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***Abstract*—Characterization of the coastal climate was required for a project considering development activities in close proximity to the low lying shoreline inside an existing harbour on Lake Erie. The coastal climate of Lake Erie was assessed using the TELEMAC open source numerical modeling code. Lake wide models capturing the effects of wind generated waves and surge hydrodynamics were developed using the TOMAWAC spectral wave model and TELEMAC-2D hydrodynamic model, respectively. The main forcing to the lake wide models were wind fields that varied in both time and space. After obtaining local water level and offshore wave conditions during times of peak surge, an ARTEMIS phase resolving wave model was used for calculations of wave agitation through the harbour entrance. The ARTEMIS model results were also used to obtain the wave conditions near the site of the proposed works. A summary of the intricacies of the numerical modeling efforts carried out in this project are presented in the paper, along with the main findings.**

I. INTRODUCTION

The North American Great Lakes are a series of interconnected fresh water ecosystems that connects to the Atlantic Ocean through the St. Lawrence River at the eastern part of the basin. The border between Canada and United States generally lies mid-way though each lake (with the exception of Lake Michigan, which is entirely within the United States). The Great Lakes formed at the end of the last glacial period, about 10,000 years ago as the retreating ice sheets moved northward and etched the then existing land mass. The result was the formation of the five Great Lakes, named Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario. The water inside the Great Lakes has been left by the retreating glaciers, with only about 1% on average originating from upland sources (rivers, precipitation and groundwater that eventually discharge into the lakes). Historically, evaporation and outflows from the Great Lakes have been balanced by the upland sources, making levels in the lakes fairly constant. Fig. 1 shows the Great Lakes systems, together with their main interconnected rivers.

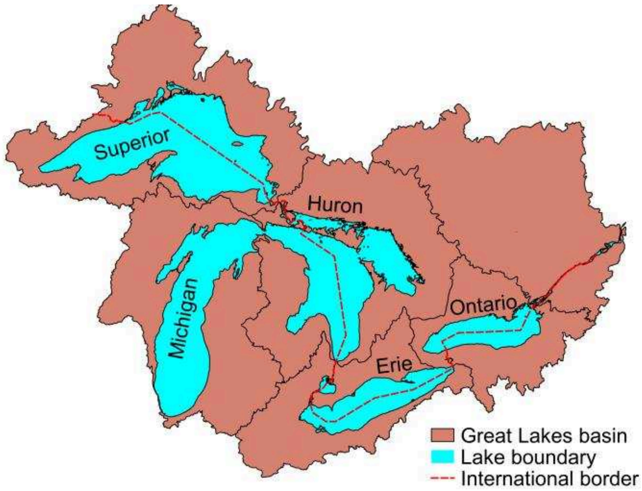

Figure 1. Great Lakes basin

Due to their physical characteristics (mainly sheer size) each of the five Great Lakes are considered inland seas. Each lake has its own wave climate and defined littoral drift characteristics, making them self sustained coastal systems. The North American climate plays significant roles in the seasonal response of the lakes. For example, approximately two months of every year large portions of the lakes are frozen, particularly near the shoreline. Basin hydrology defines long term water level in the Great Lakes, which can fluctuate in the order of one meter +/- between the seasons. Local wind climate controls the short term fluctuation of the water levels (storm surges), and governs the generation of waves for each lake.

This paper focuses on characterizing the site specific coastal climate inside a harbour on the north shore of Lake Erie. Lake Erie, the shallowest of the Great Lakes is approximately 400 km long, 100 km wide and has a mean depth of about 20 m. Maximum depth of the lake approximately 64 m and is situated on its eastern basin, offshore of the Long Point spit. Of particular concern in the site specific assessment were the 100-yr instantaneous water levels, which are governed in part by regional hydrology (which establishes mean levels) and in part by wind climate (which is responsible for storm surges in the lake). Prevailing winds are oriented parallel to the long axis and are responsible for producing storm surges for majority of its eastern shorelines. The maximum wave conditions are coincident with times of maximum surge, thus making site specific evaluations heavily sensitive to winds.

A. Literature review

The Ministry of Natural Resources (a branch of the Canadian provincial government) has developed technical guidelines titled “Technical Guide for Great Lakes - St. Lawrence River Shorelines” [1] with a focus on the evaluating hazards with the adjacent to the lakes and its connected channels (rivers that link the lakes). The Technical Guide focuses on dynamics of physical processes operating near shorelines of the Great Lakes and its connecting channels. Main physical processes covered in [1] deal with coastal flooding, erosion and dynamic beaches, and ways in which they influence and shape shorelines.

