Lake of the Woods Wind-Wave Modeling Report

US Army Corps of Engineers
St. Paul District

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1 PURPOSE

The purpose of this project is to provide local stakeholders with estimates of wind setup and wave parameters along the southern shoreline of the Lake of the Woods for use in assessment and design of shoreline erosion mitigation, water quality practices, and flood risk management measures. These local stakeholders include, but are not limited to, the Lake of the Woods County Soil and Water Conservation Service, the Roseau County Soil and Water Conservation District, the Minnesota Pollution Control Agency, and the Minnesota Department of Natural Resources.

2 BACKGROUND

The Lake of the Woods, located in the northern most part of the U.S. state of Minnesota and a southern portion of the Canadian provinces of Ontario and Manitoba, is the sixth largest freshwater lake that is partially located in the United States. The lake is located in the Northwest Angle of Minnesota which is the northernmost part of the 48 contiguous states and the only portion north of the 49^{th} parallel. The Minnesota cities of Roseau, Warroad, and Baudette are located near the lake.

The lake is fed by inflows from numerous rivers and lakes including the Rainy River, which forms part of the border between the U.S. and Canada and drains a total area of over 27,000 square miles. The lake is regulated through several dam outlet structures, with the largest outflow being the Winnipeg River which flows north to Lake Winnipeg. The lake has a total lake area of over 300,000 acres and a littoral area (less than 15 feet of depth) of nearly 80,000 acres. The maximum depth of the lake is 210 feet. With more than 14,500 islands within the lake, there are over 65,000 miles of shoreline around the 70 mile wide lake and along the islands.

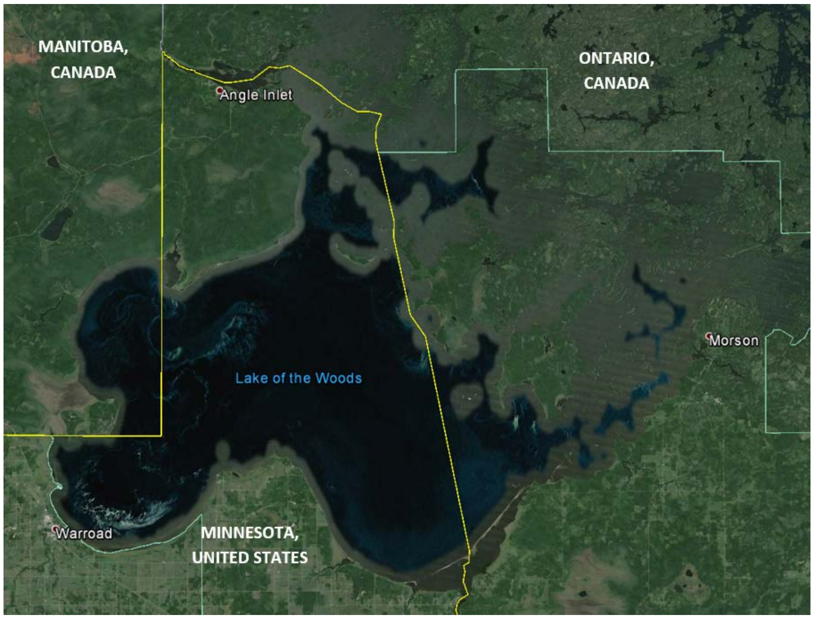

Figure 1 – Overview Map of Lake of the Woods

The purpose of the project is analyze the wind-wave conditions on the Lake of the Woods to generate wave heights and wind setup along the southern shoreline of the lake for a full range of wind speeds and directions. Wind setup, or the vertical rise in a body of water at the downwind shore, can lead to increased flood levels and overland inundation in low lying areas. The development of wave conditions with large wave heights and wave periods can exert high energy on the lake bed and shoreline leading to erosion and transport of bed material. Wave direction can impact the severity of wave attack and the rates of cross-shore sediment transport.

In the late 19th century and early 20th century, concerns with the variation of water levels in the lake have led to the construction of dam outlets. Through work completed by the International Joint Commission (IJC) in the early 20th century, the Lake of the Woods Control Board (LWCB) was established with the intent to establish operating conditions for lake level management. While the dam outlet provides benefit to the regulation of lake levels for property owners and lake users, the lake does not experience the full range of natural variation under operation. Because the lake level band is relatively narrow compared to natural conditions, waves are concentrated within a narrower band. This increased concentration of waves within a narrow band can lead to shoreline erosion and impairment to shoreline habitat within this zone.

Currently, the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) provides forecasts of wave heights throughout the lake every 3 hours from the forecasted wind conditions. While these forecasts provide recreationists and lake level managers with good approximations of the lake conditions for safety and operation decisions, there are limitations with the data provided. The main limitations with these wave condition forecasts are:

1) The resolution of the wave model is coarse (> 1 mile) and does not provide accurate wave conditions along the extensive shoreline length.
2) The forecasted conditions do not provide average annual, maximum annual or extreme conditions of waves for use in planning purposes.

Figure 2 shows an example of the NOAA-NWS forecasted wind-wave conditions for Lake of the Woods.

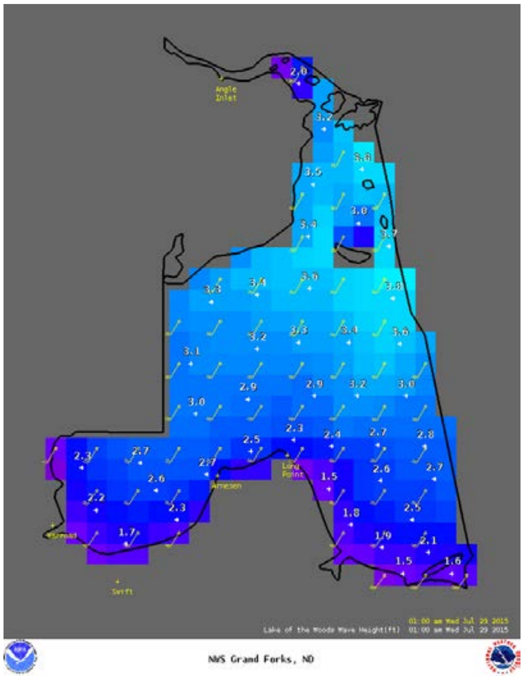

Figure 2 – Example of the coarse NOAA-NWS Wave Forecast for Lake of the Woods

3 METHODS

The Lake of the Woods is large enough in size (300,000 acres) and wide enough in wind fetch length (45-70 miles wide) to lead to substantial wave growth and wind setup conditions throughout the lake. The lake is both deep enough in maximum depth (210 feet) for wave growth and shallow enough in areas (nearly 80,000 acres of less than 15 feet in depth) to lead to wave transformation and wind setup that a detailed two-dimensional model of the wind-wave conditions is deemed appropriate for planning purposes.

The recommended approach to modeling the wind-wave conditions of the Lake of the Woods is to use a coupled two-dimensional model using the Corps of Engineers hydrodynamic model, Adaptive Hydraulic model (AdH), and the Corps of Engineers wave growth and transformation model, Steady State Spectral Wave model (STWAVE).

Adaptive Hydraulics (AdH) 2-D Shallow Water model is a two-dimensional shallow water hydrodynamic model capable of modeling wind setup.

Steady State Spectral Wave (STWAVE) Full-Plane wave model is a two-dimensional, full-plane wave growth and transformation model capable of modeling wave parameters and radiation stress gradients. Nearshore wave propagation and transformation includes wave refraction, shoaling, breaking, and generation.

Surface-water Modeling System (SMS) is a three-dimensional conceptual software used for model construction, data visualization and data extraction.

A summary of the wind-wave modeling results can then be coupled with a wind speed and direction frequency analysis in order to estimate the wind-wave hazard frequency.

3.1 Data Collection

The data requirements for this modeling effort include:

a) bathymetric and ground elevation data for model construction
b) site visit data for bed roughness estimation
c) wind speed and direction data for model calibration and frequency analysis
d) lake stage data for model calibration
e) wave height measurements for model calibration

The horizontal projection used for this modeling effort is USA Albers Equal Area Conic Projection, USGS Version, meters. The vertical datum for the modeling effort is North American Vertical Datum of 1988 (NAVD88), meters. The adjustments between various data are assumed to be as follows:

Table 1 – Vertical datum adjustments between commonly used data

Datum	Ordinary High Water, in feet	Adjustment from local datum, feet	Ordinary High Water, in meters	Adjustment from local datum, meters
NAVD88	1061.77	0.52	323.627	0.158
LOTW (1912 MSL)	1061.25	0	323.469	0
NGVD29	1060.67	-0.58	323.292	-0.177

While the modeling was computed in International System of Units (meters, meters per second, etc.), the report is primarily documented in US Customary Units (feet, miles per hour, etc.)

3.2 Modeling Surface Development

There are multiple sources of elevation data that are used in the development of a three-dimensional surface for both the wind setup hydrodynamic model and the full-plane gridded wave model. Detailed 1-meter cell LIDAR data was available for both the Lake of the Woods County and the Roseau County in Minnesota. Less detailed 30-meter cell LIDAR data was available for the Provinces of Manitoba and Ontario. These four LIDAR digital elevation models (DEMs) allowed for the construction of the shoreline and above water portions of the three-dimensional surface. The bathymetry was obtained from sounding data collected and digitized by Environment Canada (Neilson, 2009). This data was collected over the period from 1916-1999 and digitized in more recent years, referenced to the Lake of the Woods Datum. For this study, the digital sounding data was converted to NAVD 88 datum and combined with the above water elevation data to develop a three-dimensional surface using SMS. A depiction of the various sources of elevation data and the bathymetric sounding point locations is shown in Figure 3.

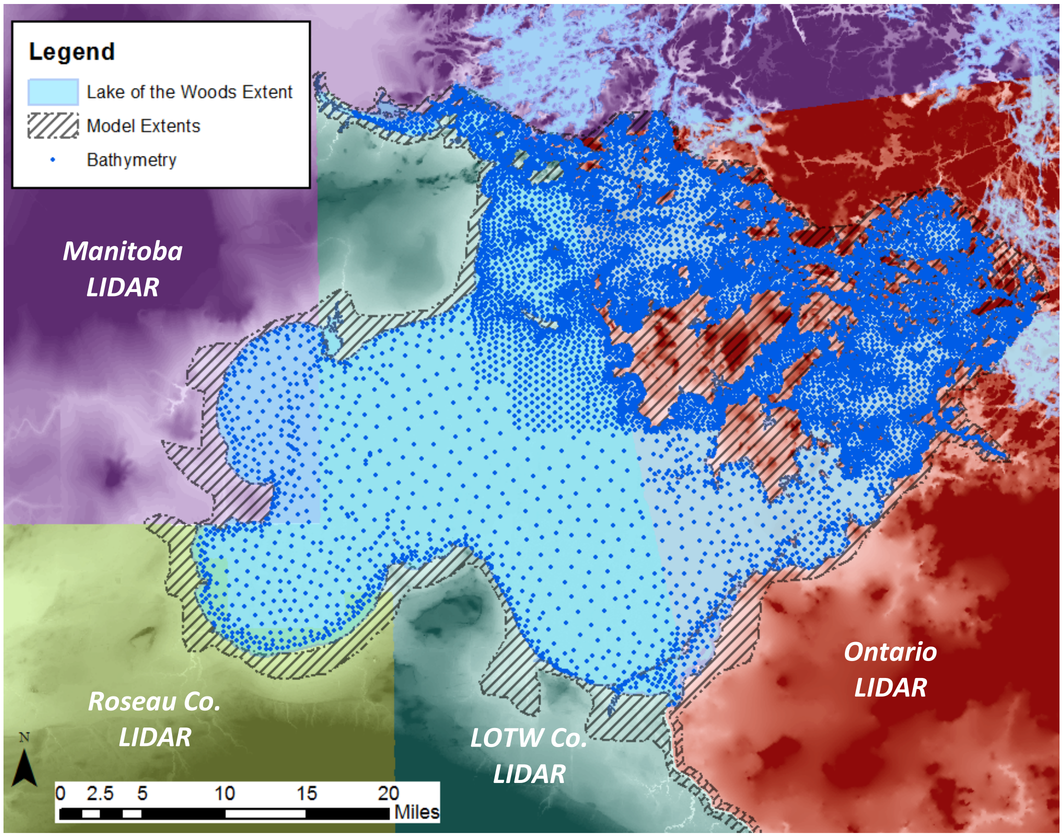

Figure 3 – Bathymetric and Ground Elevation Data Sources

3.3 Shoreline and Bed Roughness Data

Estimates of lake bed and shore roughness values were made through a coarse visual assessment of the sediment size. Vegetation is likely to contribute a smaller portion of the roughness for both the bed and the shore. Much of the southern shore of the Lake of the Woods consists of sandy beaches, rocky shores and points, and placed riprap shoreline protection. These various shoreline types are shown in Figure 4.

Figure 4 – Examples of shoreline sediment sizes from (a) sand to (b) riprap to (c) rock and boulders

Due to the relative size of the lake compared to the effect of roughness, the initial assumption is that roughness would not have a major impact on either wave heights or on wind setup magnitudes. For this reason, the roughness implementation in each model was kept simplistic. For the hydrodynamic wind setup model, two "material" types were specified in the AdH model domain: "shore" and "bed." The Manning's n-value for both materials was estimated by using the Strickler function (Chow, 1959) based on the median sediment size, or d_{50}. The shore areas were estimated to have sediments ranging from sand to stone, or 0.5 mm to 500 mm, resulting in a median size of 16 mm or 0.6 inches and an n-value of 0.021. The lake bed was estimated to consist of silts and sands 0.0039 mm to 0.5 mm in diameter, resulting in an n-value of 0.008. Since the wave model would not push water up on the shore, only one composite n-value was assumed resulting in an n-value of 0.012. A summary of these n-values and material locations is shown in Table 2 and Figure 5.

Table 2 – Manning's n-values for roughness in the wind-wave models

Material	Area	Sediment Type	Lower bound (mm)	Upper bound (mm)	Geometric Mean, D_{50} (mm)	Size, $k_s = D_{50}$ (ft)	Manning's n-value = $0.034*k_s$^1/6
1*	Shore	Sand, Stone	0.5	500	15.8	5.19E-02	0.021
2*	Bed	Silt, Sand	0.0039	0.5	0.044	1.45E-04	0.008
3**	Avg	Silt, Sand, Stone	0.0039	64	0.50	1.64E-03	0.012

* Two materials designated for hydrodynamic, AdH, model domain.
** Approximate average roughness for the entire domain, used in the STWAVE modeling.

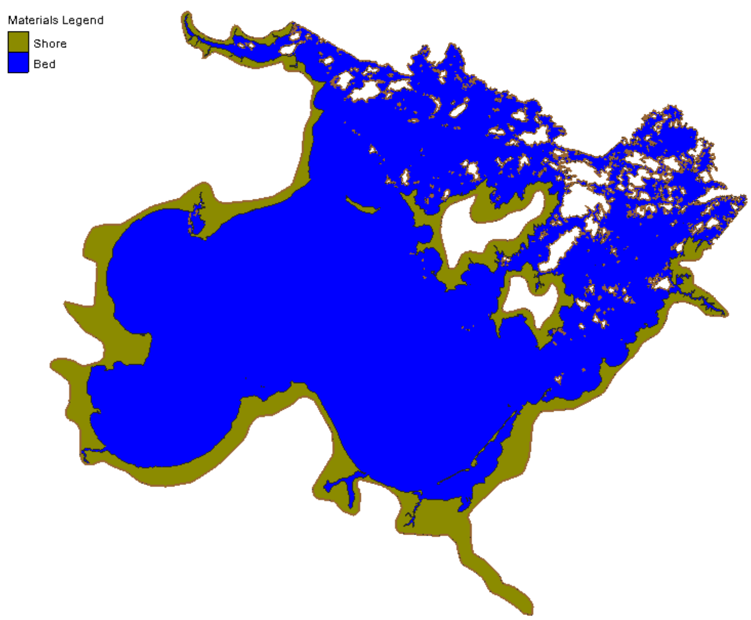

Figure 5 – Material types for different roughness values in the AdH model

Ultimately, the roughness values were not found to have a large effect on wind setup or wave height. Increasing the roughness value in the wave model by a factor of two decreased the maximum wave heights by less than 0.1 feet. Differences in wind setup results were found to be similarly minimal for changes in roughness values.

3.4 Gage Data Analysis

For both model validation and wind-frequency analysis, local gage data was obtained and analyzed for lake stages and wind anemometer stations. While the focus of the modeling is for the US shoreline, both Canadian and US gages were analyzed for lake stage and wind speed time-series. The model domain extends into the Canadian portion of the lake to capture wind fetches in the wave model and conserve the mass of the body of water for the hydrodynamic model. Figure 6 shows the extent of the modeling domain and the relevant stage gages (USGS Gages and Enviro. Canada Gages) and the wind gage utilized (NCDC Wind Station at Baudette Airport).

