Australian Government
Geoscience Australia

Record 2014/33 | **GeoCat** 75299

Local Wind Assessment in Australia

Computation Methodology for Wind Multipliers

Tina Yang, Krishna Nadimpalli, Bob Cechet

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Geoscience Australia

Department of Industry
Minister for Industry: The Hon Ian Macfarlane MP
Parliamentary Secretary: The Hon Bob Baldwin MP
Secretary: Ms Glenys Beauchamp PSM

Geoscience Australia
Chief Executive Officer: Dr Chris Pigram
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ISSN 2201-702X (PDF)

ISBN 978-1-925124-23-1 (PDF)

GeoCat 75299

Bibliographic reference: Yang, T., Nadimpalli, K. & Cechet, R.P. 2014. *Local wind assessment in Australia: computation methodology for wind multipliers*. Record 2014/33. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2014.033

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M_d = Direction multiplier

$M_{z,cat}$ = Terrain/height multiplier

M_s = Shielding multiplier

M_t = Topographic multiplier

M_h = Hill shape multiplier

V_R = Regional wind speed at return period R

V_{site} = Local or site wind speed

V_z = Wind speed at height z

u^* = Friction velocity

k = Von Karman constant usually taken as 0.4

z_0 = Roughness length

V_{ref} = Basic wind speed at 10 m height

b= Constant value depending on terrain category (b = 1.0 for open terrain category)

α= Constant value depending on terrain category

z= Height above the ground surface

z_{ref} = Reference height taken as 10 m above the ground surface

Executive Summary

Wind multipliers are factors that transform regional wind speeds to local wind speeds considering local effects of land cover and topographic influences. In order to assess the local wind hazard (spatial significance in the order of tens of metres), wind multipliers need to be computed, so that the regional wind speeds (order of ten to hundreds of kilometres) can be factored to provide local wind speeds. These local wind speeds are critical to wind-related activities that include hazard and risk assessment. The multipliers are primarily used for assessment of wind hazard at individual building locations. Other activities include agricultural growth and moisture demand applications along with energy-related applications such as wind farm developments.

This document provides background information relating to wind multipliers and describes the development of a wind multiplier computation methodology based on the Australian wind loading standard AS/NZS 1170.2. Appendix A provides an example of the wind multiplier computation methodology in the assessment of wind hazard and wind risk.

1 Introduction

Boundary layer winds are developed over kilometres of horizontal wind flow across the earth's surface through the effects of surface roughness and topography. The magnitude of wind speed varies considerably between equivalent structures located at different sites due to the variation of local roughness of the upwind terrain, shielding effects provided by upwind structures and topographic factors. These local effects have a profound influence on wind behaviour and hence on local wind speeds (Buck, 1964).

For wind hazard related research, the local wind speeds (length scale of order 1's to 10's of metres) and their effect on the natural and built environment are of interest (Ruel *et al*., 2002). To consider infrastructure and the built environment, it is essential to quantify the local wind speed experienced at a particular site (i.e. street or suburb within a town). Stewart (2003) developed a simplified probabilistic wind-field model to adjust the broad-scale regional wind speeds (length scale of order 10's to 100's of kilometres) to the site-specific level. This model accounts for terrain and shielding by classifying the site exposure into three broad categories: Foreshore (1 km from coast), Town (1-2 km from coast) and Inland (> 2 km from coast).

To quantify site-specific local wind effects, Geoscience Australia (GA) has developed a more refined approach to adjust regional wind speeds to local or site wind speeds, which employs a geographical information system (GIS) approach that produces spatial information relating to local wind effects. These local effects are quantified by wind multipliers that factor the regional wind speed to that expected at a site. The wind multipliers are numerically estimated from remote sensing techniques and digital elevation data using adaptations of formulae outlined in the Australian/New Zealand wind loading standard AS/NZS 1170.2 (2011). This approach was initially used for wind hazard assessment of peak wind gusts for the Perth region (Lin and Nadimpalli, 2005), and later refined for a national wind hazard and risk assessment (Cechet *et al*., 2010; Arthur *et al*., 2011).

Figure 1.1 illustrates the derivation of local wind speed from regional wind hazard using multipliers. Estimated 'return period' regional wind speeds (for peak gusts at a standard height in flat standard terrain roughness) are obtained from the Australian/New Zealand wind loading standard AS/NZS 1170.2 (2011) for current climate. In addition to using the regional wind speed from Australian/New Zealand standard AS/NZS 1170.2, modelled regional wind speeds were also utilised in the wind hazard assessment projects in Geoscience Australia. A preliminary assessment of Australian gust wind hazard has been undertaken by Geoscience Australia (Arthur *et al*., 2010), which includes regional assessments of the impact of climate change on wind hazard (Arthur *et al*., 2011).

The local variations from these return period regional wind speeds are determined by considering the wind direction and assessing the local effect of upwind terrain at the structure height of interest, the shielding effect of upwind buildings and the effect of topography.

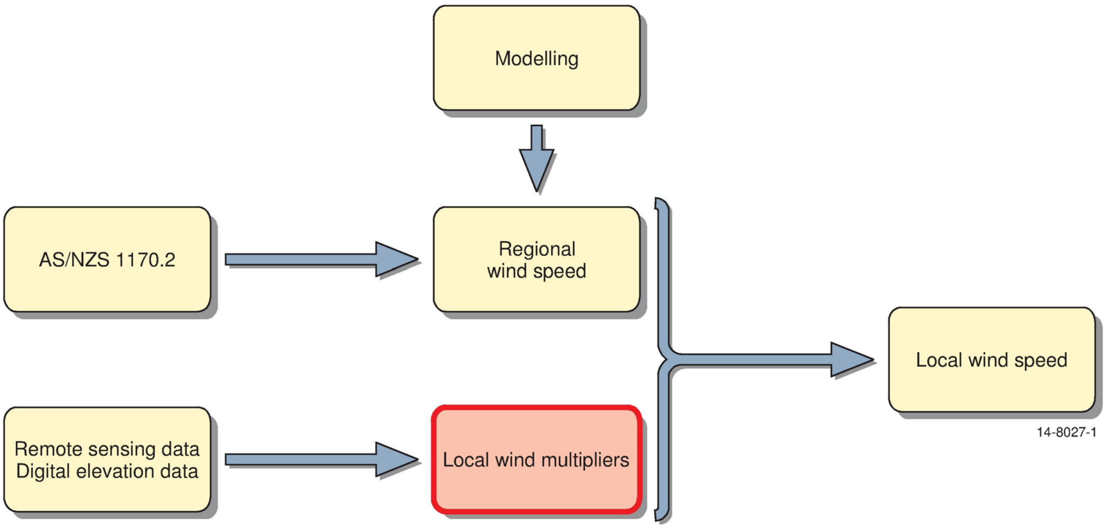


Figure 1.1 Process of deriving the local wind speed.

The document focuses on the development of the local wind multipliers (highlighted in Figure 1.1). Aspects of wind multipliers are described including concepts, modelling and applications. The methodology Geoscience Australia developed to derive the site wind multipliers and the current development status is reported in detail. This document explains the wind multipliers methodology to facilitate understanding of the principles of wind multipliers and also the application of these methods and procedures to produce these multipliers.

This document is organised in five main sections.

- Introduction—briefly describes the purpose of wind multipliers and their use.
- Background—reviews the literature on wind multipliers. What are the definitions? In which wind-related fields are they applied? What standards have been developed internationally and nationally and how do the standards deal with the wind multipliers?
- Wind multiplier computation methodology—describes the methodology by breaking down the workflow for each of the multipliers.
- Conclusions—summarises the work that has been addressed in this document.
- Appendix— presents one case study in Appendix A as an example to demonstrate how the wind multipliers have been developed and how they underpin applications such as wind hazard assessment and wind risk assessment.

2 Background

2.1 Concepts

2.1.1 Nature of wind and regional wind speeds

Wind is defined as the motion of air relative to the earth's surface. In terms of wind effects on buildings the most significant aspects of the wind hazard are the horizontal component of the three-dimensional flow and the near-surface wind phenomena. The atmospheric boundary layer can be defined as the height within which the wind speeds are affected by ground surface. The upper and lower boundaries of flow of the atmospheric boundary layer are set by the physical and thermal properties of the Earth's surface and atmosphere and the dynamics and thermodynamics of the lower troposphere (Arya, 1995). The height (thickness) of the boundary layer normally depends on three factors: wind intensity, terrain roughness and angle of latitude, and is within about 1 km from ground surface (Ghazali, 2010). The wind speed is zero at ground surface. It increases as the height above the ground increases within the boundary layer (Gardner, 2004; Holmes, 2007; Ghazali, 2010).

Throughout this document, the wind speed considered is the gust wind speed. In Australia, the regional wind speed is defined as the peak gust wind speed at 10 metres above ground surface in open terrain with a sufficiently uniform long fetch in all directions. The averaging time for current Bureau of Meteorology gust wind speed measurements is 3 seconds. Historical measurements based on the Dines anemometer chart record (i.e. non-digital; most replaced in the 1980's and 1990's by digital anemometers) have an instrument response and therefore averaging time of less than 1 second. The regional wind speed can be presented at different mean recurrence intervals.

Due to the terrain (surface roughness), the height of the structure concerned, the surrounding structures and topographic effects, the site wind speed varies considerably between various locations. The regional wind speed needs to be factored to the specific velocity for a particular site at the height of interest by introducing the influence of local environment and directionality.

2.1.1.1 Main characteristics of severe wind in Australia

In continental Australia, the mean annual wind speed is reported to be 5 to 8 m/s, with frequent gusts of 22 m/s and occasional wind speeds of greater than 33 m/s. Land or coastal gale-force winds (14 m/s or stronger) usually affect a much wider area and last much longer than thunderstorms. There is a strong correlation of severe storms with winds from west to north-westerly directions due to winds associated with the passage of cold fronts in the region. In the southern half of Australia extreme winds generally occur in winter and spring and are usually due to land gales.

