ST. ANTHONY
FALLS LABORATORY

Project Report No. 578

Quantifying wind-wave energy on Minnesota Lakes

Final Report

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The following report summarizes the outcomes of the University of Minnesota /Minnesota DNR project, “Quantifying wind-wave energy on Minnesota Lakes”, including field data collection efforts, data analysis, and model development.

I. Project objective

Lakeshore habitats are a vital component of aquatic plant and animal communities in and around Minnesota lakes. Watershed and lakeshore development activities threaten lakeshore habitat by increasing erosion, sediment loading, and nutrient loading to lakes. Healthy near-shore habitat in lakes is strongly linked to wind and wave energy. Examples include:

- Walleye spawning gravel substrates can be kept clean of fine sediment by wave energy.
- Wave energy affects the distribution of submersed aquatic plants that provide juvenile habitat for some fish species.
- Shoreline erosion is driven mainly by wind-generated wave energy.

Successful lake habitat restoration requires good information on near-shore wind and wave energy, and this information is currently not available. Although wave energy models already exist for large lakes and coastal areas, a key piece of the overall project is to determine how wind-sheltering from terrain and trees reduce wind speeds and wave energy on small to medium sized lakes in Minnesota. The short term goal of this project, addressed in this report, is to test the feasibility of combining wind-sheltering models and wave models to predict near-shore wave energy on small lakes in Minnesota. The long-range goal of this and future projects is to create easily accessible information on wave energy and near-shore habitat, to be used in habitat restoration projects that increase natural fish reproduction in Minnesota lakes.

The work described in this report included collecting wind and wave measurements on several lakes, determining relationships between wave height and the local (on-lake) wind conditions, and evaluating several models for wind sheltering, to relate wind measured at regional airports to local wind and wave conditions on a lake. This project builds on previous work at SAFL to model wind-sheltering on lakes due to trees and terrain.

II. Wind and wave field measurements

Two lake sites were selected for wave monitoring during summer 2015 in cooperation with MN DNR Fisheries: Pleasant Lake in North Oaks, MN and Belle Lake near Hutchinson, MN. A wave and wind monitoring station was installed in each lake, paired with a DNR velocity measurement station (velocimeter and anemometer) placed in a near-shore region where walleye are known to spawn. Equipment setup was slightly different at each site, as described below. In addition to the offshore wind/wave measurement stations installed by SAFL, nearshore velocity measurement stations were installed by the MN DNR at each site.

Site 1: The first site was at Pleasant Lake, in North Oaks, MN. This lake was chosen because it has an appropriate size (600 acres), has limited access, and little boat traffic. A wave measurement station was installed in Pleasant Lake on May 28, 2015 with the help of the DNR, and was removed on Sep 18, 2015. The wave station is a tripod with a submerged pressure sensor to measure water level fluctuations at a rate of 6 Hz, with a Campbell Scientific data logger to store the measurements. The wave measurement interval (2 minute duration at 30 minute increments) matches the measurement interval of the DNR velocimeter. An anemometer and a wind direction sensor were also mounted on the wave station, recording wind speed and direction at 10-minute intervals. The wave station was located approximately 50 m offshore from the velocimeter station, on the east side of Pleasant Lake (Fig. 1). The velocimeter is located directly over a nearshore area identified by the DNR as a walleye spawning area.

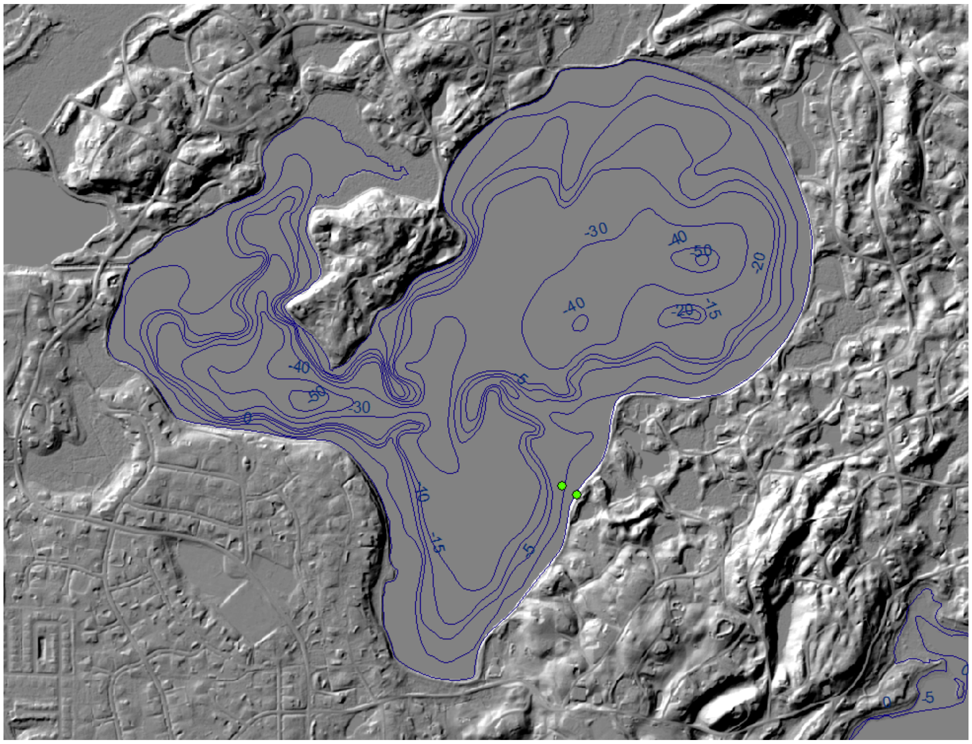

Figure 1. DEM of the terrain surrounding Pleasant Lake, overlaid with bathymetric contours from a MN DNR data layer. The two green points near the southeast shoreline indicate the location of the DNR velocimeter and the SAFL wave station, respectively.

Site 2: The second site was at Belle Lake, near Hutchinson, MN. Belle Lake (925 acres) is similar in size to Pleasant Lake, but is located in a generally flatter and more open area. A wave measurement station was installed at Pleasant Lake on July 21, 2015 with the help of the DNR, and was removed on Sep 29, 2015. Similar to Site 1, the wave recorder was also mounted on a tripod, but rather than using a submerged pressure sensor to measure water level fluctuations, a Massa Ultrasonic distance gauge was mounted above the water to measure water surface elevation directly. Measurements were made at a rate of 4 Hz, with a Campbell Scientific data logger to store the measurements. The wave measurement interval (2 minute duration at 30 minute increments) matches the measurement interval of the DNR velocimeter installed closer to shore. An anemometer and a wind direction sensor were also mounted on the wave station, recording wind speed and direction at 5-minute intervals. The wave station was located approximately 75 m offshore from the velocimeter station, on the northeast side of Belle Lake (Fig. 2, green dot).

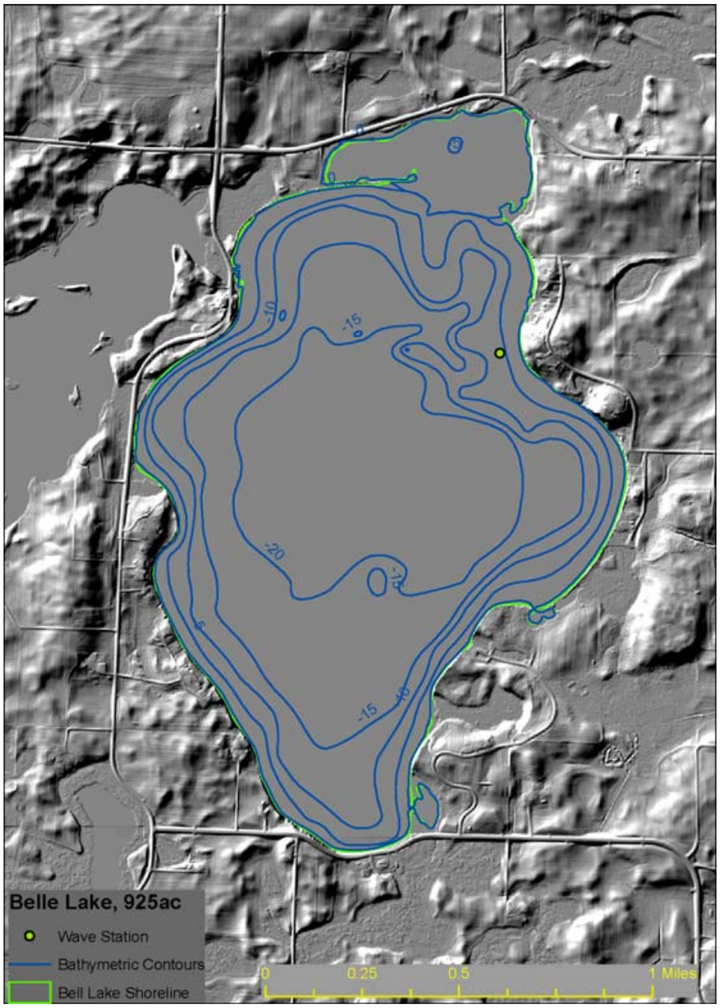

Figure 2. Hillshade DEM of the terrain surrounding Belle Lake, overlaid with bathymetric contours from a MN DNR data layer. The green point shows the location of the SAFL wave station.

