Evaluation and Adjustment of Wind Resource Map Estimates For the Pacific Northwest

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1.0 Introduction

Wind resource maps are used in a variety of ways to estimate the potential wind energy resources available at a given location. Originally, these maps were used primarily as a wind prospecting tools to identify promising locations where adequate wind resources might exist. Instrumentation could then be directed to verify the map estimates and make conclusions about an area. As confidence in resource maps increased their use was expanded to other areas including the estimation of seasonal and annual wind variations, to represent energy production for transmission integration studies and, in some cases, to plan and develop commercial wind projects.

Resource maps are relatively inexpensive and easy to use and, with the addition of special features, can provide a great deal of information about the wind characteristics for a given site. While this can be extremely useful it can also be misleading and it is important to understand their limitations. In general, it is useful to remember that resource maps are simply estimates of the long-term mean conditions for a site. Further, these estimates are based on atmospheric models that have limitations themselves and may not account for all of the physical processes that influence the winds at a given location.

This summary contains an evaluation of one set of resource maps that have been used in the Pacific Northwest to evaluate the suitability of sites for the installation of small to medium sized wind turbines. In several cases the performance of turbines has not matched the performance expected using estimates from a wind resource map. The purpose here is to evaluate the resource maps for this area and see if a simple adjustment or correction can be applied to bring the map estimates in line with observed conditions. It is important to note that the results are specific to the resource maps being evaluated and should not be generalized to other products.

2.0 Generation of Resource Maps

The motivation behind the development of resource maps is the need to estimate mean wind conditions over a wide area without going to the time and considerable expense to take measurements at a great number of locations. It is generally not feasible to acquire enough measurements to represent a relatively large area. Instead, mean wind estimates are generated using a number of techniques including the use of Numerical Weather Prediction (NWP) models. NWP models use fundamental equations of motion to account for the physical processes of the atmosphere and how they interact with the specific terrain and topographic features of a given area. A good explanation of the use of NWP models for this purpose can be found at http://www.nrel.gov/wind/integrationdatasets/pdfs/western/2010/3tier_final_report.pdf.

In general, NWP models are used to produce wind estimates at evenly spaced intervals covering an area of interest. Because models are not always perfect and contain biases and some misrepresentation, the output is often conditioned or adjusted using statistical relationships. These relationships are obtained by comparing what the model predicts to observations for either a short period of time or for specified reference sites. Although this works in general, the statistical relationships may change from specific site to site and the relationships might also change over time or from season to season. Applying this type of correction, however, only accounts for the systematic errors that might be found in a model. Non-systematic errors may still exist and are more difficult to account for.

Even with these limitations, the process of generating resource maps can be extremely useful. The result is an easy to use product that if used correctly, can provide a good indication of the wind characteristics at a particular site. The difficult part of this is understanding what is meant by “used correctly”. This will hopefully become clear by the end of this summary.

3.0 Wind Site summary and Evaluation

The general goal of this summary is to evaluate resource map estimates for a set of sites in this region (Oregon) and see if any patterns or relationships emerge that can be used to improve or adjust the resource estimates. To do this we have compiled a list of 39 sites with the appropriate wind characteristics to make such an evaluation. These sites are listed in Table 1 and have been part of the Oregon Anemometer Loan Program (ALP) sponsored by the Energy Trust of Oregon (ETO). They consist primarily of sites where 20 and 30 meter towers were installed for a period of at least one year to evaluate the resource potential. The list also contains sites with taller towers, typically 50-meter towers with several levels of instrumentation. Sensors from the 50 meter level and the 30 meter levels are considered as separate entities. These sites were also part of the Oregon ALP.

Table 1. Site information for a set of candidate meteorological sites.