In the tropical north, the strongest winds usually occur in summer and autumn, and are often due to tropical cyclones. Tropical cyclones produce extreme gusts which may exceed 55 m/s. These winds can cause extensive property damage with resulting airborne debris potentially becoming lethal missiles. The intensity of category-five cyclones near the coast is capable of causing wind gusts in excess of 83 m/s and the following landfall can still be rated as category-three or higher over one hundred kilometres inland, producing wind gusts of over 47 m/s. Tropical cyclones typically form over warm ocean waters to the north of the continent and intensify before crossing the coast, by which stage they are moving in a general southerly track. The further south cyclones move the more likely they will take a south-easterly track. This promotes landfall when approaching Western Australia from the Indian Ocean and directs cyclones away from the east coast when approaching from the Coral Sea.

Extreme windstorm events are associated with extra-tropical and tropical cyclones and winter storms. These are often accompanied by mesoscale effects including tornadoes and thunderstorm downbursts (or microbursts) and boundary layer rolls. A downburst is a small area of rapidly descending rain and ice-cooled air beneath a thunderstorm that produces a violent, localised downdraft with a horizontal scale of a few kilometres or less.

Thunderstorms are short-lived (of order of hours) and localised convective weather events that are capable of generating wind gusts in excess of 50 m/s. Thunderstorms are often associated with other severe weather phenomena such as hail, flash flooding and tornadoes. There is little knowledge of the spatial distribution of thunderstorm wind hazard. The distribution of thunder-days (days on which thunder is heard) and lightning flash incidence have been used to estimate the frequency of thunderstorms across Australia (Kuleshov *et al.*, 2002; Kuleshov *et al.*, 2006). The greatest number of thunder-days is across the tropical north of the country with areas surrounding Darwin exceeding 80 thunder-days per year. There is a higher frequency of thunder-days through the interior and over the eastern half of the continent, coinciding with the mean location of the summertime low-pressure trough systems.

Although all parts of Australia experience severe thunderstorms, their frequency and preferred seasonal occurrence vary with region. In most of northern Australia, late spring through to autumn is the most likely time, whereas in eastern Australia it is the late spring/summer period. In south-western Australia, they are most common in winter in areas nearer the coast, but in spring/early summer further inland. The geographical spread of severe thunderstorms in Australia is difficult to determine because of sparse observations over most of the continent. While records of storm impacts show that the most damaging storms have occurred in the populous south east quarter of the continent, analysis of wind, hail and tornado data suggests that severe thunderstorms are a significant threat in many coastal regions throughout the country.

As an observation, severe damaging storms are most common in the coastal regions of northern New South Wales and southern Queensland, as well as parts of northern Western Australia. For example, ‘The Gap’ storm in November 2008 in Brisbane generated wind gusts estimated at 49 m/s and damaged over 700 buildings (Bureau of Meteorology, 2008).

2.1.2 Brief description of wind multipliers

Wind multipliers can provide quantitative estimates of local wind conditions relative to the regional wind speed at each location. In the approach presented in AS/NZS 1170.2 (2011) and followed in this work in a modified form, there are four multipliers: wind direction multiplier (M_d); terrain/height multiplier ($M_{z,cat}$); shielding multiplier (M_s); and topographic multiplier (M_t). The mathematical relationship of the regional or generic wind speed V_R and site wind speed V_{site} in open terrain at 10 m height is expressed as follows (from AS/NZS 1170.2, 2011),

$$V_{site} = V_R \times M_4 = V_R \times M_d \times M_{z,cat} \times M_s \times M_t \qquad (1)$$

where,

V_{site} — local or site wind speed

V_R — regional or generic wind speed

M_4 — combined multiplier

M_d — direction multiplier

$M_{z,cat}$ — terrain/height multiplier

M_s — shielding multiplier

M_t — topographic multiplier

The wind direction multiplier M_d is the adjustment of the regional wind speed to cater for directional characteristics of the regional wind hazard at the site under consideration in eight cardinal directions. It determines the directional effect on the magnitude of the wind speed.

The terrain/height multiplier $M_{z,cat}$ is defined as the multiplier to account for variation in wind speed with variation of height z in different terrain categories (Husain *et al.*, 2008). The profile of wind speed with height is largely controlled by the roughness of the upwind fetch over which the wind has blown (Choi, 2009). Different types of terrain have different roughness effects represented as roughness length. The higher the roughness length, the more the terrain retards the wind within the atmospheric boundary layer. Therefore different roughness lengths lead to terrain multipliers with different values, modulating the regional wind speed with different intensities. The terrain/height multiplier $M_{z,cat}$ is also related to height z, as the wind speed varies with height as a gradual retardation of wind near the ground surface due to surface friction (Ghazali, 2010).

Shielding is the phenomenon where an object (e.g. a tall building) 'shields' or 'obstructs' a downwind building from the full force of the wind (Mason and Haynes, 2010). This shielding phenomenon is quantified by the shielding multiplier M_s used to adjust the wind speed when shielding objects are within the upwind shielding zone of a building. The shielding multiplier M_s in design practice leads to a reduction in design loads (Mason and Haynes, 2010).

The topographic multiplier M_t estimates the accelerating effect of wind speeds on an uphill slope downwind of a flat region caused by the shape and slope of undulating terrain. Hilly terrains greatly influence the passing wind flow, with both valleys and hill crests experiencing stronger wind speeds than over flat terrain (Turner *et al.*, 2011). Topographic effects are evident in post-event damage analysis (Powell and Houston, 1998). It is well recognised from the damage surveys following tropical cyclone Tracy (Walker, 1975), Winifred (Walker *et al.*, 1988), Iniki (Fujita, 1993), Hurricanes Hugo (National Research Council, 1994), Marilyn (Wernly, 1996) and Fabian (Mueller *et al.*, 2006) that structures located on hillsides and hilltops are more susceptible to wind damage than those located at lower elevations (Powell and Houston, 1998). The phenomenon that flow accelerates near the crests of hills with a flow separation bubble extending downwind on the lee side is also evident in the studies investigating the influence of hills and escarpments on wind flow (Powell and Houston, 1998; Schofield *et al.*, 2010). It is therefore necessary to include the topography multiplier to assess topographically induced wind gusts.

Among these local wind multipliers affecting wind speeds, the topographic multiplier potentially has the greatest increase on wind speed, whilst the shielding and terrain multipliers mainly have a decreasing impact on the wind speeds (Lin, 2004).

2.2 Applications

Wind site multipliers have been considered and applied in many wind-related studies, such as wind loading design for structures, wind energy generation, wind risk assessment, bushfire spread modelling, waterway management, pollution dispersion problems and so on. In these applications a precise knowledge of the characteristics of the approaching wind is necessary.

Wind loading on structures has undergone significant research in many countries in order to understand the behaviour of severe wind gusts acting on structures. In areas of low seismic hazard, it can be the dominant environmental loading that influences structural stability and safety. Wind loading is defined as the pressure loads produced by moving air and has great influence on the design of buildings and other types of structures (Ghazali, 2010). Because of the dominance and importance of the wind loading to structures, wind loading standards have been developed and implemented in many countries to incorporate this hazard in structural design. These standards have also been widely adopted for other wind-related applications (e.g. wind power generation).

Geoscience Australia has undertaken significant research on wind hazard assessment. As important components of the assessment methodology, the terrain, shielding and topographic multipliers have been computed in a comprehensive way as prescribed by the Australian wind loading standard AS/NZS 1170.2. For example, Schofield *et al*. (2010) applied Geoscience Australia's Tropical Cyclone Risk Model (TCRM) to simulate the Cyclone Tracy wind hazard, and further estimated building losses under current economic and societal conditions. After TCRM produced an estimate of the regional peak gust wind speed associated with tropical cyclone Tracy (on a grid of approximately 1 km resolution), wind multipliers were introduced and calculated at each specific location (25 m horizontal resolution) in order to incorporate the influence of terrain, topography and shielding, using the methodology developed at Geoscience Australia. Another example of the wind multiplier application is the National Wind Risk Assessment (NWRA) undertaken by Geoscience Australia for the Department of the Environment, where a wind risk assessment on residential buildings in all major cities in Australia was carried out (Arthur *et al*., 2011). The detailed description is provided in Appendix A. Work on multiplier application in wind risk assessment from other researchers includes Stewart and Wang (2011) and Li and Stewart (2011), who performed a risk assessment of extreme wind events in Queensland for climate adaptation strategies, where only terrain and shielding multipliers were included without considering the land classification.

Wind multipliers have also been used in Geoscience Australia for other wind-related activities. In a project of the Bushfire Corporative Research Centre (Bushfire CRC), a proof of concept for bushfire impact decision support tool has been developed. In the bushfire spread modelling component, local site variation of spatial features causes significant modification of the regional wind speed, and consequently alters the bushfire impact analysis. To compute accurate wind speeds for the decision support tool, the regional wind speeds were modified using the wind multiplier methodology. A series of wind multipliers were developed for three bushfire case study areas; the 2001 Warragamba fires, the 2006 Eyre Peninsula fires and the 2009 Victorian fires (Kilmore and Murrindindi fires) (Yang *et al*., 2013).

There are other applications of wind multipliers. Wind multipliers are considered in wind power production as the local wind climate characteristics in the study area are required for wind power assessment (Cataldo and Zeballos, 2009). Wind multipliers are also used in modelling lake flow and transport. Venäläinen *et al*. (2003) conducted a research on lake flow and transport models and found that due to the influence of topography and surface roughness, the mean wind speed values could at certain locations be about 30% weaker than those at the measurement site. On the other hand, at some other locations the wind speed was found to be about 20% higher than that at measuring site. These results show it is necessary to consider the wind multipliers to adjust the measured wind speeds to account for the local conditions. In the field of waterway management Glamore (2008) applied the wind multipliers (following AS/NZS1170.2) to estimate the site wind speed data for eight cardinal wind directions at the reference height of 10 m for the purpose of assessing the impact of boat wake waves in waterways.