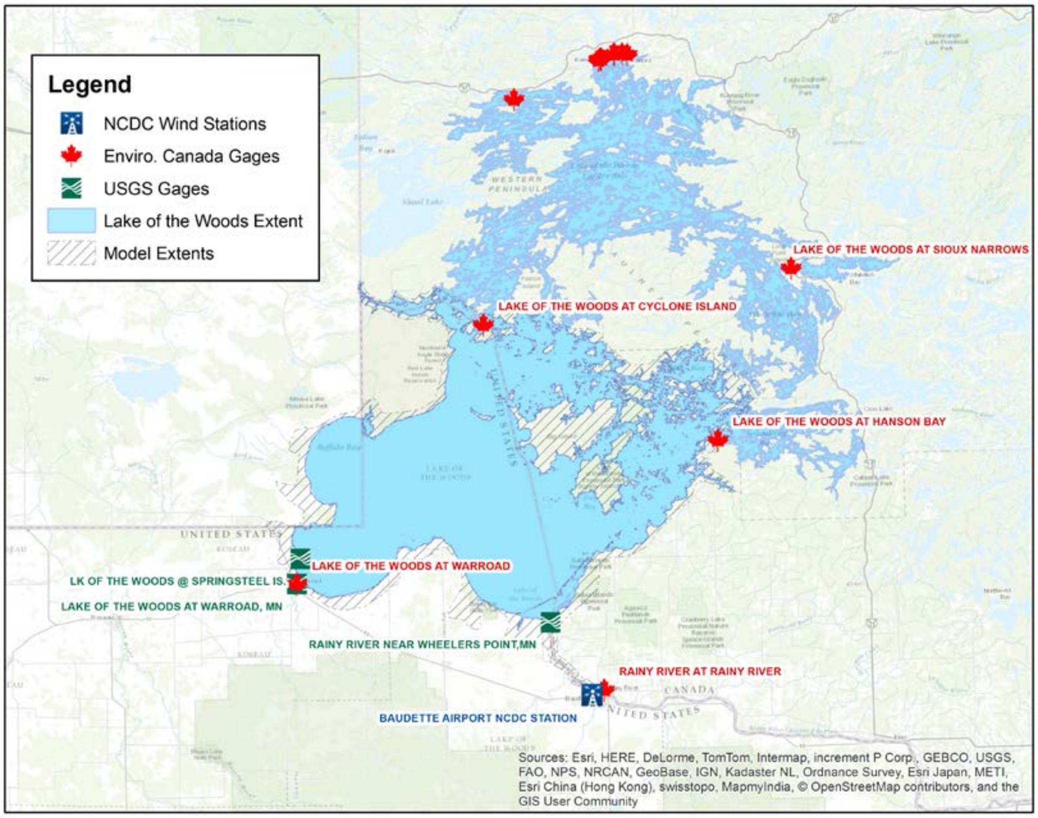

Figure 6 – Gage locations in the US and Canada for wind and stage data

The stage data at Warroad, Cyclone Island, Hanson Bay, and Wheelers Point was downloaded and adjusted to NAVD 88 datum. Various wind events were identified for calibration by noting when opposing sides of the lake showed quick rises and complimentary set downs, indicating wind setup. Three of these events are discussed in the wind setup modeling validation section of this report. Wind data from the Baudette Airport anemometer is discussed in the following section.

3.5 Wind Frequency Analysis

The wind data obtained from the Baudette Airport was reported as the fastest 2-minute wind speed and direction on a daily basis from 1998 through the present. This data was analyzed to identify the relationship between the annual duration and the magnitude and direction of wind as well as the annual chance that extreme winds exceed certain levels. The first step in this analysis was to generate a wind rose to compare the frequency of various magnitudes of wind occur in a given direction. Two wind roses were generated, one based on the average occurrence over the entire year and one based on the average occurrence during months that can experience open water between May and October. These wind roses are shown in Figure 7.

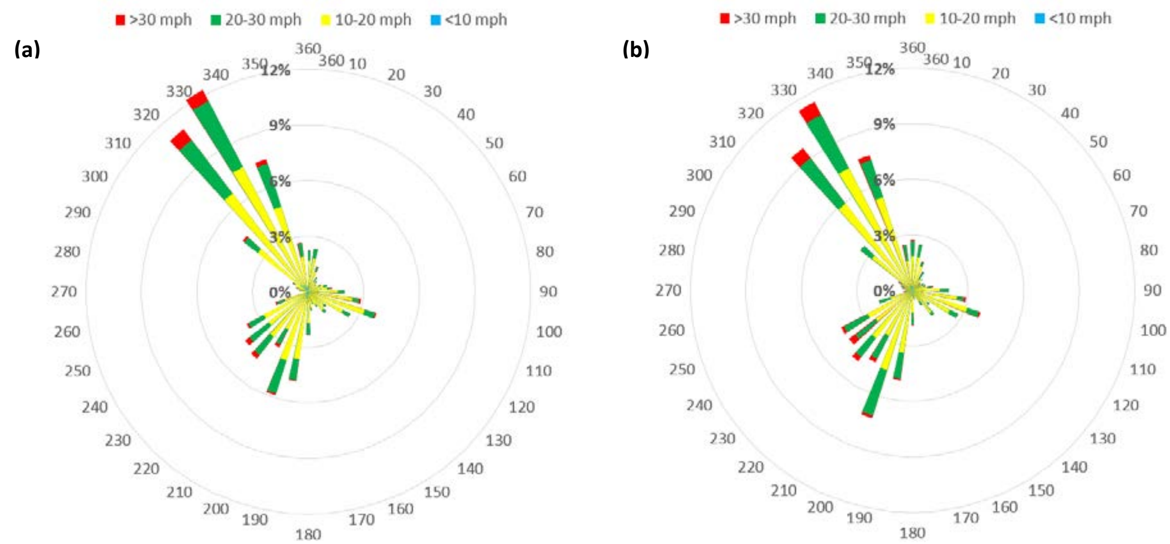

Figure 7 – Wind Rose for maximum 2-minute wind speeds for (a) all season and (b) ice-free months May-Oct

The prevalence of various wind directions is almost identical for ice-free months as it is for the entire year. Winds from the northwest are most dominant at the lake, with a 30% chance that the highest recorded wind speed for a given day is from the northwest.

Another wind rose was developed to look at maximum annual wind speeds at the lake. While daily winds are more often to be highest from the northwest, annual maximum winds have exceeded 30 mph for all wind directions and have exceeded 40 mph for north, northeast, west, and northwest winds. Since the wind directions of concern for the southern shoreline are west, northwest, north, northeast, and east, it is assumed that maximum annual winds are all-directional for the frequency analysis. Figure 8 shows the wind rose for annual maximum wind speeds.

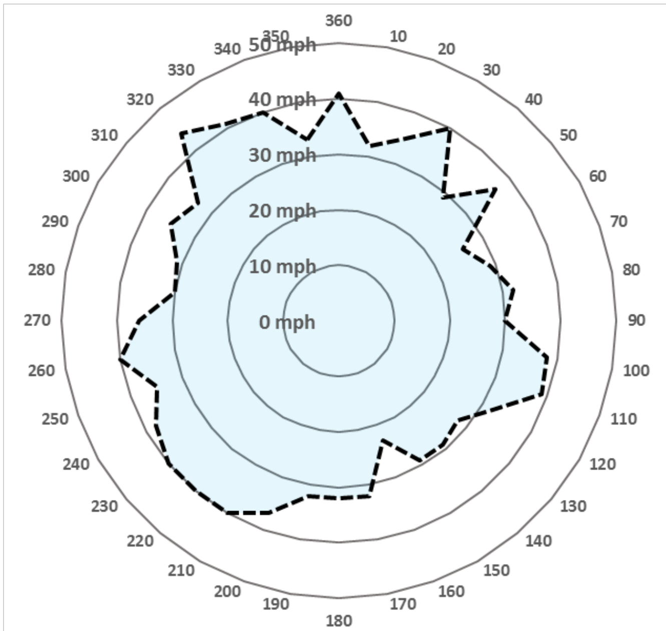

Figure 8 – Wind Rose for annual maximum 2-minute wind speeds

The maximum annual 2-minute wind speed values for each year in the record are shown in Table 3.

Table 3 – Maximum Annual 2-minute Wind Speed Values

Year	Max. annual 2-min. wind speed (mph)
2008	44.1
2007	42.9
2004	40.9
2014	40.9
1998	40
1999	40
2001	40
2002	40
2005	40
2006	40
2009	38.9
2010	38.9
2000	38
2016	38
2011	36.9
2012	36.9
2015	36
2003	34.9
2013	32

The fastest daily 2-minute wind speed and associated direction are standard wind observations to represent sustained winds. Shorter duration 5 second wind speeds are another standard observation, although these measurements represent wind gusts. While a two minute duration is considered to be sustained, it is insufficient in duration to fully develop waves and wind setup over bodies of water. Both wave growth and wind setup depend on fetch length and duration. For most lakes, fetch length is the limiting factor for the water conditions. For a given water body and wind direction, waves and wind setup will continue to grow up to a certain duration, at which point the conditions become "fetch-limited." Constant winds of the same magnitude and direction will not increase wave conditions for durations beyond the "fetch-limited duration." Open oceans and large lakes can often be "duration-limited" in that the fetch lengths are long enough that wave conditions are controlled by the duration of the sustained wind event, rather than the fetch length. The Coastal Engineering Manual (US Army Corps of Engineers, 2002) includes an equation to determine the fetch-limited duration as follows:

$$t_{x,u} = 77.23 \frac{{F_e}^{0.67}}{{U_{10}}^{0.34} g^{0.33}}$$

Where: t = duration
F = fetch length
U = wind speed
g = gravitational constant

Maximum fetch lengths were estimated for each of the considered wind directions, following the procedure described by ETL 1110-2-221, by radially averaging the fetch length +/- 12 degrees from each direction (McCartney, 1976). The wind fetches ranged from 25 miles to 32 miles with an average wind fetch for the lake of 29 miles, as shown in Figure 9.

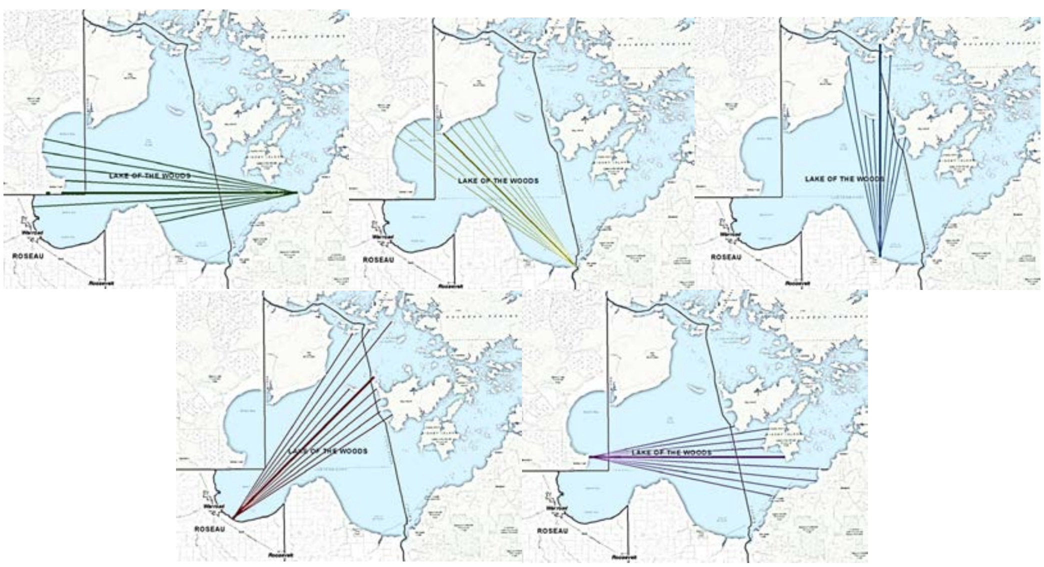

Figure 9 – Wind fetch distances for West, Northwest, North, Northeast and East Winds. Average fetch length of 29 miles.

Since the variation between fetch lengths for different wind directions only vary by +/- 15% and maximum annual wind speeds are assumed to occur from any direction, the fetch-limited durations for the wind data were based on the average fetch length of 29 miles.

The 2-minute wind data was first converted to a 1 hour duration using the first equation in a figure from the Coastal Engineering Manual, shown below in Figure 10. Then, using the second equation in the figure and the fetch-limited durations, the fetch-limited wind speeds were calculated.

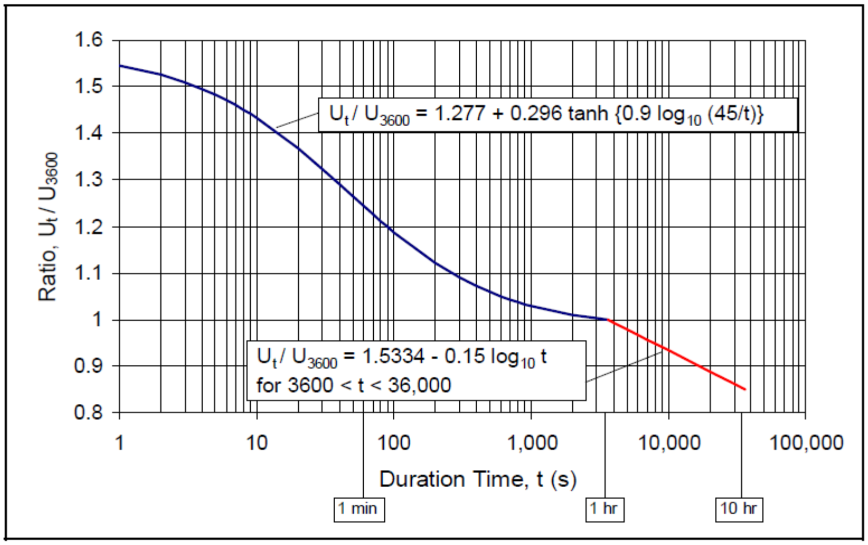

Figure 10 – Adjustment for wind speed data based on duration, from the Coastal Engineering Manual

A frequency analysis was then performed on the wind data to find wind speeds associated with various annual chance exceedance (ACE) probabilities. The ACE is the reciprocal of the return period (Tr), for example the 100 year return period is equivalent to 1/100 ACE or 0.01 ACE. The probability distribution that was found most applicable to the wind data was the Gumbel distribution (Gumbel, 1954) which has been found to be applicable to maximum values of rainfall, river discharge, and wind (Holmes, 2013). A summary of the fitted probability distribution values extrapolated to the 1/1000 ACE is shown in Table 4 and Figure 11.

Table 4 – Summary of wind speed data fit to the Gumbel probability distribution

Tr	ACE	2-min. wind speed	Fetch-lim. duration	Fetch-lim. wind speed
year	*freq.*	*mph*	*min.*	*mph*
1000	0.001	54.2	290	41.6
100	0.01	48.7	301	37.3
50	0.02	47.0	305	36.0
25	0.04	45.3	309	34.6
10	0.1	43.0	314	32.9
2	0.5	38.5	326	29.3
1.01	0.99	34.0	340	25.8

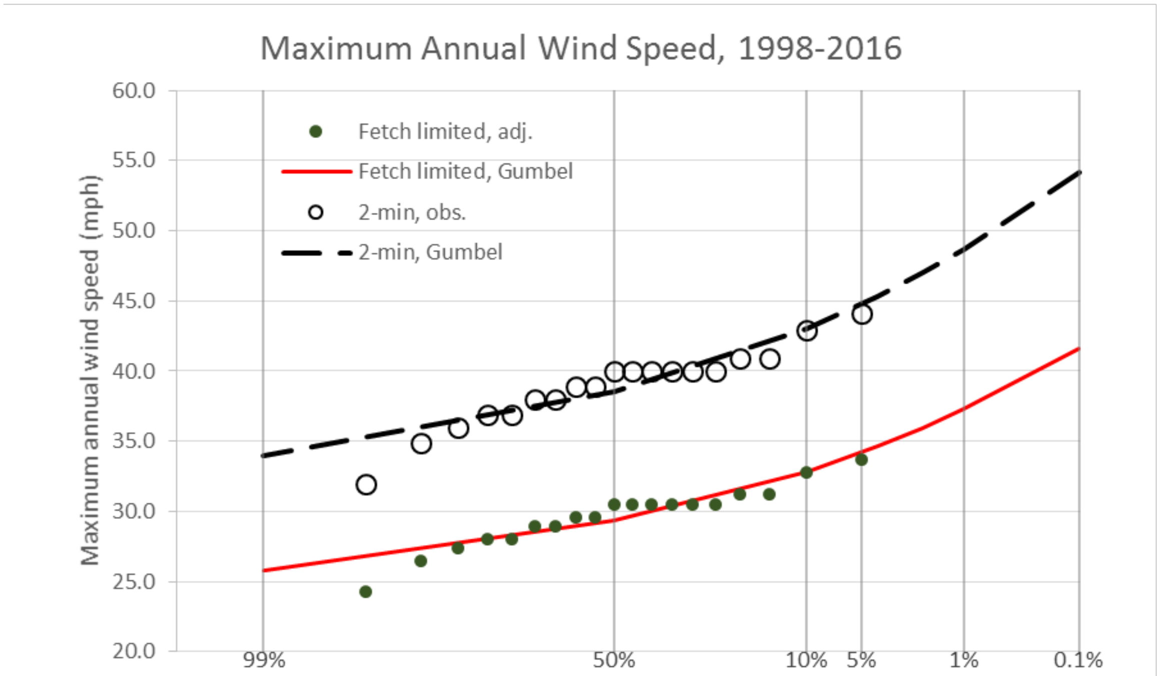

Figure 11 – Maximum annual 2-minute wind speeds and adjusted fetch-limited wind speeds fitted to Gumbel Distribution

Using this distribution, the estimated 1/100 ACE wind speed for a 2-minute duration is 48.7 mph. The equivalent wind speed adjusted to the fetch-limited duration of 290 minutes, or 4.8 hours, is 37.3 mph. While waves are likely limited by depth in the nearshore environment, the fetch-limited winds are used to assign a frequency for the open water wave heights as calculated in the wave model.

