Numerical Study of Longshore Variation in Beach Morphodynamics along Eastern Lake Erie Shoreline due to Seiche

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ABSTRACT

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Extreme coastal events and abrupt changes in atmospheric pressure in an enclosed or semi-enclosed basin can trigger low-frequency water surface oscillations known as seiches. This exploratory study numerically quantifies the effects of seiche on morphological changes along the eastern Lake Erie shoreline. The quantification is made by simulating the hydrodynamics of the lake using a coupled circulation and spectral wave model (ADCIRC+SWAN), providing the flow boundary conditions to the two-dimensional nearshore morphodynamic model, XBeach. The process-based XBeach model is used to simulate the nearshore morphological variations under two water-level conditions: the lake's actual water level and the synthetically generated seiche-free water level. The XBeach model is cross-calibrated using the process-based nearshore morphodynamic model, CSHORE, which was extensively validated using lab and field data. It is found that the seiching motions have a contribution of ~1.5% to the erosion of beaches along the 2-km stretch of the shoreline in eastern Lake Erie shoreline.

ADDITIONAL INDEX WORDS: Low-frequency oscillation, Great Lakes, suspended sediment, bed load.

INTRODUCTION

Lake Erie, accommodating approximately 12 million people in 17 metropolitan areas with more than 50,000 residents around the watershed—approximately 30% of the total population in the Great Lakes basin—is the fourth-largest lake among the five Great Lakes in North America and is 11th in surface area worldwide. The lake, with an average depth of 19 m, comprises three naturally divided basins: a very shallow western basin, a large central basin, and a relatively deep eastern basin. The western basin, with an average depth of 7.4 m, is covered with fine sediments; it is the most turbid region of the lake. The central basin is uniform in depth, with an average depth of 18.3 m and a maximum depth of 25 m. The eastern basin, which is the deepest basin, has an average depth of 24 m and a maximum depth of 64 m (United States Environmental Protection Agency, 2019). Lake Erie is known for its seiche—a standing wave in an enclosed or semi-enclosed body of water originated by strong winds (e.g., storms, hurricanes), earthquakes, tsunamis, or rapid atmospheric pressure changes. Following such an event, the water surface begins oscillating at a range of frequencies, from hours to days, until it reaches the equilibrium (Kamphuis, 2010b; Rabinovich, 2009; NOAA, National Ocean Service, 2019). Typically, Lake Erie’s seiches occur when a strong wind blows along the lake’s longer axis, from SW to NE. Following such events, large wind setups forming at one end of the lake initiate long waves propagating toward the opposite end of the lake. In 1844, a 4.3-m-high (14-ft.-high) seawall was destroyed, and 78 people were drowned by a 6.7-m (22-ft.) rise of the water level due to a seiche event in Buffalo (NOAA, National Ocean Service, 2019). A powerful storm in 2008 resulted in flooding near Buffalo (NOAA, National Ocean Service, 2019) and generated significant seiching oscillations (Farhadzadeh, Arabi, and Bokuniewicz, 2018).

Seiches occurring in the lakes have been the focus of numerous studies over the past decades (Cueva et al., 2019; Trebitz, 2006). The following summarizes the studies that investigate Lake Erie’s seiches. Platzman and Rao (1964a) spectrally analyzed Lake Erie’s hourly water levels and identified distinct peaks at the periods of 14.1 h, 9.2 h, 6.0 h, and 4.1 h. Platzman and Rao (1964b) analytically showed that those periods were attributed to the first four seiche modes, and the low-frequency oscillations were found to be more energetic in winter than summer. Furthermore, the diurnal constituent of the lake level was found to be an amphidromic Kelvin-type wave (Hamblin, 1987; Irish and Platzman, 1961; Kite, 1992; Mortimer, 1987; Platzman and Rao, 1964a,b).

