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How should acoustics adapt to meet future demands?

Atmospheric Stability Specific Noise Criteria and Noise Predictions for Wind Farms

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ABSTRACT

The South Australian EPA "Wind Farm Noise Guidelines" (2003) have been used extensively in Australia, and was based on the New Zealand Standard NZS 6808-1998 "Acoustics-The Assessment and Measurement of Sound from Wind Turbine Generators" which in turn was based on the report ETSU-97-R "The Assessment and Rating of Noise from Wind Farms" by the United Kingdom's Energy Technology Support Unit. The New Zealand Wind Energy Association (NZWEA) and Energy Efficiency and Conservation Authority (EECA) jointly commissioned an unofficial review of NZS 6808 given recent research findings, while the draft Australian Standard DR 07153 CP "Acoustics-Measurement, prediction and assessment of noise from wind turbine generators" has been in preparation for the past few years. Both standards attempt to account for the effect of atmospheric stability on the wind speed profile with height (commonly referred to the van de Berg effect). This paper describes a unique method to accurately assess the effects of atmospheric stability on the definition of noise criteria (established from noise logging) and the prediction of noise levels from wind turbines.

INTRODUCTION

Wind turbines generated noise levels are unique when compared to standard industrial noise as they are dependant on the wind conditions. The emitted noise level is a function of the wind speed experienced by the wind turbine generator (WTG). This requires a different approach to develop applicable design noise criteria when compared to usual industrial development. Standard methods require measurement of noise levels at the sensitive receivers in conjunction with wind speeds at the WTG location. They aim to determine the variance in the background noise environment at the receiver with respect to the changing wind speeds at the WTG site. However if atmospheric stability is not taken into consideration while developing noise criteria, for certain a hub height wind speed, different wind speeds will be present at ground level due to the wind speed profile which is dependant on the atmospheric stability as shown by the van den Berg effect (van den Berg 2003)

This paper shows the importance of carrying out hub height wind measurements during the background noise survey as well as accounting for atmospheric stability to ensure compliance to criteria under all atmospheric conditions.

REVIEW OF EXISTING STANDARDS

SA EPA Interim Guidelines

The interim noise guidelines developed by the South Australian Environmental Protection Authority (EPA (SA) 2007) document details the procedure for measuring background noise and wind speeds, predicting noise levels, analysing results and checking compliance.

The noise criteria set out for new wind farm development is as follows:

The predicted equivalent noise level ($L_{Aeq,10}$) adjusted for tonality in accordance with these guideline,should not exceed:

- *35 dBA, or*
- *40 dBA, in an intensive rural or primary production/rural industry zone, or*
- *the background noise level ($L_{A90,10}$) by more than 5 dBA*

whichever is greater, at all relevant receivers for each integer wind speed from cut-in to rated power of the wind turbine generator

The above-mentioned criteria have been developed to minimise impact on 'relevant' premises that *do not* have an agreement with the wind farm developer as indicated below.

EXHIBIT
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Table 1 SA EPA Guideline terminology

Relevance of SA EPA Guideline for setting criterion	Terminology	Relationship of land on which the residence is located to the wind farm project
relevant	non wind farmer	The landowner is unconnected with the wind farm project
non-relevant	wind farmer	Landowner has entered into lease with the wind farm proponent for the wind farm operation and is a beneficiary of the project

This clause however does not absolve the developer from their obligation to minimise *"adverse effect on an amenity value of an area"* due to entering into an agreement with a land owner.

The background noise should be as determined by the collection and regression analysis procedure outlined in the SA EPA Wind Farm Guidelines. The collection of noise data should be carried out within 20 meters of noise sensitive dwellings, with data being collected at 10 minute intervals so that it can be correlated with wind speed at *10 m above ground level* (AGL) at the wind farm site. A minimum of 2000 valid points of wind and noise data have to be correlated to create the regression curve. Data points which are below the cut-in wind speed of the WTG, rain effected noise measurements and noise measurements where it is obvious that an abnormal high noise activity has taken place, eg human intervention of noise logger are excluded from the analysis.