III. Wind and wave data analysis

Wind speed and water level data were collected continuously during the summer of 2015 at the wave stations on the two lakes. The data were analyzed to determine time series of characteristic wave heights, and to relate wave height to wind speed and direction at the two wave stations.

<u>Characteristic wave heights:</u> Two useful wave height characteristics were calculated from the wave measurements: (1) significant wave height, H_s (the average of the highest 1/3 of waves in a series, also known as one-third wave height, $H_{1/3}$) and (2) root-mean-square wave height (H_{rms}), which is often used to characterize wave energy. The determination of wave heights from time series of water elevation data used the Matlab package WAFO (Wave Analysis for Fatigue and Oceanography; Brodtkorb et al. 2000) . H_{rms} was then calculated directly for each 2-minute period of wave measurements from the WAFO output. H_s is approximately equal to 4 times the standard deviation of water surface elevation, and this was calculated for each 2-minute period of the raw water surface elevation data. H_s could also be determined by a second method: $H_s = 4(m_o)^{0.5}$, where m_o is the zero moment of the variance spectrum of the water elevation data, which was calculated using the R package 'psd' (another Reference?). H_s determined by these two methods agreed within a few percent.

<u>Pressure Correction:</u> The use of a submerged pressure transducer at Pleasant Lake to measure water level (wave height) required pre-processing of the raw pressure data before it could be used in the wave analysis. This was necessary because of the damping of pressure waves as water depth increases; the damping effect is greater for smaller wave amplitudes and/or greater depth of the transducer below the water surface within the water column, leading to under-prediction of wave height if this effect is ignored (Bishop and Donelan, 1987). The correction factor, which is a function of wavelength, water column depth and transducer depth (Bishop and Donelan 1987; Cavaleri et al. 1978), was determined separately for each 2-minute period of water level measurements. The multiplicative factor averaged 2.60 across the data record, and was applied to the measured water depths in the raw data.

Wind data analysis: Wind speed data, which were collected at 10-minute intervals at Pleasant Lake and at 5-minute intervals at Belle Lake, were first averaged into 30-minute bins to allow direct comparison to the measured waves. Wind direction was averaged into 30-minute bins using vector averaging (i.e. resolving wind into X-Y components and weighting by wind speed). Wind data were further summarized by frequency and magnitude as a function of compass direction using 10-degree bins to simplify comparison to airport wind data. Wind and wave data are summarized by direction on wind rose plots for Pleasant Lake (Fig. 3) and for Belle Lake (Fig. 4). For comparison to airport wind data (Fig. 7), the wave station wind data, which were collected at a height of roughly 2m, had to be corrected to a height of 10m (the standard airport station measurement height): $U_{10m} = U_{2m}*(10/z)^{1/7}$, where z is the wave station wind measurement height (z=2m in our case).

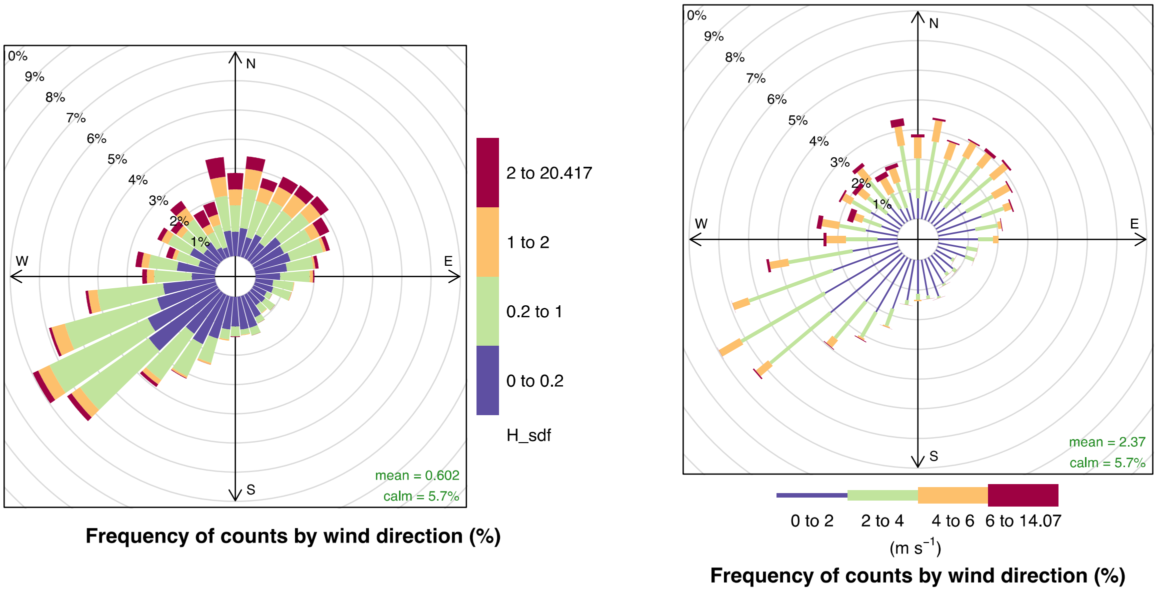

Figure 3. Pleasant Lake wave and wind data summary: [left] distribution of significant wave height (cm) as a function of wind direction, and [right] the corresponding distribution of wind speed (m/s) as a function of wind direction.

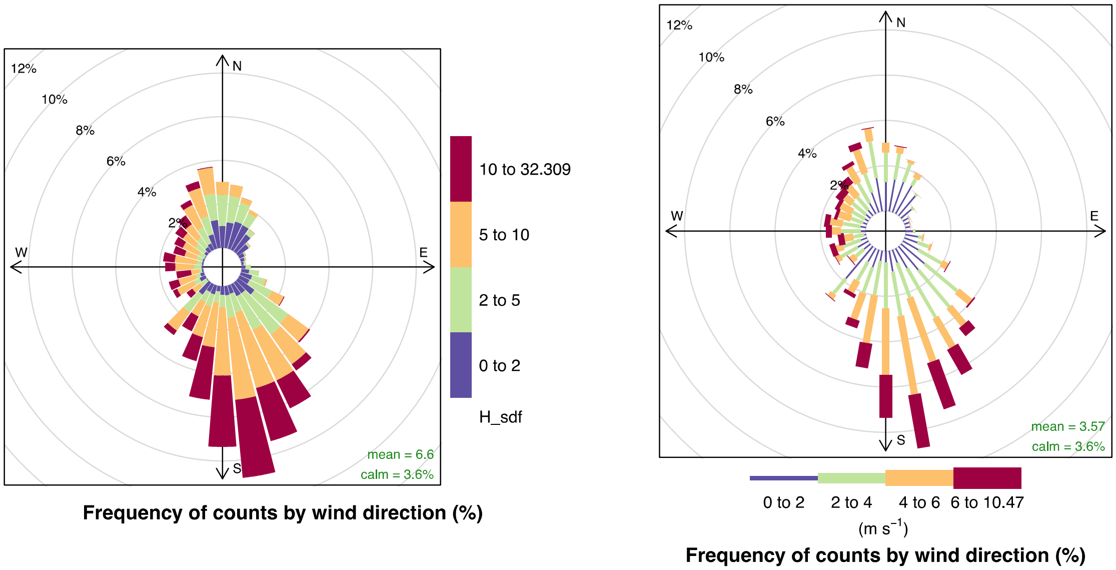

Figure 4. Belle Lake wave and wind data summary: [left] distribution of significant wave height (cm) as a function of wind direction, and [right] the corresponding distribution of wind speed (m/s) as a function of wind direction.