Site Number	20m tower Sites	County	Lat.	Lon.	Sensor Ht. (ft)	Elevation (ft.)	Annual Mean (mph)
1	Pilot Rock School District	Umatilla	45.438	118.829	66	1715	9.2
2	Milton-Freewater Orchard	Umatilla	45.954	118.421	66	900	8.1
3	Wallowa	Wallowa	45.608	117.531	66	3293	5.4
4	Nickel Mountain	Douglas	42.966	123.444	66	3550	11.7
5	Grizzly Mountain	Crook	44.908	120.962	66	4000	8.8
6	Blue Mountain Foothills	Umatilla	43.750	118.258	66	2500	11.6
7	Black Cap Peak	Lake	42.206	120.323	66	6352	13.2
8	Mason/Morrow	Morrow	45.504	119.540	66	1982	13.9
9	Tualatin Mtns	Multnomah	45.686	122.914	66	1440	8.7
10	Jackson Co. Ridge	Jackson	42.259	122.739	66	3440	8.7
11	Ashland Valley	Jackson	42.230	122.738	66	1776	8.7
12	Riversend Ranch	lake	42.497	120.278	66	4301	11.5
13	Fulton Ridge	Wasco	42.596	122.918	66	1250	12.3
14	Port of Astoria	Clatsop	46.188	123.866	66	10	10.6
15	S. Salem Hills	Marion	44.864	123.095	66	845	8.5
16	Middle Mtn 20m	Hood River	45.586	121.596	66	2610	12.9
17	Eola Hills	Polk	45.088	123.147	66	825	5.5
18	Wickiup Ridge	Clatsop	46.095	123.590	66	2420	13.9
	30m tower Sites						
19	Moro Fairgrounds	Sherman	45.482	120.716	99	1900	13.4
20	Staples	Multnomah	45.541	122.465	99	15	7.2
21	Martin Ridge	Sherman	45.671	120.742	99	1008	12.6
22	Baldwin Hills	Jefferson	44.577	120.975	99	3924	11.9
23	Middle Mtn 30m	Hood River	45.594	121.588	99	2445	10.0
	ALP Tall Tower Sites (~30m level)						
24	Sherman Co.	Sherman	45.530	120.784	98	2004	12.4
25	Morrow Co. #1	Morrow	45.508	119.559	98	1856	13.4
26	PEAMS	Sherman	45.481	120.773	98	2217	14.1
27	Middle Mtn.	Hood River	45.587	121.597	98	2628	12.8
28	Fir Mtn.	Hood River	45.611	121.475	104	2457	12.0
29	Wentz	Umatilla	45.419	118.980	98	2900	12.5
30	Sayrs	Sherman	45.498	120.775	105	2250	13.3
31	Morrow Co. 60m	Morrow	45.532	119.562	106	1549	13.1
	ALP Tall Tower Sites (~50m level)						
32	Sherman Co.	Sherman	45.530	120.784	165	2004	13.2
33	Morrow Co. #1	Morrow	45.508	119.559	164	1856	14.2
34	PEAMS	Sherman	45.481	120.773	161	2217	14.9
35	Middle Mtn.	Hood River	45.587	121.597	161	2628	13.7
36	Fir Mtn.	Hood River	45.611	121.475	164	2457	14.3
37	Wentz	Umatilla	45.419	118.980	196	2900	13.4
38	Sayrs	Sherman	45.498	120.775	196	2250	14.1
39	Morrow Co. 60m	Morrow	45.532	119.562	195	1549	13.5

To get a general overview of the magnitude of the errors involved a number of general statistical relationships can be examined. First, in order to compare map estimates with the corresponding observed value it is necessary to apply an adjustment to account for any differences between the height of the estimate and the anemometer height. The map estimates are generally at 30m while the sensor heights vary and all adjustments are made to the sensor height to maintain observational integrity. A simple power law conversion is used with an assumed coefficient of 0.10. This coefficient likely varies from site to site but is not generally known ahead of time. The value used here is a fairly conservative value and is believed to be adequate for general use. All values shown in the following figures represent the sensor height estimates for each site obtained in this manner. General error terms (represented as percentage of observed mean) are shown in Figure 1 for each of the sites in Table 1. It is clear that a majority of the sites have positive errors meaning that the estimated values exceed the observed values. In addition, the magnitudes of the positive values are much higher than for the negative values suggesting that there is a strong bias in the results.