3.6 Wave Modeling Validation

A regular gridded wave model was constructed using SMS software for use with the STWAVE model. A regular grid model means that each cell has a uniform length (i) in the x direction and a uniform length (j) in the y direction. The Lake of the Woods model was setup so that both the i & j lengths are equal to 100 meters, meaning that each cell represents a 100 x 100 meter square. Each cell in the model is represented by one averaged depth value over the cell domain. The resolution used in this model is coarse enough to provide reasonable model run-times and resolution while still fine enough to capture islands and inlets. Figure 12 shows both an overview of the entire STWAVE model domain for the Lake of the Woods and two zoomed-in locations displaying the fine resolution of the gridded geometry.

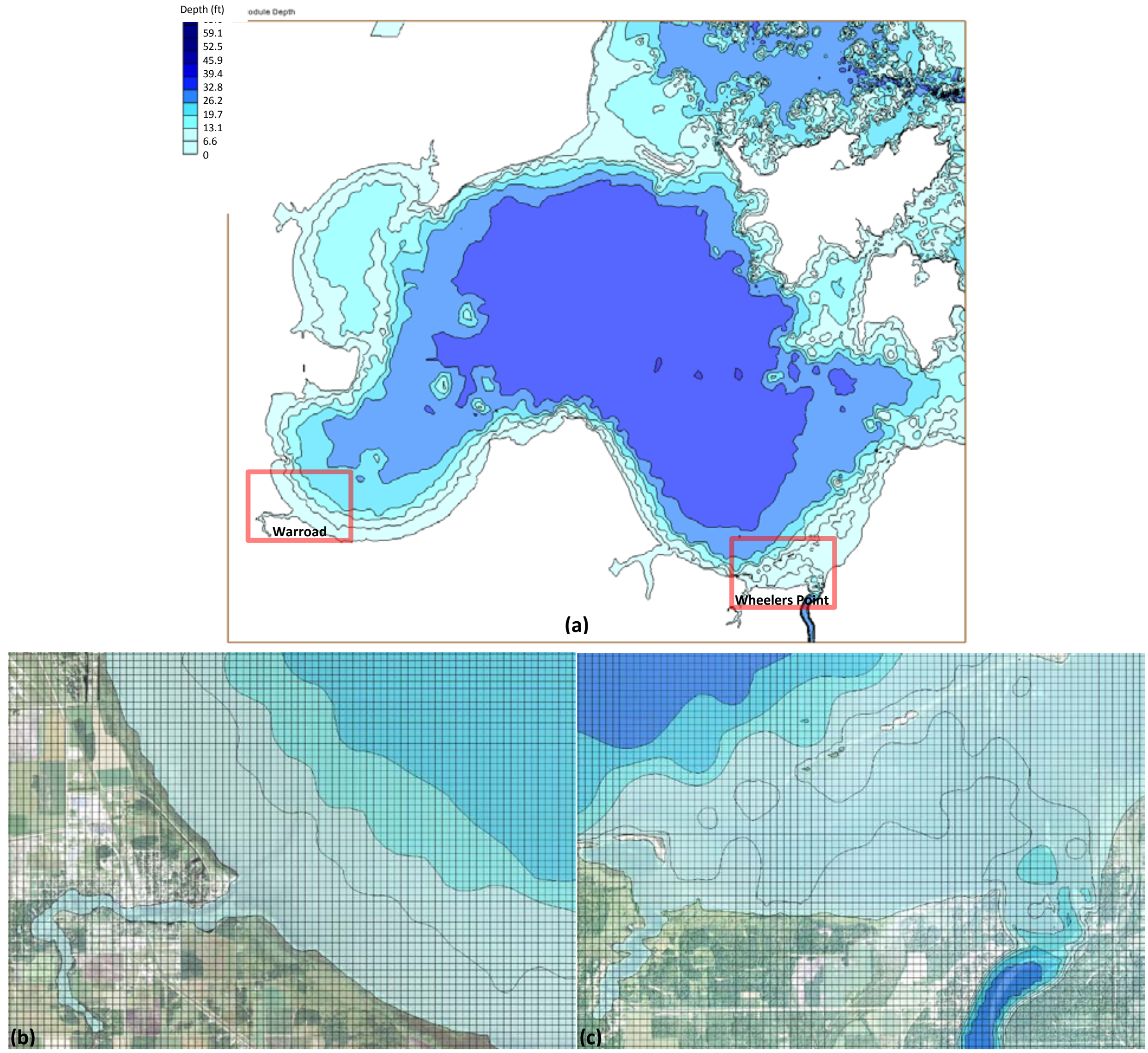

Figure 12 – STWAVE model domain (a) and model zoomed to (b) Warroad and (c) Wheelers Point.

STWAVE calculates the significant wave height, wave direction, and peak wave period. The significant wave height represents the average height (trough to crest) of the highest third of all waves for the given wind and water level conditions and is a common reference for wave calculations.

Since there are few controls available to calibrate STWAVE models, this effort was viewed as primarily validating that the model construction and assumptions provide reasonable results. Roughness, the only factor used for model adjustment in this model, has a relatively minor impact on the model results, as mentioned in Section 3.3. Grid resolution, both grid size and grid orientation, could have an impact on wave results. However, the resolution of the model is fine enough to capture major bathymetric features so it is unlikely that the results would be very sensitive to the grid size and orientation.

The St. Anthony Falls Laboratory (Herb et. al. 2005) took wave measurements in two locations on the Lake of the Woods in 2004 as part of a shoreline erosion assessment. The buoy was set near Pine Island for the first part of the summer and near Sandy Shores later in the summer. The wind conditions for the largest observed waves at each location were modeled in STWAVE. The two observed events are described in Table 1 and the results are shown in Figure 13 and Figure 14

Table 5 – Summary of Wave Model Validation

Location	Date	Wind speed (mph)	Wind Direction (degrees)	Wind Direction	Obs Wave Height, Hs (ft)	Modeled Wave Height, Hs (ft)	Percent Error
Pine Island	19-Jun-04	31.3	350	NNW	4.6	4.5	3%
Sandy Shores	11-Aug-04	24.6	30	NNE	3.4	3.0	12%

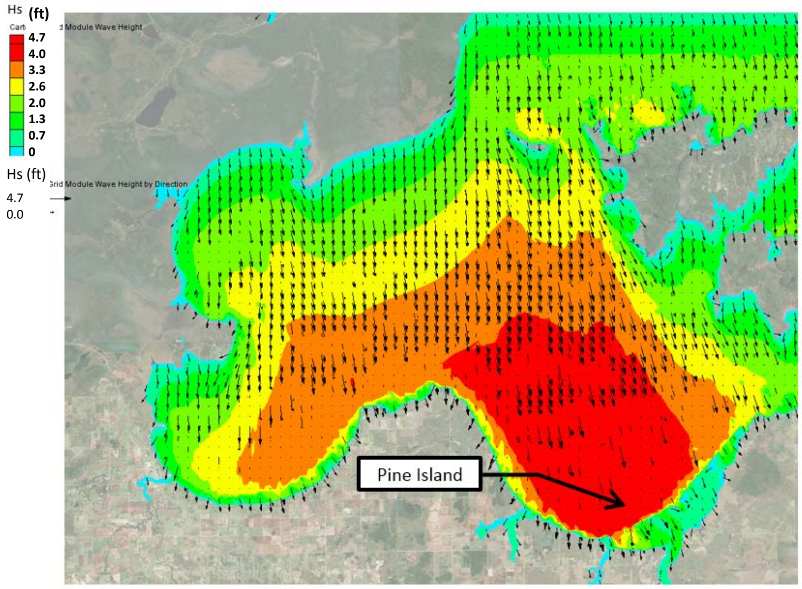

Figure 13 – Modeled wave heights (Hs, in feet) for 19-Jun-2004

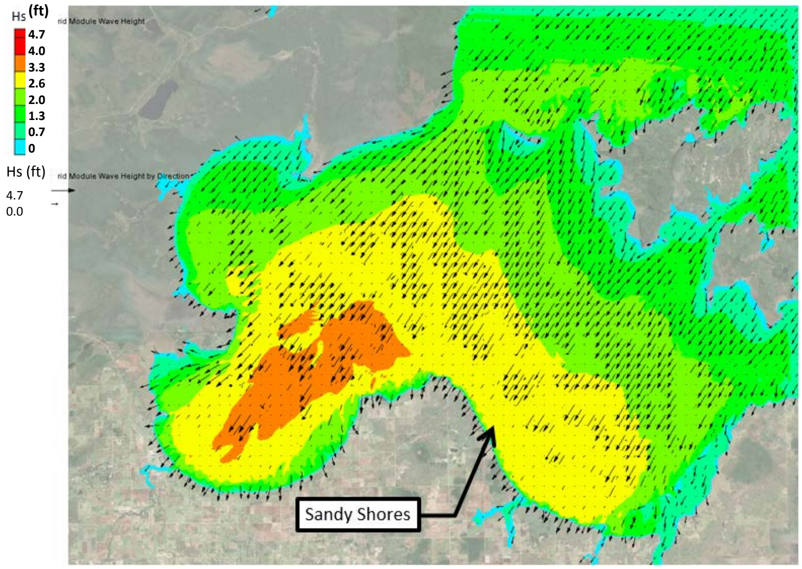

Figure 14 – Modeled wave heights (Hs, in feet) for 11-Aug-2004

3.7 Wind Setup Modeling Validation

The wind setup model was constructed in SMS software for use with the ADH hydrodynamic model. ADH utilizes an irregular mesh consisting of thousands of various sized triangular cells defined by mesh nodes and elements connecting the nodes. This irregularity of the mesh allows for more refinement in complex areas such as nearshore and at slope changes and for less refinement in deep flat areas where results are not as sensitive. The domain of the ADH model extends north further than the wave model to include Angle Inlet. Figure 15 shows the extent of the ADH modeling domain for Lake of the Woods.

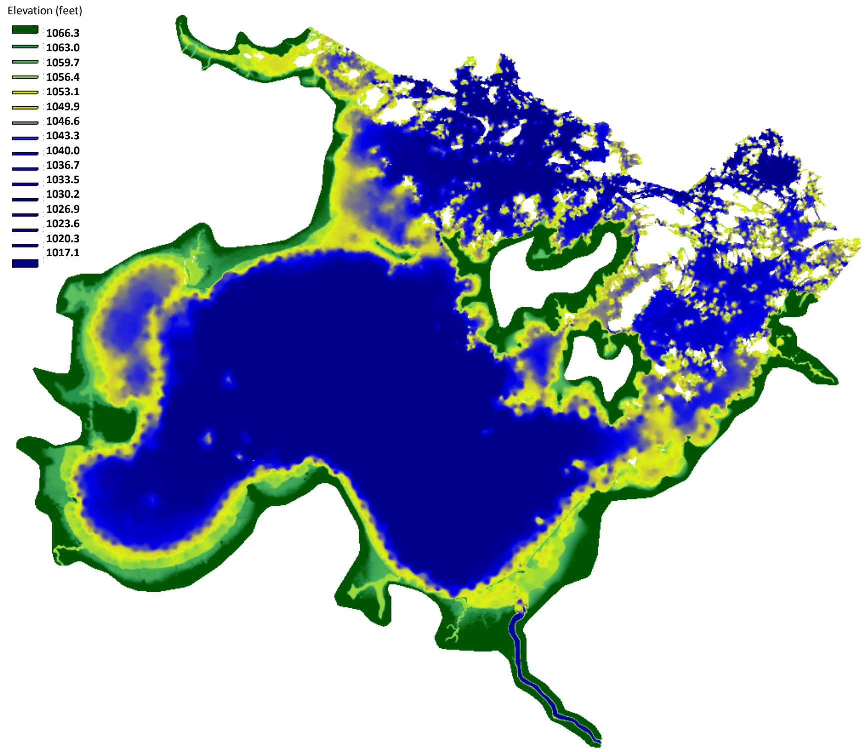

Figure 15 – ADH modeling domain

Finer resolution was added at nearshore features, such as inlets and islands, for many locations along the southern shore. Element sizes in some of these areas are as fine of resolution as 30 meters, compared to some deeper water areas where element sizes were constructed up to 1500 meters. Figure 16 shows the finer resolution elements at various locations along the southern shore.

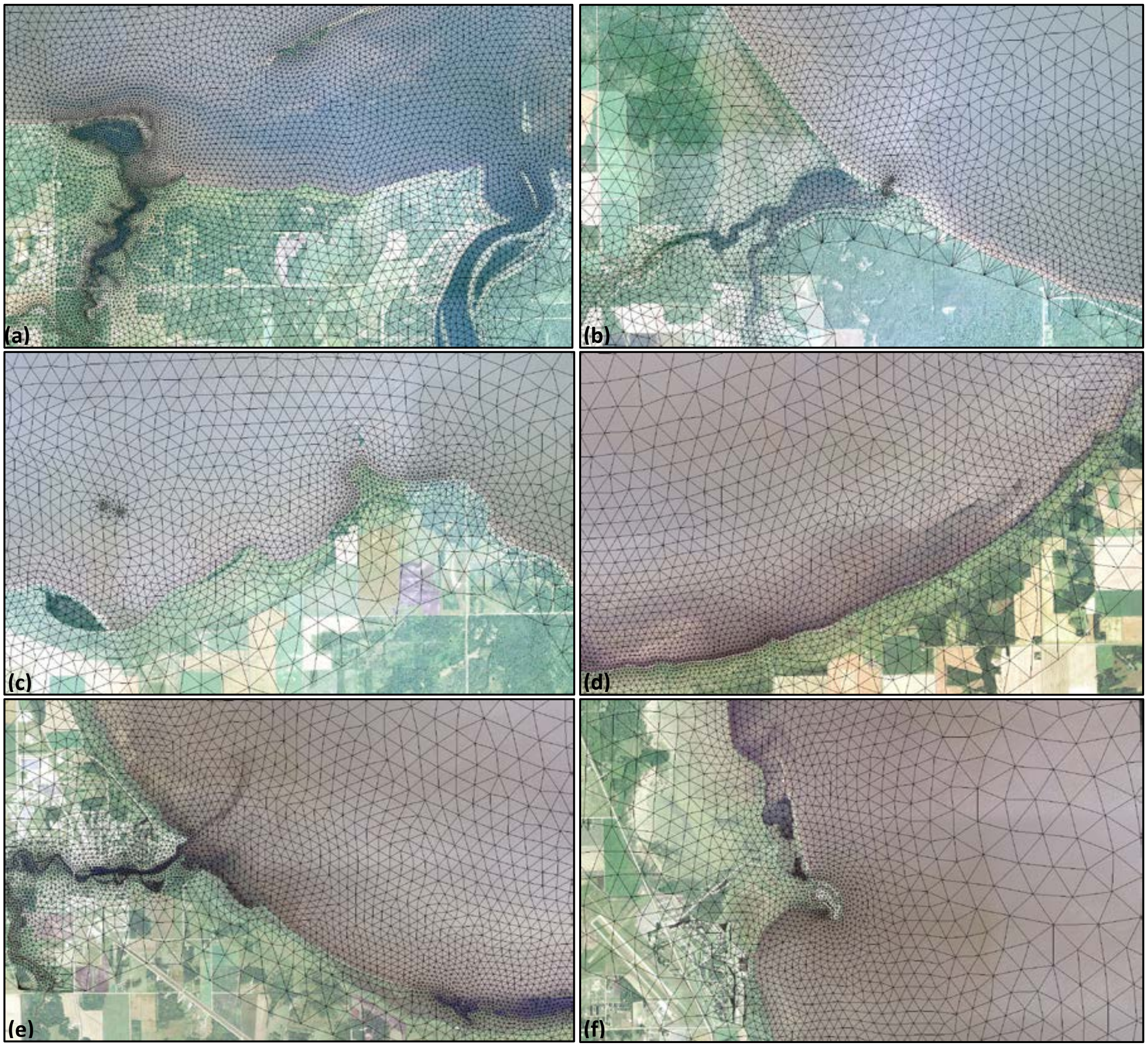

Figure 16 – ADH mesh at (a) Wheelers Point, (b) Zippel Bay, (c) Rocky Point and Long Point, (d) southern shore, (e) Warroad, and (f) Springsteel Island.