Local wind-wave relationships: At both lake sites, a strong relationship exists between mean wave height and mean wind speed as a function of direction (using 10-degree directional bins; Fig. 5). These relationships suggest that the local wind speed measured at some point in a lake, by itself, is a reasonably good predictor of wave height at that location. However, note that 1) there is scatter in the relationships and 2) the relationships are quite different between the two lake sites. The local wind speed and direction is expected to be related to the prevailing wind in the vicinity of the lake, and to be significantly affected by wind sheltering due to trees and topography (landscape, terrain) around the lake, which determine the effective wind fetch for wave generation. In general, we do not have this locally measured wind speed available for wave predictions.

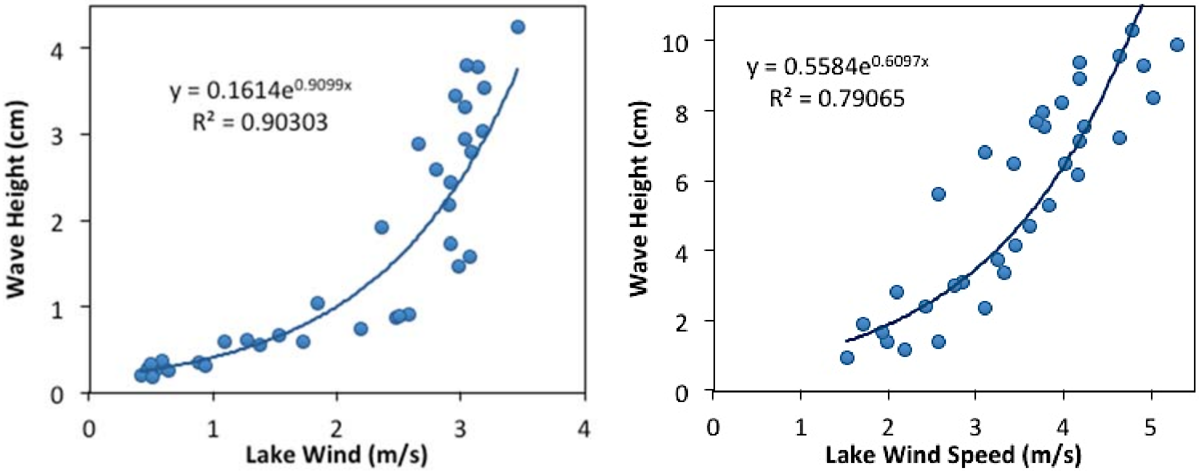

Figure 5. Observed significant wave height (cm) vs. observed wind speed (m/s) at the wave station for [left] Pleasant Lake and [right] Belle Lake. Each point represents the mean wave height and wind speed for a given 10-degree bin of wind direction. Wind speed was measured at z = 2m height above the water surface.

IV. Modeling of fetch and wind-sheltering of a lake

To relate prevailing winds (i.e. wind measured at a nearby weather station such as a small airport) to wind at a given point of interest on a nearby local lake, and ultimately to wave energy at that point, is necessary to estimate wind fetch as a function of wind direction. This wind fetch will be related both to the distance of open water and to the degree of wind sheltering by trees and by topography (landscape, terrain) in a given direction from a point of interest on the lake. Several approaches were evaluated to model the effect of wind sheltering on fetch, and to use fetch to relate synoptic (airport) wind speed and direction to local wind speed on a lake.

Data Acquisition:

(1) LiDAR data, including raw first-return point clouds and 3m-resolution DEMs, were downloaded for the terrain around Pleasant Lake and Belle Lake (MN Geospatial Commons). The first-return data were used to estimate tree heights around the lake with the LASTools software package (rapidlasso GmbH; rapidlasso.com).

(2) Prevailing wind speed data were acquired for nearby airports. For Pleasant Lake, the nearest airport

was Anoka County-Blaine Airport, located roughly 6 miles to the northwest of the lake. For Belle Lake, it was Hutchinson City Airport, about 9 miles to the southeast. Wind roses for these two airports are shown in Fig. 6. The wind observations at the two airports were similar to summer (May – September) observations at other airports in the vicinity (see Appendix A).

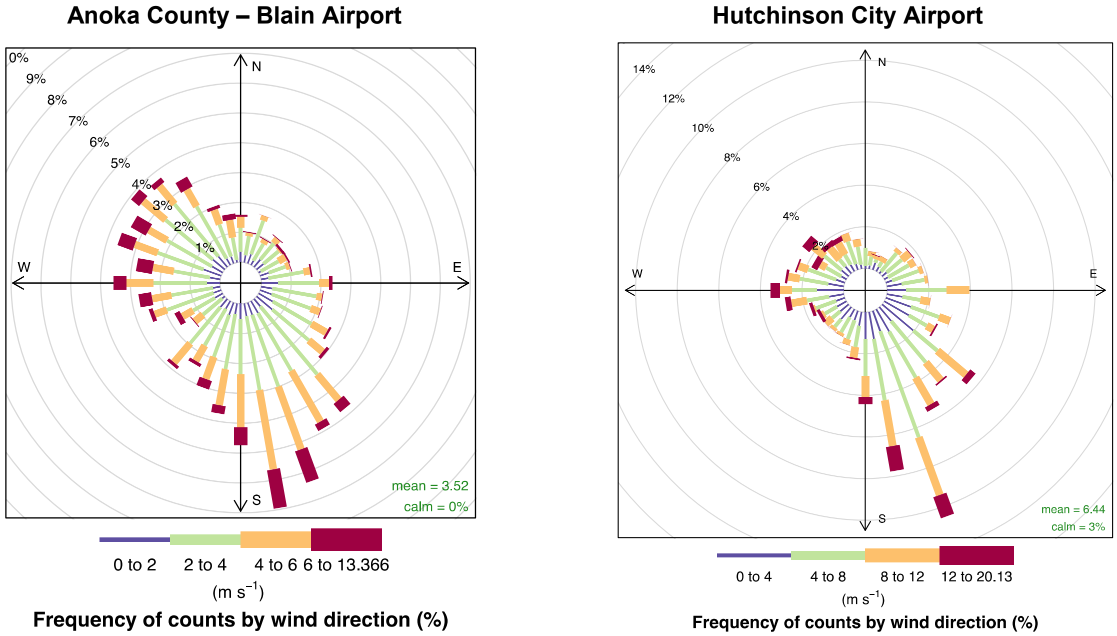

Figure 6. Distribution of magnitude and frequency of observed wind (m/s) by direction (10-degree bins) at [left] Anoka County – Blaine Airport, and at [right] Hutchinson City Airport. Wind data restricted to period of wave observations at the nearby lakes (May 28 – Sep 19, 2015 at Blaine AP; July 21 – Sep 28, 2015 at Hutchinson AP). Note differences in scales between the plots.

Wind sheltering: For each lake, the effect of sheltering was investigated by comparing mean wind speed measured at the nearest airport to the coincident (in time) wind speed measured at the wave station (Fig. 7). The assumption is that the airport is measuring the prevailing wind in the vicinity of the lake, while the wave station is measuring the wind after it has been affected by sheltering from surrounding trees and topography. The ratio between the wind speeds at the wave station and at the airport shows the amount of sheltering, as a function of direction (10-degree bins). As to be expected, the greatest amount of sheltering appears to result when wind approaches from the direction of the nearest shore (from the east for both lakes, especially for Pleasant Lake, where the wind ratio dips well below 1.0), with substantial variation for the other directions where greater open-water distance is present. For Belle Lake, the wind speeds observed on the lake are also often much larger than those observed at the airport (by a factor of 2 or more in some directions) – this may be due to the difference in surface roughness length between the airport site and the lake. Given sufficient distance, near-surface wind speeds will be higher on a lake, due to the relatively smooth surface. Together, these trends suggest a complex interaction of wind with the land surface in cases of relatively complex topography, or vegetation cover, as well as problems with the assumption that the airports are measuring synoptic wind patterns (see Appendix A).