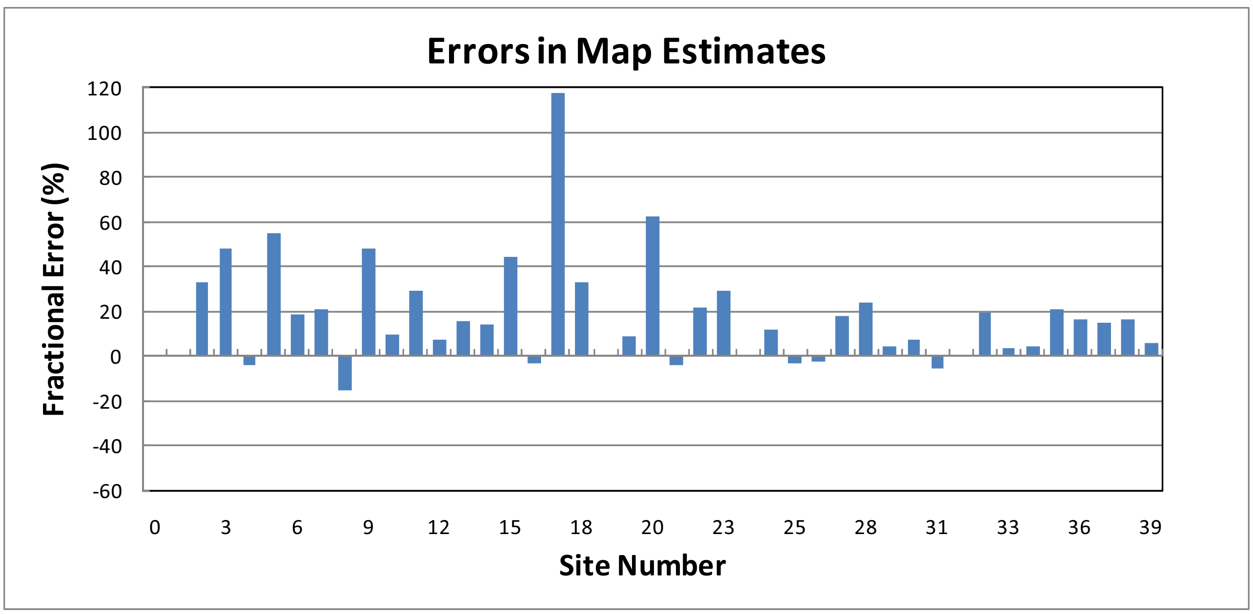

Figure 1: Fractional Error of annual mean wind speed estimates (mph) for sites in the PNS obtained from a wind resource map.

Another way to view the results is to organize the error values by magnitude and determine the number of sites within certain error ranges. This is shown if Figure 2 and illustrates how the errors are distributed over different ranges. The errors range between -15.6 to +117.5 and most are positive. A majority of the sites (3/4) have errors between -5% and 20%. Overall the average of all the errors is +19%.

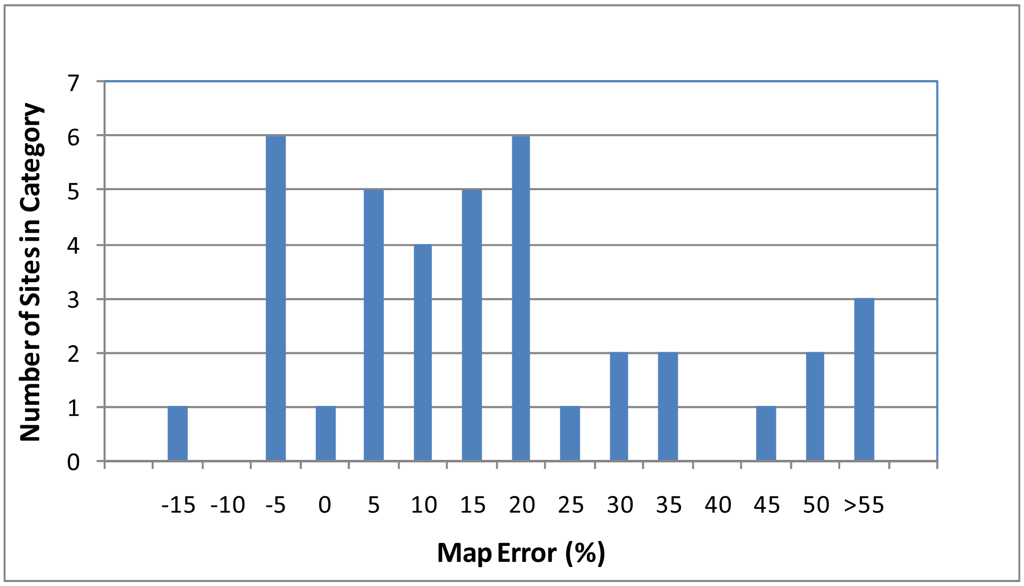

Figure 2: Distribution of fractional error for sites in the PNW obtained from a wind resource map.