Similar to the wave modeling, the wind setup model is validated against observed events with little calibration of input parameters. Again, the main factor for adjustment, roughness, has little impact on lake stages. The main source of disagreement between modeled and observed stages in the validation is the coarseness of input wind data. Sub-hourly wind data was downloaded from the Weather Underground website (Weather Underground, 2016) and utilized as input for the wind setup model, however, the wind field was assumed to be constant over the entire model domain. This does not capture the variability in the actual wind field for a domain as large as the Lake of the Woods. Despite the coarseness of the wind data, the wind setup model showed positive validation for the three events that were modeled: 29 July 2015, 12 October 2015, and 13 May 2016. The results for these three events at the Baudette, Hanson Bay, and Cyclone Island lake stage gages are shown in Figure 17.

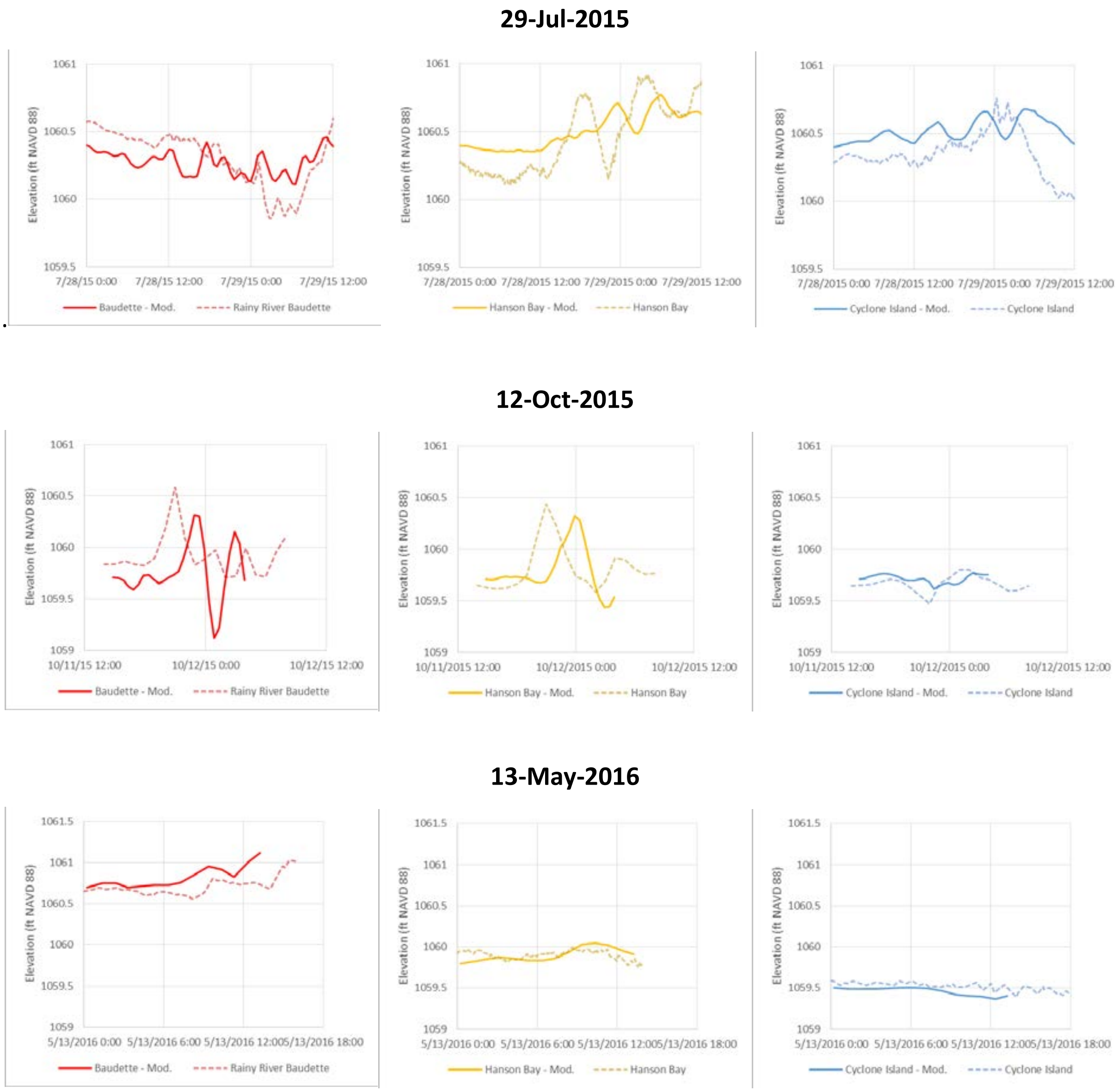

Figure 17 – Validation results for the wind setup model for three events in July 2015, October 2015, and May 2016

Error is present in the wind setup validation, however, most of the error is likely from the input wind data as opposed to roughness values or model geometry. Modeling the wind as a spatially variable field would likely yield more accurate results than applying the wind uniformly across the domain. Still, modeled peak stages are generally within 30% of the observed values, providing enough validation to use the model for uni-directional winds of various magnitudes.

4 RESULTS

The modeling output for both the wave modeling and wind setup modeling is focused along the southern shoreline of the Lake of the Woods, primarily within the United States. Wind setup values are highest at the water-shore interface along the side of the lake opposing the driving wind direction. However, wind setup values do not vary greatly over hundreds to thousands of feet of distance. Therefore, values for wind setup are reported at approximately the 2 meter depth contour that parallels the shoreline. This depth contour is generally less than 2,500 feet from the shore. Wave growth in a body of water, however, reaches a maximum wave height and wave period as the conditions approach shallower water before waves break and become limited by depth. In review of the modeling output, waves are generally limited to 60% of the depth in this study. With estimated maximum wave heights of 3 meters (~10 feet), a depth of 5 meters would capture the maximum wave heights before the occurrence of depth-limited wave breaking. Figure 18 shows an example from the STWAVE output of how wave energy is dissipated as waves approach shallower depth.

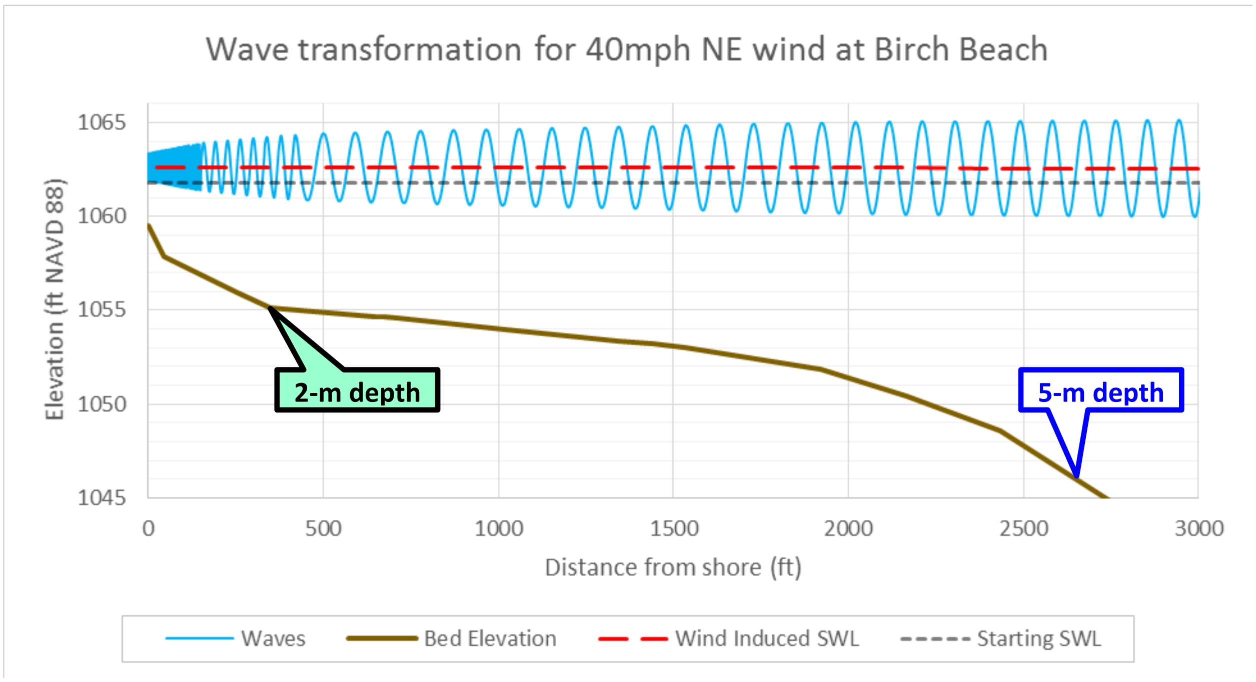

Figure 18 – Example of wave transformation as waves approach Birch Beach from wind from the NE at 40 mph

The 5-meter depth contour falls closer to 6,000 feet from shore, on average. For depths shallower than 5 meters, the wave height is assumed to be the smaller of the output wave height or a depth-limited height of 0.6 times the depth (USACE, 2002). For example, at 2 meters in depth, the maximum wave height would be approximately 3.9 feet (0.6 * 2 meters * 3.28 feet/meter).The locations of the 5-meter and 2-meter contours are shown in Figure 19.

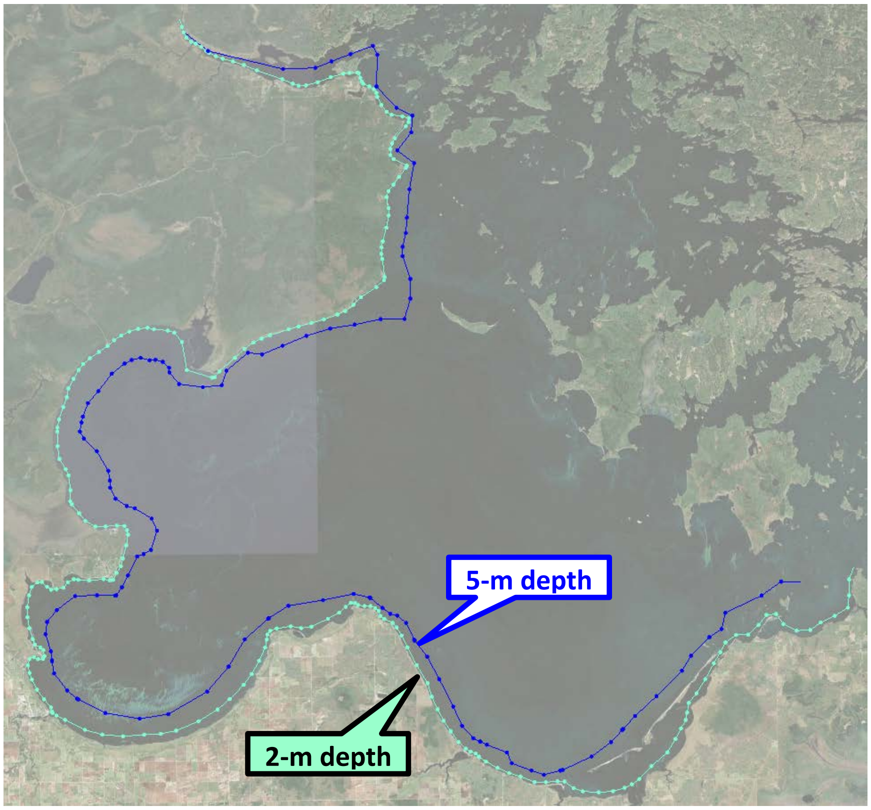

Figure 19 – 2-meter and 5-meter contour lines around the shoreline of interest

4.1 Wave Results

The results from the wave model are summarized in this section by wave height (in feet) along the 5-meter contour depth line that parallels the shore. The 0 station for the wave profile is at the three-way border between Minnesota, Manitoba, and Ontario near Angle Inlet, MN. The profile travels around the lake counter-clockwise, with Pine and Currys Islands near station 100 miles. The three profiles represent the three sustained wind speeds that were modeled: 20 mph (yellow), 40 mph (red), and 60 mph (purple). These profiles are shown in Figure 20 through Figure 24. Additional wave height summary by map can be found in Appendix A. Wave height, wave period, refracted angle of wave attack, and wind setup values at key locations can be found in Appendix B.

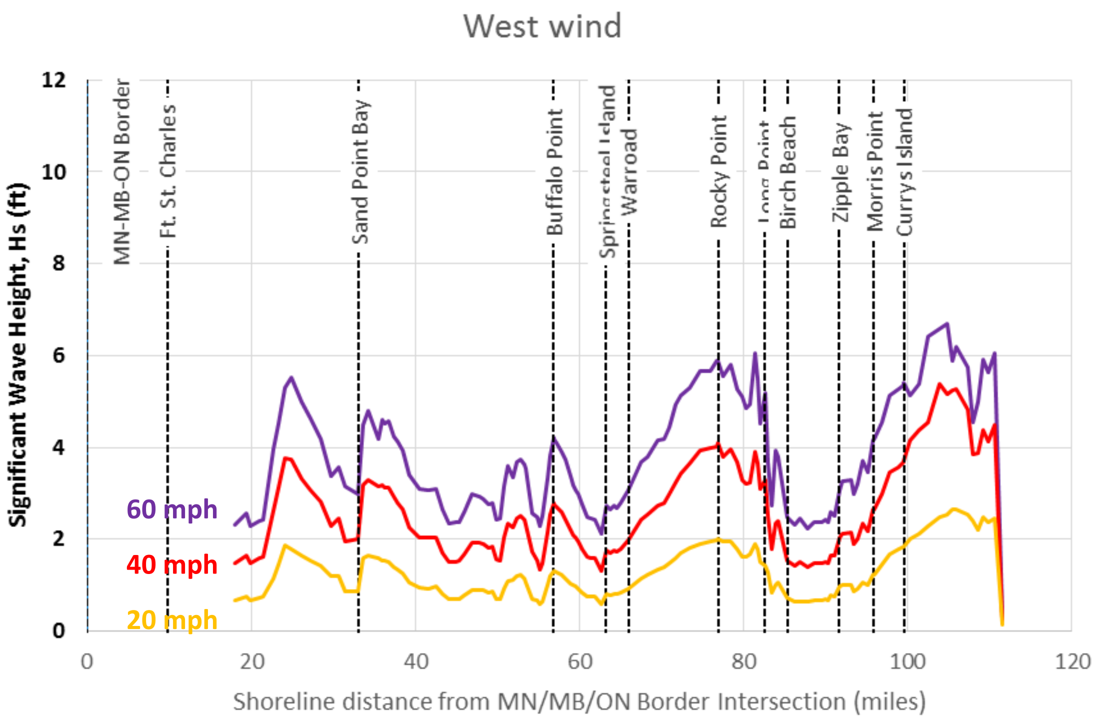

Figure 20 – Wave height profile (in feet) along shoreline for various magnitude west winds