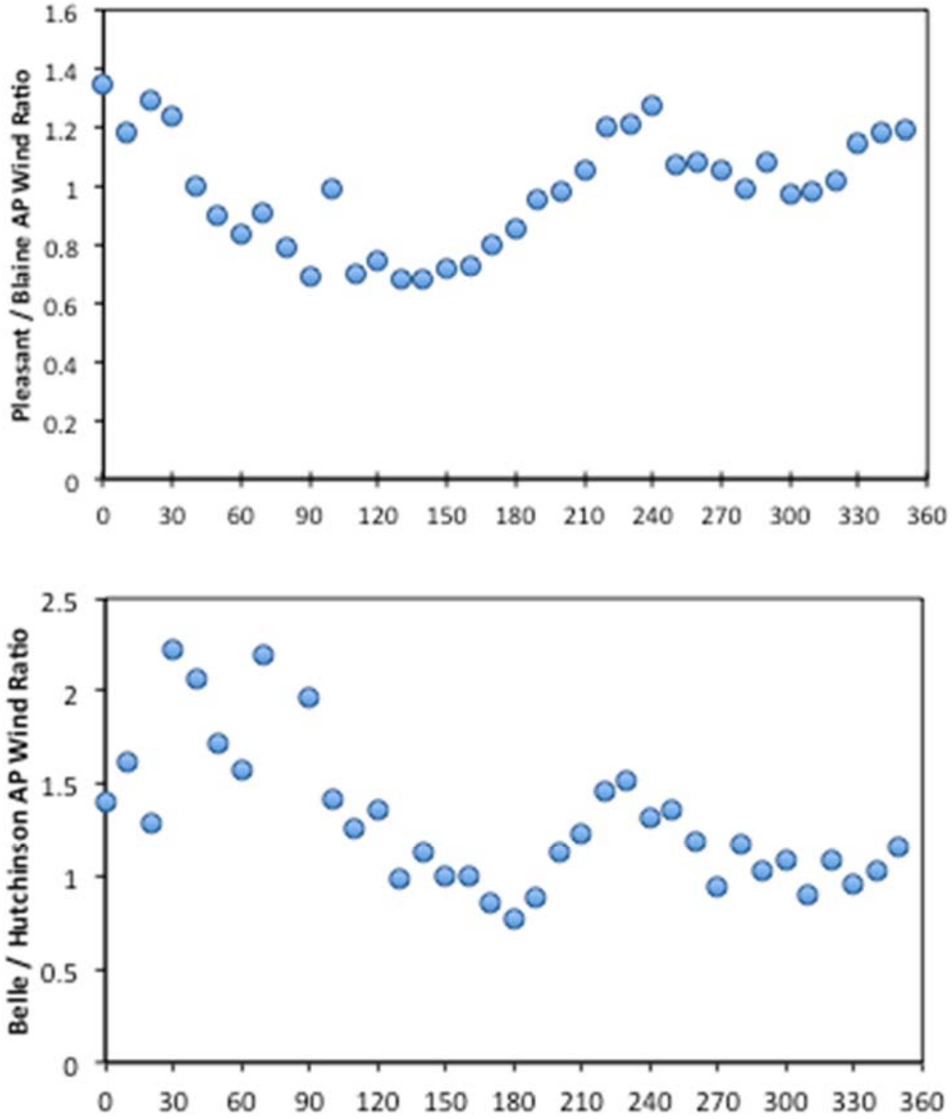

Figure 7. Ratio of wind measured at the wave station to that observed at the nearest airport, as a function of wind direction at the airport (in degrees; 0 = north). Pleasant Lake : Blaine AP shown at top, Belle Lake : Hutchinson AP shown at bottom.

Fetch/Sheltering Models: Access of wind to a lake surface can be hindered (sheltered) by obstructions such as buildings, trees, bluffs, hills and other landscape features. Fetch can be defined as the unobstructed distance across a lake surface over which wind can blow in an unhindered way. Wave development on a lake surface can be strongly affected by fetch length and duration of the wind. On small lakes, fetch can be the more important limitation. Several simplified models of estimating fetch, primarily from spatial analyses in ArcGIS, have been examined in a preliminary way (Models #1 to #3 below). A fourth model that predicts fetch as an output of a wave model (Rohweder et al. 2012), using observed wind and wave heights, was used as a check on the other models. The four models are compared for both lakes in Fig. 8.

(Model #1) Lakeshore/open water fetch: The simplest fetch model is to ignore the effect of land cover (trees) and topography on wind sheltering and to consider the open water distance across the lake by direction as the fetch. This value can serve as the upper bound or potential fetch; (the potential fetch is the fetch when the landscape surrounding the lake is totally flat and at the elevation of the lake surface; the airflow over the land has to adjust to a roughness change when it reaches the water and a new air boundary layer has to develop). The actual wind sheltering effect due to land cover and landscape then has to be introduced by other models. The potential fetch was computed as a function of wind direction (every 10 degrees, to match the wave and wind data summary) by tracing a line from the wave station to the upwind lakeshore using ArcGIS (e.g., for Belle Lake in Fig. 10). The use of a single line may be overly simplistic, even as a starting point, as the Shore Protection Manual (USACE, 1984) advises computing distance over an array of angles about the central angle.

(Model #2) Lakeshore canopy-reduced fetch: This model attempts to reduce the open-water fetch distance proportional to the height of trees near the shore. Work by Markfort et al. (2010) suggests that wind speed is effectively reduced downwind of a dense tree canopy for a distance of roughly 50 times (range: 40 to 60) the tree height. In this model, tree height (h_t) was estimated as the difference between first-return LiDAR and the ground DEM; canopy within 30m of the shore was considered. Mean tree height within this shore buffer was computed for each 10-degree sector. Open-water potential fetch (Model #1 above) was then reduced in each direction by assuming a linear decrease in fetch over the $50*h_t$ distance; i.e. for an open-water fetch > $50*h_t$, the effective (reduced) fetch was open-water distance – ½*($50*h_t$). This formula also allowed for non-negative fetch distance to be computed for open-water distances that were less than $50*h_t$.

(Model #3) Canopy and topography-reduced fetch: similar to Model #2, this model reduces the open-water potential fetch in a given direction based on all upwind obstructions, including trees and topography, at any distance from shore (Fig. 11). The assumption is that any obstruction that exceeds a 1:50 slope away from the shore (based on Markfort et al. 2010) will reduce the open-water fetch. This model checks buffers in 25m increments away from the shore for first-return excursions above the 1:50 line (Fig. 12), computes the mean excursion for a given buffer within a sector, and reduces the fetch . The lowest effective fetch among all buffers for a given 10-degree sector is assumed to be actual effective fetch.

(Model #4) Inverse wave modeling: Fetch may also be computed using a USGS-USACE wave model (Rohweder et al. 2012; based on the USACE's Shore Protection Manual (1984) and Coastal Engineering Handbook (2002)) by solving for fetch and using as input the observed wave heights (rather than as an output) in addition to the synoptic (airport) wind speed. This model was applied at the seasonal scale, using mean wave height and mean wind speed averaged over the whole summer data record as a function of direction (using 10-degree bins). Direction was defined by the wind observations at the airport.

