Severe Wind Gust Risk for Australian Capital Cities – A National Risk Assessment approach

Nadimpalli, K., R.P. Cechet and M. Edwards

Risk and Impact Analysis Group, Geospatial and Earth Monitoring Division,
Geoscience Australia, Canberra, Australia.
Email: krishna.nadimpalli@ga.gov.au

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EXTENDED ABSTRACT

A review commissioned in June 2001 by the Council of Australian Governments (COAG) entitled 'Natural Disasters in Australia: reforming mitigation, relief and recovery arrangements' concluded that a new approach to natural disasters in Australia was needed. This approach would aim to achieve safer, more sustainable Australian communities in addition to a reduction in risk, damage and losses from future natural disasters. This "new" approach involves a fundamental shift in focus beyond relief and recovery towards cost-effective, evidence-based disaster mitigation. Consequently, while reactive disaster response plans remain important, the focus has moved to anticipation and mitigation against natural hazards. Geoscience Australia is developing risk models and innovative approaches to assess the potential losses to Australian communities from a range of sudden impact natural hazards. They aim to define the economic and social threat posed by these utilising a combination of natural hazard research methods and risk assessment models. The hazards considered in this body of research include earthquakes, severe winds, floods, landslides, storm surge and tsunami.

This paper provides an overview of the methodology being employed to assess the risk that severe wind poses to major Australian communities. The fundamental components of the risk assessment model are regional wind hazard, hazard modification multipliers, exposure and vulnerability. Initially a simple model was developed but subsequently various components of the model have been improved. The hazard definition is the estimated return period regional wind speed (for peak 3 second gusts) initially obtained from the Australian/New Zealand wind loading standard and commentary [AS/NZS 1170.2 (2002); AS/NZS 1170.2 Supp 1 (2002)]. The impact of severe wind varies considerably between equivalent structures located at different sites due to local roughness of the upwind terrain, the shielding provided by upwind structures and topographic factors. The site specific adjustment of wind speeds on the return period regional speeds were made using a series of multipliers. This approach considers the effects of terrain at the height of the structure, the shielding afforded by up-wind buildings and the topography. These multipliers were developed for eight cardinal directions on a 25 by 25 metre grid across each study region. Return period regional wind speeds taken from the AS/NZS wind loading standard were utilized in conjunction with these local wind multipliers to produce local wind speeds. Exposure information also underpins the risk assessments from severe wind or cyclones and includes population demographics, building type, construction (roof and wall) type, building age, number of storeys, business type and replacement value. Finally, vulnerability models are required and those readily available in Australia were initially used to study the impacts on buildings with refined models subsequently incorporated. The refined approach now comprises a spatially variable wind hazard incorporating an improved topographic multiplier, enhanced exposure information at building level and heuristically derived vulnerability curves for appropriate construction type.

Included in this enhanced approach have been corrections for the conservative nature of the AS/NZS wind loading standard which, collectively, have resulted in a significantly improved understanding of risk. The significance of each component's enhancement and its influence on risk estimation is discussed. With several components of the risk process varied, the study region losses have been evaluated for return period winds ranging from 50 to 2000 years and subsequently compared.

It is important to keep in mind that this approach has one major shortcoming related to the return-period hazard being applied equally to the whole study region. Other studies have shown that the so called "hazard map approach" to determining risk tends to overestimate the risk compared to an "event based" approach, which endeavors to both determine the amplitude and also the spatial extent of the hazard being considered. An "event set" generally contains a representation of the full range of possible events over a significantly long length of record (climatology) and therefore consists of a large number of events. The "hazard map approach" is used here to provide indicative estimates of relative risk, while event sets are being prepared through the use of 3-dimensional climate modeling and reanalysis.

1. INTRODUCTION

In August 2002 a review of natural disaster relief and mitigation arrangements in Australia was reported to the Council of Australian Governments (COAG, 2002). One of the outcomes from this review was an endorsement by COAG of the recommendation to "develop and implement a five-year national program of systematic and rigorous disaster risk assessments". As part of a response to this commitment, Geoscience Australia undertook the development of a preliminary hazard assessment methodology for peak wind gusts for the city of Perth (Lin and Nadimpalli, 2005). This initial research has been improved upon by incorporating more sophisticated approaches and models for evaluating the wind risk of a number of Australian capital cities. These cities are located in three of the four wind regions defined in the Australian/New Zealand wind loadings standard (AS/NZS, 2002).