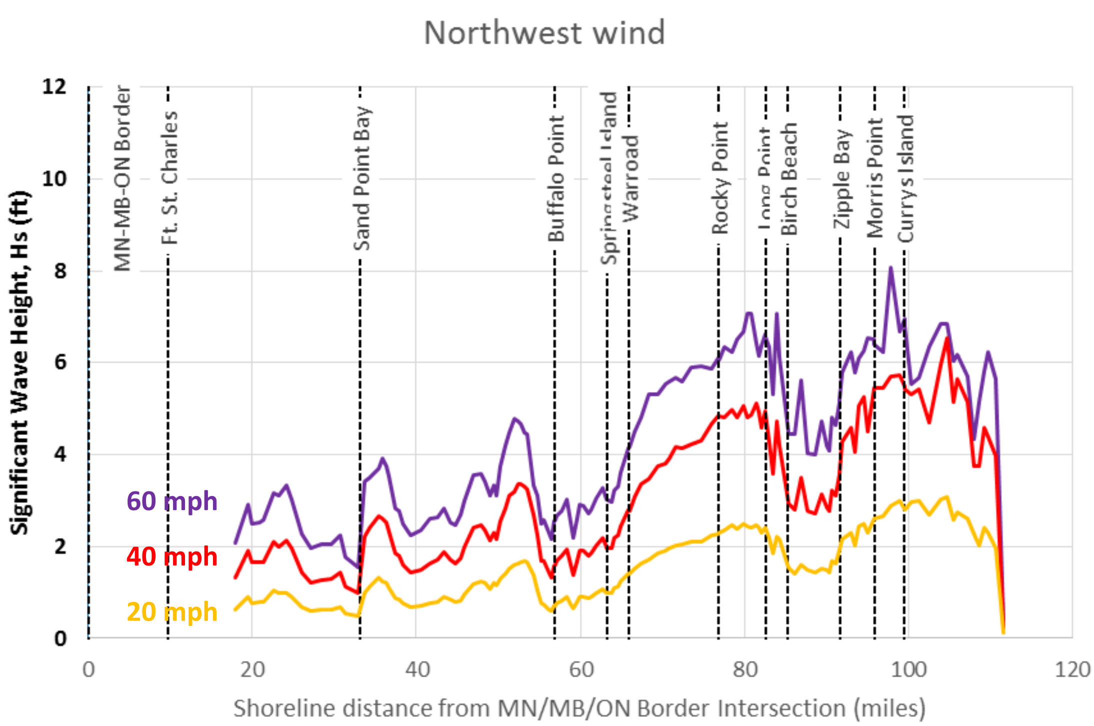

Figure 21 – Wave height profile (in feet) along shoreline for various magnitude northwest winds

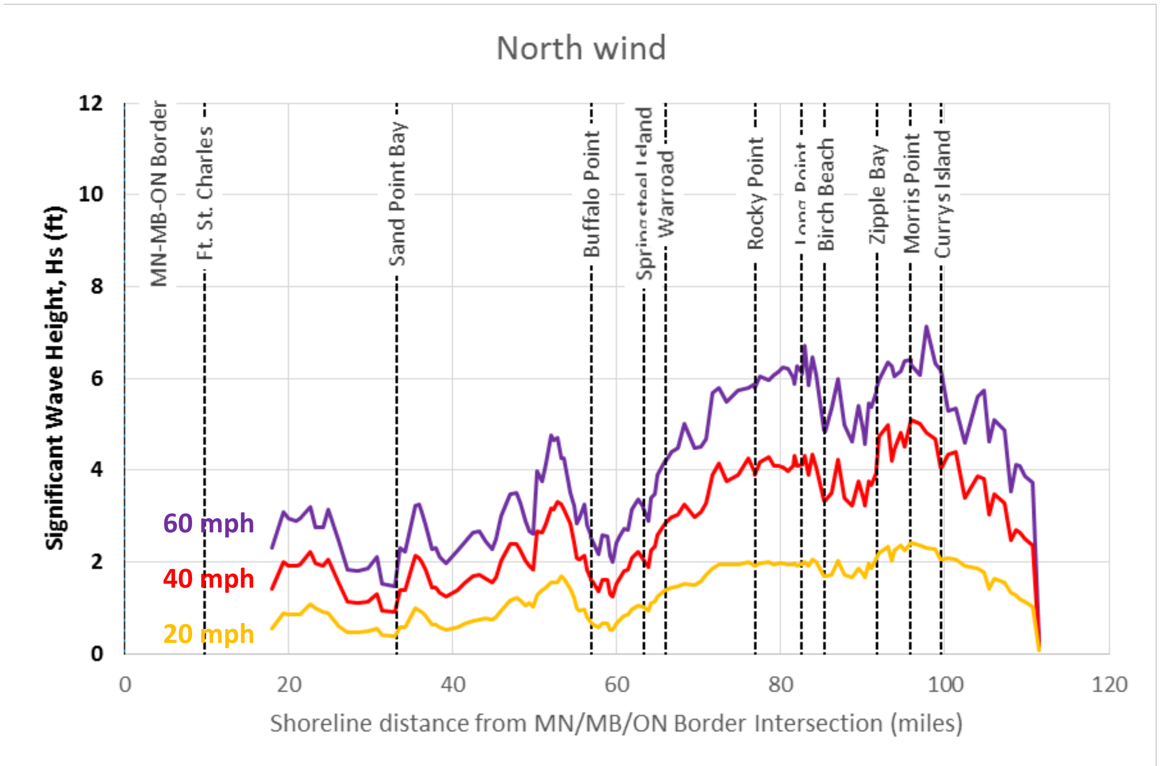

Figure 22 – Wave height profile (in feet) along shoreline for various magnitude north winds

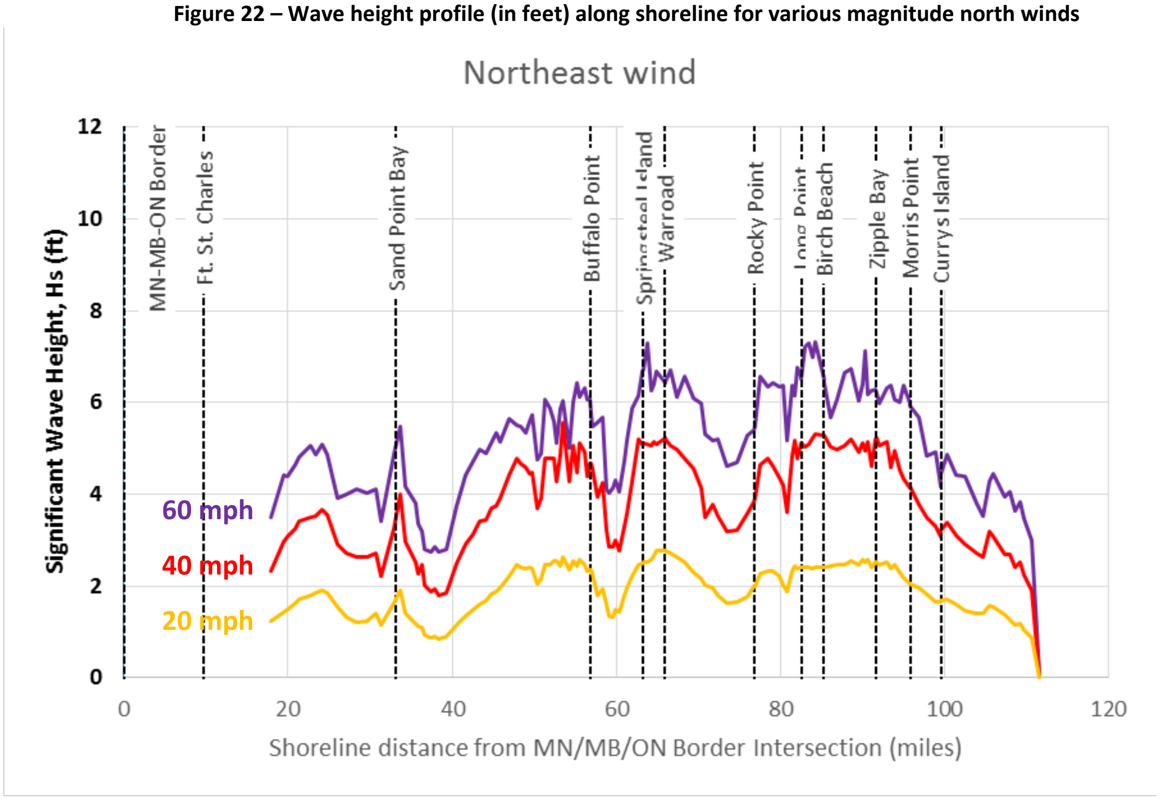

Figure 23 – Wave height profile (in feet) along shoreline for various magnitude northeast winds

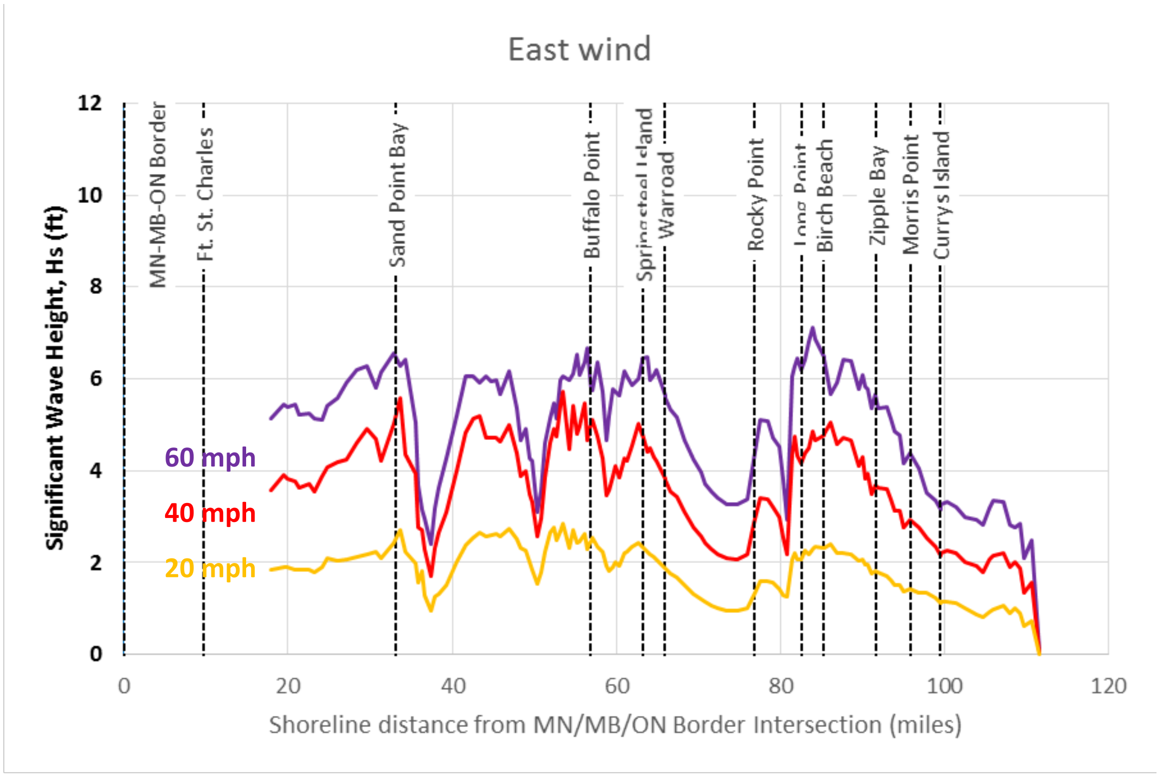

Figure 24 – Wave height profile (in feet) along shoreline for various magnitude east winds

4.2 Wind Setup Results

The results from the wind setup model are summarized in this section by stage increase (in feet) along the 2-meter contour depth line that parallels the shore. The 0 station for the profile is at the three-way border between Minnesota, Manitoba, and Ontario near Angle Inlet, MN. The profile travels around the lake counter-clockwise, with Pine and Currys Islands near station 100 miles. The three profiles represent the three sustained wind speeds that were modeled: 20 mph (bright blue), 40 mph (dark blue), and 60 mph (purple). Instances where the 20 mph profile exceeds the higher magnitude wind profiles indicates areas of wind "set-down," where upwind portions of the lake are drawn-down in the wind setup process. The wind induced water surface profiles are shown in Figure 20 through Figure 24. Wave and wind setup estimates at key locations can be found in Appendix B.

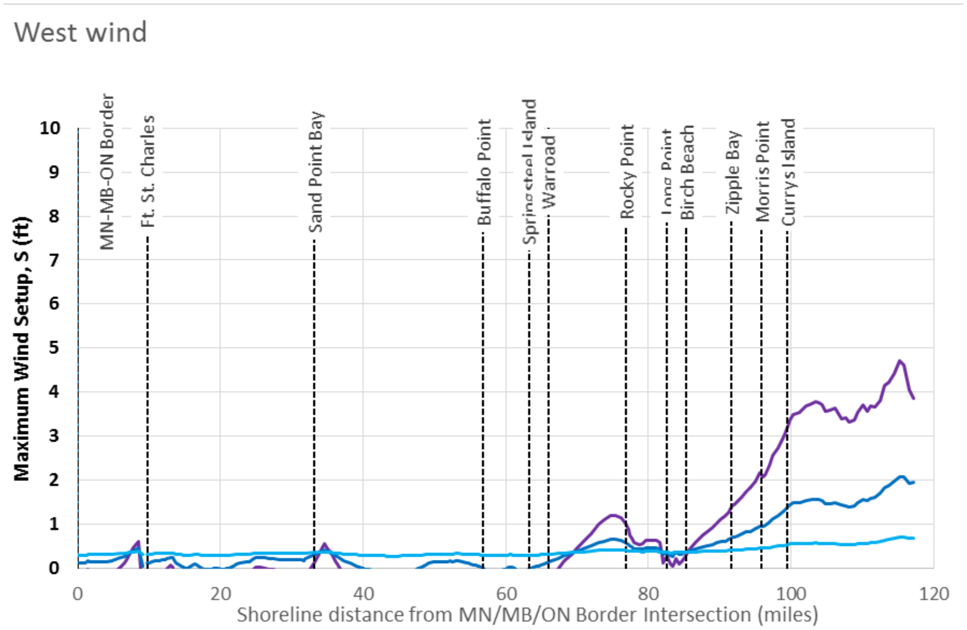

Figure 25– Wind setup profile (in feet) along shoreline for various magnitude west winds

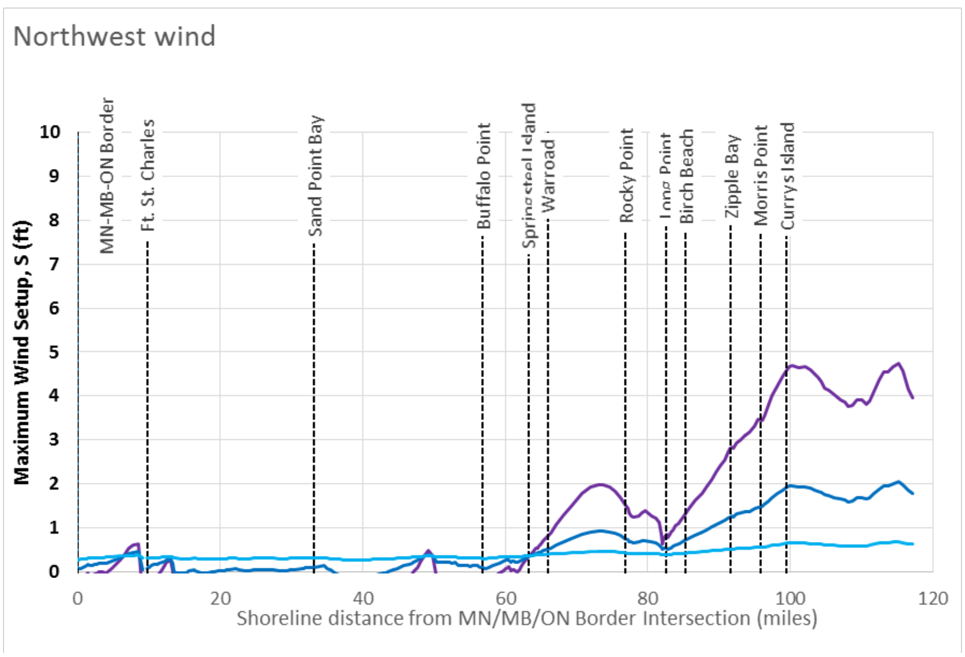

Figure 26– Wind setup profile (in feet) along shoreline for various magnitude northwest winds

