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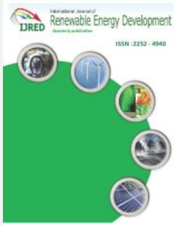

Lake Michigan Wind Assessment Analysis, 2012 and 2013

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ABSTRACT. A study was conducted to address the wind energy potential over Lake Michigan to support a commercial wind farm. Lake Michigan is an inland sea in the upper mid-western United States. A laser wind sensor mounted on a floating platform was located at the mid-lake plateau in 2012 and about 10.5 kilometers from the eastern shoreline near Muskegon Michigan in 2013. Range gate heights for the laser wind sensor were centered at 75, 90, 105, 125, 150, and 175 meters. Wind speed and direction were measured once each second and aggregated into 10 minute averages. The two sample t-test and the paired-t method were used to perform the analysis. Average wind speed stopped increasing between 105 m and 150 m depending on location. Thus, the collected data is inconsistent with the idea that average wind speed increases with height. This result implies that measuring wind speed at wind turbine hub height is essential as opposed to using the wind energy power law to project the wind speed from lower heights. Average speed at the mid-lake plateau is no more that 10% greater than at the location near Muskegon. Thus, it may be possible to harvest much of the available wind energy at a lower height and closer to the shoreline than previously thought. At both locations, the predominate wind direction is from the south-southwest. The ability of the laser wind sensor to measure wind speed appears to be affected by a lack of particulate matter at greater heights..

Keywords: wind assessment, Lake Michigan, LIDAR wind sensor, statistical analysis.

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1. Introduction

A study of wind speed and direction in Lake Michigan was conducted to help determine if the wind energy potential was sufficient for further exploration of wind farm development. Lake Michigan is an inland sea in the United States bordering on the states of Michigan, Illinois, Indiana, and Wisconsin with a maximum length of 494 km, a maximum width of 190 km, a surface area of 58,000 km2, and an average depth of 85 m. A study by Elliott et al (1986) estimated Class 5 wind power was available in the areas of highest wind energy potential. These are the exposed offshore areas, islands and exposed capes, and points along the state of Michigan shore of Lake Michigan.

The first goal of the study was to test the idea that wind speed increases with height over Lake Michigan. This idea is consistent with the wind profile power law (Elliott et al. 1986, Peterson and Hennessey 1978).

$$\frac{V}{V_0} = \left(\frac{Z}{Z_0}\right)^a \qquad (1)$$

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This relationship states that the estimation of the change of wind speed with height is obtained using a power law relationship with which the wind speed (V) at hub height (Z) is estimated from the wind speed (V_0) measured at some reference height (Z_0). The exponent, α, varies with height, time of day, season, nature of the terrain, wind speeds, and temperature. More importantly, the structure of the equation assumes that wind speed increases with height, implying that the taller the turbine the more wind speed and thus power will be obtained.

The second goal of the study was to determine if wind speed was significantly greater at the middle of Lake Michigan near the border of the states of Michigan and Wisconsin than near the shoreline near Muskegon, Michigan. The additional distance from the shore to the middle of the lake increases challenges in installation and maintenance of a commercial wind farm, particularly in the harsh winter environment on Lake Michigan. The cost of meeting these challenges can be offset by greater wind speed leading to greater energy generation. Data collection was accomplished using a laser wind sensor (LWS) or LiDAR gage mounted on a 190 square foot floating platform.

Validation of the LWS unit was a prerequisite to this study. Validation was accomplished by comparison of wind speed measurements made by the LWS unit mounted on the floating platform near the state of Michigan shoreline to those made by cup anemometers mounted on meteorological masts on the shore but near the location of the LWS unit. The validation study is discussed in Standridge et al. (2015), where an extensive review of the literature is also presented. The literature review will not be repeated here.

Typical wind speed studies both summarize wind data and extend the results to estimate wind speed at potential wind turbine hub heights above the data collection height using the wind profile power law. Often, a probability distribution is fit to the wind speed data using mathematical techniques. This distribution is used along with the power curve specific to a particular wind turbine in computing the potential power generated by that turbine. Alternatively, Law (2007) suggests the use of a proprietary heuristic which has been implemented in the ExpertFit software to fit data to a statistical distribution.