The following important issues are to be noted:

- The guideline gives no consideration to the effect of atmospheric stability
- The guideline requires all wind speeds to be expressed at 10 m above ground level

New Zealand Standard

The New Zealand Wind Energy Association (NZWEA) and Energy Efficiency and Conservation Authority (EECA) jointly commissioned an unofficial review (Malcolm Hunt & Assoc. et al 2007) of NZS 6808 with the following outcomes (applicable to this paper) that differ from the SA EPA guideline:

- Any revised version of NZS 6808 should avoid under-prediction of WTG sound levels by utilising wind speed data collected at the expected hub height of the proposed WTG or correctly adjusted with site specific wind shear to reflect hub height wind speed

Draft Australian Standard

A draft Australian Standard (Draft AS 2006), based on NZS 6808 has been in preparation over the past few years. The following important requirements of this draft standard that differ from the SA EPA guideline are:

- All sound power level and background noise data shall be referenced to the hub height wind speed of the proposed WTG
- At each nominal wind speed, the noise limit should be the higher of:
- Minimum noise level limit
- Background noise levels plus the specified amount

METEOROLOGY

Atmospheric Stability

The degree of stability in the atmosphere is determined by the temperature difference between an 'air parcel' and the air surrounding it. This difference can cause the air parcel to move vertically, and this movement is characterised by four basic conditions that describe the general stability of the atmosphere. In stable conditions, this vertical movement is discouraged, whereas in unstable conditions the air parcel tends to move upward or downward and to continue that movement. When conditions neither encourage nor discourage that movement beyond the rate of adiabatic heating or cooling they are considered neutral. When conditions are extremely stable, cooler air near the surface is trapped by a layer of warmer air above it, with this condition being called an inversion which results in virtually no vertical air motion. These conditions are favourable for noise propagation as the density of the changes increases with altitude which alters the speed of sound creating a refractive effect, which leads the sound waves that would normally radiate out to space to refract back down to surface of the earth leading to an increased experienced noise level at the receiver.

The Pasquill-Gifford (P-G) (Pasquill 1961) stability category scheme is normally used to describe atmospheric stability. Stability class under the P-G scheme is designated a letter from A-F (and sometimes G), ranging from highly unstable to extremely stable.

van den Berg Effect

While assessing complaints of noise from wind turbines, van den Berg (van deb Berg 2003) originally demonstrated the well known fact in meteorology (and in particular atmospheric boundary layer physics that effects many disciplines) that wind profiles change significantly with atmospheric stability. This is shown below in Figure 1, with the exponent of a logarithmic or power law expression for the velocity modified under differing stability conditions (see for example Irwin 1979). Prior to this work the wind profile had been assumed to be constant for varying meteorological conditions when considered in environmental noise assessments. It is apparent from Figure 1 that low ground level wind speeds and therefore low background noise levels can correlate with high upper level wind speeds under stable conditions, and therefore potential exceedance of noise criteria derived from background noise levels correlated to ground level wind speeds.

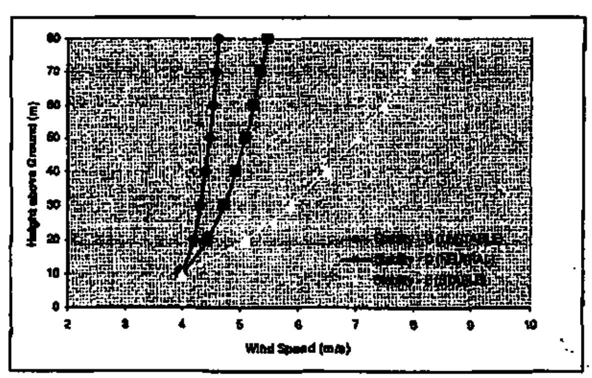


Figure 1 Wind speed profile variation with stability

The van den Berg effect has been recognised recently by the Environment Courts in New South Wales, Victoria, and New Zealand. However there remains misunderstanding as to how commentary and draft standards suggesting assessments of noise levels relative to hub height wind speeds will resolve the issue. It is demonstrated in this paper that a proper account also requires definition of hub height wind speeds relative to stability to provide a reliable prediction of noise impacts in all circumstances. The need to consider both aspects is explained further with reference to typical example in the next section.