A scatter plot can also be used to compare the sensor height estimate with the observed value such as in Figure 3. Each point on this graph represents a site. Two regression lines are added that represent the perfect correlation (black line) and the best linear fit (blue line). All of the points below the black line are the positive values in Figure 1. The linear correlation coefficient between the two is 0.715 suggesting the two quantities do show some degree of correspondence.

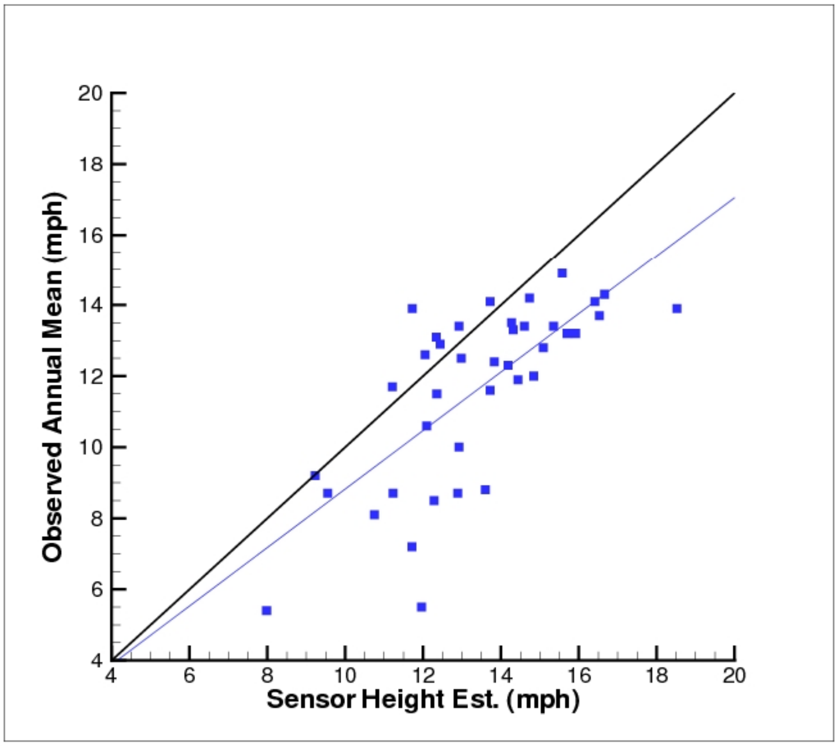

Figure 3: Scatter plot showing the estimated sensor ht. mean vs. the observed means for sites in the PNW. Plot also includes the perfect correlation line (black) and the best linear fit line (blue)

It is apparent that as a first order correction the distribution in Figure 2 could be shifted to the left to line up better with an error of zero. This is a simple error correction and in this case would mean adjusting the mean using the mean diagnosed error of 19% for each of the sensor height predictions. This is similar but slightly different than adjusting for the observed bias. However, the value of 19% seems a bit high and is likely skewed somewhat by the highest errors. While it is not advisable to simply eliminate values, we can take a closer look at the sites with the highest errors and see if there is a reason why the estimates for these sites are higher. The sites with the highest errors are listed in Table 3.

Table 3. Site information and errors for the sites with the largest estimation errors.