Tropical cyclones and other storm types such as thunderstorms and tornadoes generate extreme winds and can cause significant economic loss. The boundary-layer winds are developed over kilometres of horizontal wind flow across the earth's surface through ground roughness and natural topography. The latter effect has been noted to exert a profound influence on wind behavior and, hence, on local wind speeds (Buck, 1964). A wind risk management approach should include a method for assessing local wind speed as described in Ruel, 2002. Some damage prediction models developed for insurance or disaster management purposes incorporate a limited consideration of local effects and how these differ with wind direction. A simplified probabilistic wind field model was used by Stewart (2003) which accounted for terrain and shielding by categorisation of the site exposure into three broad categories: Foreshore (1km from coast), Town (1-2 km from coast) and Inland (>2km from coast). There is a need to develop more refined approaches for local terrain and topographic feature considerations to estimate the wind exposure. The Australian wind loadings standard (AS/NZS, 2002) considers local wind exposure effects in the design of structures and is used as a key reference in this study.

The aim of the current study is to explore a national methodology for assessing the risk that peak wind gusts pose to Australian communities. The key components of the risk assessment model include the regional wind hazard, hazard modification multipliers, exposure and vulnerability. The local effects on return period regional wind speeds were determined utilising remote sensing techniques, digital elevation data, and formulae presented in the wind loadings standard (AS/NZS, 2002). Finally, the estimation of the local wind speeds that would be equaled or exceeded within a given time period (commonly called return period wind speeds or return levels) was evaluated by combining the local wind multipliers (terrain/height, shielding and topographic) for eight cardinal directions with the return period regional wind speeds (AS/NZS, 2002) on a 25 metre grid across each study region. The wind loadings standard (AS/NZS, 2002) is a building design document that seeks to "envelope" possible wind effects rather than to provide an average assessment of local wind speed. Thanh and Letchford (2007) compared current US, Australian/New Zealand, European and Japanese wind standards and reported that the treatment of topographic effects in these design standards is on the whole conservative. Holmes (2004) proposed adjustments to remove the conservatism from the methods in the Australian wind loading standard to assess risk. These proposals and several other initiatives were adopted to improve various components of the model from its initial steps (Nadimpalli *et al.,* 2006) towards a reliable national scale wind risk assessment for Australia cities.

Currently the return period regional wind speeds (three second peak gusts) for each study region are obtained from the AS/NZS wind loadings standard. The hazard definition was improved for the Perth region by using processed data from nine weather stations to obtain a spatially variable regional wind speed model. From this an assessment has been made of the significance of using an alternative definition of regional wind speed. In this paper several other refinements are also examined which include the incorporation of a 3D topographic multiplier for Sydney, buildings level exposure definition and the application of more appropriate vulnerability models for the construction types found in each study region.

2. METHODOLOGY

An overview of the risk methodology is presented in Figure 1 and is comprised of hazard, hazard multipliers, infrastructure exposure and vulnerability. The hazard definition is based on the science behind the wind phenomena (cyclone, thunderstorm downburst, tornado, etc) and historical wind data captured at various observation sites. These can be used to simulate events of known rarity or to develop a statistical definition of return period wind speeds at various locations. The former event based modeling provides plausible scenarios for tactical planning purposes like emergency training, planning, response and capacity review. The latter probabilistic models predict the likelihood of severe wind speeds being exceeded at a particular location. For this capital city study, probabilistic wind speeds were considered for 50, 100, 200, 500, 1000 and 2000-year return periods. It should be acknowledged that applying the probabilistic wind speed across the whole study area is an approximation; presently utilized in the absence of an event set that characterizes the full range of possible events for the region being considered.