Palmer and Izatt (1972) investigated the effects of surface ice on the Lake Erie seiche by analyzing current velocity data collected from northern Lake Erie during and soon after ice-cover formation and several months later. The velocity spectra for the period of ice formation were similar to those of the ice-free condition. The spectral density of the current velocity peaked at the frequencies corresponding to the free-oscillation modes. On the other hand, the maximum current velocity of the
second timeframe was less than half of that for the first period, the ice-free condition. The velocity spectral density was not peaked at this period, pointing to the absence of seiching oscillations. Dingman and Bedford (1984) investigated the response of partially ice-covered Lake Erie to the cyclone of 26 January 1978 by analyzing the power spectral density of the lake-level fluctuations. They stated that the surface ice played a significant role in suppressing the seiches such that the tidal oscillations, which are very small for the lake, became dominant. Gerbush, Kristovich, and Laird (2008) and Wang et al. (2010) showed that the presence of the surface ice led to a reduced momentum flux exchange between the atmosphere and the lake, decreasing oscillations of the lake level. This finding supported the conclusions by Palmer and Izatt (1972) and Dingman and Bedford (1984).

Varying water levels contribute to morphological changes in beaches. The majority of Lake Erie’s New York shorelines are at a high risk of erosion (New York State Homeland Security and Emergency Services, 2014). The quantification of shore erosion requires understanding the effects of factors that influence the erosion processes. For enclosed water bodies, this includes, among others, the interpretation of seiches and their potential contribution to the beach erosion. Most of the past studies focused on the hydrodynamics of seiche, as reviewed previously. On the other hand, studies on beach morphology are mainly concentrated on the morphological changes by short waves (e.g., Bruun, 1954; Dean, 1991; Dean and Houston, 2016; Kamphuis, 1996, 2010a; Kriebel and Dean, 1985, 1993; Tomascichio, D’Alessandro, and Barbaro, 2011) and long waves such as infragravity waves, edge waves, etc. (e.g., Aagaard and Greenwood, 2008; de Bakker et al., 2016; Bertin et al., 2018; Russell, 1993; Wright and Short, 1984).

As the shallowest among the five Great Lakes, Lake Erie responds to changes in the temperature quickly. As a result, the extent of the winter ice cover on Lake Erie is greatly reduced with warmer winters (United States Environmental Protection Agency, 2019)—a trend in the recent years (NOAA, GLERL, 2019). Figure 1a shows the historical ice cover (percentage of total surface area) for Lake Erie during 1973–2017. There is evidence that shows reduced surface ice can lead to an intensification in the low-frequency oscillations following an extreme event (Farhadzadeh, 2017; Farhadzadeh and Gangai, 2017). Farhadzadeh, Arabi, and Bokuniewicz, (2018) highlighted the contribution of seiches to beach profile changes in Lake Erie. Their study, however, was limited to a 6-month timespan. Further, they used a one-dimensional (1D) numerical model, disregarding the longshore variations of such changes. This study extends the work by Farhadzadeh, Arabi, and Bokuniewicz (2018) by quantifying the contribution of the seiche to the beach evolutions in eastern Lake Erie using a suite of two-dimensional (2D) numerical models and for an extended period of time (e.g., 1 year). A broader range of variables and processes are studied here. The simulations are performed for the entire year of 2012, during which Lake Erie’s ice cover was historically low and mostly concentrated in the western basin. Hence, the impact of the surface ice on the seiche in eastern Lake Erie was believed to be negligible. Furthermore, the quality of the meteorological and hydrological data during the selected year was better than that of the other warm winters.

METHODS

The lake-wide water level and wave fields for 2012 are simulated using the coupled ADCIRC (Luetich, Westerink, and Scheffner, 1992) and SWAN (Booij, Ris, and Holthuijsen, 1999) models. The coupled circulation (ADCIRC) and spectral wave (SWAN) model using an unstructured mesh is used to generate the lake’s hydrodynamics. The coupling of ADCIRC and SWAN allows the circulation model to use radiation stress gradients calculated by the wave model as an additional forcing for storm surge predictions. Subsequently, the wave model runs on an updated water level to calculate the wave field (Dietrich et al., 2011). The use of the coupled model in a shallow water body such as Lake Erie, with a historical storm surge of up to 3 m (and set downs of nearly –3 m), is critical for an accurate prediction of wave and water level (Farhadzadeh, 2017; Farhadzadeh and Gangai, 2017).