Num	Site Name	Lat	Lon	Ht.	Elev	Ann. Mean (mph)	Sensor Ht. Est. (mph)	Error mph	Bias %
15	S. Salem	44.864	123.095	67	845	8.5	12.3	3.8	44.5
3	Wallowa	45.608	117.531	67	3293	5.4	8.0	2.6	47.8
9	Tualatin Hills	45.686	122.914	67	1440	8.7	12.9	4.2	48.1
5	Grizzly	44.908	120.962	67	4000	8.8	13.6	4.8	54.5
20	Staples	45.541	122.465	98	15	7.2	11.7	4.5	62.6
17	Eola Hills	45.088	123.147	67	825	5.5	12.0	6.5	117.5

There doesn't appear to be many common threads between these sites. They range in elevation and longitude. The one common characteristic is that they all have relatively low observed annual mean winds. This suggests that there might be something at each of these that inhibited the wind flow. Several of these were located in terrain that would not be possible for a wind model to adequately represent. Eola Hills was near the top of a ridge but there was an elevated forested area to the south at a slightly higher elevation. There was a similar situation at the Tualatin Hills site. The Staples site was likely also influenced by the fact that the immediate area was lower than the surrounding area and there were trees dispersed throughout the area. While there wasn't a vegetative influence at the Wallowa site it does sit in a valley or basin and the area is prone to long periods of low winds due to a persistent atmospheric inversion. The two remaining sites, South Salem Hills and Grizzly Mountain were in open areas with no apparent obstacles or obstructions. Considering these features we can make a case for discounting four of the six sites with the largest errors. With these four sites removed the mean error is reduced to 13.3%.

4.0 Adjustment Approaches

There are two relatively simple adjustments that can be derived using the errors assessed here. One is the application of a simple error correction that accounts for the difference between the observed and predicted wind speeds. The second would be a regression approach based the differences between the observed and predicted winds for the individual sites. In all likelihood there will not be a significant difference between these two. Other techniques might also be available and might be explored if one of these simple techniques does not prove beneficial.

It is also important to note that there are a number of limitations to using the data here to develop an adjustment procedure. There are listed below.

1. Sites were pre-screened by OSU. In order to instrument sites included as part of the Anemometer Loan Program most of the sites were evaluated prior to any data collection.

2. Observed means represent one year. Data collection and reporting has been done primarily over a single annual period. This is in contrast to the resource map estimates that are designed to represent the long-term mean conditions at a site. Any single year can be expected to vary from the long-term mean so some discrepancy should be expected. In the evaluation here this influence is somewhat mitigated by the fact that different annual periods are being used at different sites. It is expected that the differences at individual sites for individual years should average out when the sites are combined.
3. Use of a constant shear coefficient. Sensor height estimates were obtained by applying an assumed shear coefficient to the resource map estimate (alpha = 0.10). In actuality, the shear coefficient likely varies somewhat from site to site and for different times of the year. This could have some influence on the results. However, the height adjustment is not extreme in this case and this effect is expected to be moderate.

Method 1: Mean Error Adjustment. The fractional or normalized error of the predicted values can be computed as follows;

$$E = \frac{(P - O)}{O}$$

Where E is the mean error, P is the predicted value (from wind resource map) and O is the observed value. The mean error can be computed from this set of sites and was found here to be 0.133. To use this as an adjustment formula we can rewrite it in the form

$$O = \left[\frac{1}{1+E}\right]P$$

So an estimate from this particular wind resource map would be adjusted by a constant factor of [1/(1+E)].

Method 2: Regression Adjustment. A simple linear regression approach can also be used to adjust an estimate obtained from a wind map.

$$O = AP + B$$

Where O again is the long-term annual mean we hope to determine, P is the predicted value and the coefficients A and B are obtained from the best fit regression line to the points in Figure 4. For the data here the coefficients are A = 0.6429 and B = 3.4024. Other approaches could also be used including the use of other regression techniques but it is expected that these should provide enough guidance.