2.1. Hazard

The return period regional wind speeds for severe gusts were taken from the Australia/New Zealand wind loadings standard (AS/NZS, 2002). These wind speeds refer to peak 3 second wind gusts at 10m height above ground in level country and were derived from a small number of meteorological recording stations within each of the regions defined in the standard. Uncertainty in the hazard values influenced the hazard definition in the wind loading standard. The result was a national map of broad hazard zones in which the regional wind speed is considered a constant. This hazard definition was subsequently changed for this study to examine the sensitivity of the quantified risk to an alternative region hazard model which examines nine observing stations over an area of 100's of square kilometers in the Perth city and surrounding region. The spatially variable regional wind speed model proposed for the Perth region (Lin and Nadimpalli, 2005) was used to study the significance of the hazard component in risk assessment.

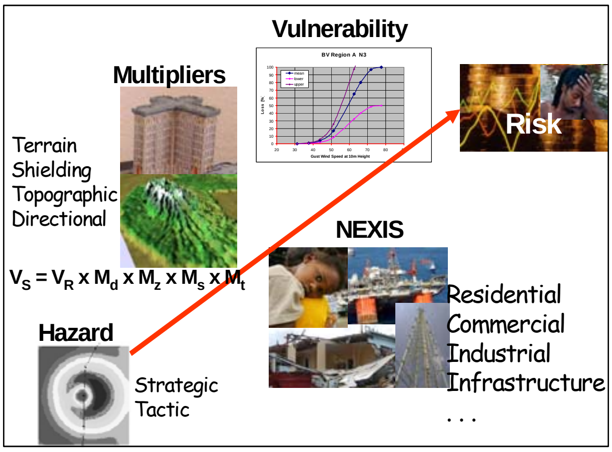

Figure 1. Components of the wind risk estimation model evaluated at each study region grid location

2.2 Multipliers

The impact of severe wind varies considerably between structures at various locations due to the geographic terrain, the height of the structure concerned, the surrounding structures and topographic factors. Wind multipliers quantify how the local conditions adjust the regional wind speeds at each location. There are four wind multipliers; the terrain (roughness) multiplier (M_z), the shielding multiplier (M_s), the topographic (hill-shape) multiplier (M_t) and directional multiplier (M_d). The relationship between the regional wind speed (V_R) in open terrain at 10 m height, the maximum local (site) wind speed (V_{site}) and the local wind multipliers is:

$$V_{site} = V_R \times M_d \times M_z \times M_s \times M_t \qquad (1)$$

Each of these multipliers is described in turn.

Directional Multiplier (M_d)

Most damage prediction models take little or no account of the effect of wind direction on regional wind hazard (Holmes, 2004). For hurricanes or cyclones, which can generate similar extreme winds from any direction, this may be a reasonable assumption. However, this is not necessarily true of other storm types which produce extreme winds with clear prevailing or dominant directional characteristics. The directional multipliers in AS/NZS, 2002 have been used for non-cyclonic regions in this research which provide a reasonable measure of the directional characteristics of regional wind hazard. For cyclonic regions a value of unity is used for M_d consistent with recommendations in the same standard.

Terrain Multiplier (M_z)

The surface roughness is needed to estimate the terrain/height multiplier and the shielding multiplier. LANDSAT Thematic Mapper (TM) data, which has a 25m spatial resolution and six frequency bands, was considered to have the best resolution to map and model the spatial variability. A terrain map for the study region was developed using the maximum likelihood algorithms of the image analysis software Imagine Version 8.0. Terrain classes from the wind loadings standard commentary (AS/NZS Suppl, 2002) were used to classify the metropolitan areas of the cities.

The terrain multiplier (M_z), as defined in (AS/NZS, 2002), can be calculated for a specific building using upwind terrain classifications within a specified distance from the location of interest and at the height of the exposed structure. Where different terrain classes existed up-wind of the location of interest, convolution filters were developed to average the roughness factors to estimate a representative terrain/height multiplier for each grid location for all eight cardinal wind directions (Nadimpalli *et al.*, 2007). The size of the upwind grid values considered in the filtering depends on the height of the buildings. The risk studies undertaken, have focused on residential structures and hence the terrain multiplier was evaluated at a height of ten metres as this is the reference height for the wind vulnerability models used. Table 1 lists the various terrain classes, the interpolated terrain categories and the corresponding terrain/height multipliers for a ten metre height. These were derived and interpolated from Table 4.1(A) of the wind standard (AS/NZS, 2002).