MNR Technical Guide [1] also presents a methodology and results of the assessment of 100-yr instantaneous water levels for the Canadian shoreline of the Great Lakes. Even though the MNR publication date is 2001, the assessment of storm surge water levels was performed in 1989 and is considered dated, especially in light of recent development in the field of storm surge modeling. Regardless, [1] used the best available methodology at the time the analysis was undertaken. Corresponding wave climate was not included in the Technical Guidelines publication, probably because a wave hindcast study carried out by the US Army Corps of Engineers produced offshore wave conditions at select nodes for the US and Canadian shoreline of the Great Lakes [2].

As it pertains to storm surges on Lake Erie, one of the first documented studies is the investigation reported in [3], where extreme wind tides (referred nowadays as storm surges) were linked with meteorological conditions over the lake. The authors analyzed water levels from a period between 1940-1959 and found that differences in levels between eastern and western ends of the lake can be expected to be excess of 2 m with a return period of 2-yrs. Analysis of storm tracks failed to reveal simple relationships between magnitude of set-up and storm paths. Work carried out by the same author in subsequent years builds on the previous work and ultimately develops a methodology for prediction of storm surges on Lake Erie based on statistical methods. The methods are heavily dependent on having a forecast of winds that vary in time and space.

Reference [4] reports on the numerical model developed using an impulse response function to forecast and hindcast water levels in Lake Erie. The storm surge model in [4] takes into account i) 2D nature of the lake and winds over it, ii) operates on an hourly time step, iii) is applicable for the entire lake, iv) incorporates physics required to explain storm surges, and v) is applicable for operational forecasting. One of the main conclusions presented in [4] is that spacial variation of the wind field is as important as the mean wind in determining peak surge levels.

A more recent US study [5] presents a methodology to generate wave and storm surge estimates for a large number of extreme wind events along Lake Michigan. The study is part of US's Federal Emergency Management Agency (FEMA), and is carried out to update coastal flood hazard information for the Great Lakes coastal communities along the US shorelines. The study uses wind and pressure fields obtained from i) on ground observed data, and ii) global circulation model outputs (NOAA's NCEP CFSR reanalysis). Hydrodynamic model ADCIRC is used to model storm surges, and wave model WAM is used for the assessment of wind generated waves.

A paper published in [6] presents a summary of investigations that looked into modeling storm surges on Lake Erie. The study was carried out using Regional Ocean Modeling System (ROMS) coupled with the SWAN wave model using wind fields provided by National Oceanic and Atmospheric Association (NOAA). The study focused on modeling aspects of storm surges prediction. In particular, reference [6] found that contribution to wave setup plays an important role in the overall prediction of surge heights.

Of the above studies presented, only the MNR study [1] presents surge characteristics for the Canadian shoreline. The analyses undertaken in the MNR Technical Guide [1] are dated, and could be quite conservative for some zones of the lakes. In order to update the characteristics of storm surges and wave climate for a site on the Canadian shore, especially as it relates to the assessment of coastal climate at an existing harbour site, new global surge and wave models were required.

B. Structure of paper

The overall purpose of the paper is to present a methodology for estimating a site specific coastal climate (surge and waves) inside an existing harbour along the north shore of Lake Erie. The coastal climate is used for providing site specific design parameters for use in impact assessment evaluations and engineering design of new waterfront structures. The rest of this paper is organized as follows: Section 2 summaries the coastal climate of the Great Lakes, focusing specifically on surge and wave characteristics of Lake Erie. The section documents specific evaluation of water levels and focuses on a methodology developed to estimate the 100-yr peak instantaneous levels at the subject site using existing data and a calibrated TELEMAC-2D storm surge model. Likewise, estimates of offshore wave height during periods of peak surge were estimated using a calibrated TOMAWAC model, simulated using the same inputs as the surge models. Section 3 of the paper presents the ARTEMIS wave model and ways it is applied to study the propagation of offshore waves to the subject site along with model results. Section 4 ends the paper with summary and concluding remarks.