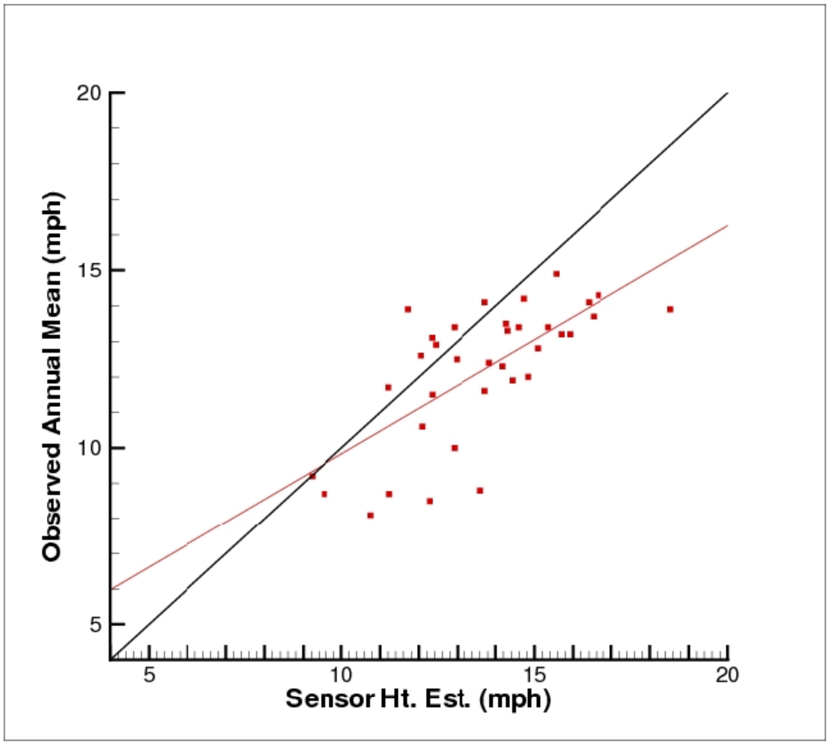

Figure 4: Scatter plot showing the estimated annual mean vs. the observed means for sites in the PNW. Plot also includes the perfect correlation line (black) and the best linear fit line (red)

5.0 Evaluation of Adjustment Methods

In order to determine if either of these adjustment relationships reduces the error of the estimated annual mean winds the root mean square error can be used as a quantitative score. Root mean square error is defined as

$$RMSE = \sqrt{\frac{\sum (P_i - O_i)^2}{n}}$$

Where O is the observed annual mean, P is the estimated mean and n is the number of sites. The root mean square error differs from the mean absolute error in that there is a greater penalty for large errors due to the squaring of the difference. Applying the adjustment methods to the 35 sites in Table 1 produces the results shown in Table 4.

Table 4. RMSE results for direct resource map estimates and two adjustment methods for 35 monitoring sites.

Adjustment Method	RMSE
Direct Map Estimate	2.145
Mean Error Adjustment	1.465
Linear Regression	1.375

For these sites the results show that the linear regression method produce slightly better results than the error adjustment method but that both reduced the overall error of the estimated values fairly significantly. However, this should be expected since the adjustments were derived from the same data set. A better test would be to use an independent set that might have different characteristics. To do this wind estimates and observed values from a separate set of 15 sites has been compiled. The sites are shown in Table 5 and include 10 sites from the National Weather Service, 2 coastal sites from the National Ocean Data Center and 3 sites from the Oregon Anemometer Loan program that were not used in the previous section.

Table 5. Site information for a set of test meteorological sites.

CMAN Sites	Sensor Ht. (ft)	Latitude	Longitude	Elevation (ft.)	Annual Mean (mph)	Sensor Ht. Est. (mph)
NWPO3	30.8	44.613	124.067	29.9	10.8	11.15
CAR03	48.9	43.339	124.375	59.4	10.8	12.61
NWS Sites	**Sensor Ht. (ft)**	**Latitude**	**Longitude**	**Elevation (ft.)**	**Annual Mean (mph)**	**Sensor Ht. Est. (mph)**
Astoria	33	46.150	123.867	9	8.5	9.64
Portland	33	45.583	122.600	20	7.6	9.84
Troutdale	33	45.550	122.417	36	7.9	9.78
Salem	33	44.900	122.983	205	6.7	9.44
Eugene	33	44.133	123.200	355	7.1	9.68
Pendleton	33	45.683	118.833	1481	7.9	7.42
North Bend	33	43.417	124.250	16	9.1	11.47
Sexton Summit	33	42.600	123.367	3837	9.7	20.03
Redmond	33	44.100	121.200	3455	7.4	8.88
Burns	33	43.583	118.950	4140	6.4	9.96
ALP Sites	**Sensor Ht. (ft)**	**Latitude**	**Longitude**	**Elevation (ft.)**	**Annual Mean (mph)**	**Sensor Ht. Est. (mph)**
Chehalem Mtns	77	45.354	122.989	1437	9.8	16.10
Gilliam Co #1	66	45.520	120.029	1250	11.4	15.50
Independence	50	44.808	123.212	350	6.9	10.13

The results are shown in Table 6. It's clear again that the adjustments do provide a significant improvement overall. However, it's also clear that the RMSE values are substantially higher than those for the original 35 sites (Table 4). This is likely due to the nature of the sites and the fact that they were not initially screened for their suitability.