Shielding Multiplier (M_s)

The shielding multiplier (M_s) of a structure depends on the number of upwind buildings located in a predefined shielding zone that have at least the same height as the structure of interest. The shielding zone in the wind standard (AS/NZS, 2002) is defined as a 45 degree sector centered on the building of interest with a radius of 20 times the structure's height. A formula is provided in the standard to assess M_s which utilises the average height, width and number of the buildings affording shielding in the upwind sector area. The requirement in the standard for a detailed knowledge of upwind structures was found impractical for the regional assessments undertaken. Instead, a spatial method was developed to furnish a representative hazard for populations of homes. The methodology also addressed the coarse stepped function shielding adjustment of the wind standard for the effect of sloping upwind topography, with the substitution of a more gradual bi-linear relationship. The averaged M_s results obtained were subjected to a GIS smoothing routine to remove outliers, a process which tended to smear the suburb boundary values slightly. The known conservatism of the wind standard methodology was corrected for by applying recommended factors (Holmes, 2004).

Table 1. Terrain multipliers (M_z) values for each terrain class in different wind regions (cyclonic & non-cyclonic

Terrain Classes	Terrain Categ.ory	Terrain Roughness	M_z *(cyclonic)*	M_z *(non-cycl)*
City Buildings	4.0	2	0.863	0.75
Forest	3.75	1	0.873	0.765
High density (Industrial)	3.65	0.8	0.882	0.778
Centres of small town	3.30	0.4	0.901	0.822
Suburban, wooded country	3.0	0.2	0.918	0.83
Orchards	2.6	0.08	0.94	0.912
Long grass,few trees	2.50	0.06	0.945	0.925
Crops	2.25	0.04	0.959	0.957
Open rough water, isolated trees, uncut grass, airfields	2.0	0.02	0.973	1.0
Cut grass	1.60	0.008	0.995	1.04
Desert stones	1.5	0.006	1.0	1.053
Mudflats, beaches, salt evaporators	1.25	0.004	1.014	1.085
Snow surface	1.0	0.002	1.028	1.12

Topographic Multiplier (M_t)

When standing on an uphill slope downwind of a flat region (plain, sports ground, etc), the wind speeds will normally appear greater than on the flat. This is called the topographic (or hill-shape) wind acceleration effect. In the wind loadings standard it is quantified by the topographic multiplier M_t which applies to the area in the proximity of a hill crest or an escarpment edge called the local topographic zone. It can be estimated using the formulae in the wind standard (AS/NZS, 2002) and also the topographic features of each metropolitan area as captured by a DEM (digital elevation model). Adjustment factors are applied to the derived multipliers to adjust for conservatism in a similar approach to that used for shielding. However, the wind standard formulae were not modified to take account of the effects of topographic shielding. This methodology has the limitations of being two dimensional, capturing linear accelerations only and not considering the 3-dimensional flow such as blocking and funneling.

Windlab Systems was contracted to calculate roughness and topographic accelerations for the cities with significant topography. The accelerations are calculated at a ten metre height using the statistical analogue method for the roughness accelerations and the Raptor model (the fine-scale model within *Windscape*) for the topographic accelerations (Ayotte and Taylor, 1995). Windlab Systems provided the topographic and roughness perturbations for 12 directions. These were processed to derive the topographic multiplier for eight directions for all study regions except Perth. Most of the Perth city is located on mildly undulating terrain for which the topographical effect is small, so the previously described 2-dimensional approach was used.