2.3 Wind loading Standards/Codes

Standards prescribing the determination of wind loads on structures have been developed in many countries around the world. At present there is no generally used international standard on wind loading and there are considerable differences in both the format and the type of information presented in the various standards (Holmes, 2007). This part provides a brief overview of the major wind loading standards currently available worldwide in section 2.3.1. Then in the later sections, the focus is on describing the provisions for determining regional wind speeds and wind multipliers from the major wind loading standards with more details on Australian/New Zealand Standard AS/NZS 1170.2.

2.3.1 Overview of major wind loading standards in the world

Several internationally recognised standards on wind loading throughout the world are described briefly in this section.

2.3.1.1 ISO 4354: 2009

The International Organization of Standardization (ISO) released a second edition of the International Standard ISO 4354 – Wind actions on structures in 2009. This edition is a full technical revision of the first edition and according to ISO may help bridge gaps in various international wind loading codes. ISO's aim is for this document to be used worldwide to determine design wind loads. It describes the actions of wind on structures and specifies methods for calculating characteristic values of wind loads for use in designing buildings and other structures.

ISO 4354:2009 gives two methods of analytical determination of design wind loads, one based on a peak velocity and the other on a mean velocity. It facilitates the conversion between peak and mean wind speed methodologies and covers three main storm types: synoptic winds, thunderstorms and tropical cyclones. The annexes within ISO 4354 provide methodologies that are not available in the majority of current wind loading standards (Melbourne and Tamura, 2011).

2.3.1.2 Eurocode 1, EN 1991-1-4

The Eurocodes are a set of European structural design codes for buildings and civil engineering applications. They combine the expertise of the member countries of the European Union and have been developed over the past decade. They provide the common set of technical rules for the design of building and civil engineering works for member states, while member states remain in control of their local differences concerning geographic, climatic and traditional building practices.

Eurocodes are intended to be mandatory for European public works and likely to become the de-facto standard for the private sector – both in Europe and world-wide. The Eurocode suite of codes has been published as 58 parts by European national standards bodies (e.g. British Standards in the UK) in all main European languages. After a period of co-existence, all existing conflicting national codes are expected to be replaced during the current decade.

EN 1991 Eurocode 1 provides comprehensive information on all actions that should normally be considered in the design of buildings and other civil engineering works. As part of EN 1991: Actions on structures, EN 1991-1-4 was published in 2005, which concerns the wind loads to be used in the structural design of buildings.

For full details about the development of EN 1991-1-4, please refer to the website http://eurocodes.jrc.ec.europa.eu/showpage.php?id=131.

2.3.1.3 ASCE Standard ASCE 7-10 Minimum design loads for buildings and other structures

American Society of Civil Engineers (ASCE) 7-10 – Minimum design loads for buildings and other structures is an integral part of the building codes of the United States. ASCE 7-10 is the latest version to provide requirements for general structural design on determining many different loads for the planning, design, and construction of buildings for residential and commercial purposes. It provides ultimate event wind maps with corresponding reductions in load factors. The significant changes in ASCE 7-10 wind loads have been highlighted in the website http://www.structuremag.org/article.aspx?articleID=1472.

2.3.1.4 AIJ Recommendations for loads on buildings

The latest version of Recommendations of the Architectural Institute of Japan (AIJ) was published in 2004. In this standard, along with other types of loads on buildings, wind loads are described in Chapter 6. This 56 page wind loading document (i.e. Chapter 6) is comprehensive and advanced and is commonly used by structural designers for buildings greater than 60 m in height, although it is not legally binding in Japan (Holmes, 2007). With respect to the wind multipliers, this version introduces a wind directionality factor and has major revisions on topographic effects. The wind loads part of the AIJ recommendations for loads on buildings is available at http://www.aij.or.jp/jpn/symposium/2006/loads/Chapter6_main.pdf.

2.3.1.5 Australian/New Zealand Standard AS/NZS 1170.2

The second edition of AS/NZS 1170.2 – Structural design actions – wind actions was released in 2011. From the previous version released in 2002, this standard became a joint wind loading standard combining the land areas of Australia and New Zealand. This standard is Part 2 of the AS/NZS 1170 series – Structural design actions, which comprises other components of load such as snow and earthquake. Its format is based on ISO 4354 – Wind actions on structures.

AS/NZS 1170.2 is referenced by the Building Codes of Australia and New Zealand (Holmes, 2007). It has been recognised as a comprehensive and contemporary reference document internationally. For example, Malaysia has developed its own standard of practice in wind loading known as MS 1553:2002 – Code of Practice on Wind Loading for Building Structure by referring and adapting itself to AS/NZS 1170.2, based on the similarity of wind climate between Malaysia and Australia (Ghazali, 2010; Husain *et al.*, 2008).

The wind multiplier assessment capability developed at Geoscience Australia is founded on the Australian/New Zealand standard AS/NZS 1170.2. It follows the principles and formulas prescribed in this document with respect to the regional wind speed and wind multipliers. The details are presented in the sections below.

2.3.2 Regional or basic wind speeds

Most strong winds that are considered design events in structural design occur in neutrally stable (i.e. well mixed in the vertical) conditions (Harris and Deaves, 1978). When the hourly-mean wind speed exceeds 10 m/s, or the 3-second gust wind speed exceeds 15 m/s at 10 m height in flat open areas, the turbulence produced by the mechanical characteristics of air flow over surface roughness dominates any thermal effects, allowing the atmospheric boundary layer to be considered neutrally stable (Cook, 1985). There are generally two methods used to determine design wind loads in the standards and codes. One is based on peak velocity and the other on mean velocity. The method based on the peak velocity is used by most practitioners for nearly all types of structures, and is preferred by the majority of the world's national wind loading standards (Melbourne and Tamura, 2011).

Table 2.1 shows the averaging time and design return period for basic wind speed affecting residential structures, which are associated with different standards and codes of practice.

Table 2.1 Characteristics of regional/basic wind speeds.

Standards/Codes	Averaging time	Basic return period (residential structures)
ISO 4354	10 minutes / 3 seconds	50 years
Eurocode 1 EN 1991-1-4	10 minutes	50 years
ASCE 7-10	3 seconds	50 years
AIJ	10 minutes	100 years
AS/NZS 1170.2	3 seconds	500 years

Source: Holmes (2007); Bashor and Kareem (2009)

ISO 4354 gives both peak and mean velocity and the relationship between them via a wind speed peak factor and the turbulence intensity, which are used to convert the wind speeds referenced for different averaging times. The most common conversions are from 1 hour mean to 3 seconds gust, from 1 hour mean to 10 minutes mean, and from 10 minutes mean to 3 seconds gust. However, the 10 minutes mean velocity is used as a basis for calculation of wind loads for basic load design return periods of 50 years (Holmes, 2007).

The regional wind speed V_R defined in AS/NZS 1170.2 is a 3-second gust wind speed at the standard meteorological height of 10 metres in open country terrain. V_R is dependent on the return period R (equal to the reciprocal of the annual probability of exceedance) and the location with respect to the wind region map in Australia or New Zealand. For a particular building, the selection of R to be used for design is specified by the Building Code of Australia and depends on the importance level of the building and its expected life.

Standard AS/NZS 1170.2 details wind actions by classifying Australia into four different regions comprising A (divided into subregions A1 to A5), B, C and D (see Figure 2.1) and provides these regions with a wind speed value for each average recurrence interval. These regional wind speeds have been determined from an analysis of long-term observational records of daily maximum gust wind speeds.

