FOREST RESEARCH REPORT
Nova Scotia Department of Natural Resources

Digital Wind Exposure Map for Nova Scotia

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Introduction

As part of the shift to ecosystem based forest management in Nova Scotia, more emphasis is being placed on partial harvesting options. Associated with this change in emphasis is increased concern over post-harvest windthrow as related (in part) to wind exposure conditions. Assessment of site exposure is required as part of pre-treatment assessments conducted in the province, and management guides developed by NSDNR incorporate exposure ratings within their decision keys (McGrath, 2011; McGrath et al., 2015ab). Currently, exposure is assessed on the ground based on an estimation of relative landscape position (Table 1). However, this assessment is difficult to accurately and consistently apply. It also does not capture variation in wind patterns across the province that would be expected to influence windthrow hazard.

To address these shortcomings, a project was initiated to develop a digital wind exposure map for the province based on average annual maximum wind speeds and relative topographic exposure (topex) measures. Project objectives were to:

- Provide a consistent and robust estimation of relative wind exposure for strategic, tactical, and operational forest management planning that reduces the uncertainty and potential error associated with current field assessment methods.

- Generate spatial data layers that can be used as inputs for other windthrow risk assessment tools or models as they are developed.

Note: this project did not consider extreme, sporadic wind events (i.e., hurricanes) that can cause damage regardless of management regime.

Table 1. Exposure classes currently used for forest management planning in Nova Scotia (from Neily et al., 2013).

Class	Description
Exposed (EX)	Sites with extreme exposure – includes upper slopes of moderate ridges immediately along the coastline and steep upper slopes of uplands open to winds from two or more directions.
Moderately Exposed (ME)	Intermediate between Exposed and Moderate – includes upper slopes of inland ridges or hills except where sheltered by a larger hill.
Moderate (M)	The topographically neutral category – includes broad flats, lower and middle slopes of strong ridges (plus sheltered upper slopes), and upper slopes of gentle relief in a flat landscape.
Moderately Sheltered (MS)	Intermediate between Moderate and Sheltered – includes middle slopes between high ridges and broad basins which are afforded some wind protection from one or more directions.
Sheltered (SH)	The most extreme category of protection from wind and atmospheric drought stress, best illustrated by lower slopes of deep valleys where protection is provided on all sides.

Methods

Wind map: Several data sets were used or generated to estimate average annual maximum wind speeds across Nova Scotia. These included:

- Nova Scotia wind atlas – modeled average wind speeds at 30 m, 50 m, and 80 m elevations across the province (http://www.nswindatlas.ca/).
- NSDNR weather station data – average maximum wind speeds from 32 stations with at least five years of data.
- Environment Canada weather station data – average maximum wind speeds from 16 stations with at least five years of data.

- Provincial digital elevation model (DEM) data – raster layer.
- Distances to nearest coast and Atlantic coast – generated raster layers.

Existing wind atlas data were generated using *Anemoscope*, a wind energy simulation toolkit developed by Environment Canada and the Canadian Hydraulics Centre (see Gagnon et al., 2009 for more details). For this project, atlas data were converted to 10 m values (approximate tree canopy height) using a standard conversion factor (UK Meteorological Office, 1982).

To estimate average annual maximum wind speeds across the province, thousands of readings from selected weather stations (Figure 1) were regressed against several variables thought to be correlated with these measures (10 m wind atlas speed, location elevation, distance to nearest coast, and distance to Atlantic coast). To better represent potential windthrow hazard, 75^{th} percentile values for maximum wind speed were used instead of mean values for this analysis.

Topex map: A topographical exposure (topex) map was generated for the province using distance-limited topex techniques described in Ruel (2002). In brief, ArcGIS was used to calculate angles from a given point to elevations at user-defined grid distances along a transect of user-defined length. The most positive (or least negative) angle calculated was then retained and added to similar values found along all eight cardinal directions – with the total representing the topex value for that point. More negative topex values indicate greater relative exposure, while more positive numbers are associated with increasing shelter. Breakpoints between exposure classes are map-specific and need to be established through trial and error based on knowledge of local conditions (Ruel, pers. comm.).

For this project, several topex maps were generated for evaluation using a range of horizon distances 0.5 km, 1 km, 2 km, and 4 km – each with 100 m grid steps. Exposure class breakpoint values for five classes: exposed (EX), moderately exposed (ME), neutral (NT), moderately sheltered (MS), and sheltered (SH) were determined based on expert opinion (NSDNR Forestry Division Ecosystem Management Group) as guided by provincial forest ecosystem classification (FEC) plot data collected across the province (Neily et al., 2013).