2.3. Exposure Information

Fundamental to any risk assessment is an understanding of exposure, which includes number and type of buildings, businesses, critical infrastructure and people. The details necessary for reliable risk assessments includes structural system, replacement cost factors, business activity and population demography. An exposure catalogue was developed to derive the residential buildings exposure aggregated to census district level. The exposure catalogue was used to estimate the risk in earlier studies. The more detailed National Exposure Information System (NEXIS) was also used, which provides nationally consistent exposure information at buildings level (Nadimpalli and Dhu, 2007). In the absence of specific information for national coverage, a set of generic rules were developed to derive the required information from available fundamental datasets. The NEXIS database is integrated with a range of hazard models (earthquake, severe wind and tsunami) along with infrastructure failure to assess structural damage and socio-economic impact. This system provides a representative assessment of exposure to various hazards at building location level resolution and demonstrates the geographic distribution of exposure for regional planning in local government areas. At the present time, NEXIS provides the residential exposure for wind risk assessment.

2.4. Vulnerability

There is a paucity of published wind vulnerability models applicable to Australian structures. The insurance and reinsurance industry have proprietary models but these are not readily available. Considerable, and sometimes inappropriate, use has been made of the models (unpublished) developed by George Walker of Aon *Re* using the insured loss data largely derived from two Australian cyclone events (Althea 1971, Tracy 1974). As vulnerability is a key component of any wind risk assessment, this national assessment of wind risk has entailed research directed at improving the knowledge of wind vulnerability. Through a series of expert workshops and the systematic collection of post event wind damage data a limited suite of residential wind vulnerability curves have been developed. These largely heuristic relationships were used alongside those developed by Walker to demonstrate the significance of utilizing more representative vulnerability relationships. Furthermore, the significance of the uncertainty in these models has been explored.

2.5. Risk Estimation

The return period of exceedence loss levels (50, 100, 200, 500, 1000 & 2000 years) were evaluated at Census Collection District (CD) level across each region. In turn the CD losses were aggregated to obtain study region losses. As a first step in assessing wind risk these were regressed to obtain a Probable Maximum Loss (PML) curve for each study region. These were subsequently used to evaluate annualised losses, which represent the average annual cost to the region of exposure to the hazard in question if viewed through a very wide window in time. For the risk studies reported, a time window of 2000 years was adopted. Expressing the annualised loss as a percentage of the total reconstruction value gives a measure of the intensity of the risk to the studied community that is not as evident from simple dollar values.

3. RESULTS AND DISCUSSION

The wind risk estimation is based on the methodology adopted and improved as to various model components viz; regional hazard, hazard multipliers, exposure and vulnerability, and is used here to provide indicative estimates of relative risk. Enhancing each of these components has improved the risk assessment.

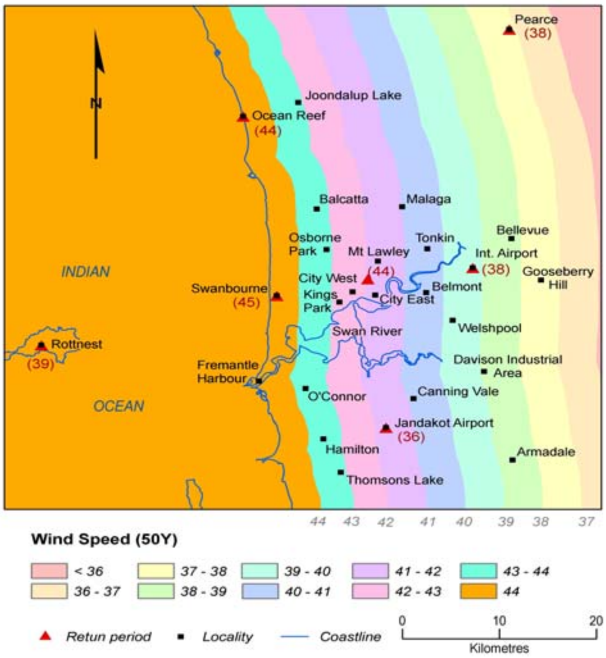

Figure 2. Interpolation of 50-yr return-period wind speeds (m/s); open terrain, 10m height, Perth region.