<u>Fetch/Sheltering Model Assessment:</u> The accuracy of the fetch models (Models #1 to #3) was assessed qualitatively by plotting fetch as a function of wind direction (Fig.8) along with the fetch predicted from the inverse wave model (Model #4). Only two of the sheltering approaches were used for Pleasant Lake. For Pleasant Lake (Fig. 8 top), the fetch models showed the greatest discrepancies vs. the inverse model for wind coming from the directions of greatest open water distance, i.e. the north and west (roughly 200˚ to 30˚), as well as directions for which wind observed at the wave station often exceeded that observed at the airport. Given the non-uniform shape of the lake and steep topography to the northwest of Pleasant Lake (Fig. 1), wind may interact with the land in a way that is not readily predictable by simple sheltering models. It is also possible that the land cover and irregular topography to the northwest are so rough that the wind speed recovers over the lake because the roughness of the water surface is so much less than that of the land to the northwest. Similarly, for Belle Lake (Fig. 8 bottom), the fetch models fared poorly for winds from the northwest and southwest, again reflecting a potentially complex interaction of wind with topography large roughness differences to the north and northwest, or even with open water of an adjacent lake further to the west and southwest. Instances of the inverse wave model predicting fetch length greater than the open-water distance (e.g. for wind directions from 50˚ to 70˚ at both lakes) may be evidence of the wave model's limitation for handling sheltering from northwesterly winds due to land cover and land forms in close proximity to shore in those directions.
The fetch models were assessed quantitatively by using the USGS-USACE wave model to predict significant wave height at an hourly time scale as a function of estimated fetch and observed hourly wind speed at the nearby airport. Root-mean-squared error (RMSE) and mean absolute error (MAE) for predicted vs. observed hourly wave heights were used to evaluate model accuracy (Tables 1 and 2a). Note that Model #4 used the wave model in reverse to predict fetch, and therefore should perform the best. In general, none of the fetch models (Models #1 to #3) proved to be an accurate predictor of the time series of hourly wave height at either of the lakes when used in the USGS-USACE wave model over the entire record length. For Pleasant Lake, Model #2 generally over-predicted observed wave heights (Fig. 9 left), while for Belle Lake the model under-predicted wave heights (Fig. 9 right). The attempt to reduce fetch due to sheltering by trees or topography (Model #2) offered only marginal improvement on the open-water potential fetch Model #1 in the prediction of hourly wave heights over the entire season of record for Pleasant Lake, while for Belle Lake, Models #2 and #3 actually performed worse than the open-water potential fetch Model #1.

When the hourly wave height predictions and observations were averaged over the entire record length by wind direction (using 10-degree bins), model accuracy improved considerably for Belle Lake (Table 2b; Fig. 9 right), though not for Pleasant Lake (results not shown). An explanation for this result is not apparent, but the result suggests that the wave model may not be appropriate for time scales as fine as an hour on small lakes, but may be useful when applied at a longer time scale (e.g. monthly or seasonal) when temporal variation in wind speed and direction may have less potential to influence results. The USGS-USACE model was developed for the case of fetch-limitation of waves (as opposed to duration-limitation), meaning that waves are assumed to adjust to the height dictated by the constraints of open-water distance (fetch) relatively more quickly than for changes in wind magnitude and direction over the time scale of interest (typically 24 hours for the wave model; Rohweder et al. 2012). Thus the hourly time scale employed in our analysis may be in violation of the assumption of fetch limitation.

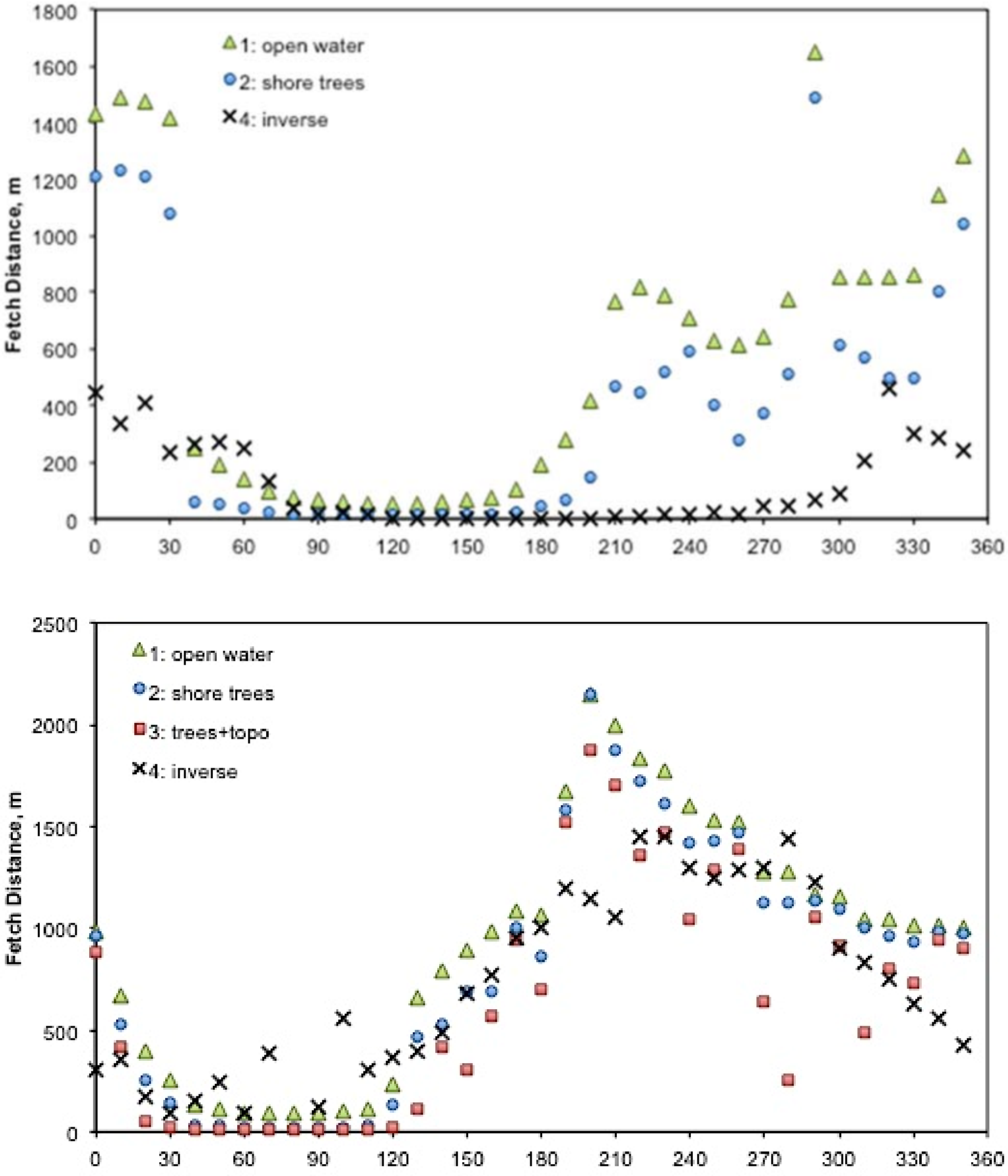

Figure 8. Estimated fetch distance (m) as a function of direction from the wave station (in degrees; 0˚=north), using (top) three different approaches at Pleasant Lake, and (bottom) four different approaches at Belle Lake (see main text for methods descriptions).

Table 1. Assessment of fetch models by comparison of hourly observed significant wave height ($H_{1/3}$) with hourly modeled significant wave height (USGS-USACE wave model; Rohweder et al. 2012) for Pleasant Lake. RMSE: root mean squared error, MAE: mean absolute error.

Model No. **Description**	1 open water	2 shore canopy	3 canopy and topography	4 inverse
Mean H1/3, obs [cm]	1.65	1.65	1.65	1.65
Mean H1/3, model [cm]	4.12	3.05	n/a	1.37
RMSE [cm]	3.12	2.31	n/a	1.98
MAE [cm]	2.54	1.63	n/a	1.10
R^2	0.62	0.59	n/a	0.42

Table 2. Assessment of fetch models for Belle Lake, by comparison of (a) hourly observed significant wave height ($H_{1/3}$) with hourly modeled significant wave height (USGS-USACE wave model; Rohweder et al. 2012), and (b) comparison of hourly observed wave heights and hourly predicted wave heights, averaged by wind direction (10-degree bins) over the whole season of monitoring.