Results and Discussion

Wind map: The best regression fit for average annual maximum wind speed (75^{th} percentile) was realized using wind atlas speed at 10 m, point elevation, and distance to Atlantic coast (R^2 = 76.7%, R^2 predicted = 72.7%) (Appendix 1). An average maximum wind speed raster map for the province was generated using this regression with five class boundaries determined by natural breakpoints found in the data (Jenks Natural Breaks algorithm) (Figure 2). Predicted speeds ranged from 4.3 - 21.5 $m \cdot s^{-1}$ (15.5 - 77.4 $km \cdot hr^{-1}$), with higher values found along the Atlantic coast and Cape Breton Highlands (in keeping with known trends in the province). Highest predicted speeds match critical damage thresholds reported by Ancelin et. al (2004) for Norway spruce in Europe ($\approx$ 21 $m \cdot s^{-1}$), suggesting coastal and Highland areas are prone to wind damage regardless of relative topographic position.

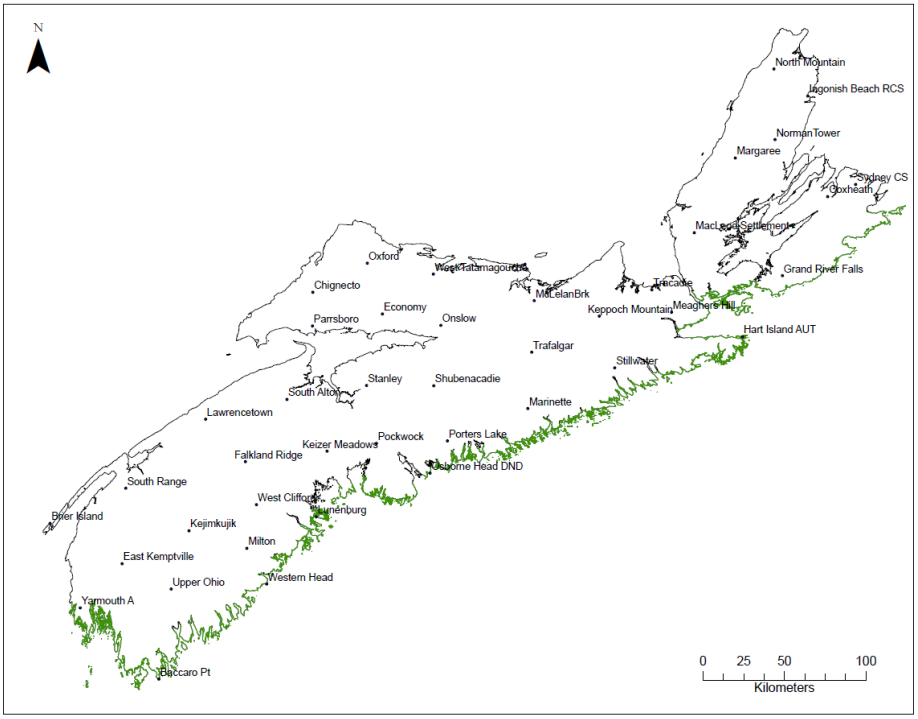

Figure 1. Selected NSDNR and Environment Canada weather stations across Nova Scotia used for baseline maximum wind speed data. The green line represents the Atlantic coast used for distance assessment.

Topex map: Through repeated assessments, it was determined that 1 km was the best horizon distance to use for topex calculations (generated values -59 to +277), but that no single set of breakpoints could adequately cover the range of topographic conditions found across the province. Topex class boundaries were therefore assessed and assigned within similar ELC ecodistrict groups (Neily et al., 2005) (Table 2). Topex maps generated for each area were then combined to make one topex map for the province (Figure 3).

Exposure Map: Analysis results suggest average maximum wind speed (Class H-VH) trumps relative topographic exposure for most areas along the Atlantic coast and Cape Breton Highlands, whereas topex class is the main wind exposure variable for inland and lower elevation areas. To derive a final exposure class map (Figure 4), a matrix was produced combining the impacts of both wind speed and topex class on overall exposure. To facilitate use of this new exposure map in current management guides, old terminology from Table 2 was used to describe exposure classes (Table 3). Area values for each exposure class by ecodistrict are provided in Table 4.