Nedaei (2012) analysed data collected at the Abadan Airport in Iran at 10 m, 40 m, and 80 m. Equation 1 was used to extrapolate results to wind turbine hub height as high as 105 m. Similarly, Ajayi et al. (2013) as well as Babayani et al. (2016 a, b) analysed data collected at 10 m and used equation 1 to project wind speeds to wind turbine heights between 50 m and 80 m. Additional studies are reported by Oyedepo et al. (2012), Olaofe and Folly (2012), Jamdade and Jamdade (2012), Bariorgas et al. (2012), Veigas and Iglesias (2012), and Lu et al. (2002). Roy (2012) discusses estimating the α parameter of the power law under a variety of conditions.

A weakness with each of these studies is a lack of validation of the projected wind speed at higher altitudes than the observed data, such as through observing wind speed at these altitudes. This study addresses this weakness by making observations at 6 heights ranging from 75 m to 175 m. Existing statistical methods are applied for comparing wind speeds between heights and locations. Furthermore, all of the studies referenced above were land-based and used cup anemometers mounted on meteorological masts. This study makes use of data collected over water using an LWS unit.

Data collection in 2012 and 2013 as well as analysis methods for summarizing and comparing results are described. The relationship between height and wind speed is analysed and discussed. A comparison of wind speeds between the two locations is made. Conclusions concerning the performance of the LWS unit are discussed as well.

2. Data Collection

To collect the data need to conduct the wind assessment study, an LWS unit was mounted on a 190 square foot floating platform and deployed in Lake Michigan. There are two independent variables of interest: height above the water surface and location in the lake. Dependent variables are wind speed as well as wind direction. The LWS has six range gates which were centered at 75 m, 90 m, 105 m, 125 m, 150 m, and 175 m as well as a cup anemometer mounted 3 m above the platform deck. Thus, data concerning wind speed and direction can be collected at each of these heights. Wind speed and direction were observed in 2012 near the mid-lake plateau close to the Michigan-Wisconsin state border approximately 56 km from the eastern shoreline and in 2013 approximately 10 km from the eastern shoreline near Muskegon, Michigan as described in Table 1.

In each year, data was collected at only one location. Thus, any differences found between the average wind speeds at the two locations may be due to the differing characteristics of the two locations or due to different average winds in 2012 versus 2013. Thus, location and year are confounded. Note also that data were gathered from approximately the first of May through mid-December of each year. The buoy was removed during the time period that harsh winter conditions could damage the instruments mounted on the buoy, late December through April.

Table 1
Observation Locations.

Year	Location Description	Co-ordinates	Dates
2012	Mid-Lake Plateau	43.20N, 87.07W	May 8 - Dec 17
2013	Near Muskegon Michigan	43.16N, 86.30W	April 28 - Dec 20

Source: Authors' Measurement.

3. Methods

An LWS unit measures wind speed and direction every second. Thus, there are 600 observations every ten minutes. The average wind speed for each ten-minute interval is computed from these 600 observations. The LWS units reports whether each observation is valid or invalid. As described in Standridge et al. (2015), a ten minute average is considered valid if at least 300 of the 600 observations are reported as valid by the device.

By a central limit theorem (Law 2007), the ten minute averages are normally distributed with the mean and standard deviation estimated from the ten minute averages. Further, the number of ten minute averages is large, greater than 32000. Thus the empirical distribution (histogram) should be sufficiently dense, with no gaps, to support computing the potential power using the power curve of a selected wind turbine. Statistical analyses were performed using equations 2-7. A discussion of each of these equations and their use is found in Devore (2012). The coefficient of variation (Cv) is a standardized statistic that is useful in comparing the variation between multiple quantities. It is computed as shown in equation 2:

$$Cv = \frac{s}{\bar{x}} \qquad (2)$$

where s is the standard deviation and $\bar{x}$ is the average.