II. Lake Erie coastal climate at the global scale

Seasonal levels of Lake Erie are linked to climate and regional hydrology which are responsible for fluctuation in monthly levels in the lake. Lake Erie water levels vary seasonally and are highest at the peak summer months. Peak storm surges typically occur during the fall months, when average levels are below the summer highs.

Lake Erie is the shallowest of the Great Lakes and is oriented such that its long axis is parallel with the prevailing southwest wind directions. These features (lake orientation and dominant winds) and the fact that most of the lake is about 20 m deep cause Lake Erie to be very responsive to wind storms, which can produce significant storm surge events. Storm surge events are defined as winds pushing the water up on one side of the lake while causing lowering of the opposite side. The dominant winds for Lake Erie are from the southwest direction, meaning the lake can experience significant increases of water levels along its northeastern shores. Increases in water levels are particularly damaging when long term monthly average water levels are high (such during the mid 1980's).

A. Assessment of water levels

Previous calculations of peak water levels presented in MNR Technical Guidelines [1] were based on the following methodology:

a) Frequency distribution of highest annual monthly lake level was derived for each lake.

b) Surge or wind setup values were obtained from recorded surges at gauging stations and by modeled surges between gauges using the Environment Canada 1980's vintage SURGE model. A frequency distribution of highest annual recorded surges was obtained.

c) A combined probability analysis was completed of the highest annual monthly mean water level and best fitting frequency distribution of surge values to obtain 100-yr peak instantaneous water levels.

The computation of flood frequencies outlined above is different than is typically the norm. Rather than using shorter records of hourly observed water levels (at time of their analysis only data between 1960-1989 were available), it was deemed more prudent to use longer records of monthly data and combine monthly averaged levels with estimated surge heights. Recognizing the fact that storm surge effects in Great Lakes vary with distance of fetch, MNR Technical Guideline [1] developed a flexible methodology that took into account long history of monthly averaged water levels, combined with estimated storm surge heights.

The conservatism in the above methodology lies in the fact that annual monthly high lake levels (which typically occur during the summer months) are added to the peak surge heights (which occurs during fall months, when monthly average levels are lower). As a result, the estimated 100-yr instantaneous water levels tend to be conservative.

Given that hourly record of water levels for the gauge at the subject site is available for the period between 1962-2013 (significantly more than during the original study), a classical frequency analysis results for the gauge at the subject site is carried out using two methods: i) annual maximum peak instantaneous water level data, and ii) peak over threshold water level data. This type of analysis eliminates the conservatism noted above.

The inspection of the available gauge record at the subject site revealed that some key storms had missing data, meaning that peak lake levels were not available. Since these storms are some with the highest recorded Lake Erie water level, they would certainly have an influence on the 100-yr water level to be computed.

In order to estimate the missing value for the storm with missing peaks, a TELEMAC-2D hydrodynamic model of Lake Erie was developed. The model was set up using a 3 km by 3 km triangular mesh, and refined to 300 m for the nearshore area of the lake adjacent to the subject site. The bathymetry for the model used was provided by NOAA. The initial condition of the model was the observed water level prior to the start of each surge event. Because of interest to this study is the hindcast of water levels, a number of simplifying assumptions were made in the modeling. These assumptions included neglecting Detroit River inflow and Niagara River outflow from the lake. Even though these inputs represent significant discharges (5,000+ m^3/s), they are not critical in the simulations of storm surges for the eastern basin of Lake Erie. Thus, the simplifications made are believed to be justified, given the scope of the modeling. Fig. 2 shows the outline of the TELEMAC-2D domain, alongside with select stations along Canadian shoreline where water levels are measured.

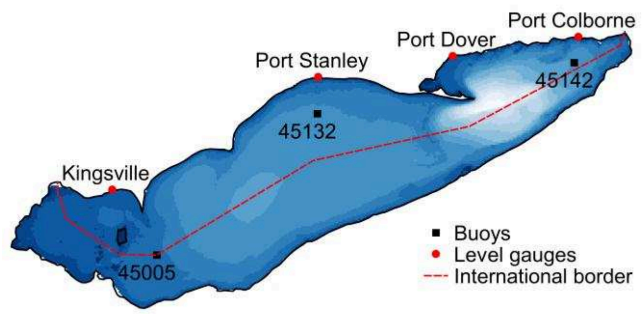

Figure 2. Lake Erie global domain

Since the phenomena that generate storm surges in Lake Erie are wind events, a number of different sources of wind information were explored. Observed wind data from land stations around the perimeter of Lake Erie were obtained from NOAA's National Climate Data Center (NCDC) along Canadian and US shores of the lake. Overlake wind magnitudes were computed from land based observations according to known relationships between air and water temperatures during times of storm surges. The winds were interpolated in space via an inverse distance weighting method algorithm by modifying meteo.f subroutine.