As to be expected, the dominant exposure condition in the province is moderate (or neutral) making up 73% of the land base, excluding water (Table 4, Figure 4). Exposed conditions (ME, EX) which could contribute to higher windthrow hazard covers about 22%, with the remaining 5% classed as sheltered (MS, SH).

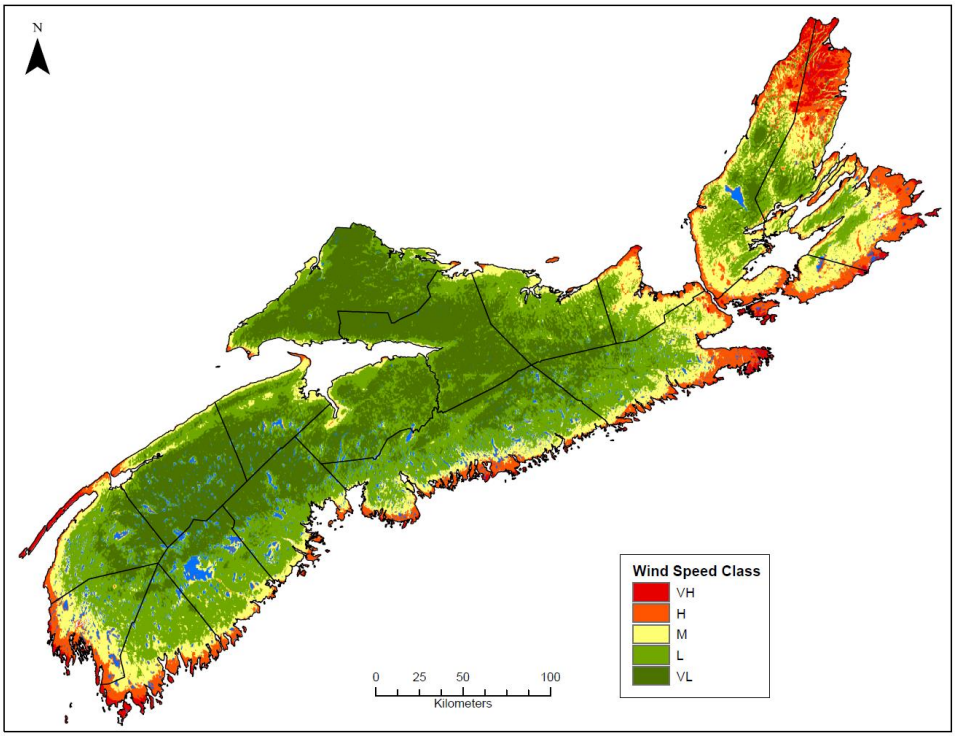

Figure 2. Regression derived average annual maximum wind speed (75th percentile) map for Nova Scotia based on data from 46 weather stations. VL = very low, L = Low, M = moderate, H = high, VH = very high.