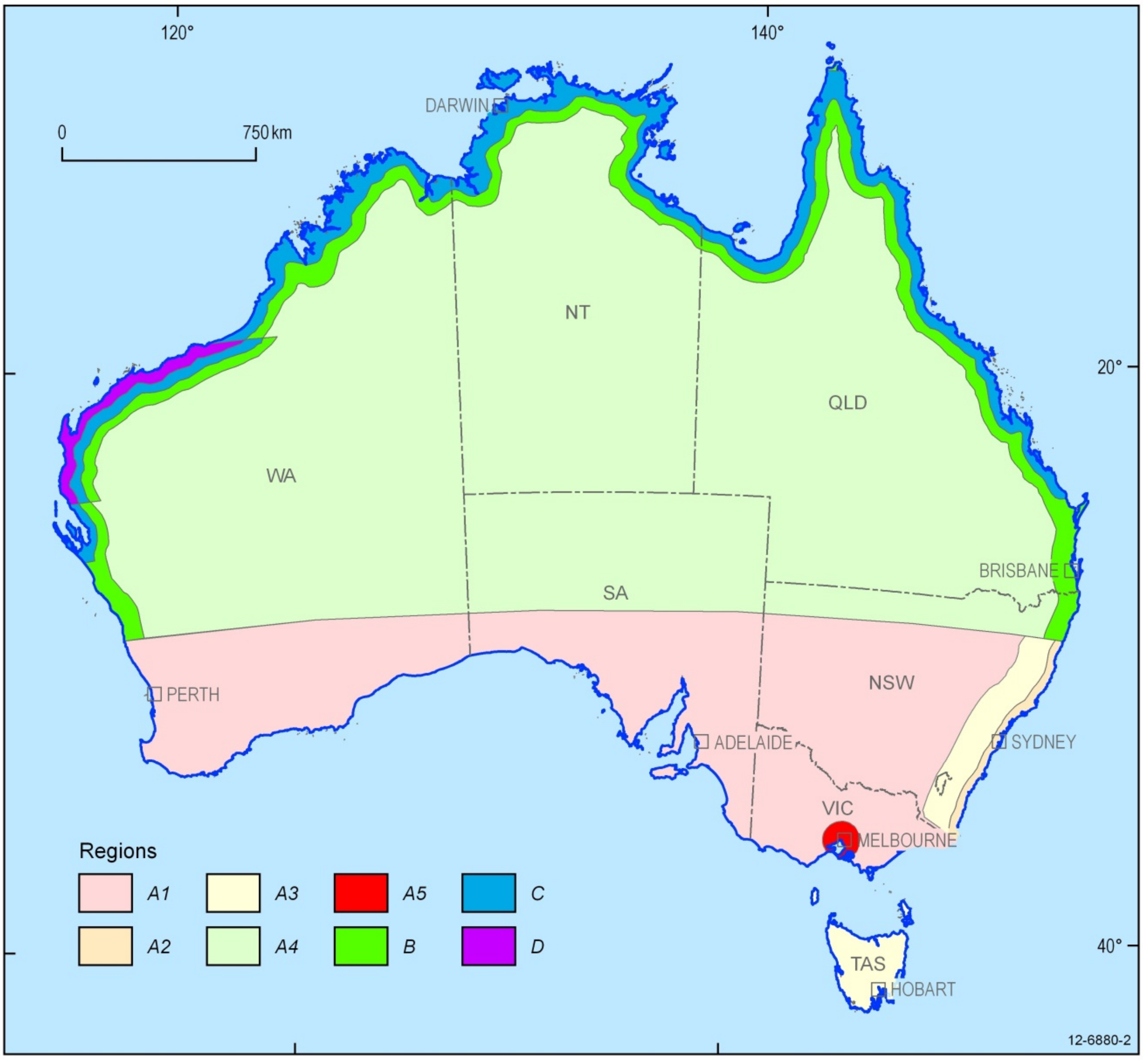


Figure 2.1 Wind regions from AS/NZS 1170.2.

For the same return period, different spatial regions of the Australian continent have different regional wind speeds with basic wind speeds increasing in magnitude from region A to D. The regional wind speeds from AS/NZS 1170.2 are shown in Table 2.2. For example, according to the standard AS/NZS 1170.2, the regional wind speed in region A (from 1 to 7) is 45 m/s for the 500 year return period (V_{500}), while in region B, C, D, it is 57 m/s, 69 m/s and 88 m/s respectively.

In Table 2.2, R represents the average interval between wind speeds exceeding the regional wind speed. For regions C and D, there are additional uncertainty factors F_C and F_D. For ultimate limit states wind speeds, the values for F_C and F_D are 1.05 and 1.1 respectively. The calculated value should be rounded to the nearest 1 m/s.

Table 2.2 Regional wind speeds.

Regional wind speed (m/s)	A (1 to 7) (Non-cyclonic)	B (Non-cyclonic)	C (cyclonic)	D (cyclonic)
V_5	32	28	F_C 33	F_D 35
V_{10}	34	33	F_C 39	F_D 43
V_{20}	37	38	F_C 45	F_D 51
V_{50}	39	44	F_C 52	F_D 60
V_{100}	41	48	F_C 56	F_D 66
V_{200}	43	52	F_C 61	F_D 72
V_{500}	45	57	F_C 66	F_D 80
V_{1000}	46	60	F_C 70	F_D 85
V_{2000}	48	63	F_C 73	F_D 90
V_R	$67 – 41R^{-0.1}$	$106 – 92R^{-0.1}$	$F_C\ (122 – 104R^{-0.1})$	$F_D\ (156 – 142R^{-0.1})$

Source: AS/NZS 1170.2 (2011)

2.3.3 Wind multipliers

According to Equation (1), the site wind speeds, V_{site} for eight cardinal wind directions incorporate multipliers for directionality, terrain/height, shielding and topography. The above standards/codes all deal with terrain and topography multipliers, although handling terrain types and wind profiles for different terrains in a different way. Only AS/NZS 1170.2 includes the shielding multiplier to account for the shielding effect of the upwind buildings and the approach gradient of the ground (Holmes, 2007).

2.3.3.1 Terrain/height multiplier

It is recognised that wind speed varies with height due to the drag exerted on the wind as it blows over rough ground. The wind speed is zero at the ground surface and increases with height above the ground within the atmospheric boundary layer. Therefore, the wind speed profile is defined as a profile of average wind speed versus height. Roughness length is used to characterise the frictional effect of surface roughness and plays an important role when estimating the wind speeds a structure might experience in a particular terrain at a particular height above the surface.

The wind speed profile in atmospheric boundary layer is commonly modelled using the logarithmic law (Stull, 1988). However the power law profile is also used to represent wind speed profile in some developed standards or codes (see Table 2.3). There is no exact correspondence between the power law and logarithmic wind profile because of their different shapes with height (Ghazali, 2010).

The logarithmic law is found to be valid in unmodified form in strong wind conditions in the atmospheric boundary layer near the surface (Stull, 1988). The main influence on the logarithmic law is the surface roughness, characterised by the parameter of roughness length, z_0. The wind speed profile represented in logarithmic law can be expressed in Equation (2):

$$V_z = (u^* / k) \ln(z / z_0) \tag{2}$$

where,

V_z — wind speed at height z
u^* — friction velocity
k — von Karman constant usually taken as 0.4
z — height above the ground surface
z_0 — roughness length

As it is easily integrated with height, the power law is more convenient when determining overturning effects at the base of a tall structure (Ghazali, 2010). The power law describing the wind speed profile can be expressed in equation form as follows,

$$V_z = V_{ref} (b(z / z_{ref})^{\alpha}) \tag{3}$$

where,

V_z — wind speed at height z
V_{ref} — basic wind speed at 10 m height
b — constant value depending on terrain category (b = 1.0 for open terrain category)
α — constant value depending on terrain category
z — height above the ground surface
z_{ref} — reference height taken as 10 m above the ground surface

Both profile equations have been used by international standards and codes of practice as summarised in Table 2.3. ISO 4354 guidelines use either the power law or logarithmic law to define the terrain/height multiplier. AS/NZS 1170.2 and Eurocode 1 Part 1-4 use the logarithmic law to define the terrain/height multiplier, while ASCE 7-10 and AIJ adopt the power law to define the terrain/height multiplier.

Table 2.3 Methods of wind speed profile.

Standards/Codes	Wind profile
ISO 4354	Both
Eurocode 1 EN 1991-1-4	Logarithmic
ASCE 7-10	Power
AIJ	Power
AS/NZS 1170.2	Logarithmic

Source: Holmes (2007); Bashor and Kareem (2009)

From Equation (2), the process to determine the terrain/height multiplier theoretically involves three steps. The first step involves the determination of the roughness length at the location of interest. Then the wind speed profile can be defined for this location. Finally by adjusting the wind speed at reference height to the height of interest for the building under consideration, the terrain/height multiplier for the location of interest can be determined. If wind speed observations are available at the place of interest, they can be used to derive the roughness length z_0 and the terrain/height multiplier to account for the local terrain characteristics by employing statistical and mathematical methods.

There is a large body of research focusing on the development of roughness length and the determination of the terrain/height multiplier. Ramli *et al*. (2009) used satellite images in order to determine the roughness length z_0 for spatially distributed land cover, utilising the normalised difference vegetation index (NDVI) derived from Landsat satellite images, as well as qualitative information (land cover roughness). The resulting z_0 parameter showed consistence with previous research.

Different types of terrain possess different roughness lengths and thus different wind speed profiles. Terrains are often classified into terrain categories, each with a particular roughness length. The number and type of terrain categories defined and the associated roughness length z_0 are different between the wind standards and codes considered above. Choi (2009) summarised the terrain category information for these various wind codes (see Table 2.4).

Table 2.4 Summary of terrain category information for various wind codes.

Standards/Codes	Number of terrain categories	Roughness length z_0 range for all terrain categories (m)
ISO 4354	4	0.003 – 3.0
Eurocode 1 EN 1991-1-4	5	0.003 – 1.0
ASCE 7-10	3	0.0039 – 0.58
AIJ	5	0.0014 – 1.82
AS/NZS 1170.2	4	0.002 – 2.0

Source: Choi (2009)

Despite the different values in Table 2.4, Holmes (2007) found a consensus between these wind standards/codes. These standards cover four main terrain categories, ranging from category 1 (very flat terrain such as lake and sea surface), through category 2 (open surface areas with slight obstructions) and category 3 (suburban areas), to category 4 (city centre areas). The roughness length value ranges shown in Table 2.4 are consistent with the value ranges specified in Table 2.5 from Holmes (2007), except that the maximum roughness value (0.58 m) specified in the ASCE 7-10 is outside the maximum value range (1-5 m) in Table 2.5.

Table 2.5 Terrain types and their roughness length value ranges.

Category	Terrain Type	Roughness length z_0 range (m)
1	Very flat terrain	0.001-0.005
2	Open terrain	0.01-0.05
3	Suburban terrain	0.1-0.5
4	Dense urban	1-5

Source: Holmes (2007)

AS/NZS 1170.2 defines four terrain categories for which the terrain/height multipliers are different for non-cyclonic regions and cyclonic regions.

Both ASCE 7 and AS/NZS 1170.2 incorporate a process to estimate how upwind changes of surface roughness will affect the design wind speed used to predict wind loading on buildings. A simple averaging procedure is used in AS/NZS 1170.2 to deal with multiple terrain types for a specified distance upwind of the structure with respect to the height of the structure.

2.3.3.2 Shielding multiplier

In contrast to all other standards/codes, AS/NZS 1170.2 has a multiplier called the shielding multiplier. It adjusts the local wind speed to account for the shielding effects from upwind buildings that are either taller or the same height as the building being considered.

Terrain categories help to define the shielding objects. The slope of the ground is also a factor which influences the shielding effect. The detailed computation of the shielding multiplier based on the terrain categories and slope of the ground is described in section 3.3.

2.3.3.3 Topographic multiplier

The major wind loading standards/codes all include the effect of topography, while the Eurocode 1 EN 1991-1-4 describes ‘topography’ as ‘orography’. These standards/codes account for the topographic effects on wind speed by using the ‘speed up’ factor or ‘topographic multiplier’. The wind speed at a given position on the hill is estimated by multiplying the speed up factor with the value of the upstream wind speed. The topographic multiplier is also termed the ‘hill-shape’ multiplier. For consistency in this document, ‘hill-shape’ multiplier is considered the same as topographic multiplier.