For surge events where observed winds were not available, NCEP CFSR reanalysis (1979-2010) and CFSRv2 (2010-present) hourly winds were obtained from the National Center for Environmental Prediction and used to force the TELEMAC-2D surge model. The CFSR winds over Lake Erie required a small amount of adjustment in order to make them consistent with observations [7]. Similar adjustments to the CFSR and CFSRv2 winds were made on a wind surge study for the Lake St. Clair [8]. Wind stations used in the global modeling is shown in Figure 3.

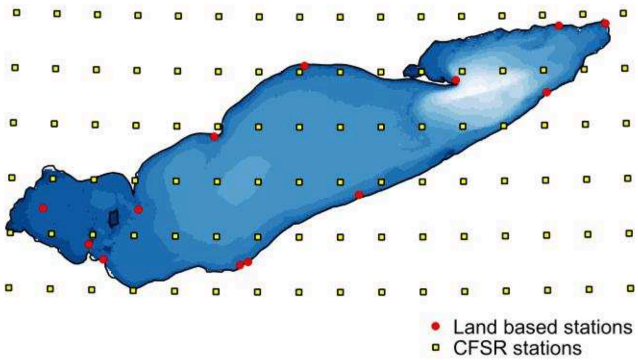

Figure 3. Sources of wind data used in surge and wave models

A sample output from the TELEMAC-2D hydrodynamic model for the storm surge of November 2006 is shown in Fig. 4 for Kingsville, Fig. 5 for Port Stanley, Fig. 6 for Port Dover and Fig. 7 for Port Colborne.

Estimating missing peak surge values via the TELEMAC-2D surge model meant the classical water level frequency analysis could be performed on the historic data (supplemented with peaks estimated from storms with missing data), resulting in more meaningful and representative estimates of the peak flood levels, without the conservatism identified previously.

B. Assessment of offshore waves

Given that TELEMAC-2D model, together with all its necessary inputs was developed as part of the surge study, assessment of wind generated waves with TOMAWAC became relatively straight forward. The same domain, bathymetry and wind forcing were used in the TOMAWAC model as was previously used in the TELEMAC-2D surge model. For purposes of producing wind generated waves offshore of the subject site, a direct coupling with the TELEMAC-2D model was not required since water levels and currents play only minor roles in the development of wind generated waves, especially in offshore locations. This justification meant that the Lake Erie global TOMAWAC model could be run simply by specifying an average water level, and a wind field that varied in time and space.

Results of the TOMAWAC simulations are compared with observations of significant wave heights recorded at three wave buoys in Lake Erie (two operated by Canadian and one by US governments). Plots showing wind generated wave heights for a 30 day period in November of 2013 for locations offshore of Cleveland, Port Stanley, and Port Colborne are shown in Fig. 8, Fig. 9, and Fig. 10, respectively. Excellent agreement is observed between observed and simulated wave heights.

For evaluations and final design, two characteristics wave heights were extracted from the TOMAWAC modeling:

