions (RMSE). For Dune Acres, the RMSE is 0.25, 0.09, and 0.14 m for the 2008 USACE LiDAR data, 2011 IOT LiDAR data, and 2012 USACE LiDAR data, respectively. The overall RMSE is 0.16 m. For Beverly Shores, the RMSE is 0.16, 0.09, and 0.03 m for the 2008 USACE LiDAR data, 2011 IOT LiDAR data, and 2012 USACE LiDAR data, respectively. The overall RMSE is 0.07 m. The result suggests that the UAV and NOAA datasets are compatible within a 0.16 m range.

2.3. UAV site surveys

Seven shoreline surveys were conducted with the UAV-based survey system between May 2018 and May 2019 (Table 1). Dune Acres was surveyed four times: 17 May 2018, 07 Nov 2018, 05 Dec 2018, and 10 May 2019. Beverly Shores was surveyed three times: 19 Nov 2018, 05 Dec 2018, and 10 May 2019. Between the November and December surveys in 2018, a large storm struck the Indiana coastline, and this was the motivation for the December 2018 surveys.

The UAV surveys covered an extent of approximately 270 m of coastline in the May 2018 survey at Dune Acres, approximately 450 m
coastline for the remaining surveys, and approximately 340 m coastline in all surveys at Beverly Shores. The flight heights were 10 m and 20 m for Dune Acres, and 30 m for Beverly Shores. It took about 10 min to deploy the system, and the actual flight time was approximately 15 min per mission. The mission planning software, DJI GS Pro, was used for setting the autonomous flight path. The system was piloted autonomously but flown manually for the areas with nearby obstacles (trees, power lines etc.).

2.4. NOAA LiDAR data

Three airborne historical LiDAR datasets that cover the area of interest are publicly available at the NOAA Digital Coast website (https://coast.noaa.gov/digitalcoast/): (1) 2008 USACE National Coastal Mapping Program (NCMP) Topobathy LiDAR - Indiana (Lake Michigan shoreline), hereafter 2008 USACE LiDAR data (OCM Partners, 2019a), (2) 2011–2013 Indiana Statewide Imagery and LiDAR Program: Lake Michigan Watershed Counties, hereafter 2011 IOT LiDAR data (OCM Partners, 2019b), and (3) 2012 USACE Great Lakes Topobathy LiDAR: Lake Michigan, hereafter 2012 USACE LiDAR data (OCM Partners, 2019c). These datasets are used as historical data comparisons in this study (Table 1). Any available bathymetric data from these surveys is not included in the analysis.

2.5. Shoreline change quantification

Shoreline changes were estimated by comparing land survey data for the UAV and NOAA LiDAR surveys. To facilitate comparison, a set of shore-perpendicular transects were defined at both beaches. The

![Fig. 3. Schematic of UAV-based MMS. Picture of flying UAV (left). The system consists of a platform, a laser scanner (A), RGB camera (B) and GNSS/INS unit (C).](image1)

![Fig. 4. Shoreline map of study sitesShoreline map of littoral cell between Burns Harbor / Port of Indiana and Michigan City, showing the field sites of Dune Acres and Beverly Shores. Also shown are the net directions of sediment transport, and the historical zones of erosion (downdrift of Michigan City, upper right) and accretion (updrift of Burns Harbor, lower left).](image2)