Ngo and Letchford (2008, 2009) reviewed four major wind loading standards (ASCE 7, AS/NZS 1170.2, AIJ and Eurocode 1, EN 1991-1-4), comparing their approaches to determine the topographic effects, and summarised significant differences in several areas, as well as the different mathematical formulations employed. For example, ASCE 7 is the only code that considers the influences of terrain roughness on the speed up effect of wind flows. ASCE 7 treats hills and ridges differently, whilst AS/NZS 1170.2 and Eurocode 1, EN 1991-1-4 treat hills and ridges identically. In addition, AIJ introduces the topographic effect on turbulence intensity. Another prominent difference between these codes is the varied upwind slope range and spatial extent for the application of the speed up factor. Table 2.6 lists the different slope ranges for the four major codes. It shows that AIJ has a higher lower limit of slope and a much higher upper limit of slope than any of the other codes.

Table 2.6 Different slope ranges for four major codes.

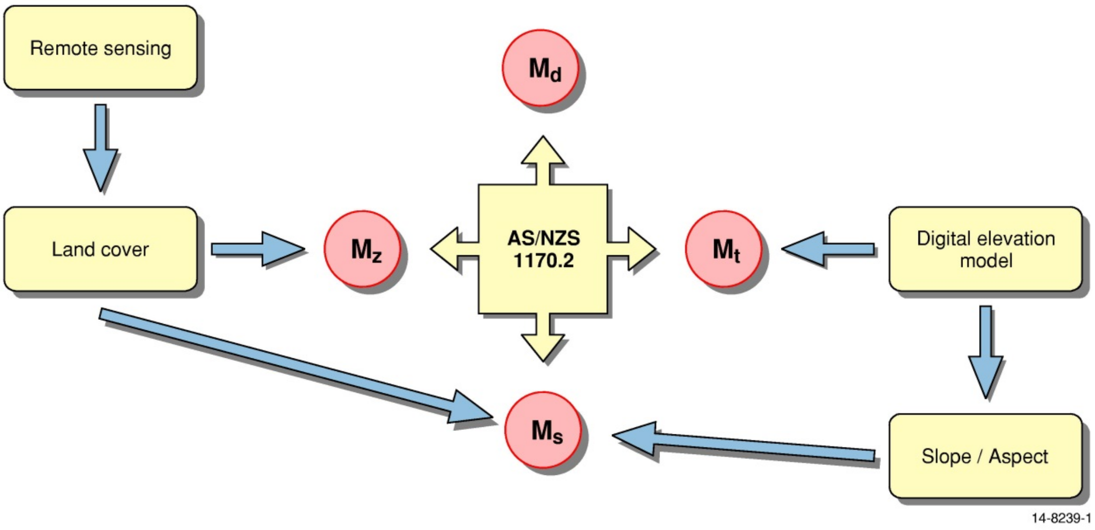
Standards/Codes	Lower limit (%)	Upper limit (%)
Eurocode 1 EN 1991-1-4	5	30
ASCE 7-10	10	25
AIJ	13.2	173.2
AS/NZS 1170.2	5	45

Source: Ngo and Letchford (2008)

3 Wind multiplier computational methodology

The methodology used at Geoscience Australia to determine the wind multipliers is based on the Australian Wind Loading Standard AS/NZS 1170.2 (2011) that provides detailed equations and tabular information to estimate the terrain/height, shielding and topographic wind multipliers. AS/NZS 1170.2 estimates the terrain/height multiplier $M_{z,cat}$ according to height of the buildings concerned and the terrain category defined by the surface roughness. The shielding multiplier M_s is estimated using the average spacing of shielding buildings in a defined upwind sector and their average height and breadth. The topographic multiplier M_t is estimated using geographical features (slope and aspect). AS/NZS 1170.2 is an engineering design document and therefore is fundamentally conservative. In order to reduce any systematic bias in the methodology, Geoscience Australia implemented a modified AS/NZS 1170.2 methodology to reduce this conservatism. This methodology was proposed and reviewed by Holmes (2004); the then Chair of the Standards Australia Wind Loadings Committee. See Section 3.3.4 and 3.4.2 for details of the adjustment of the conservatism in AS/NZS 1170.2.

The formulae prescribed in AS/NZS 1170.2 are used to estimate the wind multipliers for a single location. Efficient and effective computational methods to estimate these wind multipliers for a larger area on a fine resolution were not available before Geoscience Australia developed the methodology to compute the wind multipliers for large areas. In this methodology, Geoscience Australia uses satellite remote sensing techniques, geographic information system (GIS) software and digital elevation model (DEM) datasets to apply the principles defined in the standard AS/NZS 1170.2 to estimate terrain, shielding and topographic wind multipliers (10 m standard height) at high spatial resolution over large areas of interest. An overview diagram of this methodology is given in Figure 3.1.



$$V_{site} = V_R \times M_z \times M_s \times M_t \times M_d$$

Figure 3.1 Overview of the methodology used to determine the wind multipliers.

Note in Figure 3.1, the methodology used in Geoscience Australia is based on AS/NZS 1170.2; however it uses adaptations of formulae outlined in AS/NZS 1170.2 in order to remove the conservatism associated with the standard. The equation $V_{site} = V_R \times M_d \times M_z \times M_s \times M_t$ in Figure 3.1 is taken from Equation (1), where V_{site} is the local wind speed, V_R is the regional wind speed, M_d is the direction multiplier, M_z is the terrain multiplier, M_s is the shielding multiplier and M_t is the topographical multiplier respectively.

Remote sensing satellites can provide high resolution land cover maps detailing relevant land classifications over large areas. In order to achieve accurate results, high resolution DEM datasets are used to analyse on a fine grid local topographic features that vary significantly spatially.

In the following sections, detailed descriptions of the methodology are given for computation of each of the four multipliers.

3.1 Wind Direction Multiplier (M_d)

The four primary wind regions (A to D) of AS/NZS 1170.2 are shown in Figure 2.1. The regional wind speeds for each of these regions are the maxima across all wind directions. The Standard enables this wind speed to be reduced for some directions. Region A is further subdivided into subregions A1 to A7 in support of this adjustment.

The wind direction multipliers for eight cardinal directions in region A have been specified in the standard AS/NZS 1170.2 and are reproduced in Table 3.1. For most parts of Australia, the dominant wind direction is generally from the west. A special situation occurs in Region A5 where strong northerly winds can be experienced during the summer months.

Table 3.1 Wind direction multiplier (M_d).

Cardinal directions	Region A1	Region A2	Region A3	Region A4	Region A5	Region A6	Region A7
N	0.90	0.80	0.85	0.90	1.00	0.85	0.90
NE	0.80	0.80	0.80	0.85	0.85	0.95	0.90
E	0.80	0.80	0.80	0.90	0.80	1.00	0.80
SE	0.80	0.95	0.80	0.90	0.80	0.95	0.90
S	0.85	0.90	0.80	0.95	0.85	0.85	0.90
SW	0.95	0.95	0.85	0.95	0.90	0.95	0.90
W	1.00	1.00	0.90	0.95	1.00	1.00	1.00
NW	0.95	0.95	1.00	0.90	0.95	0.95	1.00
Any direction	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Source: AS/NZS 1170.2 (2011) – Table 3.2

In regions B, C and D, tropical cyclone and thunderstorm gust wind speeds dominate the extreme high range tail of the wind speed distribution. The prevailing direction effects from tropical cyclone and thunderstorm gusts are small, so AS/NZS 1170.2 recommends a value of unity for all directions as the wind direction multiplier. A single statistical direction multiplier of 0.95 is given for overall forces and loads for major structural elements.

The wind direction multiplier based on the AS/NZS 1170.2 has been developed by considering a limited number of Bureau of Meteorology (BOM) weather recording stations across Australia, mainly at airport locations. This method cannot capture the actual regional characteristics over a vast continent such as Australia. Sanabria and Cechet (2012) proposed a methodology to calculate the wind direction multiplier based on wind speeds and directions extracted from climate simulations, which allows a more detailed and realistic assessment, as compared to AS/NZS 1170.2, of the wind direction multiplier at a regional scale.

3.2 Terrain/Height Multiplier ($M_{z,cat}$)

The terrain/height multiplier ($M_{z,cat}$) is applicable to synoptic and cyclonic winds but not to downbursts. As defined in AS/NZS 1170.2 (2011), $M_{z,cat}$ can be calculated for a specified structure using upwind terrain classifications within an averaging distance from the structure of interest. The averaging distance is a function of the height of the structure. In other words, the terrain multiplier is related to the structure height and the terrain category defined by the roughness length.

The workflow of determining the terrain multiplier is shown in Figure 3.2. Each step is discussed in detail in the following sections.

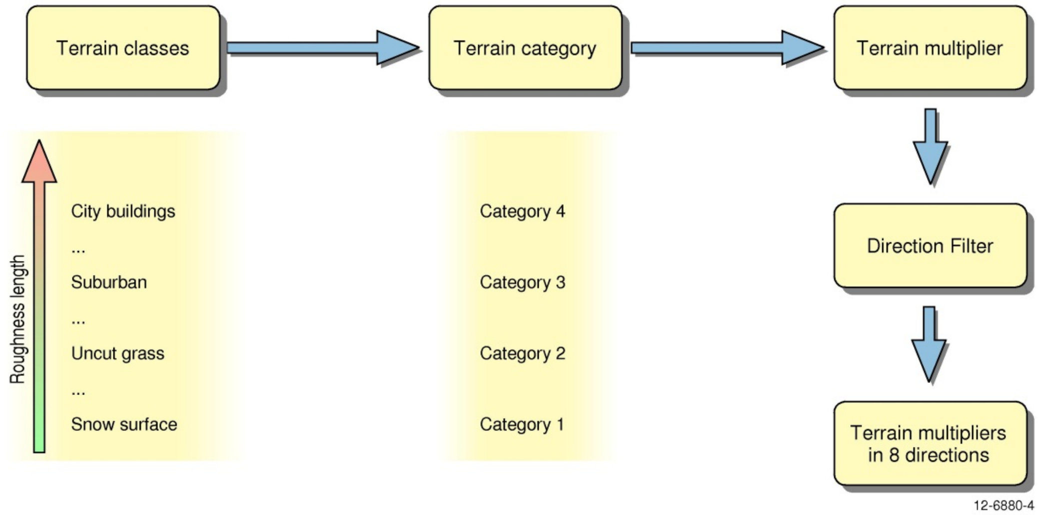


Figure 3.2 Workflow of determination of the terrain multiplier.