The spatial variations of the nearshore morphology in response to seiche motions are evaluated for the beach at Woodlawn Beach State Park in eastern Lake Erie (Figure 2). This site is selected because its sandy beach is located at the
anti-node where the seiching motions are the greatest (Farhadzadeh, 2017). The selected shoreline is approximately 2 km long and is relatively straight (Figure 2b). The beach comprises fine sand, with a median grain size of approximately $D_{50} = 0.11$ mm (Dusini, 2005; Farhadzadeh, Arabi, and Bokuniewicz, 2018; Sogut and Farhadzadeh, 2018; Thomas et al., 1976). The nearshore morphodynamics are simulated using both 1D (CSHORE: Johnson, Kobayashi, and Gravens, 2012; Kobayashi and Farhadzadeh, 2008) and 2D (XBeach: Roelvink et al., 2009, 2010) process-based morphodynamic models. The offshore boundary conditions for the morphodynamic models are supplied from the lake-wide hydrodynamic model, ADCIRC+SWAN. The XBeach model in its 1D mode is cross-calibrated against CSHORE, which has been extensively calibrated using laboratory and field data. The model was used for the Federal Emergency Management Agency (FEMA) Great Lakes flood studies (Johnson, 2012; Johnson, Kobayashi, and Gravens, 2012). The “Methods” section comprises two subsections: “Lake-Wide Hydrodynamics” and “Nearshore Morphodynamics.”

Lake-Wide Hydrodynamics
To obtain offshore boundary conditions for the morphodynamics models, lake-wide water levels and waves are generated by the coupled ADCIRC+SWAN on Lake Erie during 2012. In the following subsections, descriptions are provided for the circulation (ADCIRC) and spectral wave models (SWAN) as well as the model setup.

ADCIRC Model
The hydrodynamic circulation numerical model ADCIRC—a finite element, time-dependent, long wave model—can simulate water level and current over an unstructured gridded domain. The ADCIRC model can be applied to varying scales of motion and a broad range of hydrodynamic problems from deep ocean and lakes to flows in inlets, floodplains, and waterways. The use of an unstructured grid enables the use of finer grids where bathymetry is complex or in areas of interest. This leads to minimizing both local and global errors. In ADCIRC, elevations are obtained by solving the depth-integrated continuity equation in the generalized wave-continuity equation form. Velocities are computed from the solutions of the momentum equations, which include all nonlinear terms as well as the model setup.

SWAN Model
The SWAN (Simulating WAves Nearshore) model is a third-generation wave model that simulates random waves in coastal regions and inland waters (Booij, Ris, and Holthuijsen, 1999). It is spectral in frequency and direction and includes important physical processes such as wave generation, shoaling, refraction, transmission, reflection, diffraction, breaking, three- and four-wave nonlinear interactions, white capping, and effects of bottom friction. The SWAN modeling can be done on a regular, curvilinear, or unstructured grid in a Cartesian or spherical coordinate system. The unstructured grid allows for a higher resolution where it is needed. The model output includes 1D and 2D wave spectra, wave height, period, direction, directional spreading, wave forces, and near-bed orbital velocities. The spectral wave field is predicted by solving the wave action equation. The spectral density is computed at the vertices of an unstructured triangular mesh, and physical processes are represented at scales of wavelengths.