<table>
<thead>
<tr>
<th>Survey</th>
<th>Survey Date</th>
<th>Vertical positional accuracy</th>
<th>Horizontal positional accuracy</th>
<th>Point cloud density (#/m²)</th>
<th>Water level elevation (GND85)</th>
</tr>
</thead>
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<td>Historical airborne LiDAR datasets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>USACE Topobathy Airborne LiDAR</td>
<td>2008 Jul 29–2008 Sep 21</td>
<td>±0.20 m</td>
<td>±0.075 m</td>
<td>4.4</td>
<td>176.23 m</td>
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<tr>
<td>USACE Topobathy Airborne LiDAR</td>
<td>2012 Sep 9–2012 Sep 15</td>
<td>±0.15 m</td>
<td>±0.05 m</td>
<td>5.5</td>
<td>175.91 m</td>
</tr>
<tr>
<td>Indiana Statewide Topographic Airborne LiDAR</td>
<td>2013 Feb 14–2013 Apr 9</td>
<td>±0.125 m</td>
<td>±0.125 m</td>
<td>5.9</td>
<td>175.73 m</td>
</tr>
<tr>
<td>Purdue UAV LiDAR System Dune Acres</td>
<td>2018 May 17, 2018 Nov 07, 2018 Dec 05, 2019 May 10</td>
<td>±0.06 m</td>
<td>±0.06 m</td>
<td>740</td>
<td>177.04 m 176.86 m 176.83 m 177.21 m</td>
</tr>
<tr>
<td>Beverly Shores</td>
<td>2018 Nov 19, 2018 Dec 05, 2019 May 10</td>
<td>±0.06 m</td>
<td>±0.06 m</td>
<td>730</td>
<td>176.88 m 176.84 m 177.19 m</td>
</tr>
</tbody>
</table>

Table 1
LiDAR data collection dates, collection parameters, and water levels. Water levels are based on NOAA water level gage 9087044 (Calumet Harbor, IL).
transects were spaced 10 m apart, resulting in 45 transects for Dune Acres and 35 transects for Beverly Shores. The first UAV survey at Dune Acres did not include transects 1–20. Land elevations were extracted from each survey along transects, which extended to the water’s edge for a given survey, resulting in a set of beach profiles that could then be compared for each transect (Fig. 5(d); Fig. 6). Erroneous (non-land) data points resulting from trees and other objects were manually removed from the profiles.

Using the cross-shore transects, the eroded area was estimated under each transect. Because the lakeward extent of the profiles changed so dramatically between surveys, and because there is no bathymetric data from the surveys, transect profiles could not be simply compared between two common (cross-transect) end points. To estimate shoreline changes at each transect, “dry beach areas” were calculated and compared between profiles from different surveys. For this estimate, a landward common point was determined for each transect as a survey end point that was unchanged for all surveys, in essence serving as the farthest point inland where shoreline changes had been observed. The dry beach area was then defined as the area of sand below the beach profile and above the water elevation for the survey, between the water’s edge and the common point. Although the absolute values of the dry beach areas are specific to a given transect, temporal changes in the dry beach areas between surveys provide a means to quantify shoreline area and volume changes (Hardin et al., 2014). As defined, changes in the dry beach area will be caused by both submergence (changes in water level alone) and erosion/accretion of sand.

The cross-transect shoreline positions as well as the position of elevation contours were also analyzed. For the shoreline position, the location of the lakeward-most LiDAR point was used for a given transect, and found shoreline positions that had elevations that deviated by more than 20 cm from the water surface elevation for that survey date were rejected. Elevation contour locations were determined by linear interpolation along transects for a specified elevation.

2.6. Water levels and waves

The water level gage measurements at Calumet Harbor NOAA gauge (station ID 9087044, https://tidesandcurrents.noaa.gov/stationhome.html?id=9087044) was used in this study to determine the water surface elevation corresponding to each survey. These gage measurements are referenced to the International Great Lake Datum of 1985 (IGLD 85) dynamic heights. The NOAA vertical datum transformation tool (VDatum, https://vdatum.noaa.gov/vdatumweb/) was applied to convert the IGLD 85 dynamic heights to WGS 84 ellipsoidal heights so that the gauge measurements are consistent with the UAV LiDAR data. For the NOAA LiDAR data, when the precise flight time was not available, the water level for that survey was determined as the average over the period in which the survey was said to be conducted.