3.2.1 Terrain classes

Defined in the AS/NZS 1170.2 Supp 1 (2002), the following terrain classes are relevant to the wind hazard assessment, ordered in decreasing roughness or increasing smoothness of cover.

- City buildings
- Forests
- High density metropolitan (including industrial, commercial buildings etc.)
- Centres of small towns
- Suburban and wooded country

- Orchard and open forest
- Long grass with few trees
- Crops
- Uncut grass
- Airport runways
- Water (lakes, rivers, ocean)
- Cut grass
- Barren/mining/desert
- Roads
- Mudflats salt evaporators. Sandy beaches
- Snow cover

In order to estimate the terrain categories for large areas with fine resolution, remote sensing (RS) images are used to derive a terrain class map. The principle of RS, which can measure, map, and monitor the earth surface by recording reflected or emitted electromagnetic energy from the earth's surface, allows the discrimination of different types of objects or features such as soils, vegetation, and water by exploiting temporal and spectral properties of the reflected and/or emitted energy. RS systems are used extensively to study various features related to land. They allow accurate and real-time evaluation and continuous monitoring of land use and land cover changes. They are able to collect and analyse information about resources and the environment across large areas by observing the earth's surface from satellites and aircraft (Ramli *et al*., 2009).

In this methodology, the land cover of the area of interest is mapped by employing Landsat Thematic Mapper (TM) data, which has 7 frequency bands at 25 m spatial resolution. Further information about the data specifications can be obtained from Geoscience Australia's National Earth Observation Group's website http://www.ga.gov.au/earth-observation/satellites-and-sensors/landsat.html.

The terrain classes are developed from classifying satellite imagery (e.g. Landsat) using a supervised classification method. ERDAS Imagine and ArcGIS have been used in Geoscience Australia to perform the terrain classification.

3.2.2 Terrain categories

AS/NZS 1170.2 (2011) classifies terrain into four different categories.

- Category 1: Exposed open terrain with few or no obstructions and water surfaces at serviceability wind speeds. The roughness length is 0.002 m. For example, the natural flat snow surface shown in Figure 3.3 belongs to Category 1.
- Category 2: Water surfaces, open terrain, grassland with few, well scattered obstructions with heights generally from 1.5 to 10 m. The roughness length is approximately 0.02 m for such a site like the airport site shown in Figure 3.4.
- Category 3: Terrain with numerous closely spaced obstructions 3 to 5 m high such as areas of suburban housing (shown in Figure 3.5). The roughness length for this terrain category is approximately 0.2 m.

- Category 4: Terrain with numerous large, high (10 m to 30 m high) and closely spaced obstructions such as large city centres and well-developed industrial complexes (as shown in Figure 3.6). The roughness length for this terrain category is approximately 2 m.

Figure 3.3 to Figure 3.6 illustrate the typical classes from Category 1 to Category 4 respectively.

Figure 3.3 Typical example of terrain category 1 (smooth snow).

Figure 3.4 Typical example of terrain category 2.

Figure 3.5 Typical example of terrain category 3.

Figure 3.6 Typical example of terrain category 4.

The relationship between the roughness length (z_o) and the terrain category is defined in AS/NZS 1170.2 Supp 1 (2002) and is expressed in Equation (4):

$$z_o = 2 \times 10^{(terrain\_category - 4)} \tag{4}$$

AS/NZS 1170.2 Supp 1 (2002) defines the roughness length for some typical terrain classes, which are summarised in Table 3.2. From the defined roughness length the corresponding terrain category has been derived using Equation (5), which is an inverse function of Equation (4). The derived terrain categories are also presented in Table 3.2.

$$terrain\_category = \log_{10}(z_o / 2) + 4 \tag{5}$$

Table 3.2 Typical terrain classes with roughness length and terrain category.

Terrain classes	Terrain roughness length (m)	Terrain category
City buildings	2	4.00
Forest	1	3.70
High density (industrial) buildings	0.8	3.60
Small town centres	0.4	3.30
Suburban/wooded country	0.2	3.00
Orchard, open forest	0.08	2.60
Long grass with few trees	0.06	2.48
Crops	0.04	2.30
Open rough water, airfields, uncut grass etc.	0.02	2.00
Cut grass	0.008	1.60
Desert (stones), roads	0.006	1.48
Mudflats/salt evaporators/sandy beaches	0.004	1.30
Snow surface	0.002	1.00

3.2.3 Derivation of terrain multipliers

Subsets of Tables 4.1(A) and 4.1(B) in the standard AS/NZS 1170.2 (2011) are integrated in Table 3.3 (for heights up to 30 metres only) to illustrate the relationships between terrain multipliers, structure height and terrain category for non-cyclonic and cyclonic region respectively.

In Table 3.3, AS/NZS 1170.2 defines the terrain multiplier values for non-cyclonic and cyclonic regions respectively, considering the terrain categories and the height of interest. For intermediate values of height and terrain category linear interpolation is recommended. In Table 3.3, for cyclonic regions, terrain categories 1 and 2 have the same value of terrain/height multiplier and categories 3 and 4 also have the same value of terrain/height multiplier. For example, in cyclonic regions at height 5 m, the value is 0.95 for category 1 and 2, and 0.80 for category 3 and 4. It means there is no need for interpolation except between category 2 and category 3. To smooth and simplify the interpolation, a modified method was used for interpolation after consulting with Dr Holmes. When interpolating from this table for cyclonic regions, the value for categories 1 and 2 was assigned to category 1.5, and the value for categories 3 and 4 was assigned to category 3.5. Then these two values were used for linear interpolation.

Table 3.3 Terrain/Height multipliers for gust wind speeds with respect to the terrain categories and height of interest.

Height (m)	Terrain category 1 Non-cyclonic	Terrain category 1 cyclonic	Terrain category 2 Non-cyclonic	Terrain category 2 cyclonic	Terrain category 3 Non-cyclonic	Terrain category 3 cyclonic	Terrain category 4 Non-cyclonic	Terrain category 4 cyclonic
<=3	0.99	0.90	0.91	0.90	0.83	0.80	0.75	0.80
5	1.05	0.95	0.91	0.95	0.83	0.80	0.75	0.80
10	1.12	1.00	1.00	1.00	0.83	0.89	0.75	0.89
15	1.16	1.07	1.05	1.07	0.89	0.95	0.75	0.95
20	1.19	1.13	1.08	1.13	0.94	1.05	0.75	1.05
30	1.22	1.20	1.12	1.20	1.00	1.15	0.80	1.15

Source: AS/NZS 1170.2 (2011) – Table 4.1(A) and Table 4.1(B)

Based on Table 3.3 and linear interpolation, the terrain multipliers for the typical terrain classes (listed in Table 3.2) have been produced for non-cyclonic and cyclonic regions at 5 m and 10 m respectively. The results are listed in Table 3.4.

Table 3.4 Terrain multipliers for typical terrain classes at 5 m and 10 m height.

Terrain classes	Terrain multipliers (non-cyclonic, 5 m)	Terrain multipliers (non-cyclonic, 10 m)	Terrain multipliers (cyclonic, 5 m)	Terrain multipliers (cyclonic, 10 m)
City buildings	0.750	0.750	0.763	0.863
Forest	0.774	0.774	0.785	0.879
High density (industrial) buildings	0.782	0.782	0.793	0.885
Small town centres	0.806	0.806	0.815	0.901
Suburban/wooded country	0.830	0.830	0.838	0.918
Orchard, open forest	0.862	0.898	0.868	0.940
Long grass with few trees	0.872	0.919	0.877	0.946
Crops	0.886	0.949	0.890	0.956
Open rough water, airfields, uncut grass etc.	0.910	1.000	0.913	0.973
Cut grass	0.966	1.048	0.943	0.995
Desert (stones), roads	0.983	1.063	0.952	1.001
Mudflats/salt evaporators/sandy beaches	1.008	1.084	0.965	1.011
Snow surface	1.050	1.120	0.988	1.028

3.2.4 Derivation of directional terrain multipliers

In the built environment different surface roughness conditions often exist side-by-side. For example, the edge of urban development often spreads to undeveloped open terrain, the ocean meets land, or open park areas exist within neighbourhoods. AS/NZS 1170.2 has incorporated the effects of changing surface roughness regions. When considering a direction where the wind approaches across ground with changes in terrain category that lie within a specific averaging distance according to the structure height, the weighted average value of the terrain multipliers over the averaging distance upwind of the structure is calculated and utilised.

For the example of wind hazard studies presented in Appendices A, the structure height of interest was usually less than 50 metres, so the averaging distance upwind of the structure was 1000 metres according to AS/NZS 1170.2 (2011).