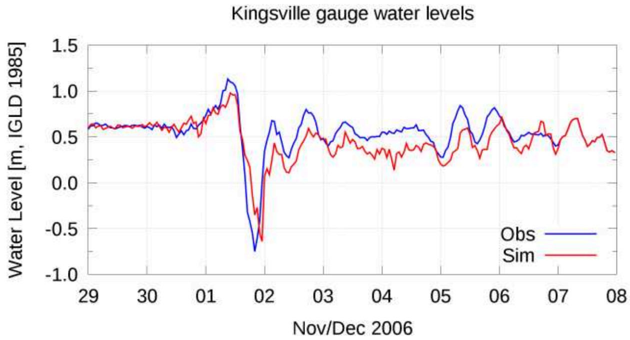

Figure 4. Kingsville water levels

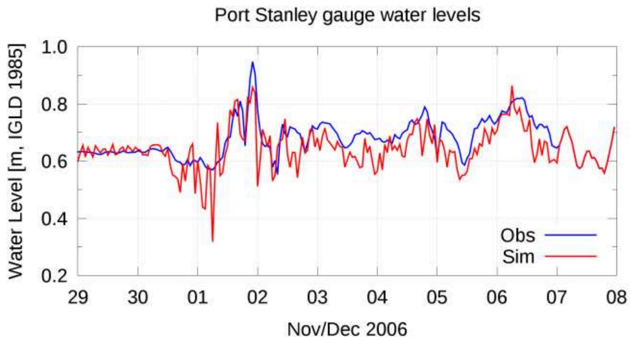

Figure 5. Port Stanley water levels

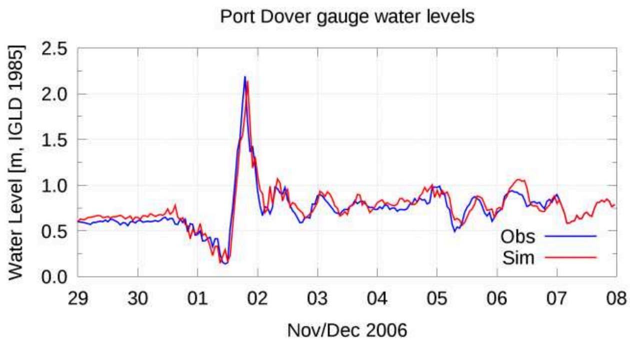

Figure 6. Port Dover water levels

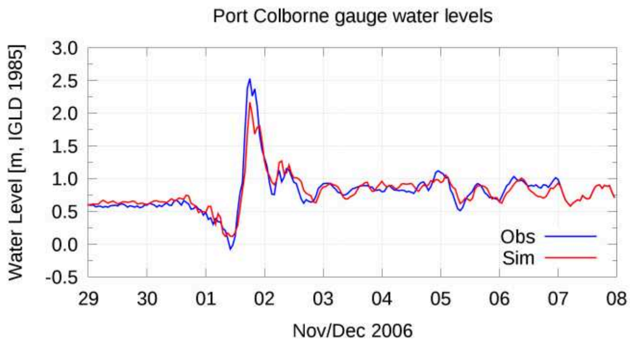

Figure 7. Port Colborne water levels

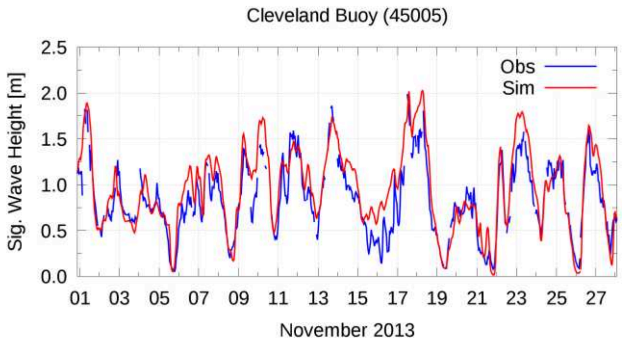

Figure 8. Cleveland wave heights

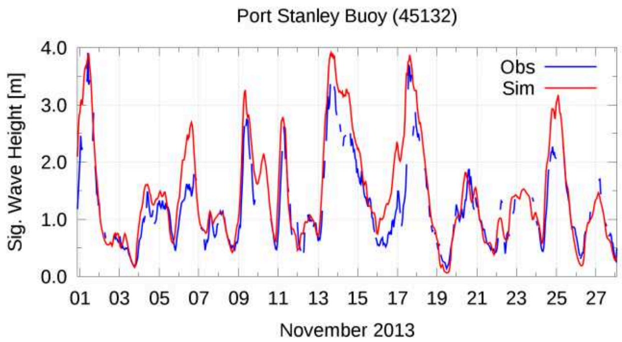

Figure 9. Port Stanley wave heights

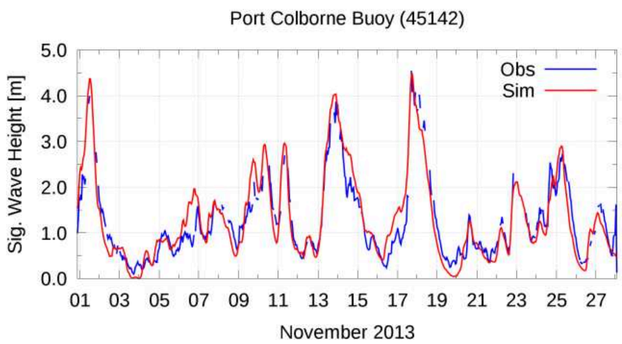

Figure 10. Port Colborne wave heights

Southwest Conditions (N225)
WL = + 2.5 m (harbour structures submerged)
Hm0 = 1.5 m
Tp = 5.05 sec
Dir = N210