For the purposed of this paper WTG hub height is assumed as 80 m above ground level, however in reality this number can vary depending on the specific model of the WTG.

Effect on Wind Turbine Noise Assessment

It is most common to determine the assessment criterion based on the 10 m AGL wind speed. The standard criterion curve of background noise relative to 10 m AGL integer wind speeds is shown on Figure 2. Background noise levels, when referenced to ground level wind speeds, will always have the same mean curve, but the variation about the mean will depend on stability. This is because the level of turbulence (or turbulence intensity) increases with growing unstable conditions.

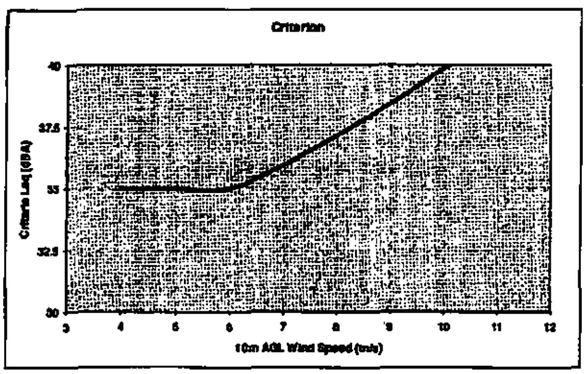


Figure 2 Noise criterion curved versus 10 m level wind speed based on background noise measurements

Using the van den Berg effect, Figure 3 describes the change in velocity profile with stability class. This shows that for a 12 m/s hub height wind speed and the applicable wind speed profile depending on the atmospheric stability condition at the time, then the 10 m AGL wind speeds vary as follows:

- Stability B (unstable) - 10 m/s
- Stability D (neutral) - 9 m/s
- Stability E (stable) - 6 m/s

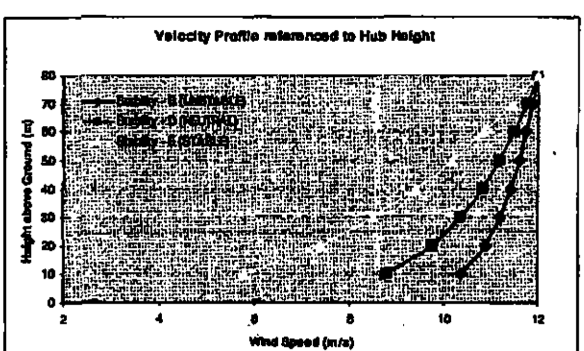


Figure 3 Velocity profile referenced to hub height

Criterion curves when referenced to hub height wind speeds can be derived from the above two data sets. That is 10 m level wind speeds of about 10 m/s (Stability B, unstable), 9 correspond to criteria of about 40 dBA, 38 dBA and 35 dBA respectively. The criterion curves can then be developed for each integer hub height wind speed using this approach, and these are shown in Figure 4.