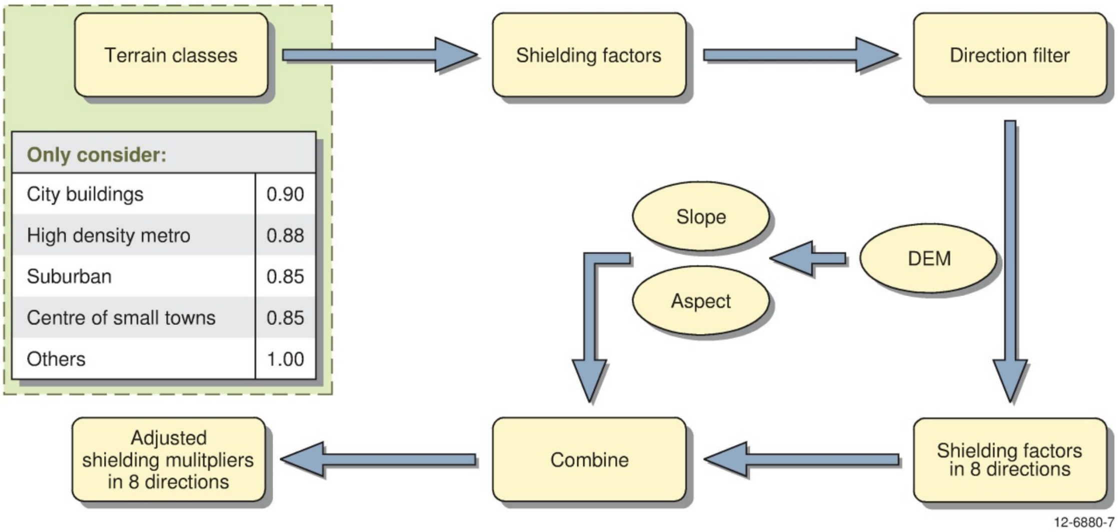
Based on above rules from AS/NZS 1170.2 (2011), a numerical averaging filter was developed for terrain classes upwind of the structures of primary interest, which smooths changes of the terrain multiplier from one terrain class to the other. Eight cardinal directions (north, south, east, west, south east, south west, north east, and north west) are considered to derive the weighted average values of the terrain multiplier. Therefore terrain multiplier values are computed for each of these eight directions.

Holmes (2004) recommends no adjustment to the AS/NZS 1170.2 derived terrain multiplier as it is considered to be an unbiased estimate of terrain roughness effects, while for shielding and topographic multipliers, it is necessary to remove conservatism inherent from AS/NZS 1170.2 (addressed in later sections).

3.3 Shielding Multiplier (M_s)

AS/NZS 1170.2 (2011) provides a formula to calculate the shielding multiplier that considers the average height, width and number of upwind buildings that provide shielding in the upwind sector area. Generally, for structures less than 25 metres high, shielding effects only result when there are upwind shielding zone structures of taller or equal height as the structure of interest. For taller structures, shielding effects can be obtained from shorter upwind structures, but only on the lower sections of the windward wall (Holmes and Flay, 2004). This approach is tailored to building design applications in which detailed knowledge of the design structure and the neighbouring upwind building population is available.

In some wind hazard studies the shielding multiplier assessment is applied at the regional level as a detailed knowledge of upwind structures cannot be obtained and applied. In such cases, it is not possible to implement the AS/NZS 1170.2 approved method which has a focus on the design of a single structure with knowledge of its environment. To overcome the problem, Geoscience Australia has developed an alternative method to derive the shielding multiplier at regional level using a methodology that also addresses the effect of upwind ground slope on shielding. The workflow of this methodology developed to determine the shielding multiplier is shown in Figure 3.7. Each step is then discussed in detail.



Only consider:	
City buildings	0.90
High density metro	0.88
Suburban	0.85
Centre of small towns	0.85
Others	1.00

Figure 3.7 Workflow of determination of the shielding multiplier.

3.3.1 Assignment of initial shielding factors

We only consider shielding in terrain classes containing building structures as the AS/NZS 1170.2 methodology only considers structures to contribute to shielding. The selected classes are city buildings, high density metro, suburban, and centres of small towns. After applying the detailed AS/NZS 1170.2 provisions to determine typical shielding multiplier values for structures within the range of these urban terrains, it was found that the corresponding M_s values were more or less constant. For the selected urban terrain classes, the typical shielding factors were trialled in several locations to obtain a representative value using AS/NZS 1170.2. These typical shielding factors from AS/NZS 1170.2 were assigned to the corresponding terrain classes as the initial shielding factors, as shown in Table 3.5. For example, a default value of M_s of 0.85 is normally taken for houses in built-up suburban terrain with upwind buildings at “normal” spacing. These values are applied to all points on the 25 m grid that are within the suburbs (for the 25 m resolution Landsat TM image describing the scene) irrespective of how close they may be to the boundary of the suburb.

Table 3.5 Initial shielding factors for terrain classes.

Terrain class	Shielding factor
City buildings	0.9
High density metro	0.88
Suburban	0.85
Centre of small towns	0.85
Others	1.0

3.3.2 Derivation of directional shielding factors

The shielding factor that is appropriate to a particular direction is the weighted average value of shielding factors within the shielding zone upwind of the structure. AS/NZS 1170.2 (2011) defines the shielding zone as a 45 degree sector centred on the building of interest with a radius of 20 times the building’s height.

To obtain the shielding factor for the point of interest marked with the yellow star in Figure 3.8, an average of the nominal shielding factor at each grid point within the upwind wedge area is calculated. Currently a 25 m grid is used that relates to the resolution of the Landsat TM imagery.

The shielding factor is derived within a wedge shaped sampling area corresponding to AS/NZS 1170.2 defined sector of influence or shielding zone. As Figure 3.8 displays, for the calculation purpose, the area covered by the 45 degree sector (in blue line) was transformed into the area (in green line); the equivalent area encloses the seven data points highlighted in green. To derive the same area, the internal angle of the blue sector was widened from 45° to 54° (green wedge) and the hypotenuse was reduced.

Following the production of the shielding factor for each cardinal direction ,the result requires further processing to consider the effects of slope and aspect (see 3.3.3), as well as removing the conservatism (see 3.3.4).

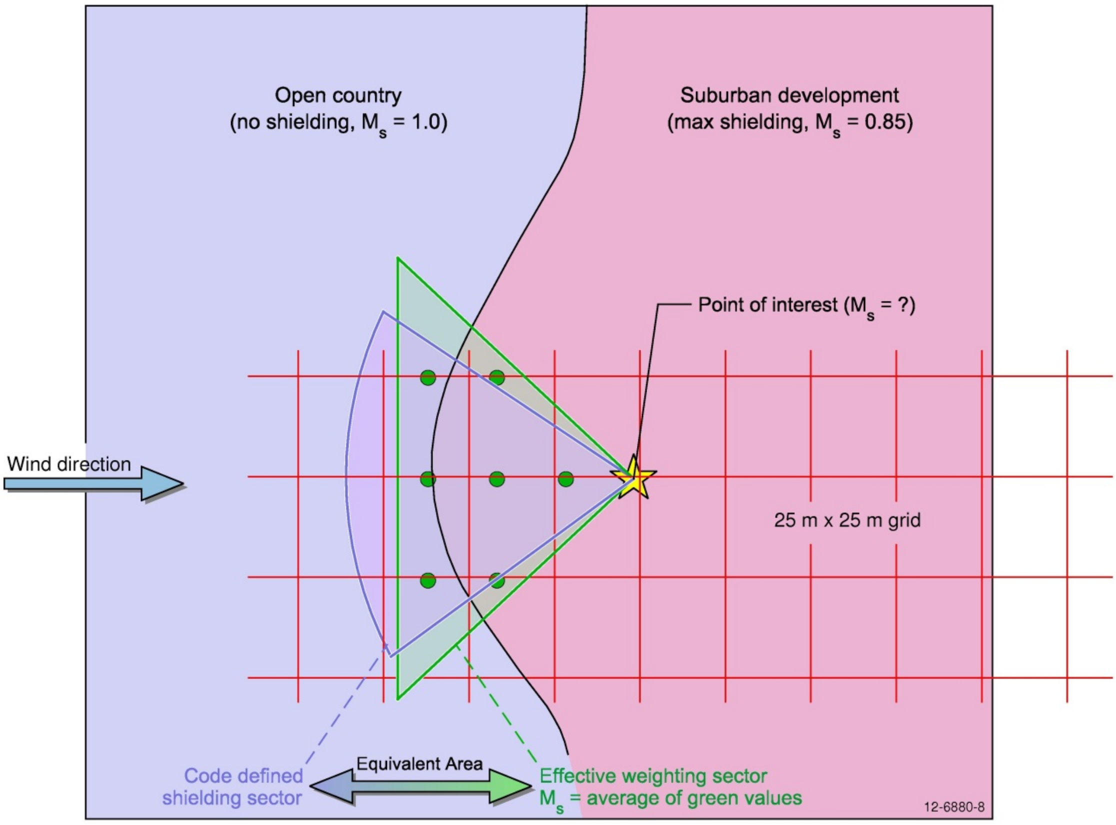


Figure 3.8 The determination of upwind shielding area.

3.3.3 Adjust shielding multiplier for the effects of ground slope

Slope and aspect (direction of slope) are both derived from a DEM. Aspect is reclassified into eight cardinal direction zones. The shielding factor is adjusted only if the wind direction is consistent with the aspect of the grid. In that case, slope value is utilised to adjust the shielding factor using a bi-linear relationship. If the slope in per cent rise is less than or equal to 5.5% (5% + 5%x10%), the shielding factor is not adjusted. If the slope in per cent rise is greater than 22.0% (20% + 20%x10%), the shielding factor is set as 1. If the slope value falls in between 5.5% and 22.0%, the linear interpolation is used to adjust the original shielding factor.

AS/NZS 1170.2 states that the shielding multiplier should be 1.0 where the average upwind ground gradient is greater than 20%. AS/NZS 1170.2 also implies that if the average upwind ground gradient is less than 5%, it is in the flat area.

3.3.4 Adjust the conservatism in AS/NZS 1170.2

After the effect of slope and aspect is considered, the last step to derive the final shielding multiplier is to remove the conservatism inherent in the AS/NZS 1170.2 approach. AS/NZS 1170.2 (2011) is a building design document that seeks to envelope possible wind effects rather than to provide an average assessment of local wind speed. It is known to be conservative in its approach to shielding by upwind buildings and also with regard to the topographic shielding of structures. Modifications were made to remove the conservatism associated with AS/NZS 1170.2 as recommended by Holmes (2004).