East Conditions (N90)
WL = + 1.5 m (harbour structures exposed)
Hm0 = 1.5 m
Tp = 8.14 sec
Dir = N140

where Hm0 (m) = significant wave height
Tp (sec) = peak period
Dir (-) = nautical direction convention

The reason two wave conditions were selected were the following: Southwest winds generate maximum wave at the Eastern Basin of the lake, which coincide with maximum surge water levels. Since southwest waves will include transformation past the Long Point Bay (located west of Port Dover) they may not result in maximum possible wave at the site. As a consequence, east winds (with the fetch from east of Port Colborne to west of Port Dover) could generate different wave characteristics that could possibly govern the structural design at the site. As a result, both southwest and east waves needed to be considered in the analysis.

The southwest and east wave conditions were used as input to the ARTEMIS phase resolving wave modeling presented in Section 3.

III. COASTAL CLIMATE AT A HARBOUR SITE ON LAKE ERIE

Requirements of a past study were to quantify the coastal climate at a site on the north shore of Lake Erie sheltered inside an existing harbour. The 100-yr peak instantaneous water level was estimated at the site using the methodology presented in Section 2.1, while the offshore waves estimated by carrying out TOMAWAC simulations using wind input that varied in time and space (Section 2.2). Since the site of interest is located inside an existing harbour where orientation of the approach structures heavily influences the propagation of waves, simulations using a phase-resolving wave model were required. For the evaluation of waves inside the harbour, ARTEMIS wave model was used. The wave boundary conditions of the ARTEMIS model are presented above, and are extracted from the TOMAWAC simulations.

A. ARTEMIS model domains

Shoreline information was obtained from existing geo-referenced aerial photography and from navigation chart produced by the Canadian Hydrographic Service. Due to the low lying nature of the site under consideration, overland propagation of the waves overtopping the existing harbour walls required evaluation. Overland topographic information from existing mapping was used, as was the survey data collected by Riggs Engineering staff. Shoreline, bathymetry and topographic information were assembled in one master file which was used to define a Triangular Irregular Network (TIN) surface of the entire ARTEMIS model domain. Breaklines that include topographic information of the harbour structures were inserted to properly represent features to be included in the TIN surface.

Two different model domains were used in the ARTEMIS modeling. A modeling domain was developed that included all overland areas inland of the harbour walls on both banks of the river. This modeling domain was necessary for the estimation of the effect of waves propagating inland over possible access roads during design water level conditions which inundate the harbour and its approach structures. Another modeling domain was developed that includes harbour structures that emerge above mean water level. This modeling domain is to be used for the assessment of waves during storms when the water level does not submerge the harbour walls.

The modeling domain that includes overland access roads has existing piers modeled with higher deck elevation than what currently exists (i.e., the piers would be submerged during the design water level conditions). The reason for extending the elevation of the piers above the design water level was purely for modeling purposes. An initial version of the model was set up with the piers fully submerged. Since the ARTEMIS model requires that reflection coefficients be assigned to boundary nodes, this could not easily be achieved with the version of the model that has the piers submerged. A consequence of not assigning reflection coefficients to the vertical piers at the harbour entrance resulted in too little wave energy entering the site of the proposed development location during peak design water levels.

In order to remedy this problem, a decision was made to artificially raise piers such that they are not submerged during design water levels. Doing this allowed assigning proper reflection coefficients, and ensured a reasonable amount of energy reached the subject property.

In all cases the mesh resolution of the ARTEMIS model was kept at 3 m in order to resolve the incident waves approaching the harbour. Furthermore, a request was made that all buildings between the beach and the subject property be excluded from the simulations during design conditions as these structures may dissipate some of the incoming wave energy.