Lake-Wide Hydrodynamic Model Setup
Figure 3 shows the bathymetry of Lake Erie, as well as the water-level stations, and wave buoys. The depth is relative to 174.0 m (NAVD88), which corresponds to the long-term average lake level. The main driving forces of water-level variations in the Great Lakes are wind and pressure fields as tides are very small (Farhadzadeh and Gangai, 2017). Hence, the use of the most accurate wind and pressure fields is critical for an accurate prediction of the water levels and waves in Lake Erie. In this study, the wind data is obtained from NOAA/GLERL Great Lakes Coastal Forecasting System, which has a grid resolution of 2 km × 2 km and covers the entire lake area. The pressure fields are obtained from Climate Forecast System Reanalysis developed by the National Center for Atmospheric Research with 0.5 global geographical resolution at 1-hour intervals provided on a Gaussian grid (Saha et al., 2010, 2011). To account for the land use and to modify the wind field accordingly, the surface canopy coefficient is also implemented in the lake-wide hydrodynamic model depending on the National Land Cover Database (Wickham et al., 2014). In addition to the wind and pressure fields, the water surface elevations at Detroit and Niagara Rivers, i.e. Fort Wayne and American Falls stations (Figure 3), are provided to the model as boundary conditions.

Nearshore Morphodynamics
The water levels and waves generated by the coupled ADCIRC+SWAN model are used as input offshore boundary conditions for the surf zone, where wave setup, resulting from wave breaking, can be large.
conditions for the morphodynamics models, quantifying the morphological changes of the nearshore bathymetry on eastern Lake Erie during 2012. In the following subsections, descriptions are provided for the models, study area, grid sensitivity, and the model setup.

**XBeach Model**

The XBeach is a process-based numerical model for simulating the morphodynamic processes of sandy coasts (Roelvink et al., 2009, 2010). The model simulates hydrodynamic processes of short-wave transformation, including refraction, shoaling and breaking, long wave (infragravity wave) generation, propagation and dissipation, wave-induced setup, unsteady currents, overwash, and inundation (Sallenger, 2000). The morphodynamic processes include, among others, bedload and suspended sediment transport, dune erosion, and breaching. The model has been validated extensively using analytical, laboratory, and field data.

The wave action equation is solved for the wave height variations on the scale of wave groups. It employs a dissipation model with wave groups and a roller model accounting for momentum at the water surface once waves break. The forcing applied through the radiation stress gradients on the water column can generate low-frequency harmonics such as infragravity waves as well as unsteady currents. These processes are solved in XBeach using the nonlinear shallow-water equations. Thus, wave-induced currents such as longshore current, rip currents, and undertow can be simulated by the model.

The sediment transport formulation is based on the depth-averaged advection-diffusion equation (Galappatti and Vreugdenhil, 1985) to calculate sediment concentration in the water column using a source-sink term depending on the equilibrium suspended sediment and bed load concentrations. The sediment is assumed to be mobilized or deposited depending on the comparison of the actual sediment concentration with the equilibrium sediment concentration. If the actual sediment concentration is less than the equilibrium sediment concentration, the sediment will be transported. Otherwise, it is considered to be deposited. The bottom elevation is updated based on the gradient in sediment transport formulation.

**CSHORE Model**

The CSHORE model, which is currently used for FEMA flood-mapping studies, among other coastal-related applications, is a process-based nearshore morphodynamic model. The current version of CSHORE includes a combined wave and current model based on time-averaged continuity, momentum, wave action, and roller energy equations; a sediment transport model for bed and suspended load coupled with the continuity equation of bottom sediment; a permeable layer model for porous flow; and a probabilistic swash model on impermeable (fine sand) and permeable (gravel and stone) bottoms (Johnson, Kobayashi, and Gravens, 2012; Kobayashi and Farhadzadeh, 2008).

The CSHORE model assumes unidirectional irregular waves and alongshore uniformity along each cross-shore line. The hydrodynamic model in the CSHORE predicts the mean and standard deviation of the free-surface elevation above the still water level and depth-averaged cross-shore and longshore velocities. The equivalency of the time and probabilistic averaging is assumed to reduce computation time considerably. In the wet zone, the probability distributions of the free surface and velocity are assumed to be Gaussian. In the wet and dry zone, the wave angle was assumed to be small and remains the same as the wave angle at the still water shoreline. The probability distribution of water depth in the swash zone is assumed to be exponential. The time-averaged continuity and momentum equations are used together with the wet probability for the presence of water (Kobayashi et al., 2010).