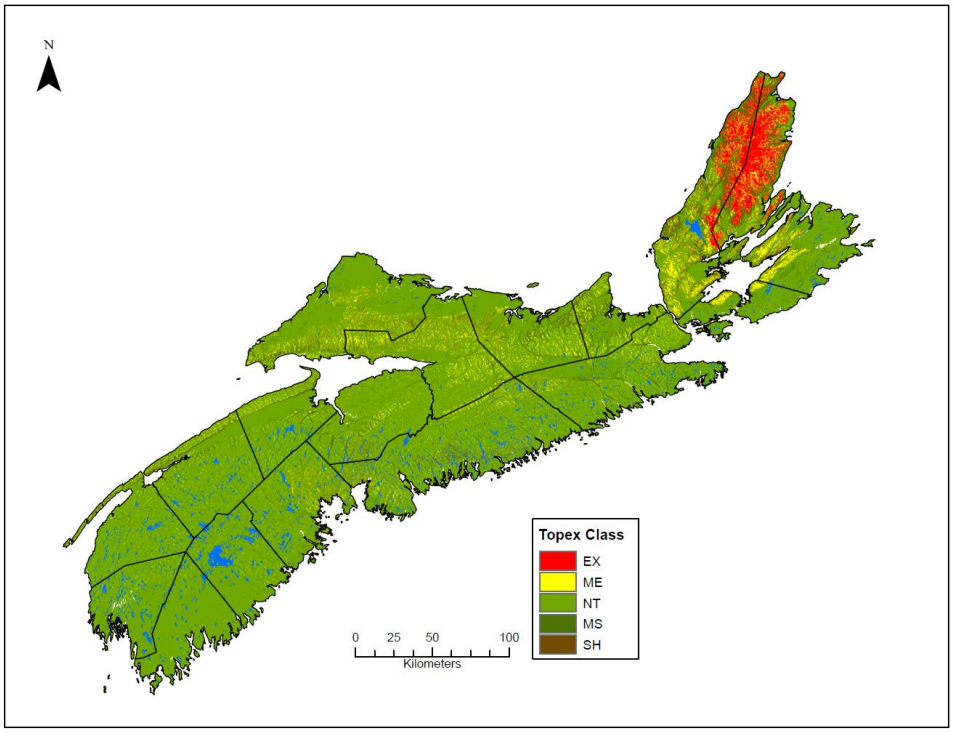

Figure 3. Topex class map for Nova Scotia from combined ecodistrict group maps.

Table 2. Ecodistrict groups used for topex assessment with exposure class boundary values.

Ecodistricts	Exposed	Mod. Exposed	Neutral	Mod. Sheltered	Sheltered
100, 210	≤ 7.0	7.0 to 15	15 to 20	20 to 30	30+
310	≤ -1.5	-1.5 to 4.0	4.0 to 22	22 to 50	50+
330, 360, 380, 910	≤ -5.5	-5.5 to 1.0	1.0 to 13	13 to 30	30+
340	≤ -1.5	-1.5 to 2.0	2.0 to 22	22 to 50	50+
350, 540	≤ -1.5	-1.5 to 1.0	1.0 to 22	22 to 50	50+
220, 320, 370, 510, 520, 530, 550, 560, 610, 620, 760, 810, 820, 830, 840	≤ -6.1	-6.1 to -2.0	-2.0 to 10	10 to 20	20+
440, 630, 710, 720, 730, 740, 750, 770	≤ -5.5	-5.5 to -0.5	-0.5 to 13	13 to 35	35+
410, 920	≤ -5.5	-5.5 to 0.7	0.7 to 13	13 to 30	30+
430, 450, 780	≤ -1.5	-1.5 to 1.0	1.0 to 15	15 to 50	50+

Table 3. Matrix used to assign overall exposure class based on average annual maximum wind speed and topex class. SH = sheltered, MS = moderately sheltered, M = moderate, ME = moderately exposed, EX = exposed.

Topex Class	Wind Speed Class				
	VL	L	M	H	VH
SH	SH	SH	SH	M	ME
MS	MS	MS	MS	ME	EX
NT	M	M	M	ME	EX
ME	ME	ME	ME	EX	EX
EX	EX	EX	EX	EX	EX