Comparison of wind speeds from multiple heights and two locations is central to this study. In general terms, there are two possibilities when comparing two samples, depending on whether each observation in one sample has a natural partner in the other. For instance when comparing wind speed observations at two heights at the same location and over the same period of time, each sample at one height has a natural partner in the sample at the other height as both observations were taken at the same time. In this case, the paired-t method is used. Alternatively when comparing wind speed observations from two different locations each taken in a different year, there are no natural partners. Thus, the two sample t-test must be used.

When using the two sample t-test, the 1-α confidence interval for the difference in the two sample means with equal but unknown variances is computed using equation 3.

$$(\overline{x_1} - \overline{x_2}) \pm t_{1-\frac{a}{2},df} * s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \qquad (3)$$

where $\overline{x_1}$ and $\overline{x_2}$ are the two sample means, $t_{1-\frac{a}{2},df}$ is a percentage point from the Student's t distribution with df degrees of freedom, s_p is the pooled standard deviation of the two samples, n_1 is the number of observations in the first sample, and n_2 is the number of observations in the second sample. Using the pooled standard deviation assumes homogeneity of variance, a commonly used assumption that is known from experience to be robust.

The degrees of freedom df is computed using equation 4.

$$df = n_1 + n_2 - 2 \qquad (4)$$

The pooled variance is computed using equation 5.

$$s_p^2 = \frac{(n_1-1)*s_1^2+(n_2-1)*s_2^2}{n_1+n_2-2} \qquad (5)$$

Each ten minute average computed from observations at one height has a natural partner in the ten minute average computed from observations made at another height for the same ten minute time interval, t. Thus, the paired-t method applies. The fundamental equation of the paired-t method generates a time series of differences as show in Equation 6. A difference is valid if both of the ten minutes averages are valid.

$$\text{difference}_t = \text{Height1}_t - \text{Height2}_t \qquad (6)$$

The application of equation 6 results in a time series of wind speed differences between the two heights. The confidence interval for the mean difference is computed using equation 7.

$$\overline{x_{diff}} \pm t_{1-\frac{a}{2},n-1} * \frac{s}{\sqrt{n}} \qquad (7)$$

where $\overline{x_{diff}}$ is the sample mean difference, $t_{1-\frac{a}{2},n-1}$ is a percentage point from the Student's t distribution with n-1 degrees of freedom, s is the sample standard deviation, and n is the number of observations.

A confidence interval can be thought of as a set of plausible values for a true but unknown mean. Interpretation of confidence intervals of the average differences generated by the paired-t method and the two sample t-test requires consideration of the precision of the wind gage. Both the LWS and cup anemometers used in this study have the same precision: 0.1 m/s. If such a confidence interval does contain -0.1 or 0.1, a conclusion of an operationally significant difference in average wind speeds between two heights or locations is not supported by the data. In other words, since the range of operationally insignificant values is [-0.1, 0.1] and if a confidence interval overlaps with this range, strong statements cannot be made about the average difference being significant that is greater in magnitude than 0.1.

The comparison of wind speeds between the two different locations is desirable. However, wind speed is confounded with the year in which the observations were made. To address this confounding, generally available wind speed data from surface level buoys near the two LWS locations was examined. Buoy location information is given in Table 2. Station ID 45007 corresponds to the mid-lake plateau site used for the

LWS unit in 2012. Station ID 45161 corresponds to the near Muskegon site for the LWS unit used in 2013. The surface level buoys collect data as follows:

- 45007 –1 average per hour from April 1 through November 30 for both years
- 45161 – 1 average per hour for both years but from July 6 to October 25 in 2012 and from April 18 to November 30 in 2013

Table 2
Location of Surface Level Buoys

Station ID	Owner	Location	Site Elevation above Sea Level (m)	Anemometer Height above Site Elevation (m)
45007	National Data Buoy Center	42.674 N 87.026 W	176.4	4
45161	Great Lakes Environmental Research Laboratory	43.178 N 86.361 W	176.0	2

Source: http://www.ndbc.noaa.gov

4. Results and Discussion

Wind speed and direction data are summarized. The confounding factor of year with location is addressed. Comparison of wind speeds from the two different locations are presented. The differences in wind speed with height is discussed.