Table 6. RMSE results for direct resource map estimates and two adjustment methods for 15 test sites.

Adjustment Method	RMSE
No Adjustment	3.672
Mean Error Adjustment	2.606
Linear Regression	2.661

It had been hoped that other factors might be included in these adjustments that might provide further improvement. The three main factors expected to be important are 1) the height of the local vegetation, 2) the height of the surrounding terrain particularly to the south and southwest where the strongest cool seasons winds come from and 3) the upwind slope angle which appears to be important for steep hills or ridgelines. Several methods of including this information were looked at but it proved difficult to objectively quantify these characteristics.

Instead, it is expected that a simple conditional approach might work best. This is most easily applied to the error adjustment method by simply selecting the magnitude of the error factor base on one of several considerations.

Table 7. Guide for error factors to be used for subjective error adjustment approach.

Case:	Error Factor (E)
Clear open and exposed	0.133
Tall Trees to west or southwest	0.300 - 0.500
Tall hills to the south or southwest	0.300 - 0.500
Tall ridge, hill, mountain or steep slope to west or southwest	0.500

The default approach would be to use the standard error factor computed using the test sites (0.133). This would be sufficient for site with good exposure and relatively level terrain. Further improvement could be obtained by increasing this value under the conditions listed in Table 7. Generally, the higher the error factor the more the direct map estimate will be reduced. An increase in the error factor would be dependent on the scale of the terrain and vegetation obstructing the flow. An error factor of 0.50 is also suggested for sites on tall peaks or ridges with steep slopes as the model wind map tends to overestimate these significantly. Values chosen for the 15 reference sites can be found in Table 8.

Table 8. Subjective error coefficient, and adjusted mean wind speed estimate for 15 test sites.

CMAN Sites	Sensor Ht. (ft)	Elevation (ft.)	Annual Mean (mph)	Sensor Ht. Est. (mph)	Error Factor E	Adjusted Est. (mph)
NWPO3	30.8	29.9	10.8	11.15	0.13	9.87
CAR03	48.9	59.4	10.8	12.61	0.13	11.16
NWS Sites	**Sensor Ht. (ft)**	**Elevation (ft.)**	**Annual Mean (mph)**	**Sensor Ht. Est. (mph)**	**Error Coef.**	**Adjusted Est. (mph)**
Astoria	33	9	8.5	9.64	0.13	8.53
Portland	33	20	7.6	9.84	0.30	7.57
Troutdale	33	36	7.9	9.78	0.40	6.99
Salem	33	205	6.7	9.44	0.50	6.29
Eugene	33	355	7.1	8.68	0.13	7.68
Pendleton	33	1481	7.9	7.42	0.13	6.57
North Bend	33	16	9.1	11.47	0.30	8.82
Sexton Summit	33	3837	9.7	20.03	0.50	13.35
Redmond	33	3455	7.4	8.88	0.13	7.86
Burns	33	4140	6.4	9.96	0.13	8.81
ALP Sites	**Sensor Ht. (ft)**	**Elevation (ft.)**	**Annual Mean (mph)**	**Sensor Ht. Est. (mph)**	**Error Coef.**	**Adjusted Est. (mph)**
Chehalem Mtns	77	1437	9.8	16.1	0.50	10.73
Gilliam Co #1	66	1250	11.4	12.54	0.13	11.10
Independence	50	350	6.9	10.13	0.13	8.96

The choice of these factors is somewhat subjective but is likely the simplest approach to improve on the simple error adjustment technique. Results show that, overall, a significant improvement can be obtained using this approach (Table 9). For the 15 reference sites, 13 showed improvement over the direct map estimates and overall the RMSE was reduce to 1.381. This is roughly half that obtained using the default adjustment. A comparison of the site estimates using the different adjustment methods is shown in Figure 5. It is clear that the direct sensor height map estimates with no adjustment (red squares) generally over-predict the observed mean (blue diamond). The three adjusted values are generally between these two.