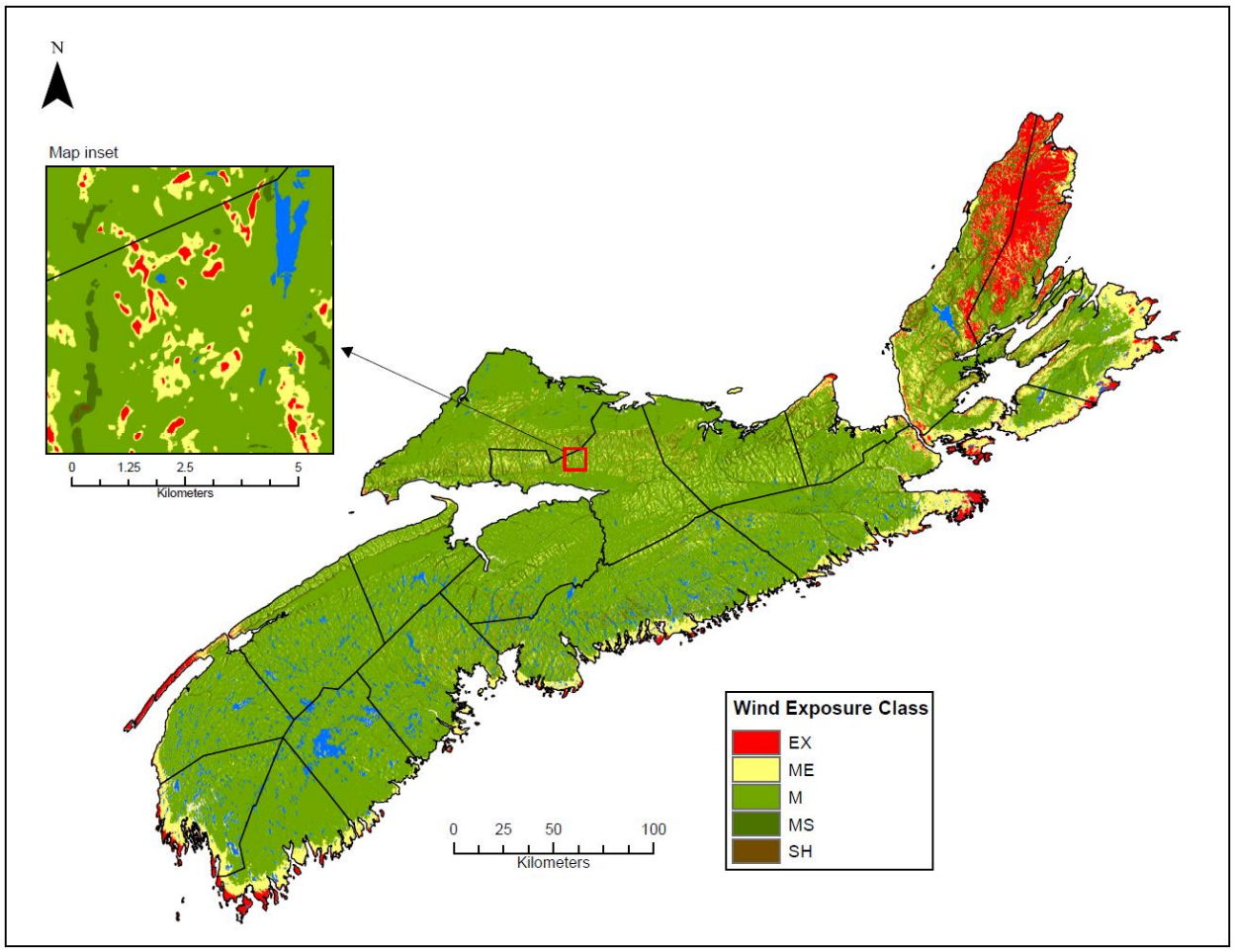

Figure 4. Provincial wind exposure map and smaller section example based on combined average maximum wind speed data and topex class.

Assumptions and Limitations

Average wind speed was assumed to be the main driver of exposure for areas classed as H-VH (Figure 2). The high (H) wind speed class threshold is 10.5 $m \cdot s^{-1}$ which is 50% of the critical wind speed value reported by Ancelin et al. (2004) and the approximate speed where windthrow hazard started to noticeably increase in model simulations conducted by Anyomi et al. (2017) for Ontario stand types. Wind classes VL-M were considered the same with respect to exposure hazard, so topex class was the main exposure driver where these lower wind speeds were mapped (Table 3).

Except for the "distance to Atlantic coast" variable in the wind speed regression, the final exposure map does not directly take wind direction into account. However, topex class is the main exposure variable for most of the province and this value reflects "average" topographic exposure from eight different directions. It is assumed that this will capture most wind direction influence not already captured in the wind speed map. Still, it is recognized that there may be some areas in the province

where specific combinations of dominant wind direction and localized relief may result in frequent wind funneling and a potentially higher hazard class than is currently mapped.

Table 4. Exposure class area values by ecodistrict. SH = sheltered, MS = moderately sheltered, M = moderate (neutral), ME = moderately exposed, EX = exposed. Area values do not include water.