Model No. **Description**	1 open water	2 shore canopy	3 canopy and topography	4 inverse
(a) hourly wave prediction				
Mean H1/3, obs [cm]	6.43	6.43	6.43	6.43
Mean H1/3, model [cm]	5.04	4.55	3.83	6.75
RMSE [cm]	5.02	5.22	5.53	5.28
MAE [cm]	3.72	3.87	4.12	3.98
R^2	0.081	0.081	0.074	0.094
(b) hourly waves averaged by direction				
RMSE [cm]	1.53	1.77	2.41	0.73
MAE [cm]	1.13	1.31	1.86	0.50
R^2	0.81	0.79	0.69	0.98

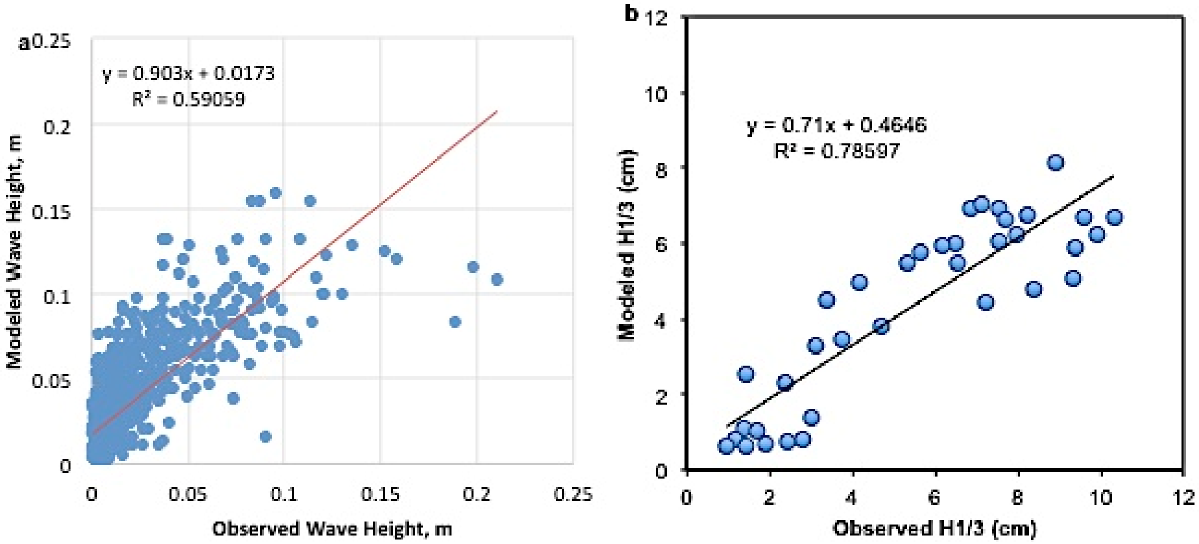

Figure 9. Modeled vs. observed hourly significant wave height (H1/3) at (left) Pleasant Lake (all hourly data points), and (right) Belle Lake, averaged over the season's data record and binned by wind direction (i.e. each dot represents mean hourly wave height for a given 10-degree bin). Model #2 (shore canopy) was used for the fetch model in both cases.

Sources of Error: *Sources of error:* Several factors can contribute errors to the results. First, the results may reflect a limitation of the USGS-USACE wave model and not of the fetch models, as the wave model was developed from studies of coastal areas, i.e. much larger bodies of water and much higher waves than were monitored in this study. I It may also not be a suitable model for use at time scales as fine as an hour (as in this study) or for small bodies of water.

Other sources of error could come from the wave and wind measurements. For example, if the wave station rotated or was not oriented properly at installation, the wind direction measured at the station would not match that at the airport. In addition, the wind measurements at the airport may not be representative of synoptic winds in the vicinity of the lakes. The similarity of wind measurements at other airports near both lakes (Appendix A) suggests that the wind measurements used were at least representative of general wind patterns, local effects from topography, buildings, and surface vegetation height (roughness length) need further consideration. . Wind speeds measured at Belle Lake in particular were much higher than those measured at either of the closest airports (Hutchinson or Litchfield; see Fig. 7).

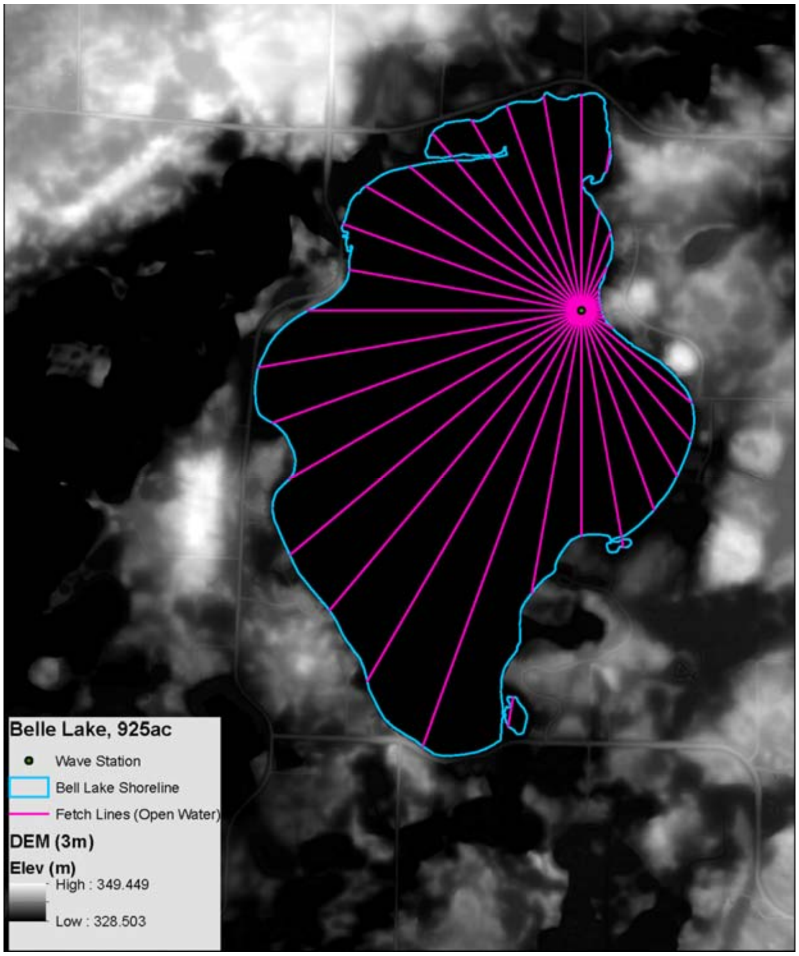

Figure 10. Open-water fetch (pink lines) from wave station, on Belle Lake.

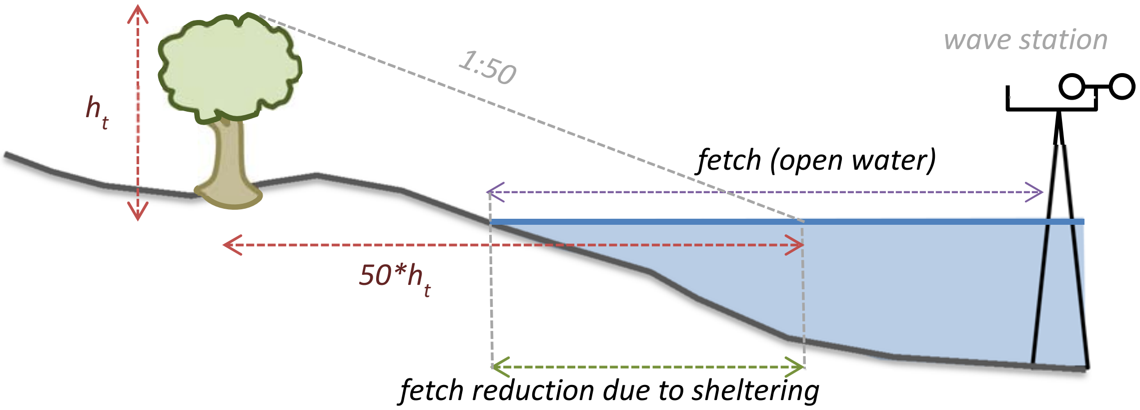

Figure 11. Reduction of open-water fetch due to steep topography or to trees located near shore; reduction effect occurs downwind of the tree canopy for 50 x the tree height above the water surface, h_t *(Markfort et al. 2010).*