4.1 *Effect of Years*

The first two questions to address are the following:

- Is the wind speed in 2013 at the mid-lake plateau slower or faster than in 2013?
- Is the wind speed in 2013 near Muskegon slower or faster than in 2012?

Table 3 shows wind speed summary statistics for each surface level buoy for 2012 and Table 4 shows the same information for 2013. Table 5 gives an analysis of the difference in the average wind speed for the two years. The statistics presented in these three tables can be used to answer the two questions.

Table 3
Horizontal Wind Speed (meters per second) Statistics by Surface Level Buoy for 2012

Statistic	Station 45007 – Mid Lake 1 hour averages 4/1 - 11/30	Station 45161 – Off Muskegon 1 hour averages 7/6 – 10/25
Possible Obs.	5856	2688
Total Obs.	5828	2409
% Total Obs.	99.52	89.62
Average	5.8	5.1
Std. Dev.	3.1	2.6
Coefficient of Variation	0.53	0.51
Minimum	0	0
Quartile 1	3.7	3.0
Median	5.5	4.8
Quartile 3	7.7	6.9
Maximum	19.4	13.0
99% CI– Lower Bound	5.7	5.0
99% CI -- Upper Bound	5.9	5.2

Source: Authors' Analysis

Table 4
Horizontal Wind Speed (meters per second) Statistics by Surface Level Buoy for 2013

Statistic	Station 45007 – Mid Lake 1 hour averages 4/1 - 11/30	Station 45161 – Off Muskegon 1 hour averages 4/18 – 11/30
Possible Obs.	5856	5448
Total Obs.	5817	4478
% Total Obs.	99.33	82.20
Average	5.5	4.8
Std. Dev.	3.1	2.7
Coefficient of Variation	0.56	0.56
Minimum	0	0
Quartile 1	3.1	2.9
Median	5.1	4.4
Quartile 3	7.4	6.4
Maximum	17.5	14.3
99% CI– Lower Bound	5.4	4.7
99% CI -- Upper Bound	5.6	4.9

Source: Authors' Analysis

Table 5
Horizontal Wind Speed (meters per second) Comparison of 2012 and 2013

Statistic	Station 45007 – Mid Lake 1 hour averages	Station 45161 – Off Muskegon 1 hour averages
Average Difference (2012-2013)	0.38	0.25
Pooled Std. Dev.	3.1	2.6
99% CI– Lower Bound	0.23	0.08
99% CI -- Upper Bound	0.52	0.42

Source: Authors' Analysis

As shown in Table 5, the average difference in wind speeds is positive indicating that average wind speed at each location was slower in 2013 than in 2012. Since the confidence interval for the average wind speed difference at the mid-Lake does not overlap the range [-0.1, 0.1], the average difference is statistically significant ($\alpha = 0.01$). However, the confidence interval for the average wind speed difference near Muskegon does overlap this range. Thus, the average difference is not statistically significant

4.2 *Effect of Location*

The next question to address is as follows:

- For each observation height, is there a difference in wind speed between locations?

Table 6 shows wind speed summary statistics for each LWS range gate for 2012 at the mid-lake plateau and Table 7 shows the same information for 2013 near Muskegon. Table 8 gives an analysis of the difference in the average wind speed for the two locations. The averages and standard deviations are computed using data from May 8 through December 17 of each year. These are the dates for which data was collected in both years. Positive differences indicate a higher average wind speed at the mid-lake plateau.

Note that the results show a slower average wind speed in 2013 near Muskegon than in 2012 at the mid-lake plateau ($\alpha = 0.01$) for all heights. The largest differences are at 75 m and 90 m. Differences tend to be smaller as height increases.

4.3 *Effect of Height*

A final question to address is as follows.