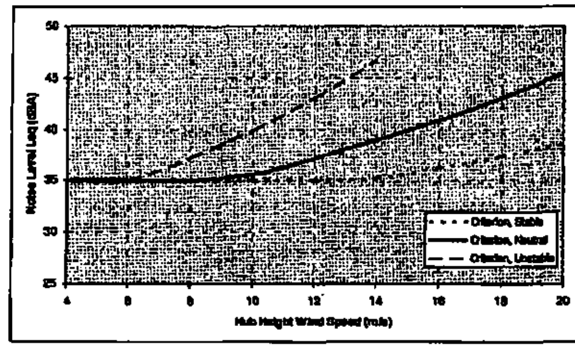
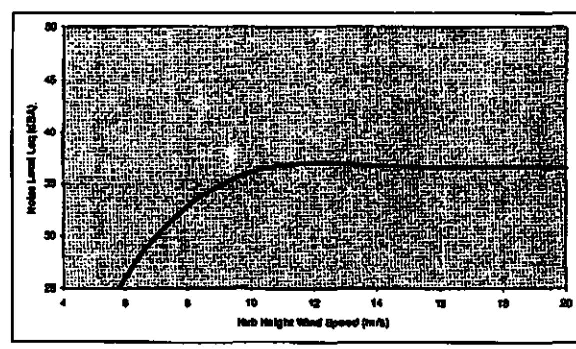


Figure 4 Criterion curves for different atmospheric stabilities relative to hub height wind speeds

Figure 5 shows the predicted turbine noise level at an arbitrary receiver relative to hub height wind speed. This is based on a typical noise curve for a wind turbine generator as shown in Table 2 below.

Table 2 Wind turbine noise curve

Wind speed (m/s) at hub height	Mode 0 Sound Power Levels (dBA)
5.6	97
7.0	102
8.4	105.8
9.8	108.2
11.2	109.3
12.6	109.4
14.0	106.7
15.3	105.9
16.7	105.7
18.1	105.7



Note: Predicted noise levels ignore meteorological, shielding and ground absorption effects associated with noise propagation

Figure 5 Wind turbine noise levels at an arbitrary receiver relative to hub height wind speeds

In summary, the criterion curves change with stability class, while the turbine noise level profile is unchanged with stability class. The combined curves are shown in Figure 6 and demonstrate that without considering stability (usually neutral conditions prevail), wind turbine noise levels comply with the criterion curve. In contrast, under stable conditions the criterion curve is exceeded by about 3 dBA in the example shown in Figure 6. Under unstable conditions noise from wind turbines will not exceed the criterion curve.

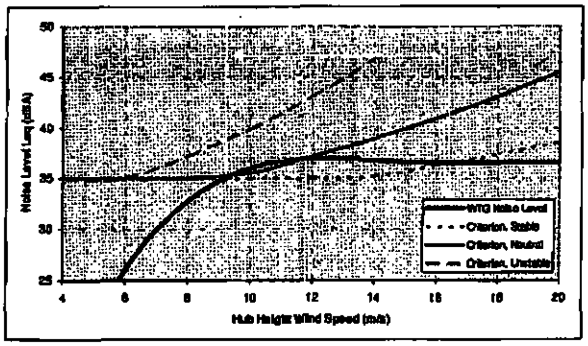


Figure 6 WTG noise assessment during various stabilities

For the assessment shown in this paper atmospheric stability was included in as follows:

- Short Term: For the regression analysis of background noise levels referenced to hub height wind speeds have been classified by determining stability class from the standard deviation of the change in wind direction as measured at 80 m for the proponent's reference mast location using the method developed in the United States (US EPA 1987).
- Long Term: The effect of atmospheric stability on velocity profile has been well known in the field of air quality dispersion modelling with Australian models such as AusPlume and TAPM having been developed by the Victorian EPA and the CSIRO respectively. These models use meteorological data either from the Bureau of Meteorology's (BOM) weather stations or predicted from synoptic weather data. Predicted stability categories were used from these models in preference to analysis of weather station data from the BOM as it is often very difficult to obtain reliable data from the BOM, given stability is usually determined from cloud cover and ceiling height therefore requiring observations and most standard weather stations are unattended (other methods to determine stability require measurements of temperature and insolation which are also not usually included in standard weather stations). The approach used herein was to predict weather for an entire year (in this case 2001 was considered to be a representative year) and from this determine stability class throughout the year. The variation of hub height wind speeds with stability could then be determined.