The sediment components of CSHORE are as follows: a cohesionless sediment transport model for suspended load and bedload; a continuity equation of sand bottom for beach profile evolution prediction; and a soft cliff erosion model for downwash erosion of consolidated sediment comprising cohesive and cohesionless materials (Kobayashi and Weitzner, 2015; Kobayashi and Zhu, 2020).

**Morphodynamic Model Setup**

The model validation is performed by the cross-calibration procedure through which input parameters of XBeach are calibrated until it produces nearly identical results as CSHORE, which has already been validated for the Great Lakes shore erosion and flooding applications, as discussed previously. This procedure is followed because of the lack of beach survey data for the study area. The simulations are completed using the actual water level and wave conditions for the two selected transects shown in Figure 2b (P1 and P2). The cross-calibrated model parameters are summarized in Table 1.

The sensitivity of the cross-calibrated 1D XBeach and CSHORE models to the grid resolution is evaluated for selecting the optimal grid size. Three different grid sizes, \( dx = 5 \text{ m}, 10 \text{ m}, \) and \( 20 \text{ m} \), are considered. The results show that the two models are relatively insensitive to the grid resolution. Table 2 summarizes the comparisons of the eroded area above mean sea level (MSL) for pairs of grid sizes.

Although XBeach is more sensitive to the grid resolution than CSHORE, refining the grid size by four times, from \( 20 \text{ m} \) to \( 5 \text{ m} \), results in only an 8.6% difference in the computed eroded area. Hence, to reduce the computation cost, \( dx = 10 \text{ m} \) is selected for the 2D morphodynamics modeling.

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### Table 1. Parameters of the cross-calibrated XBeach and CSHORE morphodynamics models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>CSHORE</td>
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<tr>
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<td>gamma</td>
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RESULTS

To evaluate the performance of the lake-wide hydrodynamic model, the simulated water levels are compared with the measurements at the water-level stations, operated by NOAA and Canada’s Department of Fisheries and Oceans (Figure 3). The normalized root mean square error (NRMSE) is used to quantify the accuracy of the ADCIRC+SWAN model results. The NRMSE of the surge levels calculated based on the long-term average lake level (Figure 4) ranges between 3.4% and 7.6%. The largest differences are observed in the southern part of the lake, Fairport and Cleveland, Ohio. Although the error values are relatively high at these stations, the range of water-level variations is small and perhaps within the error range.

In addition to the surge comparisons, the coupled model is evaluated for the prediction of the wave field. Figure 5 shows the comparisons of the simulated and measured significant wave height (Hs), peak wave period (Tp), and mean wave direction (Dir°) for the three wave buoys (Figure 3) operated by National Data Buoy Center. Although the model predicts the significant wave height within an approximately 3–5% error margin, the error increases to ~5–14% for the peak wave period. The simulated and measured mean wave directions are in agreement for the West Erie wave buoy, which is the only

<table>
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<th>Comparison</th>
<th>XBeach</th>
<th>CSHORE</th>
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<tr>
<td>10 m–20 m</td>
<td>3.6</td>
<td>3.6</td>
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</table>

Table 2. Grid sensitivity analysis of XBeach and CSHORE morphodynamics models.

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buoy with these data. Overall, it is concluded that the coupled ADCIRC+SWAN model performed well in predicting the water level and wave fields for 2012.

Figure 6 shows the results from the calibrated morphodynamics models for the two selected transects shown in Figure 2b (P1 and P2). The hourly time series of the wave and water level, obtained from the ADCIRC+SWAN model, are applied as the offshore flow boundary condition for the transects P1 and P2. The comparisons of the initial \((z_0)\) and final \((z_f)\) bed profiles show that erosion occurred mostly above the MSL, and the eroded material is deposited offshore of the shoreline where the depth is 1 m–2 m.