- For each observation location, is there a difference in wind speed between heights?
  This question can be addressed through asking a more specific question.
- For each pair of heights, is the wind speed greater at the higher range gate than at the lower range gate?

Table 6
Horizontal Wind Speed (meters per second) Statistics by LWS Range Gate – Mid-Lake

Statistic	Cup	75m	90m	105m	125m	150m	175m
Good Obs.	32216	30076	30951	30882	29265	21101	12226
% of Total (32256)	99.9	93.2	96.0	95.7	90.7	65.4	37.9
Average	6.2	8.7	8.9	9.0	8.9	9.2	9.5
Std. Dev.	3.1	4.7	4.8	4.8	4.9	5.2	5.0
Coeff. of Variation	0.50	0.54	0.54	0.53	0.55	0.57	0.53
Minimum	0.0	0.2	0.2	0.2	0.2	0.2	0.3
Quartile 1	4.0	5.1	5.3	5.4	5.1	5.2	5.7
Median	5.9	8.0	8.3	8.4	8.2	8.4	8.8
Quartile 3	8.2	11.6	11.9	12.0	11.9	12.4	12.5
Maximum	19.3	28.3	28.7	29.2	29.8	30.2	31.5
99% CI– Lower Bound	6.2	8.6	8.8	8.9	8.8	9.1	9.4
99% CI -- Upper Bound	6.2	8.8	9.0	9.1	9.0	9.3	9.6

Source: Authors' Analysis

Table 7
Horizontal Wind Speed (meters per second) Statistics by LWS Range Gate – near Muskegon

Statistic	Cup	75m	90m	105m	125m	150m	175m
Good Obs.	33899	25806	29532	32394	32731	30482	23050
% of Total (34128)	99.3	75.6	86.5	94.9	95.9	89.3	67.5
Average	5.9	8.0	8.2	8.5	8.7	8.8	9.2
Std. Dev.	3.2	4.3	4.3	4.4	4.4	4.4	4.3
Coeff. of Variation	0.54	0.54	0.52	0.52	0.51	0.50	0.47
Minimum	0	0.2	0.2	0.1	0.2	0.2	0.3
Quartile 1	3.5	4.9	5.1	5.3	5.4	5.6	6.1
Median	5.4	7.3	7.6	7.9	8.2	8.3	8.7
Quartile 3	7.8	10.4	10.7	11.1	11.3	11.4	11.7
Maximum	19.6	80.9	49.7	57.0	53.6	56.4	33.3
99% CI– Lower Bound	5.9	7.9	8.1	8.4	8.6	8.7	9.1
99% CI -- Upper Bound	5.9	8.1	8.3	8.6	8.8	8.9	9.3

Source: Authors' Analysis

Table 8
Comparison of Locations – Mid-Lake and Near Muskegon

Statistic	Cup	75m	90m	105m	125m	150m	175m
Average Difference (2012-2013)	0.27	0.72	0.71	0.53	0.23	0.36	0.20
Pooled Std. Dev.	0.31	4.6	4.5	4.6	4.6	4.7	4.5
99% CI– Lower Bound	0.21	0.62	0.62	0.44	0.13	0.25	0.07
99% CI -- Upper Bound	0.34	0.82	0.81	0.63	0.33	0.47	0.33

Source: Authors' Analysis

The effect of height can be assessed using the same data for which the statistics shown in Tables 6 and 7 were computed. The effect of height is examined for each location independently. The paired-t method is used. The difference in wind speeds for adjacent range gates pairs is studied. Each difference is computed as higher range gate value – lower range gate value. As was discussed in the methods section, only valid differences, those where each of the two 10 minute averages was comprised of at least 300 observations, were included.

Table 9 shows results for the mid-lake plateau in 2012 and table 10 shows results for 2013 near Muskegon.