BACKGROUND NOISE AND WIND SURVEY

The noise survey was conducted at four locations within 2 km surrounding the proposed wind turbine farm development to represent the noise environment at the affected relevant receivers. Hub height wind speed measurements at the proposed WTG locations were carried out in conjunction with the noise logging. The site can be described as having complex topography, with the potential WTG sites located along a mountain ridge that is up to 250 m higher than then altitude of the receivers, creating an overall difference of over 300 m between the height of the source and receiver. Data was collected over a four week period, with the minimum 2,000 usable data points being reached at each location after filtering the collected data to exclude periods of inclement local weather conditions as per the requirements in the SA EPA Guidelines.

DESIGN CRITERIA

The design criteria were developed using regression analysis as described by the SA EPA interim Guidelines with the ex- height wind speeds *not* 10 meters AGL. For comparison reasons two sets of criteria were developed one using the standard approach which does not take into account atmospheric stability and the second approach which provides specific criteria for atmospheric stabilities occurring at the site. These are outlined in Table 3 below.

Table 3 Overall and atmospheric stability specific assessment criteria

		Criterion $L_{Aeq,10}$ (dBA) for each Hub Height Wind Speed (m/s)								
	Stability Criterion	4	5	6	7	8	9	10	11	12
R1	None	35	35	35	35	35	35	37	38	40
	B	35	36	38	41	-	-	-	-	-
	D	35	35	35	35	35	35	37	38	40
	E	35	35	35	35	35	35	35	35	35
R2	None	35	35	35	35	35	37	38	40	42
	B	35	36	38	39	-	-	-	-	-
	D	35	35	35	35	35	37	38	40	42
	E	35	35	35	35	35	35	35	35	35
W1	None	35	35	35	35	36	37	38	39	41
	B	35	35	35	35	-	-	-	-	-
	D	35	35	35	35	36	37	38	39	40
	E	35	35	35	35	35	35	35	35	35
W2	None	35	35	35	35	35	35	35	36	37
	B	35	35	37	42	-	-	-	-	-
	D	35	35	35	35	35	35	35	36	37
	E	35	35	35	35	35	35	35	35	35

NOISE MODEL

The ISO 9613-2 noise prediction model has been used in this assessment. This standard predicts noise levels under meteorological conditions favourable to propagation. Conditions favourable to propagation are defined as "downwind propagation" (wind speed between approximately 1 m/s and 5 m/s) or "propagation under a well-developed moderate ground based temperature inversion, such as commonly occurs at night". However it should be noted that the wind speed range refers to wind "measured at a height 3 to 11m above the ground", which can vary quite significantly when compared to wind at hub height above the ground, especially during stable conditions due to the van den Berg effect.

Papers note the improved accuracy of the ISO 9613-2 method compared to other prediction models including CONCAWE, with in particular Bass (Bass et al 1996:12) noting:

> …The accuracy of output from the ISO model is impressive. Agreement with sound pressure levels measured under conditions of an 8 m/s positive vector wind speed has been measured to within 1.5 dBA on flat, rolling and complex terrain sites. The only observed exceptions to the excellent accuracy achieved by the model occur in the presence of marginal or partial acoustic screening, and also where the ground falls away significantly between the source and receiver. However, these two situations are easily accounted for by means of simple

Bass (Bass et al 1996:12) recommends the following correction factors:

- The excess attenuation attributable to the barrier effect should be limited to no more than 3 dBA, given that a positive component of wind from the source to the receiver can significantly reduce the effective barrier performance
- Where the ground falls away significantly between the source and receiver, such that the mean propagation height is at least 1.5x that over flat ground and particularly where the ground falls away steeply from the receiver, it is recommended that 3 dBA be added to the calculated sound pressure level. This accounts for the reduction in excess ground attenuation due to the increased height of propagation
- Provided the suggested correction factors are applied to the output of the ISO model, the calculated sound pressure levels have been validated to agree to within 2 dBA of noise levels measured under practical "worst case" conditions at distances of up to 1000 m from a noise source.

These corrections have been included in the model and have accounted for less than a 0.5 dBA increase in the noise level at receivers.