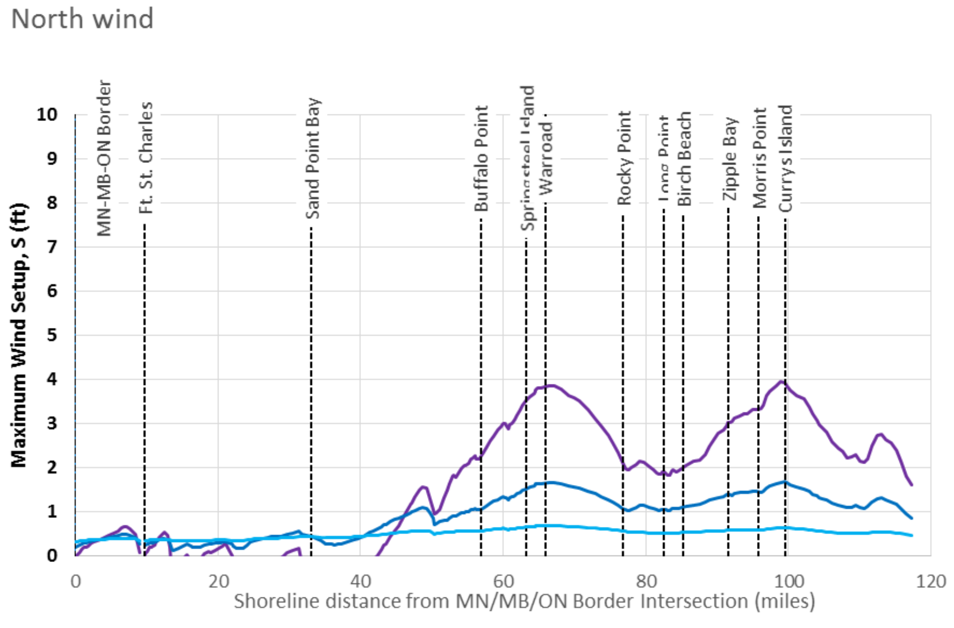

Figure 27– Wind setup profile (in feet) along shoreline for various magnitude north winds

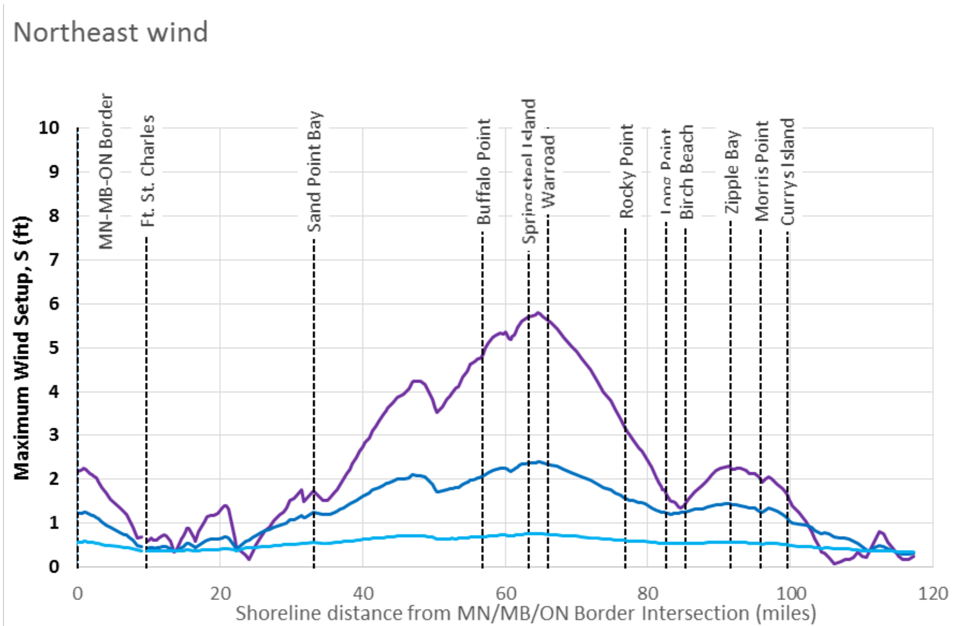

Figure 28– Wind setup profile (in feet) along shoreline for various magnitude northeast winds

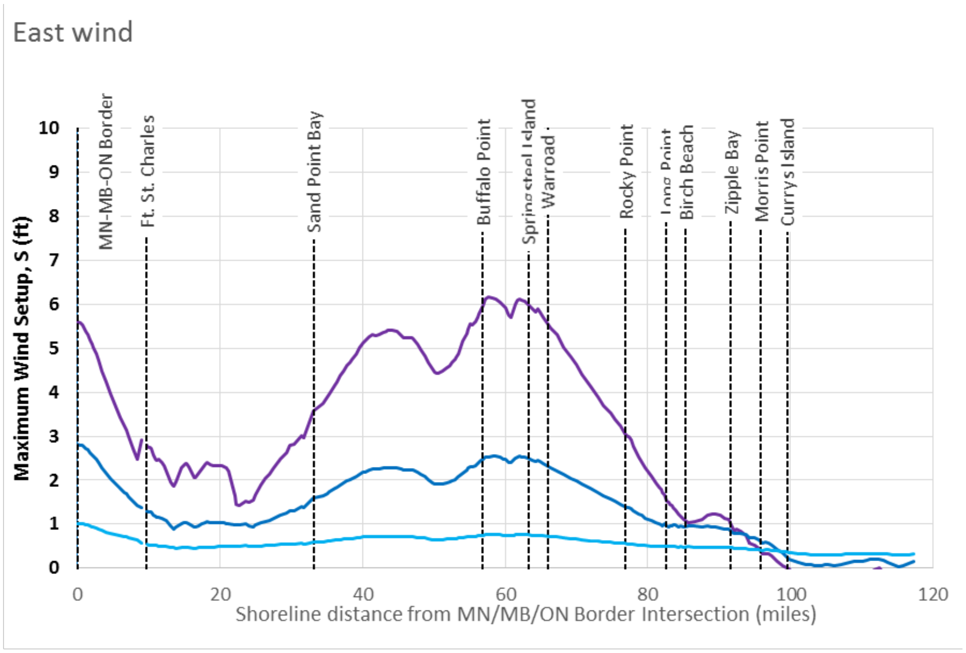

Figure 29– Wind setup profile (in feet) along shoreline for various magnitude east winds

4.3 Wind Frequency Results

The wind frequency curves developed in Section 3.5 are shown again in Figure 30. Since these wind speeds are assumed to be all-directional and maximum annual wind speeds can occur from any direction, these speeds can be applied to the modeled wind setup and wave height values for key locations around the lake. Table 6 shows the annual chance that values of wind setup and wave height will be exceeded at one key location per relevant wind direction. More detailed modeled values for these locations can be found in Appendix B.

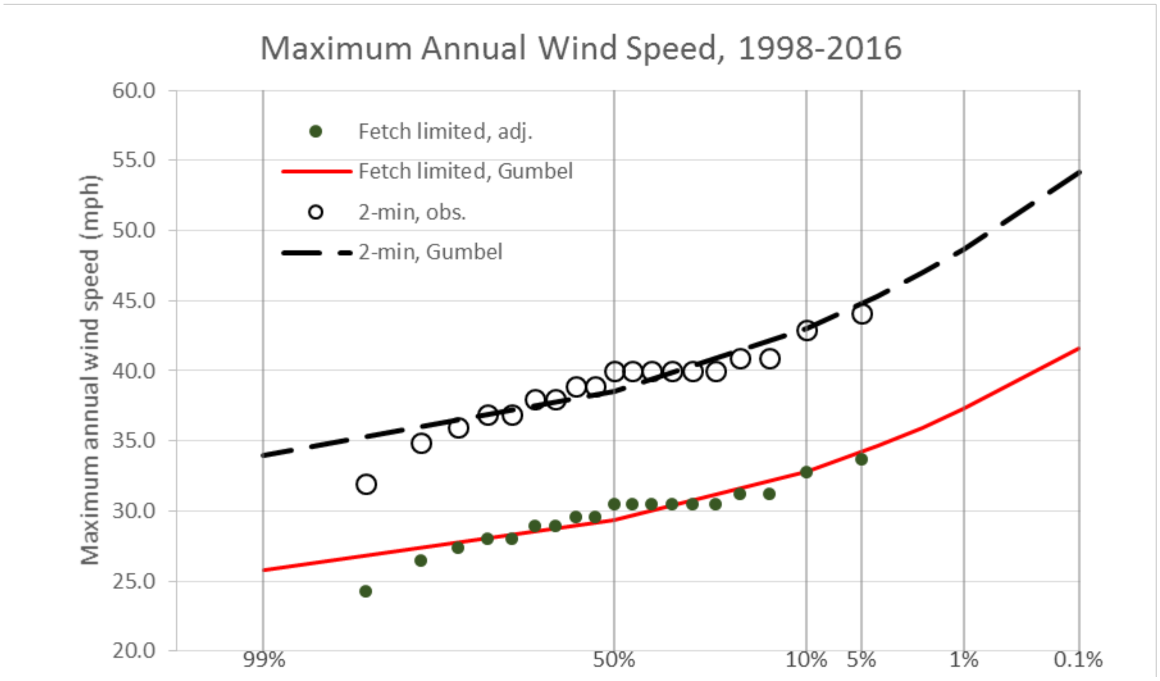

Figure 30 – Wind speed frequency curves for Lake of the Woods

Table 6 – Annual chance that wave height and wind setup values will be exceeded for key locations

Tr	**ACE**	**Fetch-lim. duration**	**Fetch-lim. wind speed**	**W - 270° at Currys Island**		**NW - 315° at Pine Island**		**N - 0° at Morris Point**		**NE - 45° at Birch Beach**		**E - 90° at Warroad**	
year	*freq.*	*min.*	*mph*	*Hs, ft*	*S, ft*	*Hs, ft*	*S, ft*	*Hs, ft*	*S, ft*	*Hs, ft*	*S, ft*	*Hs, ft*	*S, ft*
1000	0.001	290	41.6	4.5	1	5.9	1.6	5.3	1.5	5.6	1.4	4.5	2.8
100	0.01	301	37.3	4	0.8	5.4	1.3	4.8	1.3	5	1.2	4	2.3
50	0.02	305	36.0	3.8	0.8	5.2	1.3	4.6	1.2	4.8	1.1	3.8	2.2
25	0.04	309	34.6	3.7	0.8	5	1.2	4.4	1.2	4.6	1.1	3.7	2.1
10	0.1	314	32.9	3.5	0.7	4.7	1.1	4.2	1.1	4.4	1	3.5	1.9
2	0.5	326	29.3	3.1	0.7	4.3	1	3.7	0.9	3.9	0.9	3.1	1.6
1.01	0.99	340	25.8	2.7	0.6	3.8	0.8	3.2	0.8	3.3	0.8	2.7	1.3

5 CONCLUSIONS

The modeling results from this study will provide local stakeholders with estimates of wind setup and wave parameters along the southern shoreline of the Lake of the Woods for use in assessment and design of shoreline erosion mitigation, water quality practices, and flood risk management measures. The output is available in gridded datasets for use in multiple GIS applications. For access to the modeling output from this study, contact:

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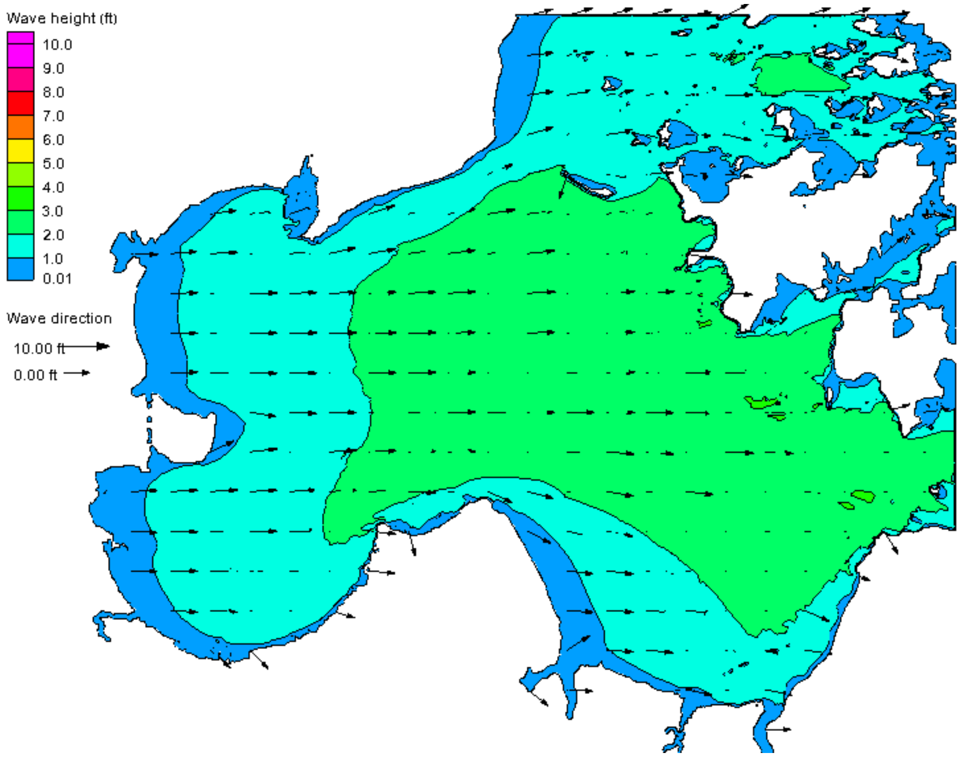