Table 9
Wind Speed Average Difference by Pairs of Adjacent LWS Range Gates –Mid-Lake

Statistic	90m-75m	105m-90m	125m-105m	150m-125m	175m – 150m
Good Obs.	30050	30848	29251	21074	12199
% of Total (32256)	93.2	95.6	90.7	65.3	37.8
Average	0.26	0.076	-0.13	-0.43	-0.92
99% CI– Lower Bound	0.25	0.07	-0.14	-0.44	-0.95
99% CI -- Upper Bound	0.27	0.08	-0.12	-0.41	-0.88

Source: Authors' Analysis

Table 10
Wind Speed Average Difference by Pairs of Adjacent Range Gates – Near Muskegon

Statistic	90m-75m	105m-90m	125m-105m	150m-125m	175m – 150m
Good Obs.	25641	29404	32184	30428	23035
% of Total (34128)	75.1	86.2	94.3	89.2	67.5
Average	0.50	0.37	0.19	0.066	-0.012
99% CI– Lower Bound	0.49	0.36	0.19	0.060	-0.030
99% CI -- Upper Bound	0.51	0.37	0.20	0.070	0.0

Source: Authors' Analysis

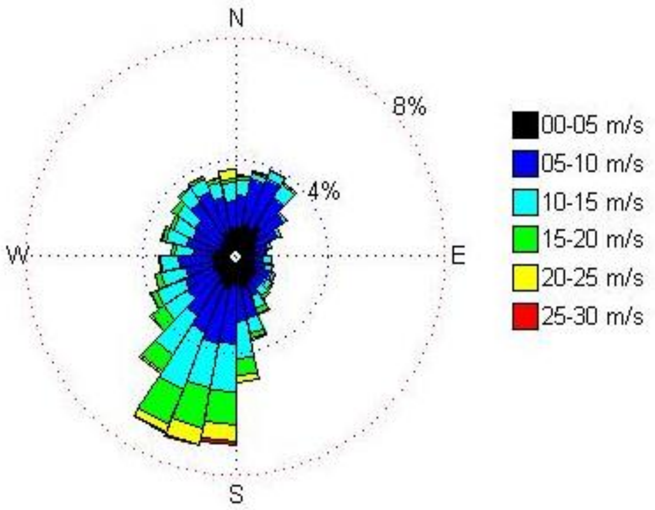

Figure 1. Average Wind Speed and Percent Time by Direction at 125 m – Mid-Lake

Note that the average wind speed stops increasing with height between 105 m and 125 m at the mid-lake plateau in 2012 as well as between 125 m and 150 m near Muskegon in 2013. The difference in average wind speeds between 125 m and 150 m near Muskegon is less than 0.1 m/s, the precision of the gage and thus is not significant.

4.4 Wind Direction

Wind rose graphs show the wind speed by direction as well as the percent of time the wind was blowing in each direction. The percent of time the wind was coming from a particular direction is shown by the inner and outer circles. The inner circle represents the wind coming from a particular direction 3% or 4% of the time and the outer circle 6% or 8% of the time as labeled on the graph. Note that for each range gate height, the dominate wind direction is south-southwest (SSW). On the buoy deck, the dominate wind direction is south mid-lake and SSW near Muskegon.

The wind rose graphs are similar for all range gates. To illustrate, the wind rose graphs for 125 m are presented in Figures 1 (mid-lake) and 2 (near Muskegon).