Year-round wave measurements are not available in Lake Michigan so output from the Great Lakes Coastal Forecasting System (GLCFS) was analyzed for a 19 m depth location offshore of Beverly Shores and Dune Acres (https://www.glerl.noaa.gov/res/glcfs/). For the storm wave and beach energy flux analysis, only waves traveling towards the shore were considered (wave angles $\theta < 65^\circ$ and $\theta > 245^\circ$). A bulk metric of nearshore wave energy, the shore-incident wave energy flux (power), was then estimated as $P = E g \alpha$, where $E$ is the wave energy density, $g$ is the group velocity associated with the peak period, and $\alpha$ is the wave ray angle (U.S. Army Corps of Engineers, 2002).
3. Results

3.1. Waves and water levels – 2008 to 2020

Lake Michigan water levels were below average for the three airborne LiDAR flights used for comparison (2008, 2012, 2013), after which they rose steadily almost 2 m until peaking in July of 2020 (Fig. 1). The water levels for the three UAV surveys were between 0.5 and 0.8 m above average. Simulated (GLCFS) waves and wave energy for the past decade, including the UAV survey period, are shown in Fig. 7. Highlighted in this figure are peak storm waves that approached the coastline with significant wave heights that exceed 3 m, which occurred on average 5.9 times per year during the 9.5 year simulation record. From the record it can be seen that the years 2011–2013 experienced numerous very large storms, with several storm events having peak wave heights exceeding 4 m including that associated with Hurricane Sandy in 2012. In comparison, only 3 storm events hit the coastline in the one year period over which the UAV flights occurred. Between the May and November 2018 surveys, one storm on October 20 produced large waves from the north, with a maximum significant wave height of 3.4 m (~5-month recurrence period). Between the second and third survey dates (November and December 2018), a storm produced large waves from the north (maximum simulated wave height 4.2 m, recurrence interval of 1.4 years). During the winter period between UAV surveys (Dec 2018–May 2019), several weaker storms struck the Indiana coastline. However, taken in sum, these estimates suggest that the wave energy along the Indiana coastline during the 2018–2019 UAV survey period was actually 32% lower than what that coast generally experiences.

3.2. Decadal-scale shoreline volume changes (2008–2019)

All shoreline change metrics show that both beaches were growing or stable through 2012, but have eroded significantly since then. Firstly, the shape of the profiles show qualitative changes. Prior to 2012, when water levels were relatively stable and below average, the beaches are seen to have mild slopes and are backed by 3–4 m tall, mound foredunes that are slowly accreting over time (Figs. 6 and 8). The profile shapes are mildly-sloped with slopes between 1:7 and 1:9 between the water’s edge and the top of the foredune. Some accretion is seen on the foredunes of both beaches between 2008 and 2013, with the Beverly Shores foredune advancing 5.9 m and the Dune Acres foredune advancing 3.4 m (Table 3), suggesting a slow rebuilding of the dunes during the low water period as expected. Then, between 2013 and 2018, the character beach profiles at both beaches changed substantially as the Lake Michigan water level rose. The primary changes in the beach profiles occur in the foredunes backing the beach, which have shifted from being mildly-sloped to having 2–3 m tall, steep faces with slopes steeper than 1:1, that are actively eroding (see Figs. 6 and 8). Available aerial photographs for this period show that this transition to an actively eroding foredune with a sharp lakeward edge occurred at both beaches somewhere between 2011 and 2015.

The shoreline and foredune positions (Fig. 9, Table 3) have receded significantly during the period of water level increase. The median shoreline recession at Dune Acres and Beverly Shores between the 2012 survey and the May 2019 survey was 34 m for both beaches. Submergence alone accounts for about 14 m for Beverly Shores shoreline recession and 18 m for Dune Acres. During this time the beach-backing foredunes also receded, at an equal amount of 12 m for both beaches (the two beach exhibits a remarkable amount of synchrony in spite of their geographic separation). Defining the beach width as the difference between the shoreline position and the foredune contour, the beach widths at both beaches decreased substantially over the period of water level increase, from 33 m to 16 m at Dune Acres, and from 37 m to 15 m at Beverly Shores.