The water-level output from the lake-wide hydrodynamic model at the offshore boundary of the nearshore morphodynamics model is filtered to synthetically create a seiche-free (SF) condition. To remove the seiching oscillations, first the low-frequency oscillations in Lake Erie are identified through the spectral analysis of the hourly water levels. The power spectral density (PSD), \(S_{xx}(f)\), of a real stationary signal, \(x(t)\), is the Fourier transform of its autocorrelation, \(R_{xx}(\tau)\).

\[
S_{xx}(f) = \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-2\pi i f \tau} d\tau
\]

The predominant storm-induced seiching motions are considered to have a period larger than 2.5 h but shorter than two weeks, consistent with the previous studies (Farhadzadeh, 2017; Farhadzadeh, Arabi, and Bokuniewicz, 2018). Hence, to generate the synthetic SF water levels, the oscillations beyond this range are filtered by applying a band-pass filter. Figure 7 shows the PSD of the measured and computed lake levels for Buffalo and Sturgeon Point, New York, stations for 2012. Several distinct peaks can be identified at the frequencies 1.7, 2.6, 4.1, and 5.8 cycles per day, which are related to the first four seiche modes corresponding to the periods of 14.2, 9.2, 5.9, and 4.1 h (Farhadzadeh, 2017; Platzman and Rao, 1964a; Sogut and Farhadzadeh, 2018). The comparison of the measured and modeled water-level spectra for the two stations (Figure 7) indicates that the lake-wide hydrodynamic model can satisfactorily reproduce the spectra of low-frequency motions where the spikes correspond to the seiche motions.

To quantify the contribution of the seiche to the annual beach evolutions in eastern Lake Erie, the 2D XBeach simulations are performed under the actual (A) and the synthetically created SF water-level conditions. The wave data, generated by

Figure 5. Comparisons of predicted and measured (a) significant wave height; (b) peak wave period; (c) mean wave direction for West Erie wave buoy. Dashed line represents perfect agreement.
the lake-wide hydrodynamics model, are directly used at the offshore boundary with the two water-level conditions without any modifications, assuming that the effects of the low-frequency lake-level variations on the waves at the offshore boundary are negligible.

Figure 8a,b shows the time history of the water level measured at the nearest water-level station to the study area (i.e., Sturgeon Point, New York) during 2012, as well as the simulated water level at the offshore boundary of the XBeach model. The lake-level time series indicates that major storms took place in the winter and fall during the timespans of January–March and October–December, whereas the spring and summer months, i.e., May–September, were relatively calm. The figure also shows that the water-level gradually decreased throughout the year by about 0.5 m.

The synthetic SF water-level time series is derived by applying a band-pass filter, in the frequency domain, to the water-level data and eliminating the oscillations corresponding to the first four modes of the seiche. Then, the signal is transformed back to the time domain. The comparison of the actual and SF water levels at the offshore boundary of the model following a major storm in mid-November in 2012 is represented in Figure 8c. Note that the filtered oscillations following the peak of the storm correspond to the poststorm seiching motions.

Figure 9 shows the plan views of the 2D XBeach model results for the monthly averaged root mean square wave height ($H_{rms}$), wave direction (Dir), current velocity ($U = \sqrt{u^2 + v^2}$), bed load ($q_b$), and suspended load ($q_s$), as well as the bottom variation for each month ($z_{ch} = z_{final} - z_{initial}$) under the actual lake level conditions. The parameters $z_{initial}$ and $z_{final}$ are the bottom elevations at the beginning and end of each month, respectively. As indicated in the figure, the plots are related to the storm season in 2012. It is expected that seiching motions contribute to the nearshore morphological changes during the storm season. Figure 10 presents the model results for the same quantities under the synthetic SF condition.

**DISCUSSION**

At the southern boundary of the domain, the nearshore current velocity is strong likely because of the shoreline alignment. There, the relative orientation of the predominant incident waves with respect to the curved shoreline leads to the formation of a strong longshore current. As Figures 9 and 10 show, the longshore current is strongest in January, when a higher number of storms took place, followed by February and December. The velocity field demonstrates a relatively similar pattern for the six storm months—the current near the

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**Figure 6.** Cross-calibrated cross-shore profiles for transects: (a) P1, and (b) P2 shown in Figure 2.