This is substantiated by recent research in New Zealand/Australia, as it has also been shown recently (Malcolm Hunt & Assoc et al 2007) to provide more accurate estimates of emissions from turbines, though it was based on worst case downwind noise propagation with a "well developed moderate ground based temperature inversion" as used by ISO 9613-2. This report also states:

> The goal of any noise prediction method should be to assist wind farm developers to design a wind farm which complies with noise limits, without requiring an excessively onerous safety margin due to prediction uncertainty
>
> In cases where the distances between turbines and receivers are significant and have significant, correctly understood terrain features, the ISO 9613-2 model produces more accurate results. As typical setbacks to NZ wind farms are 800 m or more, ISO 9613-2 would appear to most accurately predict measured sound levels. To achieve this, the model needs to be well informed with respect to terrain information (necessitating the use of digital terrain models in most hilly situations)
>
> The inclusion of the directional wind factor in either the ISO 9613-2 or the CONCAWE model made negligible difference to the noise levels predicted

Inputs into the SoundPLAN model have been entered as follows:

- Positions of sources, receivers and ground contours input from electronic data created for this project with features specified in the MGA coordinate system
- Meteorological inputs used by ISO 9613-2;
- Relative humidity
- Ambient temperature
- Atmospheric pressure
- Wind rose data as per predictions carried out by TAPM software for each stability class

A *further safety factor was applied using C_{met} (long term* meteorological correction factor).

PREDICTED NOISE LEVELS

Noise levels due to the operation of wind turbines are shown in the tables below for each wind speed (at hub height) without taking into account atmospheric stability as well as in the applicable atmospheric stability criteria. Worse case sound powers emitted by the WTG have been used in the calculation with an adjustment being made depending on the wind speed. It has been assumed that all WTG are exposed to the same wind speeds therefore simultaneously all emitting the same sound power. This is not likely to occur, however it allows the assessment of the worse case when all WTG are emitting the maximum sound power level. Noise predictions were only made up to the maximum wind speed experienced at each stability criteria based on meteorological survey wind data and TAPM predicted wind data. At wind speeds over 12 m/s the sound power of the wind turbines decreases (as shown in Table 2) while the criterion increases, hence if compliance occurs at 12 m/s there is no need to present levels above that wind speed.

Table 4 Predicted Noise Levels at each receiver *not* taking into account atmospheric stability

Receiver	Predicted L_{Aeq} (dBA) at various Wind Speeds (m/s)								
	4	5	6	7	8	9	10	11	12
R1	13	20	25	29	31	33	35	36	36
W1	15	21	26	30	33	35	36	37	37
R2	17	23	29	32	35	37	[illegible]	39	40
R3	14	20	26	29	32	34	36	36	37
R4	14	20	25	29	32	34	35	36	36
R5	17	23	28	32	35	[illegible]	[illegible]	[illegible]	39
W2	8	15	20	23	26	28	30	30	31

Note: Highlighted noise levels exceed the design criteria, W1 and W2 are wind farmer residences

Table 5 Predicted Noise Levels at each receiver for Stability Class B

Receiver	Stability B Predicted L_{Aeq} (dBA) at various Wind Speeds (m/s)			
	4	5	6	7
R1	15	21	27	30
W1	17	23	28	32
R2	19	25	31	34
R3	15	22	27	30
R4	16	22	27	31
R5	19	25	31	34
W2	10	16	22	25

Note: Noise levels have not been predicted for wind speeds up to 12 m/s as wind speeds during Stability B have only been predicted to reach 7 m/s

Table 6 Predicted Noise Levels at each receiver for Stability Class D

Receiver	Stability D Predicted $L_{Aeq,10}$ (dBA) at various Wind Speeds (m/s)								
	4	5	6	7	8	9	10	11	12
R1	12	18	24	27	30	32	34	34	35
W1	14	20	26	29	32	34	36	36	37
R2	16	22	28	31	34	36	38	38	39
R3	13	19	24	28	30	33	34	35	35
R4	13	19	25	28	31	33	35	35	36
R5	16	23	28	31	34	36	38	38	39
W2	7	13	18	22	25	27	28	29	29