3.1. Hazard

Initially the risk was estimated for Australian capital cities using the three second gust wind speeds from the standard (AS/NZS, 2002), two dimensional multipliers and a CD resolution exposure catalogue. In the Perth region, a statistical analysis of the historic wind data was undertaken. Spatially variable regional wind speeds were estimated using data from nine weather stations and linear interpolation techniques (Lin and Nadimpalli, 2005). A significant upward gradient in wind speed was identified between the Perth airport site (used in AS/NZS, 2002) and the coastal region to the west, where most of the Perth building stock is located. Figure 2 shows the spatial interpretation of the 50-year return period speeds (m/s) for wind gusts in open terrain at a 10m height across the Perth region. The losses derived from these wind speeds were significantly higher than those predicted using the Region A wind speeds of AS/NZS 1170.2 (Table 2). A statistical model utilizing the Generalised Pareto Distribution (GPD) to determine return period wind hazard based on daily maximum wind gust observations (Sanabria and Cechet, 2007) will improve observing station-based hazard definition in future wind risk estimation.. In addition, the use of a regional climate model to produce local-scale wind speed climatologies is expected to enhance the hazard the spatial definition.

3.2. Multipliers

Initially the multipliers were developed using the definitions in the standard (AS/NZS, 2002) with the conservatism removed (Holmes, 2004) for shielding and topography. In the AS/NZS approach, the wind

Table 2. Percentage losses for the Perth at each of six return periods using AS/NZS wind loading standard and the spatially variable hazard approach

Return Period	AS/NZS	Spatial Variable
50-yrs	0.07	0.12
100-yrs	0.13	0.21
200-yrs	0.24	--
500-yrs	0.38	0.9
1000-yrs	0.48	1.3
2000-yrs	0.74	--
Annualised Loss	0.0039	0.008

speeds accelerates (1 < M_t <1.72) in hilly terrain and never reduces the wind speed (M_t = 1). The methodology for topographic multipliers was improved by adopting the Windlab Systems values (Ayotte and Taylor, 1995). There is a significant improvement in topographic multiplier values in a hilly terrain where M_t < 1 in the lee of hills. The approach also predicts more acceleration than the wind standard approach on slopes facing the wind direction. The factor ratio ($M_{t\ Windlab}$ / $M_{t\ Wind\ Standard}$) of W to E approaches for the Sydney region are plotted in the Figure 3. The ratio varies significantly in hilly terrain (along A-B), increasing the Standards derived windspeed on upwind slopes and reducing it on the leeward slopes. The influence is insignificant in the urban area (along B-C). The results of these two approaches have made a significant improvement in risk calculations. The annualised losses for Sydney derived from both types of topographical multipliers are summarised in Table 3.

Table 3. Percentage of losses for the Sydney at each of six return periods using AS/NZS and Windlab multiplier approach.

Return Period	M_t (AS/NZS) & Catalogue	M_t (Windlab) & Catalogue	M_t (Windlab) & NEXIS
50	1.37	0.80	0.72
100	1.94	1.11	1.01
200	2.68	1.51	1.38
500	3.64	2.01	1.85
1000	4.21	2.31	2.12
2000	5.56	3.01	2.77

3.3. Exposure

Initially the exposure catalogue was used to estimate the risk. This was subsequently refined by the use of the NEXIS residential exposure to estimate the annualised losses for the Sydney region. Brick veneer walls with tiled roof is considered representative of the majority of residential construction in Sydney and the corresponding model was applied to estimate the risk