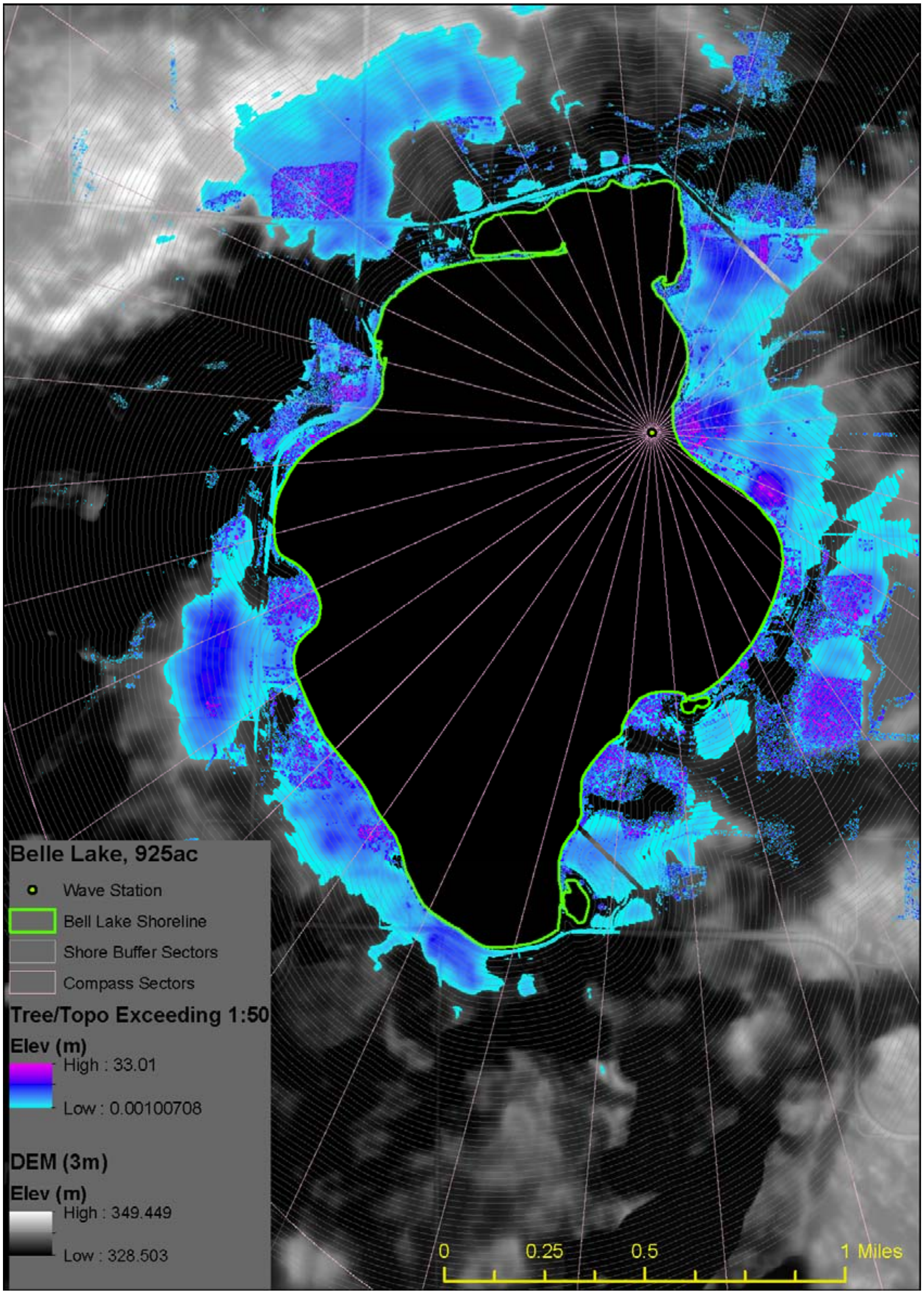

Figure 12. Trees and topography (from first-return LiDAR data) surrounding Belle Lake that exceed a 1:50 slope in elevation away from the lake shore; pink shading indicates areas with greatest excursions and sheltering potential. Shore buffers used to compute mean exceedences (and resulting fetch reduction) are also shown.

V. Summary and Future Work

Using wave and wind observations over several months (roughly June to September, 2015) at two lakes, (Belle Lake and Pleasant Lake) this study has shown that a strong relationship exists between observed wind speed and observed wave heights at the location of two wave stations of interest, i.e. locations near walleye spawning areas. This result suggests that if wind speed could be accurately predicted for a location of interest in a lake, characteristic wave heights and associated wave energy could be estimated.

We attempted to predict local wind speeds from wind observations at nearby airports along with estimations of sheltering from trees and topography around the lake. Three approaches were developed. A wave model developed by the USGS and USACE was used to predict wave heights from observed wind speeds and the fetch estimated by the models; these predictions were compared to observed wave heights at the two lakes. In general, none of the models appeared to be a large improvement over simply using the unobstructed open-water distance as the fetch estimate. The wave model was also used inversely to predict fetch (as a function of wind direction) from the observed wave heights and wind speeds. This fetch estimate was used as an approximation of the actual fetch, to which the other estimates were compared. In general, these fetch models performed better for predicting wave characteristics that were averaged, for example, over the entire measurement period, compared to hourly- or daily-averaged wave predictions. Ultimately, we expect such a model will be used to predict long-term averaged wave characteristics, so the current models may not be far off from giving useful predictions.

Future work will include application of a wave model developed by the USGS and USACE (Rohweder et al. 2012) to the data set. Activities related to this model can include the following:

(1) More explicit consideration of the land and water surface roughness length should be explored in the models for local wind conditions and fetch. Previous work on the adjustment of wind profiles to changes in roughness may be useful (e.g. Belcher et al. 2003). Such a model could even include an estimate of the roughness length in the vicinity of the airport from which prevailing winds are measured.

(2) Differences between the modeled and measured wave heights as a function of wind direction may identify portions of the lake or directions for further fetch model development.

(3) A sediment suspension module is included in the USGS/USACE wave model, and its capabilities may be worth exploring in future work.

(4) If a suitable fetch/sheltering model can be developed, it will be useful to test its application to more than one location of interest in a lake, with multiple wind/wave stations.

(5) To relate incoming waves to nearshore water velocities, the relationships between incoming wave characteristics and the corresponding nearshore velocities need to be explored, utilizing the velocity data collected by the MN DNR.