Figure 1 – 20 mph sustained wind from the west

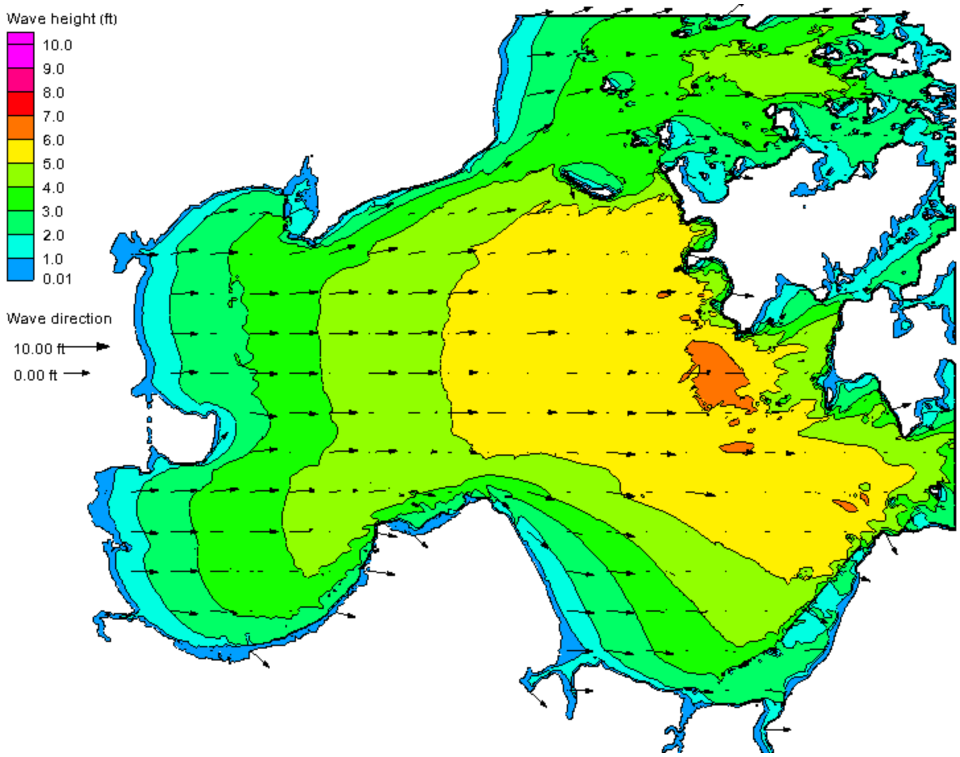

Figure 2 – 40 mph sustained wind from the west

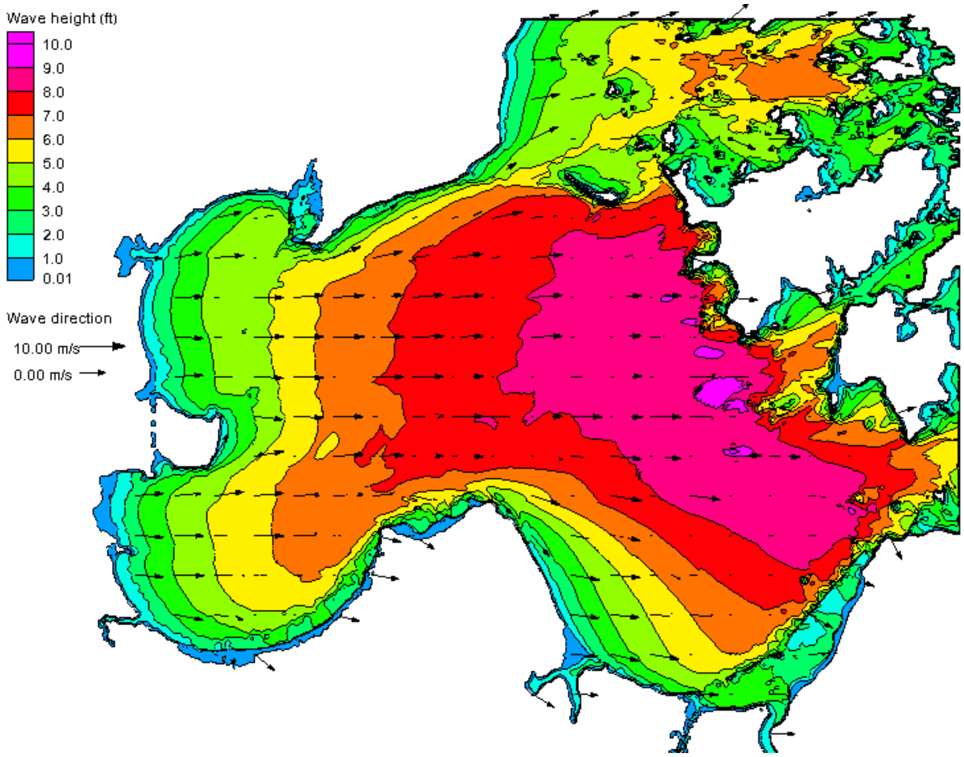

Figure 3 – 60 mph sustained wind from the west

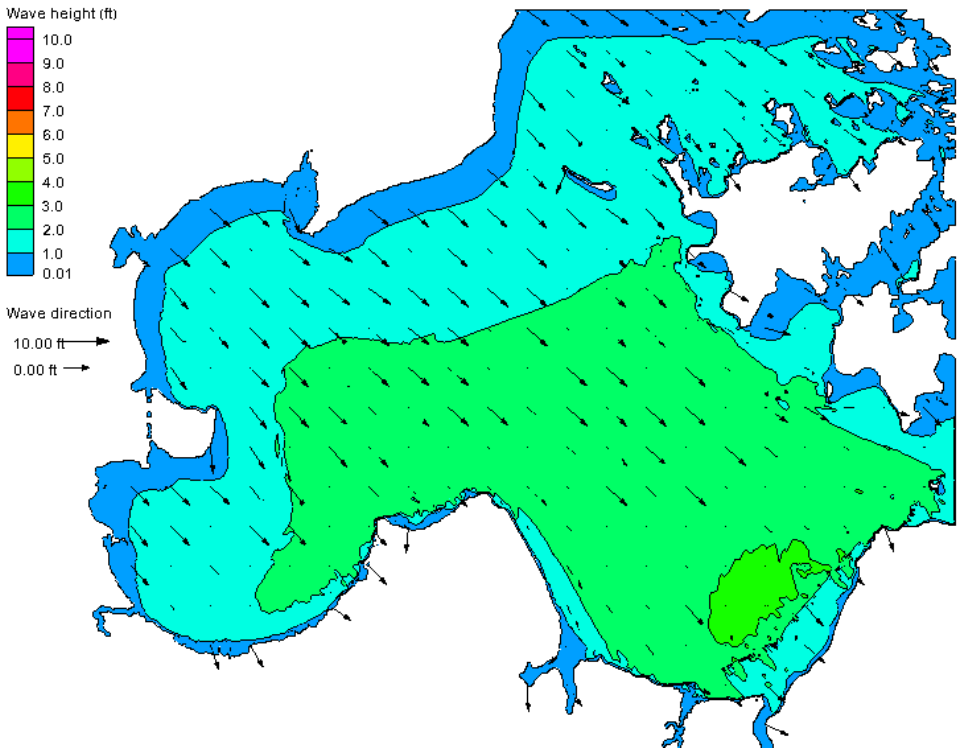

Figure 4 – 20 mph sustained wind from the northwest

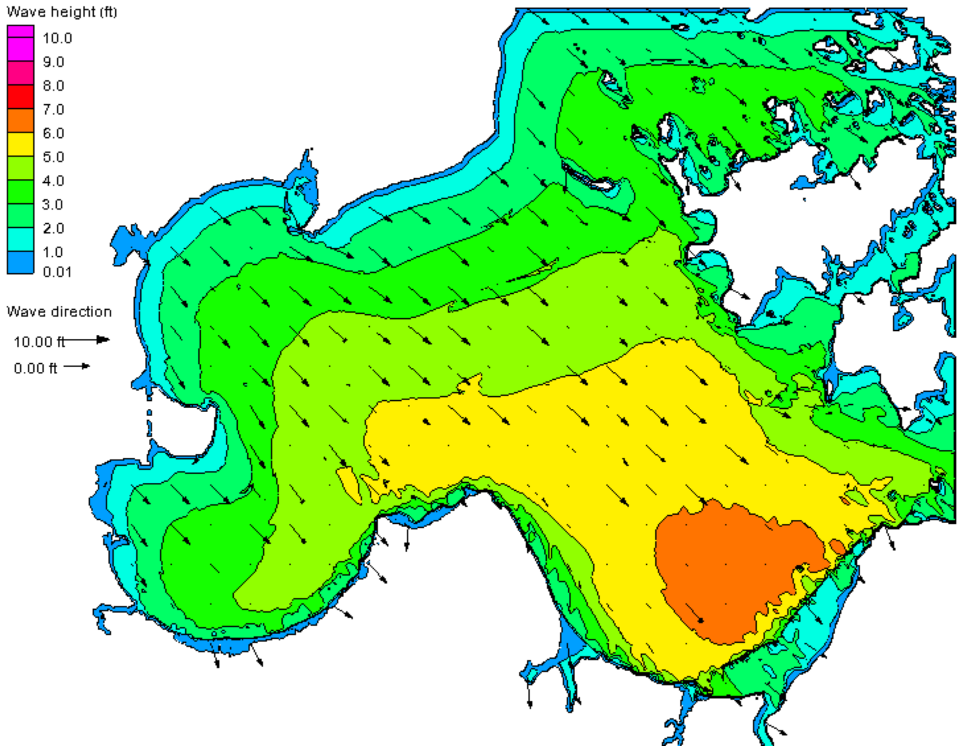

Figure 5 – 40 mph sustained wind from the northwest

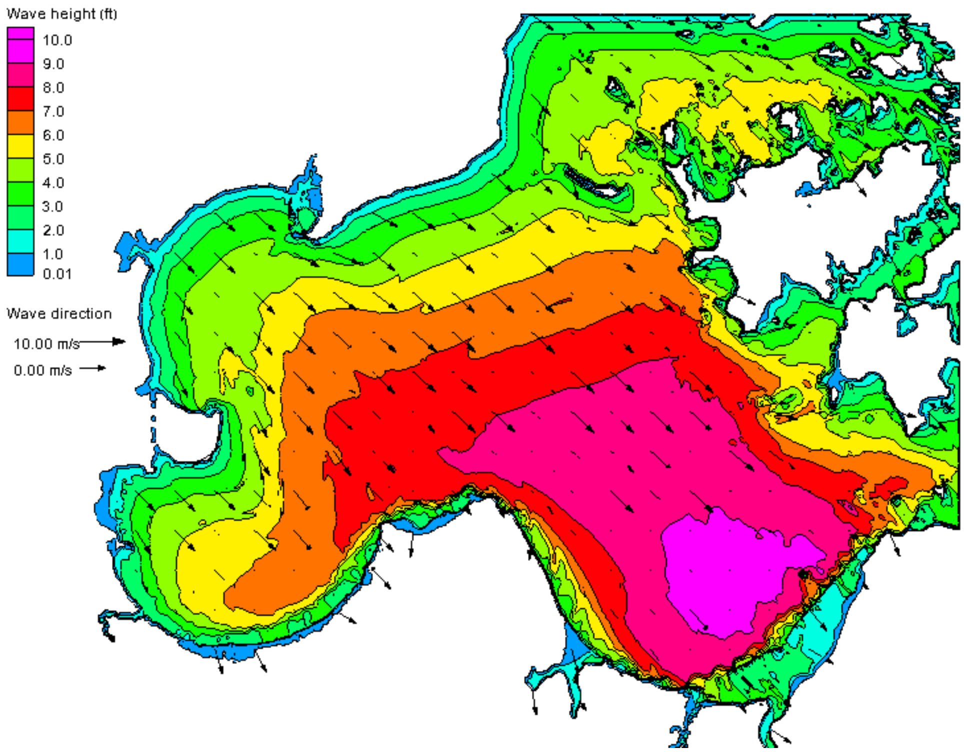

Figure 6 – 60 mph sustained wind from the northwest

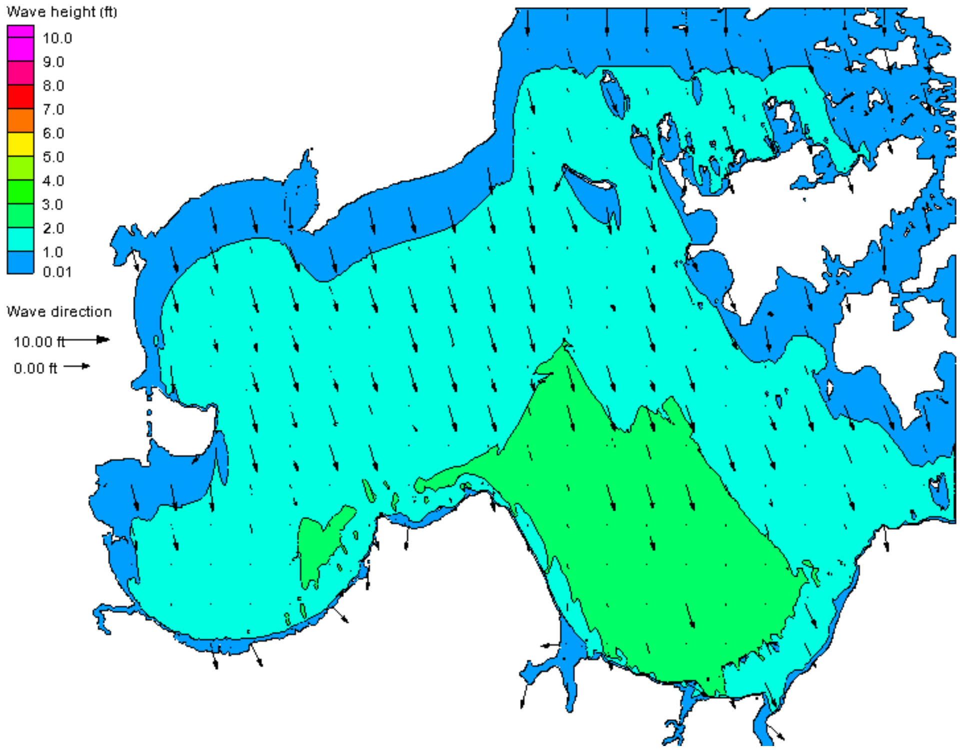

Figure 7 – 20 mph sustained wind from the north

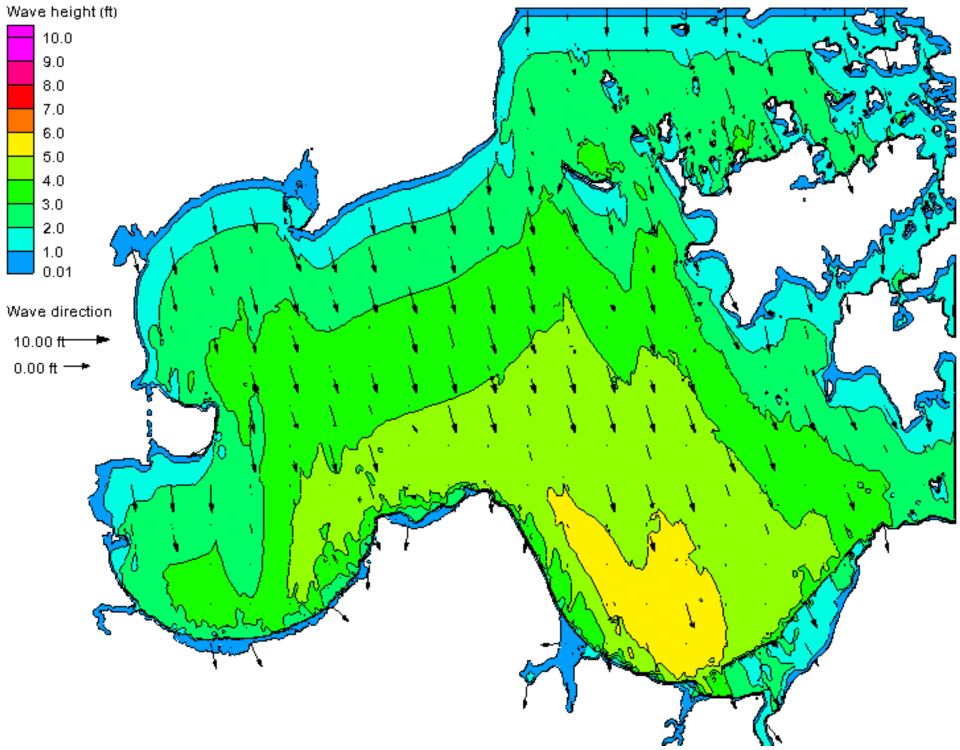

Figure 8 – 40 mph sustained wind from the north

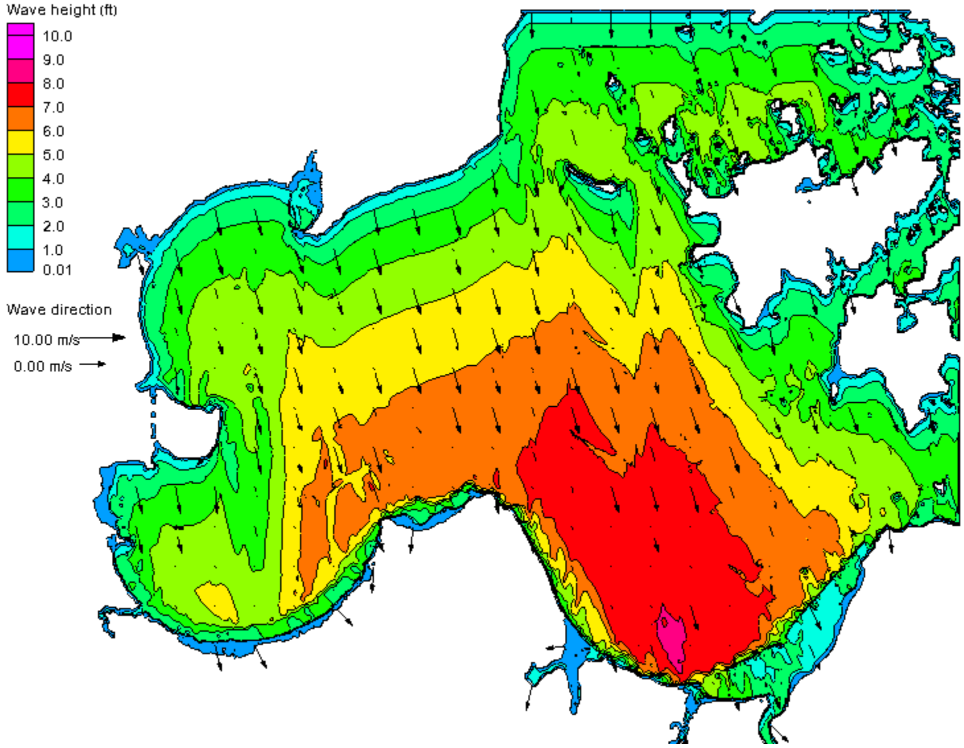

Figure 9 – 60 mph sustained wind from the north

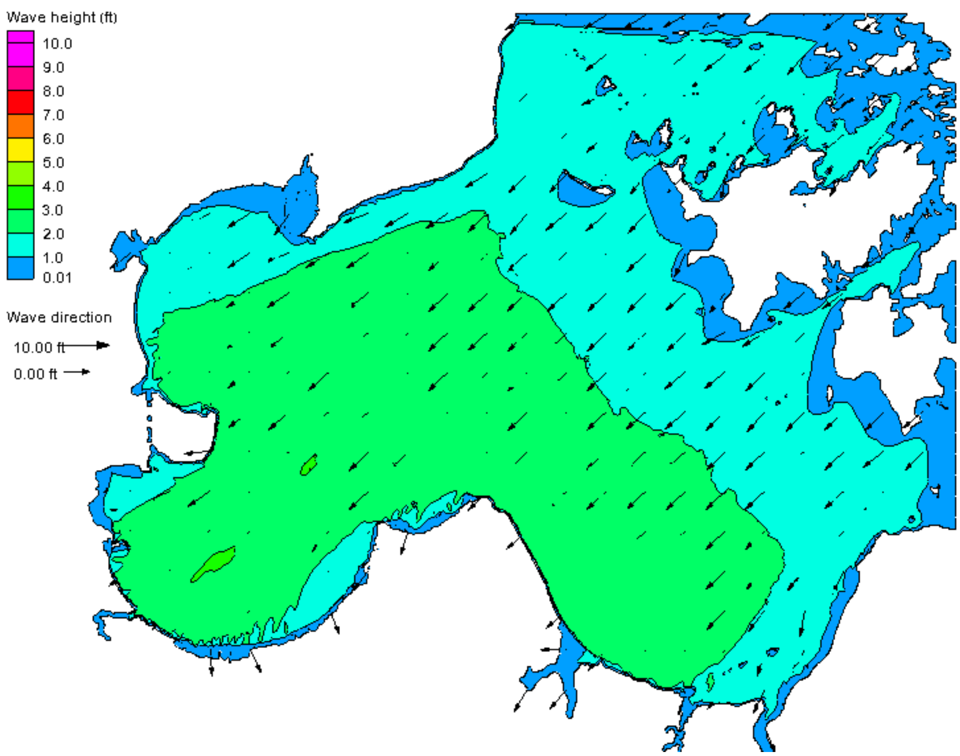

Figure 10 – 20 mph sustained wind from the northeast

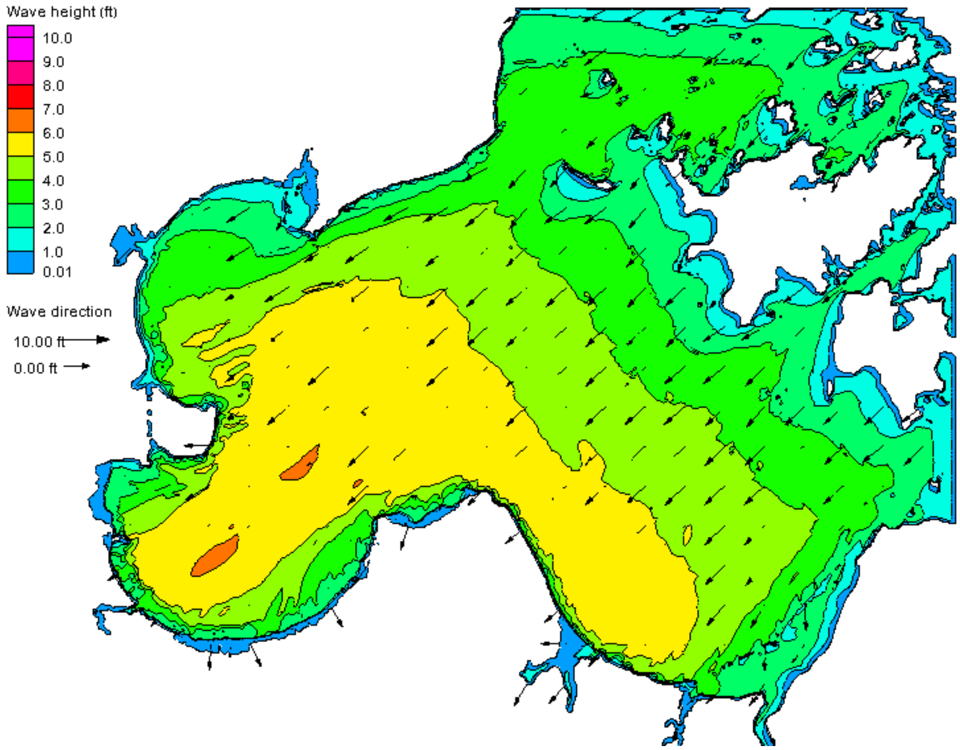

Figure 11 – 40 mph sustained wind from the northeast

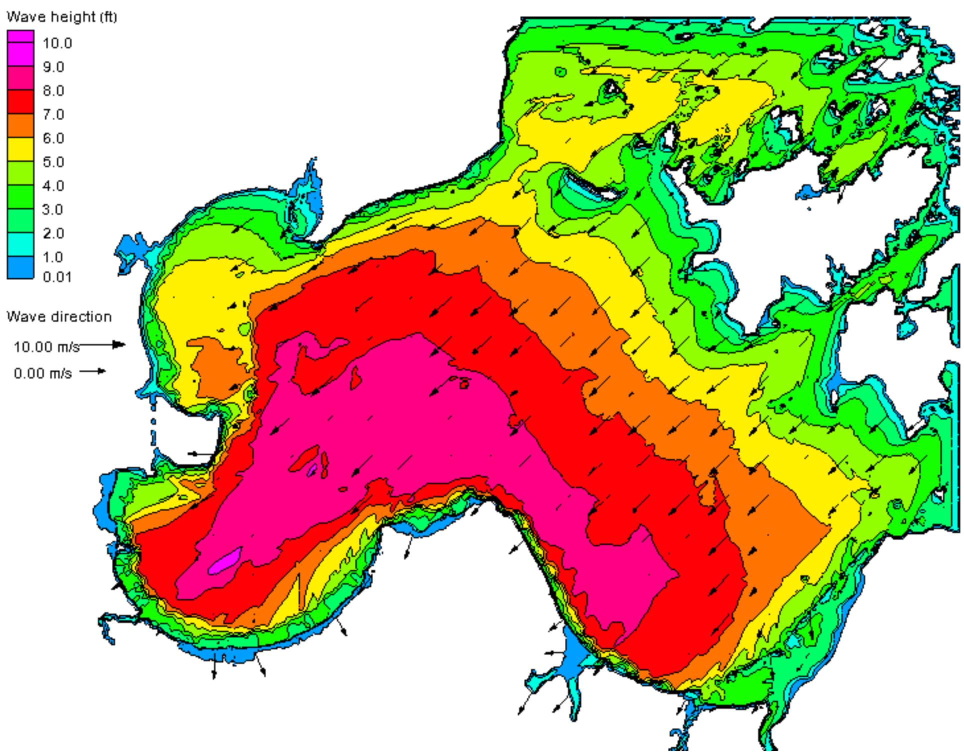

Figure 12 – 60 mph sustained wind from the northeast

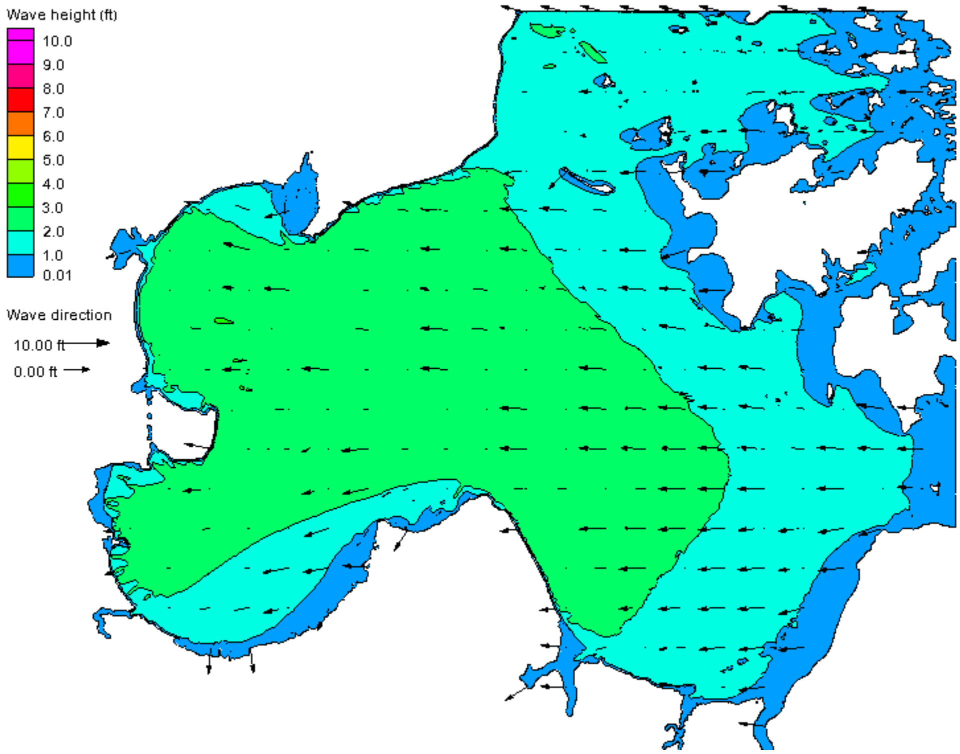

Figure 13 – 20 mph sustained wind from the east

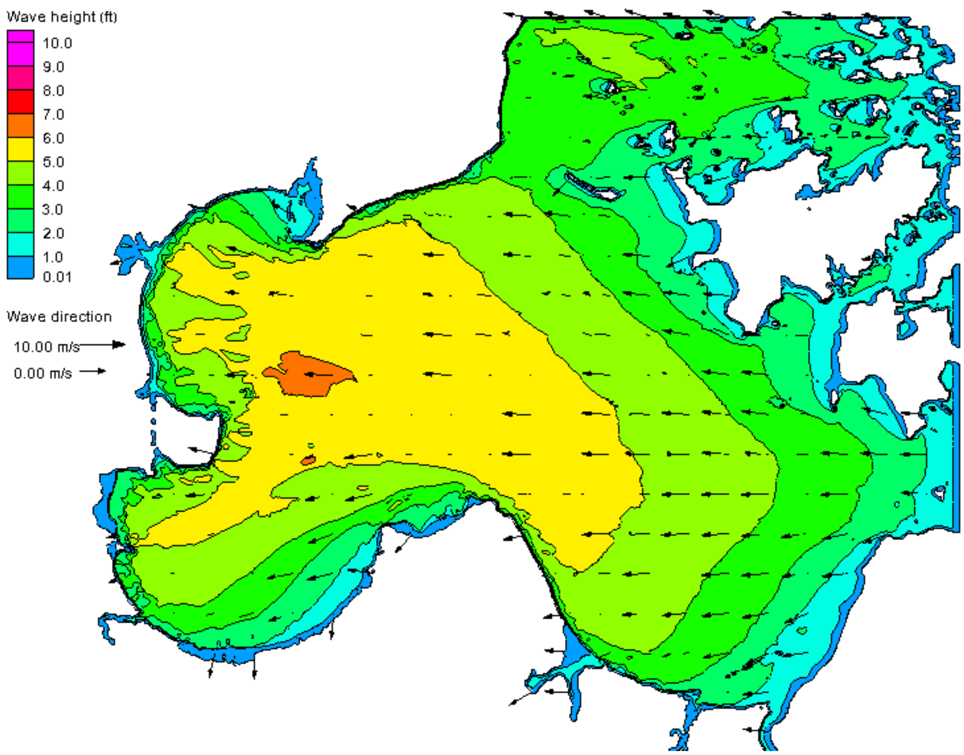

Figure 14 – 40 mph sustained wind from the east

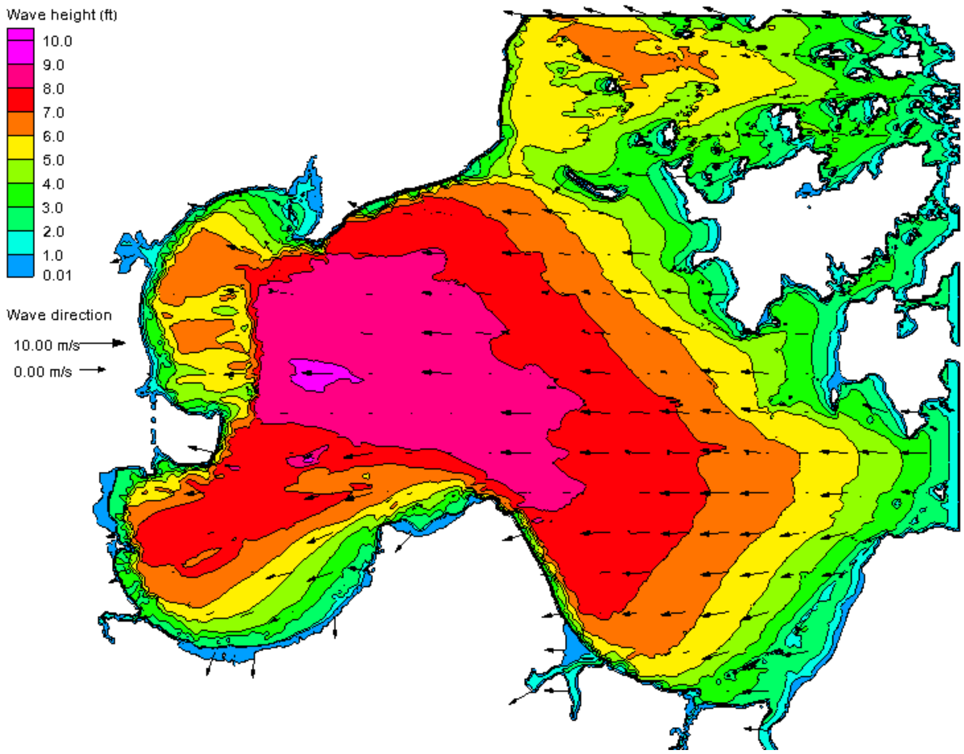

Figure 15 – 60 mph sustained wind from the east

		Warroad				Rocky Point				Birch Beach				Zippel Bay				Morris Point				Currys Island			
Udir	**Umag**	**S**	**Hs**	**T**	**λ**	**S**	**Hs**	**T**	**λ**	**S**	**Hs**	**T**	**λ**	**S**	**Hs**	**T**	**λ**	**S**	**Hs**	**T**	**λ**	**S**	**Hs**	**T**	**λ**
deg	*mph*	*ft*	*ft*	*s*	*deg*	*ft*	*ft*	*s*	*deg*	*ft*	*ft*	*s*	*deg*	*ft*	*ft*	*s*	*deg*	*ft*	*ft*	*s*	*deg*	*ft*	*ft*	*s*	*deg*
W (270°)	20	0.3	1.0	1.9	272	0.4	2.1	2.9	349	0.4	0.8	2.0	287	0.4	1.0	1.9	272	0.4	1.4	2.3	280	0.4	2.0	2.8	276