B. ARTEMIS model inputs

The main model inputs in the ARTEMIS wave modeling are the incident wave properties approaching the harbour. These are obtained from the TOMAWAC modeling and are given in Section 2.2. Three cases of incident waves are simulated including:

- case 1 - southwest winds during design peak stillwater level,
- case 2 - east winds during high monthly average water levels, and
- case 3 - southwest winds using high monthly average water levels.

The ARTEMIS model is simulated using mono-directional random waves, implying each incident wave direction is simulated as a separate scenario. Random nature of the waves in the ARTEMIS model is represented by superimposing several monochromatic waves of different periods that are randomly out of phase with one another. The resulting wave energy is computed as the sum of the energy of each component monochromatic wave. In the simulations in this work, five different monochromatic waves were used.

Different reflection coefficients were applied to vertical walls, beach boundaries, and shoreline reaches with revetments and breakwaters.

C. ARTEMIS model results

The results of the ARTEMIS wave modeling for case 1 are shown in Figure 11 using the incident wave information obtained from the TOMAWAC simulations. In this scenario all lands below +2.5 m elevation are submerged (including portions of the harbour walls) and represent areas over which waves can propagate. The results of the simulations indicate that as the waves overtop the harbour structures and the beach on the west side they lose a significant portion of their overall energy. Waves propagating through the harbour entrance can travel upstream to reach the project site. The significant wave height that eventually reaches the development site is computed as being approximately 1.0 m. The remaining portion of the access roads has nominal wave heights (less than 0.2 m).

Case 2 ARTEMIS simulations are those that capture wave propagation through the harbour entrance during strong east winds. Note that the incident wave height for the east winds is higher than for the southwest winds, although this condition occurs much less frequently. For case 2 water surface elevation were set as the maximum monthly average level for Lake Erie, and thus excludes overland portions that were included in case 1 above. Simulations for case 2 are shown in Figure 12 where incident waves are reflected and diffracted off the existing harbour structures. In this case, higher magnitude waves can reach the project site (although they do not become overland wave bores). In the extreme, the modeling shows that the significant wave height in front of the proposed redevelopment can exceed 1.0 m.

Case 3 is used to capture conditions of southwest winds occurring during times of high monthly average water levels (but not the peak stillwater levels). Wave heights can reach the proposed redevelopment location at amplitude in the range of 1.5 m (see Fig. 13) for this case.

D. Impact assessment and structural design

Given the results of numerical analyses providing surge levels, wind generated waves and wave propagation though the harbour implies that site specific assessment of impact of the proposed development to be located on the low lying shoreline could be completed. In particular, assessment related to access/egress during time of peak surge could be evaluated against existing regulations. The analysis was completed according to MNR Technical Guidelines [1], satisfying floodproofing, protection works and access standards. Further, the wave characteristics obtained though the modeling was used in the design of wave protection structures to be installed to mitigate the quantified wave attack.

IV. SUMMARY AND CONCLUSIONS

A site specific assessment of the coastal climate was required to evaluate impacts associated with proposed development activity to be located adjacent to the low lying shoreline inside an existing harbour on the north east shore of Lake Erie.