The dry beach volume changes associated with the erosion at both beaches prior to 2018 are significant and exhibit some alongshore variability (Fig. 10, Table 2). Between 2008 and 2012, both beaches were accretional, gaining an average of 6.7 and 24.1 m$^3$/m of sand per m of shoreline for Dune Acres and Beverly Shores, respectively (Table 2). The Dune Acres accretion is less uniform over the beach, with more accretion near the sheet pile wall on the eastern edge of the beach. Between 2013 and 2018, when the first survey was accomplished with the UAV at each beach, both beaches lost significant sand volumes. Over this period, Dune Acres lost an average volume of 60.5 m$^3$/m, with losses concentrated on the eastern end of the beach. Beverly Shores lost a greater volume, 62.0 m$^3$/m, with these losses distributed more uniformly over the beach. Overall between the low water NOAA survey of 2013 and the most recent UAV survey in May 2019, both beaches showed similar average dry volume losses of 70.7 m$^3$/m for Dune Acres and 64.8 m$^3$/m for Beverly Shores.

3.3. Shoreline changes during recent UAV survey period (May 2018–May 2019)

The UAV surveys in 2018 and 2019 reveal the recent and continuing shoreline changes at both beaches. Between May 2018 and May 2019, Dune Acres continued to experience significant erosion, primarily along the eastern side of the beach (average 8.5 m$^3$/m of lost material), whereas over the same time period, the Beverly Shores beach lost much less material (2.7 m$^3$/m; Table 2, Fig. 10). This recent erosion at both beaches was concentrated at the base of the steep, eroding faces of the foredunes backing the beaches (Fig. 8). Elevation change maps show more than 3 m of elevation change due to the recent storms, which reflects the localized collapse of the steep foredune backing the beach. As the dunes collapsed and eroded, the dune ridge receded horizontally, and the maximum foredune ridge horizontal recessions exceeded 7 m between May 2018 and May 2019 for Dune Acres, and were nearly 4 m for Beverly Shores between November 2018 and May 2019. Fig. 9 shows the complex spatial and temporal character of the recent beach transect changes revealed by the UAV surveys. Temporally, the increasing slopes of the cumulative erosion lines for Dune Acres transects indicate that the overall erosion rates observed with the LiDAR system between 2018 and 2019 are accelerated relative to 2012–2018.
Fig. 8. Dune Acres and Beverly Shores cross-shore transects. Cross-shore transects at Dune Acres and Beverly Shores beaches, as measured by the UAV system in 2018 and the airborne LiDAR system in 2008, 2012 and 2013. Elevations are IGLD85 and all surveys end at the water’s edge for that particular survey.

Table 2
Dry beach volume changes.

<table>
<thead>
<tr>
<th>Period</th>
<th>Dune Acres, IN</th>
<th>Beverly Shores, IN</th>
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<tbody>
<tr>
<td></td>
<td>Mean volume change (m$^3$/m)</td>
<td>Mean volume change rate (m$^3$/yr)</td>
</tr>
<tr>
<td>2008–2012</td>
<td>+6.7</td>
<td>+1.7</td>
</tr>
<tr>
<td>2012–2013</td>
<td>+4.8</td>
<td>+9.7</td>
</tr>
<tr>
<td>2013–2018</td>
<td>-60.5</td>
<td>-11.7</td>
</tr>
<tr>
<td>May 2018–Nov 2018</td>
<td>-14.9</td>
<td>-31.2</td>
</tr>
<tr>
<td>Nov 2018–Dec 2018</td>
<td>-8.0</td>
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</tr>
<tr>
<td>Dec 2018–May 2019</td>
<td>-0.5</td>
<td>-1.1</td>
</tr>
<tr>
<td>2013–May 2019</td>
<td>-70.7</td>
<td>-11.5</td>
</tr>
<tr>
<td>2018–2019</td>
<td>-24.9</td>
<td>-25.4</td>
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Table 3
Shoreline and foredune contour movement. Provided are the median cross-shore transect and shoreline movements between survey pairs. Positive values indicate lakeward shoreline and contour movement, and negative values indicate recession.