**Figure 7.** Power spectral density of measured and predicted water levels for Eastern Lake Erie for 2012. The $f_1$, $f_2$, $f_3$, and $f_4$ correspond to the first four seiche modes.

**Figure 8.** Time histories of (a) actual water levels (WL) at Sturgeon Point, New York (measurement: circles; predicted: solid line); (b) actual (black solid line) and SF (WL$_{SF}$: dashed line) water levels at the offshore boundary of XBeach model in 2012; (c) comparison of poststorm actual (WL) and SF (WL$_{SF}$) water levels at the offshore boundary of XBeach model in 2012.
southern boundary is directed northward and then offshore before turning northward and onshore around the northern boundary.

A shoal in the northern part of the study area (Figure 2b), formed possibly because of the sediment deposit discharged from the Blasdell Creek and Rush Creek at Woodlawn Beach State Park, appears to influence the current velocity pattern. At this shallow zone, the current velocity is higher than that of the nearshore area. Furthermore, at this shoal, the current velocity for the SF condition is greater than that of the actual water-level condition. Additionally, the shoal creates a sheltering effect by reducing the wave height on its leeside, which is extended further north. The central and southern parts of the study area are more exposed to the direct impacts of larger waves and thus are morphologically more dynamic resulting in a higher rate of sediment transport, thanks to a more regular bathymetry and a straight shoreline.

The monthly averaged shore evolutions presented in Figures 9 and 10 show an erosion zone closer to the shoreline and an accretion area at a distance offshore, indicating a net offshore-directed sediment transport during the storm season. The beach profile between the shoreline and the 2 m deep contour line is morphologically the most active zone. Because the beach material is mainly fine sand, the transport mode is primarily suspended load, which is nearly 10 times the bed load. The comparisons of the maxima of the wave height ($H_{\text{rms}}$) along the initial shoreline position indicate that seiche motions increase the maximum wave height $\sim 3$ mm for the actual water-level condition, $\sim 0.179$ m. This small increase in the maximum nearshore wave height results in a slightly larger maximum current velocity ($U$), $\sim 0.0001$ m/s, for the actual water-level condition, $0.013$ m/s. On the other hand, the minimum current velocity for the SF water-level condition is determined to be $\sim 0.0001$ m/s larger than the one for actual water-level condition. This difference is assumed to be related to the depth-limited wave breaking. The maxima of the bed load ($q_b$), $\sim 2.3 \times 10^{-7}$ m$^3$/s, and suspended load ($q_s$), $\sim 4.6 \times 10^{-6}$ m$^3$/s, along the initial shoreline position for the actual water-level condition are found to be $\sim 0.1 \times 10^{-7}$ and $0.4 \times 10^{-6}$ larger compared with those of SF condition, respectively.

The winter wave height, current velocity, and total sediment transport ($q = q_s + q_b$) roses for the actual and SF water conditions at points A and B, located at approximately 100 m offshore (Figure 2), are presented in Figure 11. Although the patterns of the nearshore wave heights and current velocity are not significantly different for the actual and SF conditions for point B, the current velocity for point A, near the southern boundary, is much stronger under the SF condition. Such a difference is likely attributable to the depth-limited wave breaking, which is reflected in the wave rose of point A. Comparing the total sediment transport for the actual and SF water-level conditions, the contribution of the seiche motions on the sediment transport appears along the NE direction at point B. However, for point A the total transport patterns for the two water-level conditions appear to be similar. This is likely related to the shoreline orientation as well as the