Ecodistrict		Exposure Class area (ha)									
No.	**Name**	**SH**	*%*	**MS**	*%*	**M**	*%*	**ME**	*%*	**EX**	*%*
100	Northern Plateau	34	*0.1*	76	*0.2*	116	*0.3*	1,180	*2.9*	39,329	*96.5*
210	Cape Breton Highlands	1,674	*0.9*	2,505	*1.4*	4,351	*2.4*	28,141	*15.2*	148,478	*80.2*
220	Victoria Lowlands	2,397	*13.8*	1,543	*8.9*	2,432	*14.0*	6,875	*39.5*	4,155	*23.9*
310	Cape Breton Hills	15,440	*4.2*	46,211	*12.6*	155,168	*42.1*	107,220	*29.1*	44,132	*12.0*
320	Inverness Lowlands	5,180	*12.4*	9,936	*23.8*	19,731	*47.3*	6,247	*15.0*	614	*1.5*
330	Pictou Antigonish Highlands	2,111	*1.6*	17,000	*12.8*	84,733	*64.0*	25,369	*19.2*	3,181	*2.4*
340	Cobequid Hills	238	*0.1*	7,975	*4.3*	138,454	*74.6*	32,234	*17.4*	6,796	*3.7*
350	Cobequid Slopes	4	*0.0*	448	*1.2*	31,229	*84.4*	4,396	*11.9*	920	*2.5*
360	Mulgrave Plateau	29	*0.0*	4,496	*4.5*	71,055	*70.7*	22,123	*22.0*	2,760	*2.7*
370	St Mary's River	160	*0.2*	7,682	*9.4*	73,430	*89.4*	835	*1.0*	11	*0.0*
380	CentraI Uplands	142	*0.1*	7,543	*5.9*	99,710	*77.7*	20,898	*16.3*	72	*0.1*
410	Rawdon Wittenburg HilIs	134	*0.2*	5,377	*8.8*	45,343	*74.1*	10,305	*16.8*	59	*0.1*
430	Eastern Granite Uplands	3	*0.0*	4,607	*8.6*	42,033	*78.5*	4,759	*8.9*	2,137	*4.0*
440	Eastern Interior	197	*0.0*	14,077	*3.3*	383,129	*90.0*	27,133	*6.4*	1,007	*0.2*
450	Governor Lake	0	*0.0*	582	*1.0*	49,393	*82.6*	8,399	*14.1*	1,393	*2.3*
510	Bras d'Or Lowlands	3,680	*1.4*	23,197	*8.7*	159,554	*59.8*	73,925	*27.7*	6,597	*2.5*
520	St George's Bay	788	*0.9*	11,236	*12.9*	58,155	*66.8*	16,377	*18.8*	464	*0.5*
530	Northumberland Lowlands	700	*0.3*	10,033	*3.6*	260,158	*93.7*	6,799	*2.4*	74	*0.0*
540	Cumberland Hills	0	*0.0*	790	*0.9*	74,568	*82.3*	13,067	*14.4*	2,226	*2.5*
550	Cumberland Marshes	19	*0.1*	197	*1.2*	16,791	*98.4*	63	*0.4*	0	*0.0*
560	Chignecto Ridges	181	*0.2*	2,546	*3.4*	70,575	*95.6*	510	*0.7*	7	*0.0*
610	AnnapoIis Valley	1,025	*1.1*	6,999	*7.8*	80,612	*89.6*	1,333	*1.5*	49	*0.1*
620	Minas Lowlands	96	*0.2*	1,601	*3.9*	39,258	*94.6*	529	*1.3*	4	*0.0*
630	CentraI Lowlands	35	*0.0*	7,209	*2.7*	247,594	*92.9*	11,581	*4.3*	95	*0.0*
710	Valley Slope	414	*0.5*	7,777	*8.8*	73,161	*83.1*	6,527	*7.4*	170	*0.2*
720	South Mountain	104	*0.0*	6,737	*1.6*	395,162	*93.5*	20,076	*4.8*	384	*0.1*
730	Clare	172	*0.1*	915	*0.5*	143,386	*82.5*	26,040	*15.0*	3,199	*1.8*
740	LaHave Drumlins	32	*0.0*	7,297	*2.9*	227,480	*91.6*	13,008	*5.2*	543	*0.2*
750	Rossignol	174	*0.2*	433	*0.4*	92,112	*94.2*	4,931	*5.0*	87	*0.1*
760	Sable	165	*0.1*	1,133	*0.4*	269,300	*96.6*	8,045	*2.9*	155	*0.1*
770	Western Barrens	1	*0.0*	39	*0.1*	72,707	*96.0*	3,009	*4.0*	2	*0.0*
780	St Margaret's Bay	1	*0.0*	4,499	*2.6*	142,800	*83.6*	18,144	*10.6*	5,278	*3.1*
810	Cape Breton Coastal	30	*0.0*	2,323	*2.2*	24,810	*23.1*	60,071	*55.9*	20,144	*18.8*
820	Eastern Shore	200	*0.1*	4,487	*2.9*	45,356	*29.5*	81,928	*53.2*	21,906	*14.2*
830	South Shore	39	*0.0*	1,941	*1.6*	46,902	*37.6*	56,330	*45.2*	19,451	*15.6*
840	Tusket Islands	0	*0.0*	122	*0.3*	8,496	*22.4*	19,511	*51.5*	9,756	*25.8*
910	Parrsboro Shore	1,118	*2.6*	8,771	*20.4*	25,333	*59.1*	6,790	*15.8*	885	*2.1*
920	North Mountain	526	*0.5*	6,089	*6.3*	55,580	*57.3*	20,903	*21.6*	13,895	*14.3*
Totals		**37,243**	*0.7*	**246,426**	*4.7*	**3,830,157**	*73.0*	**775,612**	*14.8*	**360,415**	*6.9*