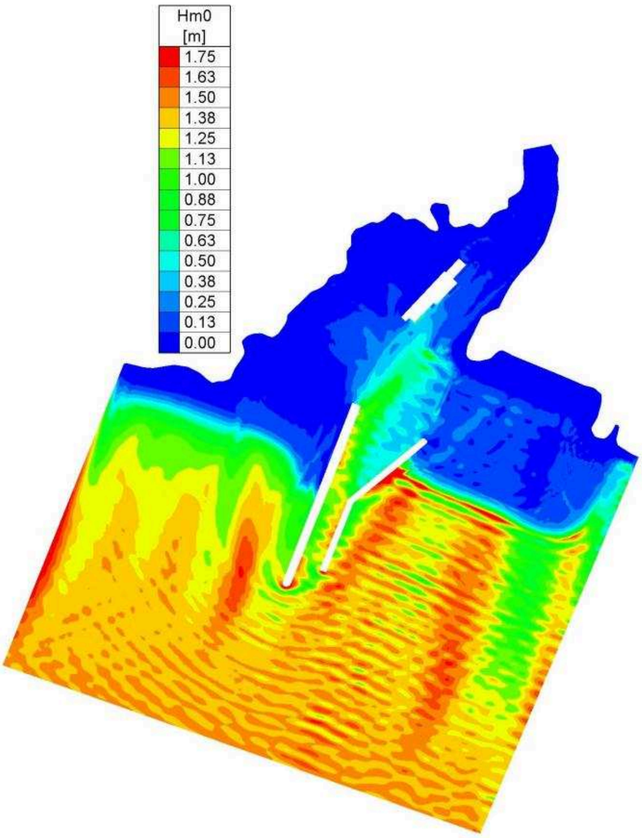

Figure 11. ARTEMIS simulations, significant wave height case 1

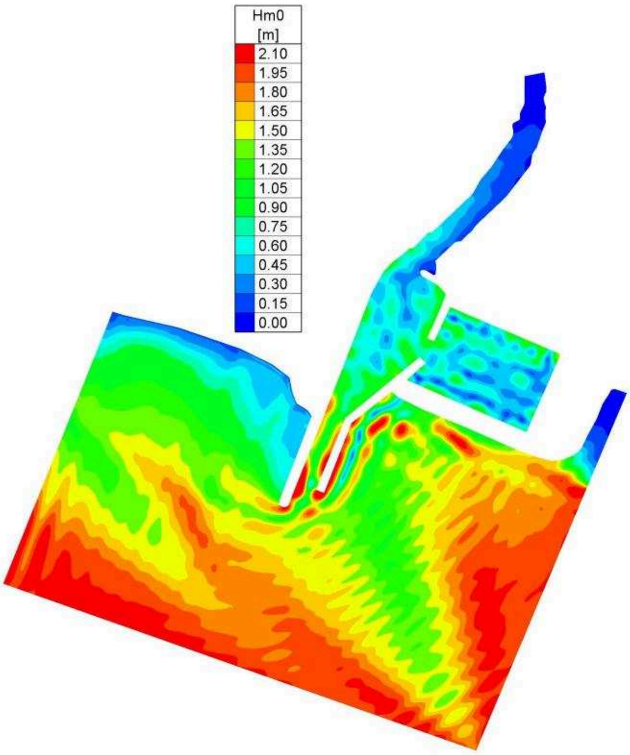

Figure 12. ARTEMIS simulations, significant wave height case 2

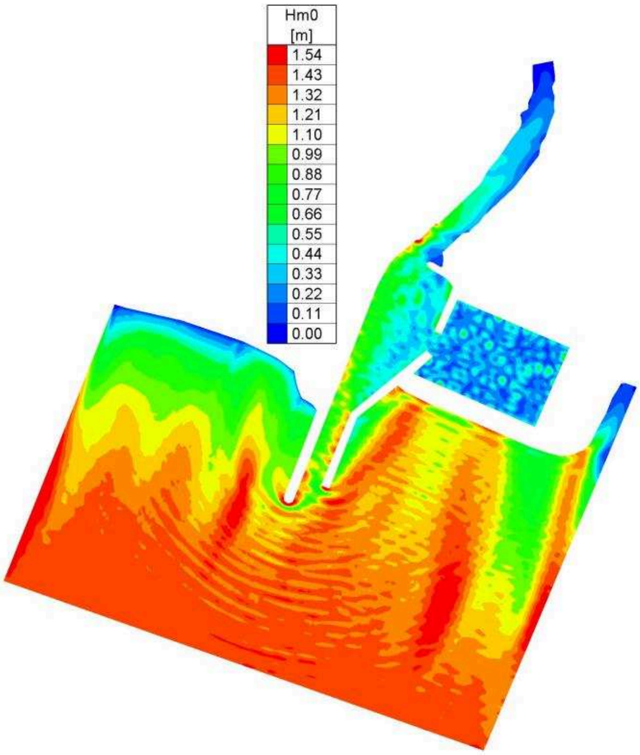

Figure 13. ARTEMIS simulations, significant wave height case 3

The proposed development location is located in an area that could be subject to coastal flooding from storm surges and its corresponding wave attack. With an aid of numerical modeling tools available in the TELEMAC suite of solvers, a site specific evaluation of storm surges, wind generated waves offshore, and propagated waves though the harbour could be evaluated. The results of the modeling were used to establish:

- Site specific 100-yr peak instantaneous water level at the subject site,
- Most appropriate offshore wave corresponding to the calculated surge, and
- A design wave propagated though the harbour entrance, eventually reaching the subject site.

The analysis and results presented in this paper are derived from an existing project recently completed by the author. Names and locations of the property have been omitted in order to preserve client confidentiality.

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