	40	0.0	2.2	2.4	274	0.6	4.3	3.8	273	0.5	1.7	2.5	290	0.4	2.1	2.4	275	0.7	3.0	3.0	282	0.9	4.3	3.7	278
	60	-0.8	3.4	2.8	276	1.0	6.5	4.4	276	0.6	2.7	2.9	291	0.6	3.3	2.8	278	1.4	4.6	3.6	286	2.0	6.3	4.3	279
NW (315°)	20	0.3	1.4	2.2	321	0.5	2.4	3.1	318	0.4	1.7	3.1	334	0.4	2.1	3.0	329	0.5	2.6	3.6	325	0.6	3.0	3.6	315
	40	0.2	3.1	2.9	324	0.9	5.0	4.1	318	0.7	3.1	3.9	341	0.8	3.9	3.6	331	1.3	5.5	4.7	327	1.4	5.7	4.7	313
	60	0.0	4.6	3.3	326	2.0	7.2	4.7	317	1.2	4.4	4.6	345	1.6	5.5	4.1	332	2.8	8.2	5.5	328	3.3	8.2	5.5	313
N (0°)	20	0.6	1.4	2.3	347	0.6	2.0	2.9	342	0.5	1.9	3.0	350	0.5	2.2	3.1	348	0.6	2.4	3.3	345	0.6	2.2	3.1	340
	40	1.4	3.0	3.1	349	1.4	4.1	3.7	341	1.1	3.7	3.9	-5	1.1	4.1	3.9	351	1.4	5.1	4.4	345	1.5	4.4	4.0	337
	60	3.1	4.6	3.6	351	3.1	6.2	4.4	340	1.9	5.2	4.5	-2	2.1	5.8	4.5	353	3.0	7.7	5.1	345	3.3	6.7	4.7	334
NE (45°)	20	0.7	2.9	3.7	47	0.7	2.4	3.3	37	0.6	2.5	3.2	47	0.5	2.6	3.3	43	0.6	2.1	3.1	36	0.5	1.8	2.8	32
	40	2.3	5.6	4.7	47	1.9	4.6	4.2	30	1.3	5.4	4.2	46	1.3	5.2	4.3	40	1.4	4.4	4.0	31	1.4	3.6	3.7	22
	60	5.4	7.8	5.4	47	4.2	6.5	5.0	25	2.0	7.9	5.0	47	1.7	7.7	5.0	39	2.3	6.6	4.7	26	2.1	5.3	4.3	17
E (90°)	20	0.8	2.0	2.9	78	0.6	1.8	3.0	68	0.5	2.4	3.2	86	0.5	1.9	2.8	82	0.5	1.5	2.3	82	0.4	1.3	2.1	84
	40	2.5	4.3	3.9	74	1.7	3.6	3.7	64	1.0	5.0	4.2	83	1.0	4.0	3.7	75	0.9	3.0	2.9	75	0.7	2.7	2.8	76
	60	6.1	6.4	4.6	72	3.9	5.5	4.3	60	1.9	7.4	4.9	81	1.1	6.0	4.4	69	1.0	4.4	3.4	69	0.5	4.0	3.2	69

Udir, the direction of wind

Umag, the magnitude of wind speed in miles per hour

S, the maximum wind setup in feet above average water surface

Hs, the significant wave height representing the average of the highest 1/3 of waves for the wind conditions, in feet

T, the wave period associated with the modeled wave heights, in seconds

λ, the angle from north at which the wave is approaching the shoreline