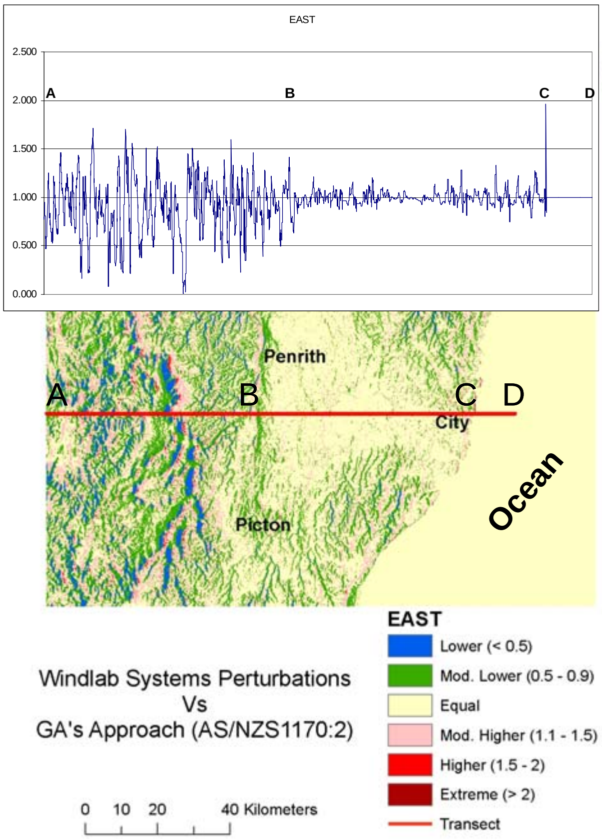

Figure 3. Comparison of M_t (AS/NZS) and M_t (Windlab) across Sydney region.

for all separate and semi-detached houses. By this process the local wind speed is assigned to each individual structure leading to a significantly improved determination of risk. The annualised losses derived from each of these methods for Sydney are presented in Table 3.

3.4. Vulnerability

The return period city losses for Perth and Cairns were evaluated using both the George Walker and the wind workshop curve suites. The latter curves also have 5%-ile and 95%-ile confidence limits defined which were also used to calculate return period loss and risk. The results obtained are presented in Table 4 below. The results clearly highlight the sensitivity of the results to choice of vulnerability model. The annualised losses for Perth have increased by an order of magnitude due to a more appropriate choice of model than the Walkers' North Queensland model. Losses for Cairns have also increased with the earlier Walker results lower than the 5%ile confidence limits of the workshop curves. The higher results have been largely driven by the older Cairns building stock for which a more comprehensive vulnerability curve suite will be required in the future. Future research will be directed at making a more effective location assignment of improved vulnerability relationships to the exposed national building stock.

Table 4. Severe wind losses for Perth and Cairns as derived from two sets of vulnerability curves.

Return Period	City of Perth		City of Cairns			
	George Walker (Pre-1980)	Heuristic Workshop Curve	George Walker Pre & Post 1980	Heuristic Workshop Curves (including 5% ile and 95% ile confidence limits)		
				Lower	Median	Upper
50	0.068	0.72	2.04	3.83	5.89	8.83
100	0.135	1.12	3.84	5.51	8.48	12.7
200	0.24	1.67	7.44	8.12	12.5	18.6
500	0.383	2.44	13.0	11.2	17.3	25.4
1000	0.479	2.93	19.4	14.0	21.6	31.4
2000	0.74	4.14	25.3	16.2	25.0	35.7
Annual-ised Loss	***0.0039***	***0.0354***	***0.124***	***0.211***	***0.581***	***0.605***

4. CONCLUSIONS

This work has highlighted several enhancements to a national wind risk assessment methodology for severe wind. Notwithstanding these, there is considerable uncertainty in the assessed risks due to both incomplete data and the modelling assumptions made. Initially, the regional return period wind gusts were used as defined in the AS/NZS wind loadings standard. The hazard definition has a very direct bearing on the assessed risk and improved assessments of regional wind speed are required. To this end GA is working with other Australian Government agencies to assess the spatial variation of regional wind speed over the Australian continent. The statistical hazard approach has limitations and tends to over-estimate risk. GA is moving from the hazard map approach to one which is event based. This will involve the use of both a tropical cyclone wind model and a general synoptic wind model for the Australian region. Stochastic "event-based" modelling of the assumed climatology will then follow using a Monte Carlo sampling technique to allow the full range of environmental parameters to be explored. Wind multipliers greatly influence the local wind speeds, particularly the topographical multiplier. Building vulnerabilities directly influence damage assessment. Work is continuing with the Cyclone Testing Station of James Cook University to develop residential vulnerability models for a wide range of structure types. Adopting the three dimensional topographic wind adjustments, exposure information at buildings level and appropriate vulnerability curves will enable the models to assess the risk more accurately.

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