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Characterizing the Great Lakes hydrokinetic renewable energy resource: Lake Erie wave, surge and seiche characteristics

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ABSTRACT

Lake Erie is the fourth largest, in surface area, of the Great Lakes. Seiching events in the lake have in the past led to breaches of the flood wall in Buffalo (at the eastern end of the lake), causing loss of life, and significant loss to properties. Here, we analyze the potential of Lake Erie for generating electricity from its storm surge, seiching, and wave energy resources. We find that there is significant potential energy in the lake that may be suitable for generating meaningful levels of electricity from seiches and storm surge; for instance, by developing an artificial 'lagoon'. It is shown that an extreme surge event similar to that of January 30, 2008 which generated a surge of approximately +3 m at the eastern end and a corresponding set-down of nearly −2.7 m at the western end of Lake Erie, could contain a total theoretical potential energy of approximately 5×10^7 kWh. If such energy could, practically, be harnessed using a surge lagoon with a surface area of 2 km^2 near Buffalo, the potential energy would be 2.3×10^4 kWh, enough energy to power the equivalent of 40 homes for an entire month. The cost of such a lagoon could be partially offset by the potential of such a structure, and the operation of such a lagoon, to help alleviate flooding during extreme events. Furthermore, as an example, the analysis of the lake-wide wave data for 2011 shows that the monthly mean wave power is greater in the central and eastern basins of Lake Erie. Wave power was highest in October and November when the monthly mean wave power reached 10 kW/m. In contrast to most oceanographic environments, the wave power resource is reduced in winter, mostly due to the presence of surface ice in the lake. The surface ice appears to significantly reduce wave height and power during winter months, resulting in a relatively low annual mean wave power. However, the monthly mean wave power was the lowest in late spring and during summer when the monthly mean wave power was around 2.5 kW/m. Although this study represents the first attempt to assess the marine renewable energy of Lake Erie, further research is necessary to examine the feasibility of energy extraction in the lake.

1. Introduction

As the world population continues to grow against a backdrop of increasing economic development and urbanization, the demand for energy continues to grow. There are, however, limited fossil fuel reserves to meet the world's energy demands, and so more sustainable and less polluting renewable sources of electricity generation are sought, including hydrokinetic energy.

The Electric Power Research Institute (EPRI) estimated the annual energy potential from wave energy along the outer shelf (notional 200 m depth contour) and inner shelf (notional 50 m depth contour) of the US East Coast as 237 TWh and 172 TWh, respectively. In the state of New York, the annual available wave energy resource along its outer and inner shelf was estimated to be 16 TWh and 12 TWh, respectively [1]. However, the report does not account for the renewable wave energy potential of the Great Lakes bordering this state, *i.e.* Lake Ontario and Lake Erie. A study by the New York State Energy Research and Development Authority (NYSERDA) suggested that, if fully developed, the available primary renewable resource without regard for cost, social, or technological restrictions, could supply 41% of New York State's total primary energy demand by 2030. If energy for transportation is excluded from the projection, renewable resources have the technical

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capacity to supply 54% of the State's total energy needs by 2030. Based on an assessment, in 2010, less than 10% of New York State's total energy demand, including transportation, was supplied by renewable energy [2]. This estimate does not include the resources available in the Great Lakes, which contain about 21% of the world's surface fresh water. Among the Great Lakes, Lake Erie with a surface area of approximately 26,000 km^2, is the fourth largest and the smallest in volume [3]. It is also the eleventh largest lake in the world, bordering with States of New York, Pennsylvania, Ohio, and Michigan in the US, and the Province of Ontario in Canada.

Offshore wind energy of the lake has attracted some interest among communities and researchers. Lake Erie Energy Development Corporation (LEEDCo) was initiated in 2009, as a nonprofit organization, to develop offshore wind energy in Lake Erie. A 20.7 MW wind project off the Ohio coast has been planned as a pilot project to demonstrate the feasibility of offshore wind, and to facilitate and expedite future offshore wind projects [4]. The suitability of offshore wind projects in this area has been reported in the academic literature (*e.g.*, [5]).

Lake Erie's hydrokinetic renewable energy resources are characterized through this study. Firstly, Lake Erie's characteristics and the data used in this study are presented. Then, the method and tools used for the analyses of the data are described, namely in situ and numerical modelling. Following this, the results are presented, and finally some conclusions are made.