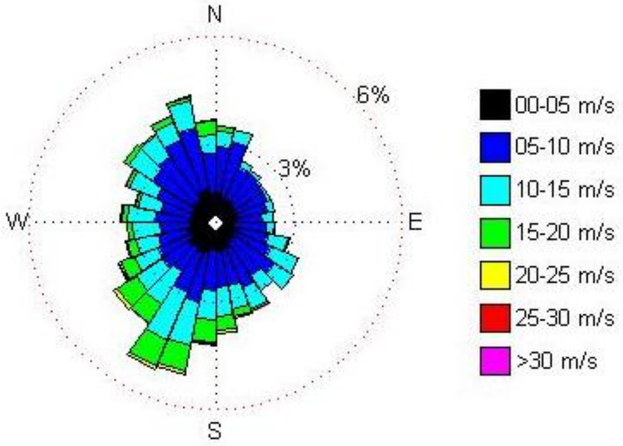

Figure 2. Average Wind Speed and Percent Time by Direction at 125 m – Mid-Lake

5. Conclusion

The data and statistical analysis results are best interpreted in light of what impact they can have on future wind farm development. First the difference between average wind speeds at the two locations is assessed. This requires dealing with the confounding of the year of data collection with location. The analysis results shown in Table 5 concerning the surface level buoys which collected data in both 2012 and 2013 are used. Based on this analysis, it can be concluded that there is no significant difference between the average wind speed in 2012 and 2013 at the water surface near Muskegon. The confidence interval for the difference in average wind speed shown in Table 5 includes values less than the precision of the gage ($\alpha = 0.01$).

Thus, we infer that since there is no significant difference in average wind speed near the surface that there is no significant different at any height at which the LWS unit collected data between the two years. Thus, the data collected by the LWS unit in 2012 at the mid-lake plateau can be directly compared to the data collected in 2013 near Muskegon and conclusions drawn as to the difference in wind speed between the two locations.

The analysis results in Table 8 support this comparison. These results show that the average wind speed is greater at the mid-lake plateau in 2012 than near Muskegon in 2013. The average differences generally decrease with height and range from 2% to 9% of the average wind speed near Muskegon. Thus it can be concluded that more energy could be harvested by a wind farm located at mid-lake than at Muskegon. The increase in energy harvested would need to be balanced against the increased cost of installing and maintaining such a wind farm further from the shore line.

Next, the difference in average wind speeds by the six heights at which the LWS unit collected data is examined. The analysis results for the mid-lake plateau are shown in Table 9. At the mid-lake plateau, average wind speed starts to decrease between 105 m and 125 m. The difference in average wind speed between 90 m and 105 m is less than the precision of the gage and not statistically significant. That is, there is no evidence that wind speed increases between these two heights. Thus, it can be concluded that the average wind speed at the mid-lake plateau reaches its maximum value between 90 m and 105 m.

The analysis results for the location near Muskegon are shown in Table 10. The average wind speed starts to decrease between 150 m and 175 m. Furthermore, the difference in average wind speed is less than the precision of the gage for 125 m versus 150 m and 150 m versus 175 m. Thus, the average wind speed appears to reach its maximum value between 125 m and 150 m.

These results are inconsistent with idea that higher wind turbines will result in more energy being harvested. In addition, the results are not consistent with the wind profile power law given in equation 1. The results indicate the importance of directly measuring wind speed at a proposed hub height when planning a wind farm as opposed to the current reported practice in the studies cited above of measuring wind speed at a lower height and using the wind profile power law to estimate wind speed at hub height. More study is needed in this regard. It is also of interest to examine data concerning the prevailing wind direction. Figures 1 and 2 show this direction to be SSW both at the mid-lake plateau and near Muskegon. Thus it can be concluded that the orientation of the wind farm regardless of its location should be SSW.

Finally, the performance of the LWS is accessed. At the mid-lake plateau, Table 6, the percent of good observations decreases consistently with height and drops noticably drops at 150 m and 175 m versus lower heights. Average wind speed is relatively constant between 75 m and 125 m as well as increasing between 125 m and 175 m. Near Muskegon, Table 7, the same general pattern is seen in the percent of good observations though the reduction is much less at higher heights. The percent noticably drops at 175 m. The average wind speed consistently increases with height.

These observations can be explained as follows. The LWS unit relies on detecting particle movement in the airflow. There is less mixing of the air layers in the mid-lake versus near shore resulting in less movement of particulate matter. Furthermore, there is likely a lack of such particles at the mid-lake plateau versus near shore which is more pronounced as height increases. Thus, it can be concluded that higher average wind speeds at 150 m and 175 m versus lower heights particularly at the mid-lake location are consistent with the LWS unit observing only faster wind speeds due to the lack of particle movement at lower wind speeds.

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