Management Implications

For the purposes of pre-treatment assessment (PTA), exposure refers to potential wind exposure associated with geographic location and topographic position, it is not intended to represent exposure related to past management treatments and/or adjacent land-use. In other words, the purpose is to assess wind exposure as a permanent site feature. As such, this new raster-based wind exposure map provides a consistent and robust estimate of wind exposure and may be considered the definitive "first call" for PTA related exposure classification in Nova Scotia.

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Appendix 1. Regression output for weather station annual maximum wind speed (75th percentile).

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	164.50	54.834	46.19	0.000
Raster Elevation (m)	1	19.23	19.233	16.20	0.000
Distance Atlantic Coast (m)	1	12.99	12.991	10.94	0.002
WS Model (mps)	1	150.42	150.416	126.69	0.000
Error	42	49.86	1.187		
Total	45	214.36			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.08960	76.74%	75.08%	72.71%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2.632	0.710	3.70	0.001	
Raster Elevation (m)	-0.00648	0.00161	-4.02	0.000	1.30
Distance Atlantic Coast (m)	-0.000015	0.000005	-3.31	0.002	1.07
WS Model (mps)	1.800	0.160	11.26	0.000	1.23

Regression Equation

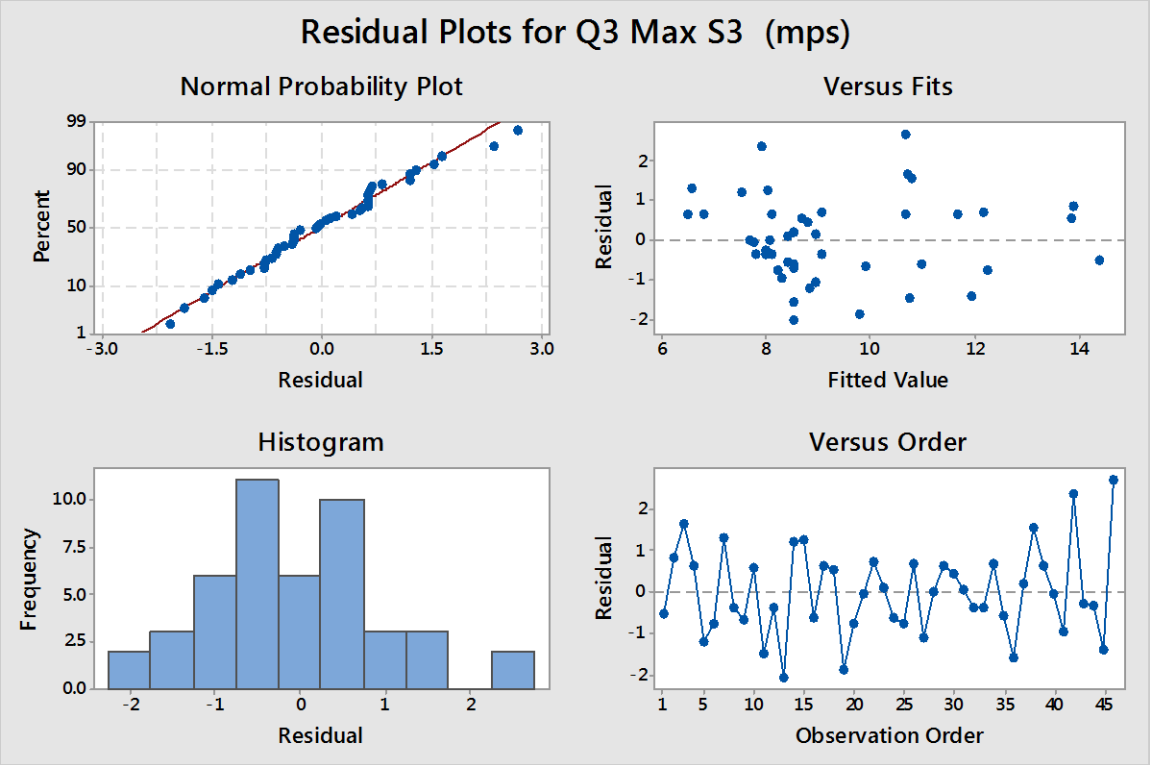
Q3 Max S3 (mps) = 2.632 - 0.00648 Raster Elevation (m)
- 0.000015 Distance Atlantic Coast (m) + 1.800 WS Model (mps)