<table>
<thead>
<tr>
<th>Period</th>
<th>Dune Acres, IN</th>
<th>Beverly Shores, IN</th>
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<tbody>
<tr>
<td></td>
<td>Shoreline position change (m)</td>
<td>179.5 m contour change (m)</td>
</tr>
<tr>
<td>2008–2012</td>
<td>+6.5</td>
<td>+1.8</td>
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<tr>
<td>2012–2013</td>
<td>-4.9</td>
<td>+1.6</td>
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<td>2013–May/Nov 2018</td>
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<td>May 2018–Nov 2018</td>
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<td>-0.6</td>
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<td>Nov 2018–Dec 2018</td>
<td>-2.7</td>
<td>-1.4</td>
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<tr>
<td>Dec 2018–May 2019</td>
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<td>-0.1</td>
</tr>
<tr>
<td>2013–May 2019</td>
<td>-29.2</td>
<td>-15.2</td>
</tr>
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Dune Acres transects also exhibit a much larger range of variability in erosion than Beverly Shores. In contrast, the 2018–2019 erosion at Beverly Shores occurred at roughly the same rate as the period 2012–2018. Both beaches were almost entirely erosive in response to the two November storms captured by the short-interval UAV surveys in 2018, as seen by the positive cumulative erosion slopes over this period. However, for the winter/spring period of 2019 following these storms, the beaches are not uniformly eroding. For Dune Acres over this period, the eastern edge of the beach was actually accreting (high transect numbers) and the western portion of the beach was eroding (low transect numbers). The opposite is true for Beverly Shores, where the eastern transects (high numbers) are seen to be eroding over this same period.

3.4. Shoreline position changes with water level

Using the LiDAR data sets, the shoreline position for the two beaches was tracked between 2008 and 2019 to quantify the relationship between shoreline recession and water level increase (Fig. 12). The total shoreline recession for both beaches is quite similar, with a net shoreline movement of 34 m between 2012 and May of 2019, at an average rate of 5 m/year. A shoreline recession slope was defined as the change in water level divided by the shoreline movement, which was determined using linear regression on the cross-shore beach shoreline positions against the water level elevation (Fig. 12). The shoreline position for a given survey was taken as the cross-transect location where the median of the minimum (lakeward) elevations were found in the LiDAR transects. For Beverly Shores, determined shoreline movement slopes ranged between 1:26 and 1:38 with a value of 1:29 for the median shoreline position, and the Dune Acres shoreline movement slopes were between 1:23 and 1:53 with a median value also of 1:29.

4. Discussion

The Lake Michigan beach surveys provide timely information regarding the magnitude and timing of shoreline erosion along the Indiana shoreline during the current high water period. Firstly, the magnitude of sand lost at both beaches since the low water levels of 2012–2013 is large for these beaches. From the low water survey in 2012 to the most recent May 2019 survey, the Dune Acres dry beach lost an average of 70.7 m$^3$/m of sand, and the Beverly Shores beach lost an average of 64.8 m$^3$/m of sand. These amounts are not large relative to erosion volumes seen on ocean coastlines, but for these smaller beaches, they represent losses of approximately 62% of the initial beach volumes in 2013 when water levels began to rise. Similarly, the Dune Acres and Beverly Shores beach widths decreased by 54% and 40%, respectively. For perspective, that is about 6–7 truckloads of sand per meter of shoreline, with an associated replacement cost of roughly $500–1000.
per m of shoreline (American Shore and Beach Preservation Society, n. d.). This cost is likely beyond the means of small communities looking to maintain their shorelines for property owners and beachgoers.

Shoreline erosion at both beaches continued in 2018–2019 at an overall pace equaling or exceeding the erosion rate between 2013 and 2018. Between the low water survey in 2013 and the first Dune Acres survey in May 2018, the beach lost on average 11.7 m$^3$/m/year of sand, whereas in the year spanning May 2018 to May 2019, the beach erosion rate was more than twice that at 25.4 m$^3$/m/year (Table 2). Wave energy was diminished in 2018–2019 (Fig. 7), so this increased pace of erosion seems likely to be associated with higher water levels allowing waves to reach and erode the base of the erodible foredunes backing the beaches, which is supported by the transect erosion patterns (Figs. 6 and 8). This process of accelerating erosion is expected to continue while lake levels are high and the beach is striving to reach the equilibrium beach profile that matches the new lake level. These erosion rates are much larger than what Hands (1980) reported for southern Lake Michigan during an earlier period of high water (6.1 m$^3$/m/year, his Table 1).