Acknowledgments

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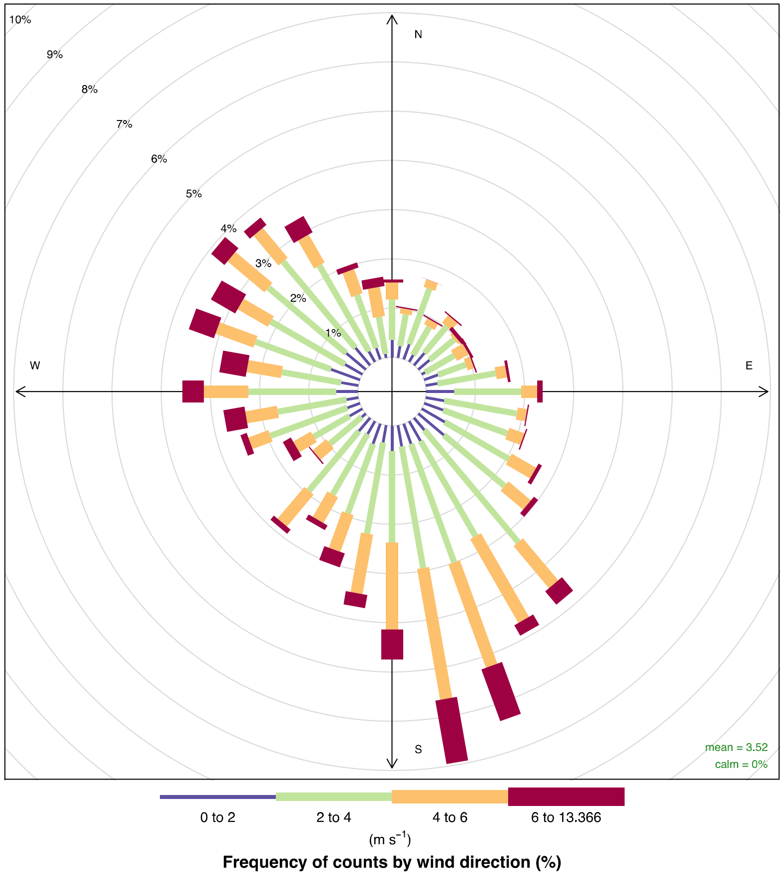
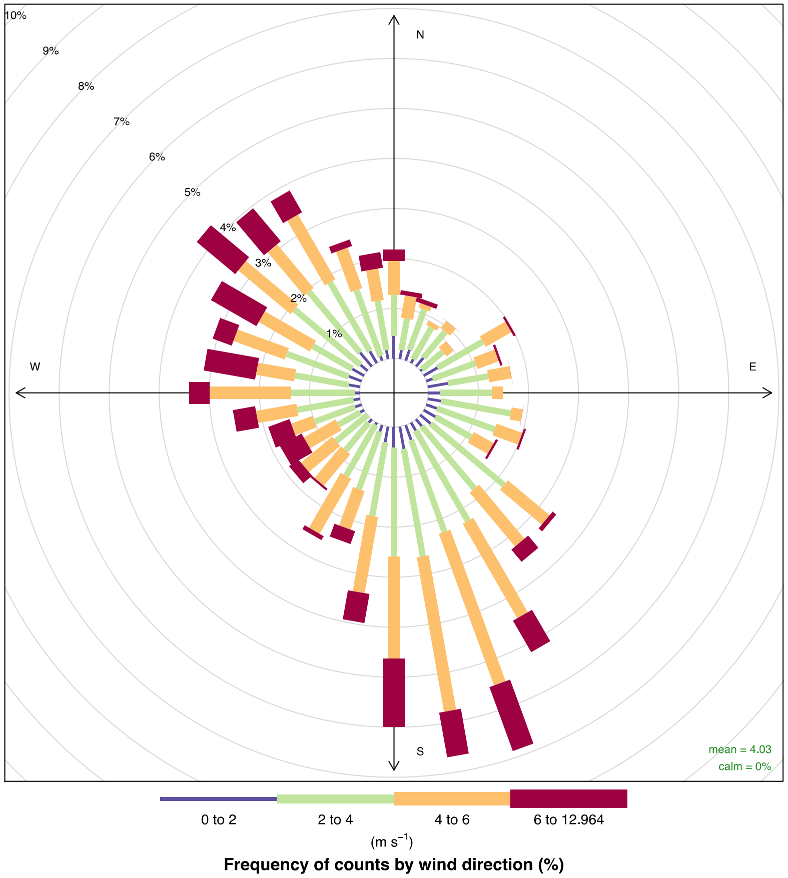
Appendix A: Distributions of Observed Wind Frequency and Magnitude (Wind-Rose Plots) at Several Airports near Study Lakes (Pleasant Lake and Belle Lake), June 1 – Sep 30, 2015

A-1. Wind Observations at Weather Stations near Pleasant Lake: Anoka County – Blaine Airport, Crystal Airport, and Minneapolis-St. Paul International Airport

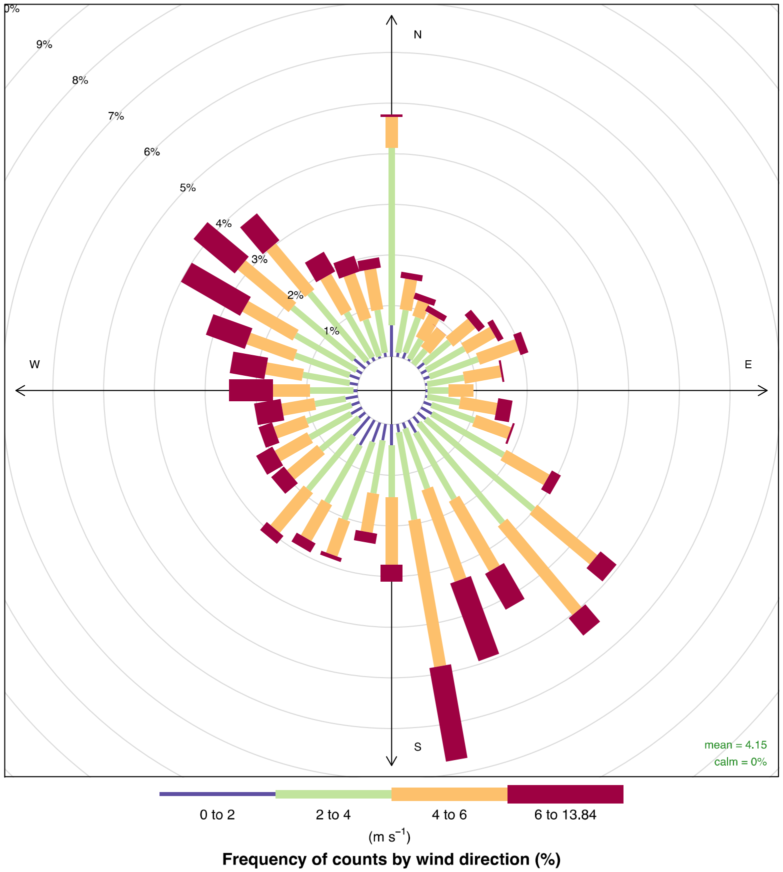
Anoka County – Blaine Airport: June 1 – Sep 30, 2015



Crystal Airport: June 1 – Sep 30, 2015

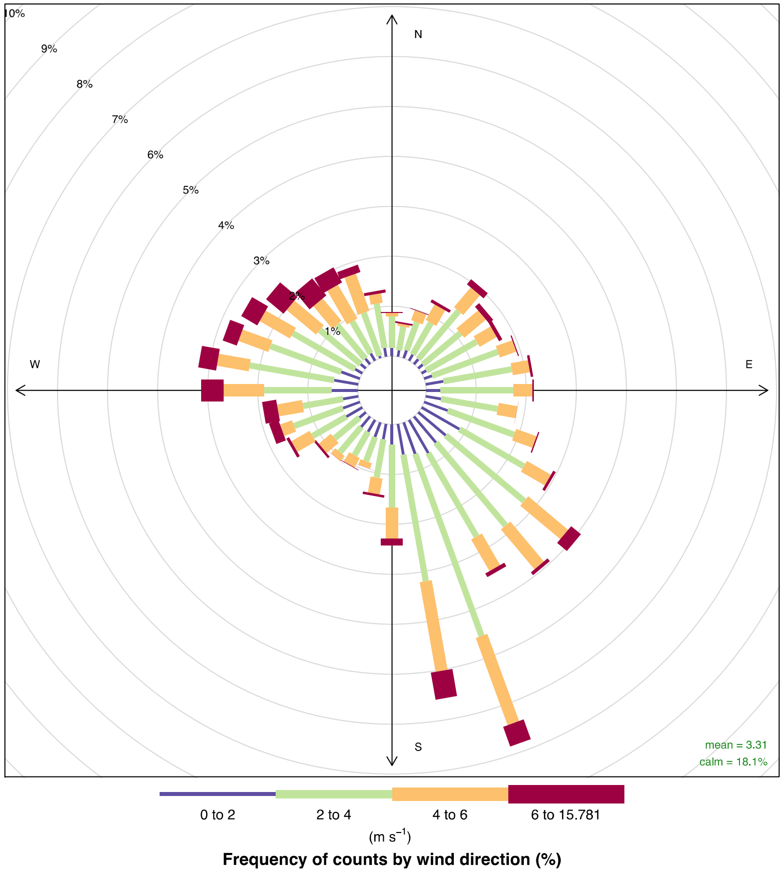


Minneapolis – St. Paul International Airport: June 1 – Sep 30, 2015



A-2. Wind Observations at Weather Stations near Belle Lake: Hutchinson City Airport, and Litchfield City Airport

Hutchinson City Airport: June 1 – Sep 30, 2015



Litchfield City Airport: June 1 – Sep 30, 2015