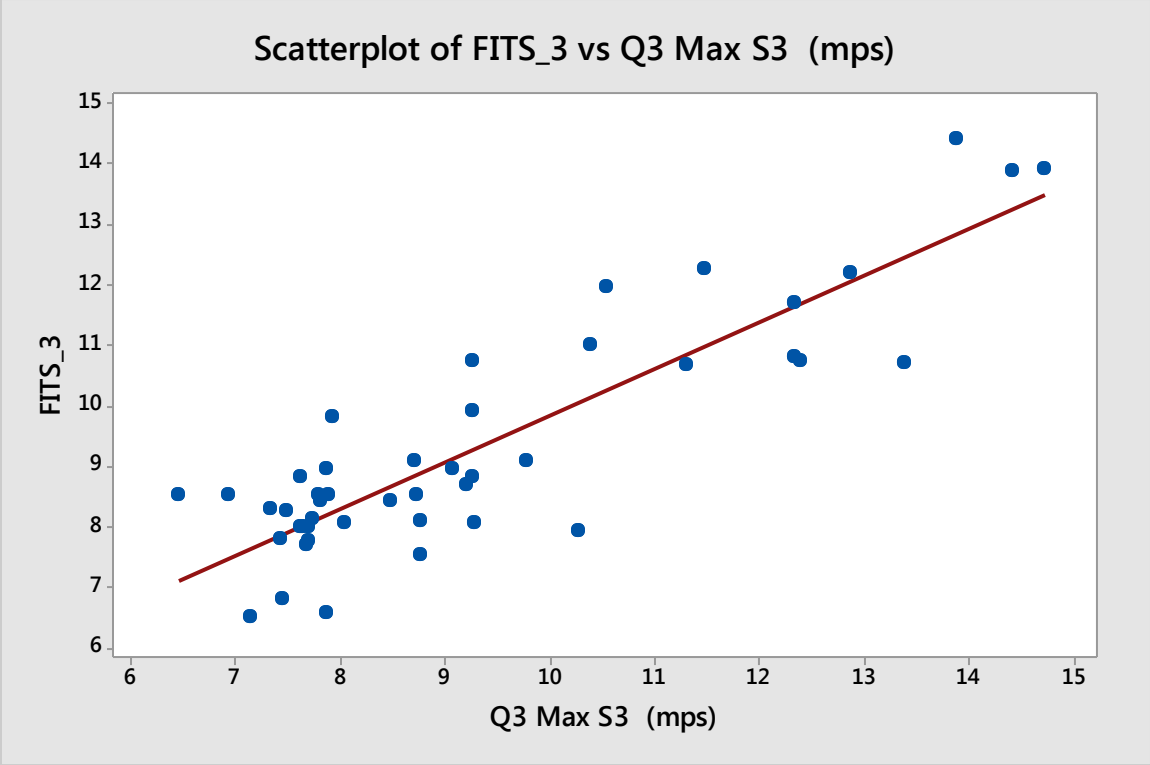
Fits and Diagnostics for Unusual Observations

Obs	Q3 Max S3 (mps)	Fit	Resid	Std Resid	
24	10.389	10.996	-0.607	-0.65	X
25	11.472	12.250	-0.778	-0.86	X
26	12.861	12.190	0.671	0.74	X
42	10.278	7.914	2.364	2.22	R
46	13.389	10.692	2.697	2.56	R

R Large residual
X Unusual X

Note: Two stations (Osbourne Head and Debert) were removed with high Cook's Distance (outliers). Final n = 46.





Graphs showing data distributions (top) and regression predicted (FITS_3) versus measured (Q3 Max S3) wind speed data from weather stations (bottom).