Existing shoreline models are not currently formulated to simulate interannual shoreline changes driven by rapid, large water level fluctuations such as those experienced in the Great Lakes. Locally-calibrated shoreline models have recently shown promise to model shoreline changes on a range of timescales from episodic to interannual (Splinter et al., 2014; Dean and Houston, 2016; Montaño et al., 2020; Jaramillo et al., 2020). These models can be pared down to simulate wave-driven shoreline change associated with cross-shore sediment transport, or extended with additional terms to include effects of alongshore sediment transport, beach nourishment, and other processes (Dean and Houston, 2016; Vitousek et al., 2017). However, shoreline changes associated with sea level fluctuations, when modeled with additional terms, aim to capture only shoreline recession associated with long-term sea level rise, typically modeled with the Bruun Rule (Bruun, 1954).

Vitousek et al. (2017) point out that the shoreline position change ($Y(t)$) in response to rising sea levels ($S(t)$) can be phrased most generally as

$$\frac{dY}{dt} = \frac{1}{\tan \alpha} \frac{dS}{dt} \quad (1)$$

This simple model passes all of the modeling complexity to the term $\tan \alpha$, which is here termed the “recession slope”, effectively the ratio of water level rise to shoreline recession ($\tan \alpha = \Delta S/\Delta Y$). As explained by Vitousek et al. (2017), the recession slope $\tan \alpha$ has unambiguous meaning in two opposite timescale limits, shown schematically in Fig. 14. In the short-timescale limit of “passive flooding” (or the opposite, beach exposure resulting from falling water levels), where the profile experiences no change in form as the water level changes rapidly,
the slope \( \tan \alpha \) is simply the average cross-shore beach profile slope over the zone of inundation or exposure. The passive flooding case occurs regularly for ocean coasts during calm (no sediment transport) periods when water levels fluctuate between low and high tides, submerging and exposing the beach. In the tideless Great Lakes, passive flooding and exposure occurs over seasonal timescales during periods when storms are absent but water levels are changing in response to seasonal hydrologic variations.

For water level fluctuations on annual and longer timescales, such as the case of long-term sea level rise, the recession slope \( \tan \alpha \) is generally modeled as the Bruun Rule (Dean and Houston 2016; Vitousek et al., 2017), for which \( \tan \alpha \) is the total profile slope from the berm to the depth of closure:

\[
\tan \alpha = \frac{h_0 + B}{W}. \tag{2}
\]

Here we follow the Dean and Houston (2016) notation where \( h_0 \) is the depth of closure over the timescale of interest, \( B \) is the berm height, and \( W \) is the cross-shore distance to closure.

The key assumption for the Bruun Rule, which is a geometric argument, is that the cross-shore profile maintains its form during the period of water level increase (Bruun, 1988). This can be seen to be obviously violated for the Lake Michigan case discussed herein, as evidenced by the changing profile shapes (Figs. 6 and 8). Dean (1991) showed equation (2) can also be applied for the case of storm erosion with an accompanying surge, provided that the profile shape and relative water level position are unchanged, and that the closure depth and distance are those corresponding to the active profile for the storm (e.g. surf zone).

For the study locations examined herein, LiDAR surveys and wave model output can be utilized to estimate the shoreline change associated with the passive flooding (short-term) and Bruun rule (long-term) limits. Median beach slopes over a zone 5 m adjacent to the water line for the two beaches examined are 0.072±0.040 (~1/14) and 0.086±0.136 (~1/12) for Beverly Shores and Dune Acres, respectively. Wave model output utilized with the Nicholls et al. (1998) closure depth formula and an appropriate profile parameter for the beach sand (\( A = 0.10 \text{ m}^{1/3}/\text{m}, \text{Stockberger and Wood, 1991} \)) lead to closure depth and distance estimates of 8.7 m and 810 m, respectively, for the period 2007-2019. The berm height for the actively-eroding portion of the profiles (Fig. 6) is approximately 5 m. Using these values, equation (2) gives a predicted Bruun rule recession slope of \( \tan \alpha = 1/59 \), i.e. an expected 118 m of shoreline recession for the 2.0 m of water level rise over the recent period.