Table 9. RMSE results for direct resource map estimates, two adjustment methods and a conditional error adjustment method for 15 test sites.

Adjustment Method	RMSE
No Adjustment	3.672
Mean Error Adjustment	2.606
Linear Regression	2.661
Conditional Error Adjustment	1.381

The two sites where no improvement was made were one coastal site (#1-NWPO3) and one NWS site (#8-Pendleton). The direct sensor height map estimates for these two sites were close to the observed value and it's likely that any adjustment would produce an error. This also shows that the use of any adjustment method should work well overall, but it is possible that there could be an increase in the area for specific sites. As shown here, however, this will not generally be the case.

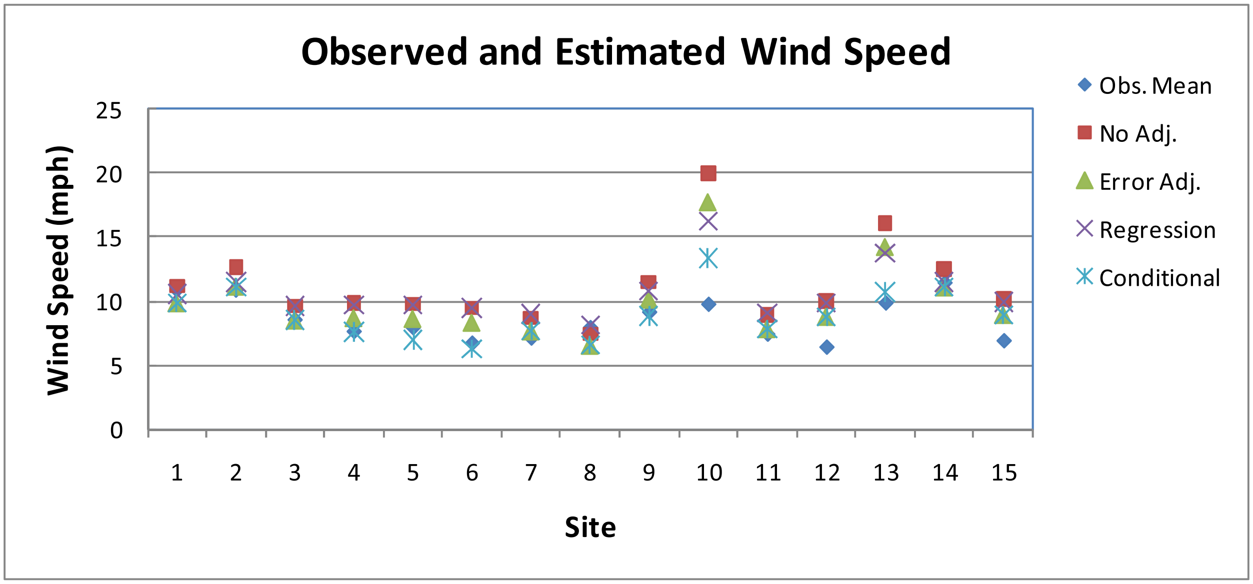

Figure 5. Observed annual mean (blue diamond) and estimated annual mean using direct sensor height estimates ("no Adj" - red square), and estimates from three adjustment methods for 15 test sites. "Error Adj refers to the error adjustment approach (method 1), "Regression" refers to the best linear fit approach (method 2) and "Conditional" refers to the the method utilizing values selected from Table 7.

6.0 Summary

Annual wind speed measurement from a number of wind sites in the Pacific Northwest were use to evaluate wind resource map estimates. Fractional errors is estimates for the first set of sites were found to be around 19% and were reduced to 13.3% when four of the sites with the highest errors were removed from consideration. Relationships between the sensor height estimates and the observed annual means at these sites were used to develop two simple adjustment methods, one based on the fractional errors of the estimates and one based on a simple linear regression between the estimated and observed. The adjustment methods were tested using data from 15 additional sites and were found to improve site estimates significantly. Further improvement was obtained by applying a conditional error factor based on terrain characteristics at a site. This conditional method is expected to provide the best improvement especially in the low wind, high obstruction areas generally considered by the Energy Trust of Oregon.