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Figure 9. Spatial variations of monthly-averaged root mean square wave height ($H_{\text{rms}}$), wave direction in nautical coordinates (Dir), current velocity ($U$), bed load ($q_b$), suspended load ($q_s$), as well as bed-level change ($\zeta_{ch}$) predicted by XBeach for the actual water-level condition.
The presence of the shoal offshore of Point B. The alongshore variations of the accretion and erosion, as well as the total transport rate, are presented in Figure 12 for three distinct regions: The straight section of the shoreline (Region 1), the leeside of the shoal (Region 2), and the NW-oriented shoreline (Region 3). For Region 1, the straight section of the shoreline, the total erosion, and accretion for the actual water-level condition are approximately 2% more than those of the SF condition. The presence of the shoal in Region 2, which provides a shelter for the shoreline from the wave, influences the nearshore flow patterns, hence, reducing the beach evolution. The eroded and deposited sediment volumes for Region 2 are around 1.5% more under the actual water level compared with those of the SF condition. For Region 3, where the shoreline is oriented toward the NW, the actual water level results in about 1% more erosion and deposition than those of the SF condition. Figure 12c,d shows the alongshore variations of the deposited and eroded sediment volumes for the actual and SF water-level conditions. Because the seiche-induced current flows in a counterclockwise direction in the lake (Hamblin, 1987; Irish and Platzman, 1961; Kite, 1992; Mortimer, 1987; Platzman and Rao, 1964a,b), the difference between total deposited and eroded materials could be attributed to the longshore sediment transport gradient along the shoreline in the computation domain.

The variations of the monthly eroded and deposited sand volumes for the entire shoreline under the actual water-level condition are plotted in Figure 13a. The deviations of the accreted and eroded sediment volumes for the SF condition from those of the actual water level are presented in Figure 13b. As mentioned before, during May–September fewer storms occur, which results in a significant reduction in the bathymetric changes. Therefore, the difference between the actual and SF bottom changes is insignificant during this calm period. This difference becomes greater during the winter months.

Over the 1-year period, the total accretion and erosion under the actual water-level condition are estimated to be approximately 114,630 m$^3$ and 112,745 m$^3$, respectively. Under the SF condition, the accreted and eroded sand volumes are $\sim112,889$ m$^3$ and 110,878 m$^3$, respectively—approximately 1.5% and 1.7% less than the ones for the actual water level condition, respectively. Overall, the eroded or deposited sand volume, during the 1-year period, is found to be $\sim1.5\%$, more under the actual lake condition compared with that of the SF lake; this difference can be attributed to the contribution of the seiche.

CONCLUSIONS

This exploratory study numerically demonstrates the contribution of the seiche to the morphological changes in eastern Lake Erie. The lake-wide hydrodynamics model, the coupled circulation, and spectral wave model (ADCIRC+SWAN) provided the flow-boundary conditions for the 2D process-based morphodynamic model, XBeach, for the entire year of 2012. The computational domain for XBeach includes an area of nearly 2 km alongshore and 2 km cross-shore, encompassing...
Woodlawn Beach State Park, south of Buffalo, New York, where the beach comprises fine sand. The model results indicate that the suspended sediment transport is the dominant transport mode in the study area and that the seiches exacerbate the erosion processes along the beach.

The alongshore variations of the accretion and erosion, as well as the total transport rate, are divided into three distinct regions. In Region 1, in the south where the shoreline is straight, the total erosion and accretion for the actual water-level condition are approximately 2% more than those of the SF condition. For Region 2, the central section of the study area, an offshore shoal provides a shelter for the shoreline from the wave. This shoal appears to influence the nearshore flow patterns, hence, reducing the beach evolution. The eroded and
deposited sediment volumes for Region 2 are around 1.5% more under the actual water-level condition compared with those of the SF condition. Region 3, the northern segment of the shoreline, is oriented toward the NW. In this region, the actual water level results in about 1% more erosion and deposition than those of the SF condition. Furthermore, it is found that over the 1-year period, 2012, the seiche motions contribute to approximately 1.5% of the total accretion/erosion, along the selected stretch of shoreline. These findings are the results of the numerical simulations, which require validations using field data, including beach profiles and sediment sampling. In addition, techniques such as composite modeling (Kamphuis 1996, 2010a; Tomasicchio, D’Alessandro, and Barbaro, 2011) can potentially be used to further analyze the effects of seiching on beach morphology.

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