The measured shoreline recession slope \( \tan \alpha \) is 1/29, which falls exactly between the (instantaneous) passive flooding limit (1/14–1/12) and the long term Bruun Rule erosion (1/59), which is highlighted in Figs. 9 and 12. This recession slope is suggestive of a shoreline that has not yet eroded enough to reach a new equilibrium. If lake levels stabilize but erosion continues to allow the profile to reach a new equilibrium, recession will continue, relaxing the recession slope towards the Bruun estimate.

Hands’ (1980) analysis of shoreline changes along Lake Michigan’s southeastern coast for a 9 year period over which the water level rose by a more modest 0.2 m found that the recession slope changed over time as the profile moved towards an equilibrium with the higher water level, with a 1/68 recession slope over the entire period that actually matched the Bruun Rule estimate for the conditions. The better agreement with the Bruun rule for that case would suggest that the profile had sufficient time to reach a new equilibrium with the slightly increased water level.

The comparison of the present results with Hands’ (1980) results suggests that the timescale of shoreline equilibrium with increased water levels is dependent on the magnitude and timing of the water level increase, which limits the utility of the Bruun Rule used in (1) as a predictive model unless this timescale dependence can be incorporated.

This unresolved ambiguity highlights the need for the development of shoreline models that can not only model wave disequilibrium as a driver for shoreline change, but also water level disequilibrium. Presently available shoreline models do not account for water level disequilibrium, because they have been developed for ocean coasts where the primary driver of shoreline change is wave disequilibrium. It could be argued that existing equilibrium models effectively alias water level disequilibrium into wave disequilibrium, since storms generally bring both waves and surge, and surge is not explicitly modeled.

The UAV data sets taken immediately before and after the large November 2018 storm highlight the disproportionate role of storms in causing shoreline changes, as well as highlighting the ability of the UAV system to resolve episodic shoreline changes (Fig. 13). At Dune Acres, this single storm removed nearly 1800 m\(^3\) of sand from the beach (8 m\(^3\)/m), an amount corresponding to 76% of the total sand lost for the year (May 2018–May 2019). In contrast, Beverly Shores experienced considerably less erosion from that storm, losing only 300 m\(^3\) (1.6 m\(^3\)/m), a relatively small amount, and even experienced some accretion from the storm along the western edge of the survey (Figs. 10 and 11). The amount of volume lost at Dune Acres due to the storm is large relative to other recent short-timescale erosion measurements for Lake Michigan (Theuerkauf et al., 2019), but in keeping with what has been reported for storm-induced erosion along ocean coasts (e.g. Armaroli et al., 2013; Splinter et al., 2018).

Alongshore differences in shoreline change can also be detected using the UAV LiDAR datasets. At Dune Acres, recent (>2018) shoreline changes differ across the beach (Figs. 10 and 11), with the eastern edge of the beach (high transect numbers) showing larger magnitudes of recent shoreline change, both erosional and accretional. In contrast, Beverly Shores displayed a more uniform response over the beach. At Dune Acres, this variability may be related to the presence of a curved sheet pile wall at the eastern edge of the beach. This structure can potentially trap sediment for storms causing eastward drift, causing accretion, but potentially block sand for storms that cause westward sand transport, leading to erosion. The dominant (long-term) drift direction for both beaches is westward. The role of hardened shoreline features leading to sediment imbalances and erosion is a well-known effect, highlighted recently in Lake Michigan by Lin and Wu (2014). Future work with the UAV storm-resolving data will target the elucidation of the mechanisms underlying the differences in storm response both within and between beaches, such as those captured in storm impact scales that compare storm wave runup with dune toe and crest elevations (e.g. Sallenger, 2000).