Table 7 Predicted Noise Levels at each receiver for Stability Class E

Receiver	Stability E Predicted $L_{Aeq,10}$ (dBA) at various Wind Speeds (m/s)								
	4	5	6	7	8	9	10	11	12
R1	13	19	24	28	31	33	34	35	35
W1	15	22	27	30	33	35	37	37	38
R2	17	23	28	32	34	37	38	39	39
R3	14	20	25	29	32	34	35	36	36
R4	14	20	26	29	32	34	36	36	37
R5	17	23	28	32	34	36	38	39	39
W2	8	14	20	23	26	28	30	30	31

Note: Highlighted noise levels exceed the design criteria (See Table 9)

It can be observed from the above results that when stability is not taken into account, exceedance of the criteria is only predicted at receivers R2 and R5 over a narrow range of wind speeds (see Table 8). On the other hand when noise levels are assessed against stability specific criteria exceedances occur at receivers R2, R3, R4 and R5 over a wider range of wind speeds which shown in Table 9.

Table 8 Predicted exceedances of the criterion at each receiver which *do not* take into account stability

Receivers	$L_{Aeq,10}$ (dBA) at various Wind Speeds (m/s)								
	4	5	6	7	8	9	10	11	12
R2									
Predicted	17	23	29	32	35	37	39	39	40
Criterion	35	35	35	35	35	37	38	40	42
Exceedance	-18	-12	-6	-3	0	0	[illegible]	-1	-2
R5									
Predicted	17	23	28	32	35	37	38	39	39
Criterion	35	35	35	35	35	35	37	38	40
Exceedance	-18	-12	-7	-3	0	[illegible]	[illegible]	[illegible]	-1

Table 9 Predicted exceedances of the criterion at each receiver for Stability Class E

Receivers	Stability E $L_{Aeq,10}$ (dBA) at various Wind Speeds (m/s)								
	4	5	6	7	8	9	10	11	12
R2									
Predicted	17	23	28	32	34	37	[illegible]	[illegible]	[illegible]
Criterion	35	35	35	35	35	35	35	35	35
Exceedance	-18	-12	-7	-3	-1	2	[illegible]	[illegible]	[illegible]
R3									
Predicted	14	20	25	29	32	34	35	[illegible]	[illegible]
Criterion	35	35	35	35	35	35	35	35	35
Exceedance	-21	-15	-10	-6	-3	-1	0	[illegible]	[illegible]
R4									
Predicted	14	20	26	29	32	34	[illegible]	[illegible]	[illegible]
Criterion	35	35	35	35	35	35	35	35	35
Exceedance	-21	-15	-10	-6	-3	-1	[illegible]	[illegible]	[illegible]
R5									
Predicted	17	23	28	32	34	36	[illegible]	[illegible]	[illegible]
Criterion	35	35	35	35	35	35	35	35	35
Exceedance	-18	-12	-7	-3	-1	[illegible]	[illegible]	[illegible]	[illegible]

CONCLUSION

Current reviews of existing Australian and New Zealand guidelines for the assessment of noise from wind turbine farm developments have identified the need to take into account the van den Berg effect to increase the accuracy of predicted noise emission relative to background noise at the relevant receivers.

However this paper shows that without the inclusion of atmospheric stability through the specification of stability specific noise criteria, noise levels emitted by the WTG can exceed the calculated criteria under certain atmospheric conditions which were not originally predicted. The included example wind farm noise assessment demonstrates this limitation by identifying exceedances at more receivers and over a wider range of wind speeds when atmospheric stability specific crieteria were used compared to the standard method of assessment that only takes into account relating criteria to hub height wind speeds. Not identifying these exceedances can lead to future problems for Wind Farm operators due to complaints and potential litigation from the affected relevant receivers.

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