2. Methods

Historical water level data collected at several National Oceanic and Atmospheric Agency's (NOAA), as well as Canada's Department of Fisheries and Oceans, water level stations were analyzed to identify short-term extreme events (*i.e.,* storms). Return period analysis of the extreme events was carried out to determine the frequency of occurrence of the events. The primary goal here is to propose a potential methodology to harness extreme surge and seiche energy by adapting the tidal lagoon concept (*e.g.*, [6]) which could also alleviate coastal flooding in coastal Lake Erie. The extreme event analysis will also provide information regarding the magnitude and number of extreme events per year that could be used to estimate annual energy of storm surge and seiching in the lake that could be extracted using the lagoons.

To characterize the levels of energy associated with various modes of seiching, spectral analysis of long-term hourly lake level time-series were carried out, and the power spectral density (PSD) of the water levels at various locations around the lake developed.

A two-dimensional coupled circulation and spectral wave model was used to simulate lake-wide variation of the lake level during storms. The potential energy contained in individual extreme events was estimated using the predicted water level during extreme events.

Lake Erie undergoes extensive surface ice cover during winter months. The effect of ice cover on storm surge was quantified by comparing the lake level responses to atmospheric forcing under the actual ice-covered, and a hypothetical ice-free lake for a storm event.

To characterize wave energy in Lake Erie, historical wave data from three active wave buoys were used. Furthermore, lake-wide monthly averaged wave power maps were developed and presented for year 2011, selected as an example. The maps are generated based on the hindcast wave data provided by the US Army Corps of Engineers (USACE).

2.1. Study area

Lake Erie's length and width are approximately 400 km and 90 km, respectively. Lake Erie has mean and maximum depths of about 20 m and 63 m, respectively (see Fig. 1).

The water levels in Lake Erie undergo various cycles of changes at intra- and inter-annual timescales. Short-term lake level variation occurs due to storm surge induced by high wind and low pressure systems moving over the Great Lakes region. The historical water level data shows that eastern Lake Erie experiences storm surges of up to 3 m. Annual lake level change occurs due to seasonal climate variability that affects the amount of water flowing into and out of Lake Erie, the contribution of groundwater, and precipitation & evaporation directly into and from the lake. The lake level is normally highest during late spring and early summer, and lowest during winter. Long term fluctuations are primarily due to deviation from the average climatic condition. For instance, higher or lower than average precipitation occurring in several successive years can deviate the long term water level from its average. Climate change is expected to result in more powerful, more frequent, and longer duration storms in the Great Lakes basin [7]. Lake Erie, the shallowest of the Great Lakes, is known for its high storm surge and low frequency oscillations (*i.e.,* seiches). Following a strong wind blowing along the longer axis of the lake from Toledo in the southwest toward Buffalo in the northeast (the predominant wind direction), or vice versa, standing waves or seiches are developed in the lake, travelling back and forth and rotating counterclockwise around the lake until their energy dissipates. A combination of factors, including water level, waves, and currents, results in extreme events that can cause flooding and erosion in coastal areas. A seiche event in 1844, considered as "one of the greatest natural disasters in Buffalo's recorded history", reportedly "occurred without warning, breaching the 4.5 m floodwall, flooding the waterfront, and drowning at least 78 people" [8]. In 2008, a powerful storm that created up to 5 m high waves and a storm surge of about 3 m resulted in flooding near Buffalo [9]. Analysis of water level and flow rate data shows that the impact of seiche waves can potentially extend beyond the lake, especially along streams and rivers.

Lake Erie's seiche has been the subject of several early studies [10]. Attempts were made to identify the frequencies corresponding to the modes of free oscillations based on limited lake level data. Spectral analyses showed that low frequency oscillations of the lake level were more energetic during winter than summer, but less concentrated at the frequencies related to the first and second seiching modes. Using standard harmonic analysis, the tidal amplitude and phase of lunar semidiurnal tides was determined. The tide is insignificant in Lake Erie. A counterclockwise rotation of high water level corresponding to diurnal and lower order seiches was identified using spectral analysis of limited lake level data [11–13]. The relationship between meteorological forcing and water level oscillation in Lake Erie was studied using wind and water level data [14–16]. The propagation of seiche waves under ice-free and ice-covered Lake Erie was studied and it was found that the surface ice can suppress the low frequency oscillations of the lake water level [17].

As the shallowest of the five Great Lakes, Lake Erie warms up more rapidly in summer, and freezes over in winter more frequently and more extensively than the other lakes. Almost every winter, Lake Erie is characterized by extensive surface ice. The historical ice data show that the Annual Maximum Ice Cover (AMIC) index, defined as the maximum percentage lake surface area covered by ice during a given year, was greater than or equal to 80% between 1973 and 2014, with the exception of 6 winters. The ice data also reveal that in the recent years, Lake Erie experienced less severe winters, resulting in lower levels of surface ice concentrations [18].