While the amount of observed shoreline change is large in a relative sense for these beaches, it appears to be in keeping with amounts of observed erosion observed during previous high water periods. There have been several historical periods of rapid water level rise that caused extensive shoreline erosion, including the period from 1964 to 1974, over which the water level rose steadily more than 1.5 m (Fig. 1). During this time, the shoreline recession rate was estimated at 3.4 m/year for Dune Acres and 4.3 m/year for Beverly Shores (Wood et al., 1988). For the analysis, between the 2012 and May 2019 surveys, the shoreline recession rates are approximately 5 m/year for both beaches, which slightly exceeds these historical values but is consistent with the faster water level rise for the present conditions. Hands (1980) estimated an average of 24 m of shoreline recession for southern Michigan beaches during the period 1967–1975, which is less than the ~35 m observed here (Fig. 9) but consistent with the fact that the recent water level increases are larger and closer to 2 m (Fig. 1).

5. Conclusions

In conclusion, the UAV LiDAR surveys along two Lake Michigan beaches in Indiana show that the shoreline erosion and recession associated with record water levels has been large and continued through 2019. However, comparison with published values during previous high
Fig. 13. Shoreline changes associated with 2018 November storm. Map coloring (m) represents elevation change between surveys, with negative values indicating elevation decrease.

Fig. 14. Schematic of shoreline recession ($\Delta Y$) scenarios for rising water level ($\Delta S$). Scenarios shown are (a) passive flooding, for which the profile does not change position or form; (b) non-equilibrium erosion, for which the profile changes position and form; and (c) Bruun Rule recession, for which the profile changes position but not form. The water level rise is the same for all cases, but recession increases from (a) to (c); recession slope $\tan \alpha = \Delta S/\Delta Y$ decreases from (a) to (c).

water periods suggest that the level of shoreline change is generally consistent with the historical response of the southern Lake Michigan shoreline. It is expected that this erosion will continue where the shoreline is not hardened, as the beaches have likely not yet reached equilibrium with the high water levels, given the rapidity with which the lake levels have risen between 2012 and 2013 and May 2019. The shoreline recession that occurred during this period occurred with a median shoreline recession slope of 1:29, i.e. 29 m of shoreline recession for every 1 m of water elevation change. This amount of relative recession is less than predicted by the Bruun Rule, which predicts more than twice this amount. The discrepancy between the observed recession and the Bruun Rule prediction can be explained by the lack of equilibrium between the recently eroded shorelines and the increased water level (see Fig. 14). While the Bruun Rule has clear limitations, this disagreement also highlights the need for shoreline models that can account not only for wave disequilibrium as a driving factor for shoreline change, but also water level disequilibrium.

The use of LiDAR-equipped UAVs for shoreline surveying to obtain timely, high-resolution and site-specific shoreline data that can be used to quantify shoreline changes over short timescales, in turn aiding the development of models that can predict shoreline changes. The episodic nature of shoreline change, highlighted by the present measurements in which a single storm was responsible for 76% of the annual erosion at Dune Acres beach, makes high temporal resolution survey data extremely valuable to shoreline change models. This is particularly true if detailed companion measurements of storm hydrodynamics are available (they are not available for this dataset), and future UAV deployments will be timed around nearshore measurement campaigns.

A limitation of most UAV systems to-date with respect to shoreline surveys, including the presently-described LiDAR-equipped system, is the lack of bathymetric surveying capabilities. In the present application to Lake Michigan shoreline erosion there are still open questions as to where the eroded beach sand has been transported, and whether it is still available to naturally rebuild the beaches if water levels recede. Hands’ (1980) analysis of beach profiles during the 1967–1974 high water period showed that, at least on average, the volume of shoreline sand eroded was balanced by offshore accretion, but without bathymetric data at present it is difficult to know whether eroded sand is available offshore, or whether it has been transported along the shore elsewhere. Current work involves adding bathymetric survey capabilities, but in the near term a newly-acquired topobathymetric Lake Michigan dataset by the USACE will provide essential information that will help to answer this question and allow for a more widespread, comprehensive update on the Lake Michigan shoreline conditions following this recent period of water level increase.

CRediT authorship contribution statement

Cary D. Troy: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Visualization, Project administration, Funding acquisition. Yi-Ting Cheng: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Yi-Chun Lin: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Ayman Habib: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


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