For open country with an M_s value of 1, no adjustment is made. For an M_s value of 0.9 or less, a factor of 0.9 is applied. For an M_s value between 0.9 and 1.0, the factor is squared to avoid an abrupt drop in shielding values which do not reflect the true wind exposure.

3.4 Topographic Multiplier (M_t)

The Geoscience Australia computational topographic multiplier methodology utilises the spatial algorithms developed from the wind multiplier formulae detailed in AS/NZS 1170.2 (2011) and AS/NZS 1170.2 Supp 1 (2002) to estimate the influence of topography (Lin and Nadimpalli, 2005).

3.4.1 M_t formulae from AS/NZS 1170.2

The topographic effect has a profound influence on wind behaviour, local wind speeds and the spatial pattern of wind damage (Walker *et al.*, 1988). The topographic or "hill-shape" wind effect is caused by the convergence of generally horizontally flowing wind when it meets a hill-slope (see Figure 3.9). Standing on an uphill slope will normally feel windy compared to standing at the base of the slope. In wind engineering the "speed-up" of the horizontal wind speed due to the topography is quantified by the topographic (or hill-shape) multiplier M_t which applies to the region in the proximity of a hill crest or an escarpment edge called the local topographic zone. The topographic effect on wind speed is recognised in AS/NZS 1170.2 by utilising a topographic multiplier, M_t or hill-shape multiplier M_h (in mainland Australia, $M_t = M_h$), which depends on the hill's shape and steepness, and the site's proximity to the hill crest. It can be estimated using the following formulae taken from AS/NZS 1170.2 (2011):

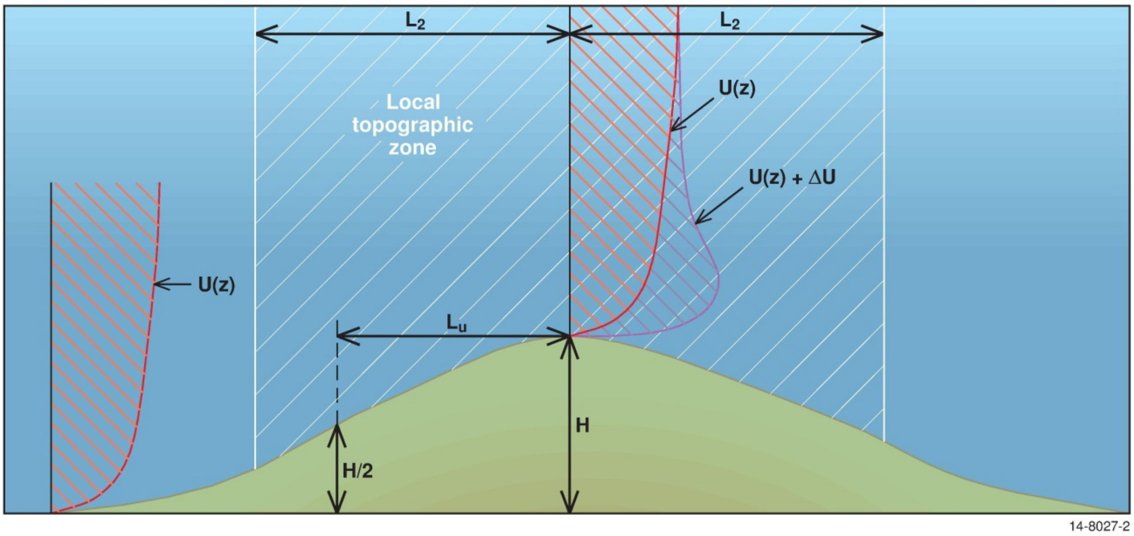


Figure 3.9 Development of a vertical wind profile over a hill (developed from Figure 4.2 of AS/NZS 1170.2).

$$M_h = \begin{cases} 1.0 & \text{for } H/(2L_u) < 0.05 \\ 1 + \left(\dfrac{H}{3.5(z+L_1)}\right)\left(1 - \dfrac{|x|}{L_2}\right) & \text{for } 0.05 \le H/(2L_u) < 0.45 \text{ or} \\ & \text{within the local topo zone when } H/(2L_u) > 0.45 \\ 1 + 0.71\left(1 - \dfrac{|x|}{L_2}\right) & \text{for } H/(2L_u) > 0.45 \text{ and within the separation zone} \end{cases} \quad (6)$$

where

M_h — hill shape multiplier, equal to topographic multiplier M_t in most parts in Australia

H — vertical distance from base to crest

x — horizontal distance upwind or downwind from structure to crest

Z — height of the structure above the local ground level

L_u — horizontal distance from crest to 1/2 H below crest

L_1 — the greater of 0.36 L_u and 0.4 H

L_2 — local topographic zone, to be 4 x L_1 for upwind, and for downwind is also 4 x L_1 for the cases of hills and ridges or 10 x L_1 for escarpments.

Equation (6) specifies that slopes below 5% are assigned a M_h of 1 and slopes of 45% and above are assigned a M_h of 1.71 within the local topographic zone. For the slopes between 5% and 45%, Equation (6) provides the values for M_h within the local topographic zone. Table 3.6 provides M_h values for a variety of hill slopes. It can be seen that the hill-shape multiplier has a minimum value of 1 but a maximum value of 1.71 when the slope is equal to or greater than 45% (or 24.2 degrees). A wind "separation zone" located on the leeward side of a ridge or crest is also defined in the standard but is only applicable for slopes greater than 45% in inclination.

Table 3.6 Hill-shape multiplier at crest (|x| = 0) when z = 0.

Hill Slope (fraction)	Hill Slope (in degrees)	Mh
<0.05	< 2.9	1.0
0.05	2.9	1.08
0.10	5.7	1.16
0.20	11.3	1.32
0.30	16.7	1.48
≥ 0.45	≥ 24.2	1.71

Source: Table 4.4 of AS/NZS 1170.2 (2011)

In the application of Equation (6), the value of z (height of the structure above the local ground level) is set 10 metres to be consistent with the other multipliers.

The above algorithm is used to evaluate the topographic multiplier at a high spatial resolution (Geoscience Australia uses a 30 m grid) using digital elevation datasets to capture the topographic features of the areas.

3.4.2 Adjust M_t for the conservatism in AS/NZS 1170.2

Ngo and Letchford (2007) compared current US, Australian/New Zealand, European and Japanese wind standards and reported that the treatment of topographic effects in the standards was on the whole conservative. For the purpose of wind hazard estimation, it is beneficial to remove the conservatism associated with the topographical multiplier derived from AS/NZS 1170.2 (2011). Our current approach is based on the recommendations of Holmes (2004).

Minor modifications are made to the topographic multiplier (M_t) as follows:

- For essentially flat terrain (flatter than 1 in 20 or outside the local topographic zone), no adjustment to M_t is made;
- For topographic features such as shallow hills and escarpments where $M_t < 1.4$ a 5% reduction in the multiplier is adopted, and;
- For topographic features such as steep hills and escarpments where $M_t \geq 1.4$ a 10% reduction in the multiplier is adopted.

Complex topography was not considered as a special case.

3.4.3 The impacts of removing conservatism from shielding and topographic multiplier

By removing the conservatism of both shielding and topographic multipliers derived from the AS/NZS 1170.2 (2011), the combination of shielding and topographic multipliers appears reasonable as a representation of the average situation, without there being any direct experimental (e.g. wind tunnel) evidence for the numbers utilised (Holmes; personal communication). Holmes (2004) suggests the above methodology is a representation of the average situation, and also allows for greater variability when topography and shielding act in combination.

In the extreme case, at some locations, shielding and topographic multipliers could both be reduced by 10%. However, buildings are rare on very steep hills and escarpments. This means buildings tend to only have 10% reduced shielding multiplier, while the topographic multiplier remains as defined by the standard.

3.4.4 DEMs

Digital Elevation Models (DEMs) are data files that contain the elevation of the topography over a specified area, with a fixed resolution over the earth's surface. A DEM can be represented as a raster or as a vector-based triangular irregular network (TIN). They are normally built from remote sensing data, although they can also be produced from survey data.

In the context of multipliers, DEMs are used for addressing issues relating to the wind speed over topography in the fields of disaster management, water security, environmental management and climate change.

The topographic multiplier is very sensitive to the resolution of the DEM used to compute it. A DEM with higher resolution represents the terrain shape more accurately, and thus the topographic multiplier is more accurate.

Geoscience Australia uses DEMs for computing multipliers from the National Elevation Data Framework (NEDF) that was developed to ensure that decision makers, investors and the community have access to the best available elevation data. NEDF allows users to search, discover and access elevation data for Australia on line. More details can be found on http://www.ga.gov.au/topographic-mapping/digital-elevation-data.html.

3.5 Example calculation (site gust wind speed at point location)

The following is an example calculation for a point location. It demonstrates how the computational methodology, which has been applied over a high-resolution spatial grid, functions as a point calculation. The calculation determines the site specific gust wind speed (V_{site}) from the regional gust wind speed (V_R) provided in AS/NZS 1170.2. According to Equation (1), for convenience reproduced below:

$$V_{site} = V_R \times M_d \times M_{z,cat} \times M_s \times M_t \tag{1}$$

Where

V_{site} — local or site wind speed

V_R — regional or generic wind speed speed at the reference height z, regional 3 sec. gust wind speed, for annual probability of exceedance of 1/R (Table 2.2)

M_d — wind directional multiplier; eight cardinal directions (Table 3.1)

$M_{z,cat}$ — terrain/height multiplier (Table 3.3 and Table 3.4)

M_s — shielding multiplier (Table 3.5 and remove conservatism according to Section 3.3.4)

M_t — topographic multiplier (Table 3.6)

V_R is the basic design regional gust wind speed that is the maximum 3-second wind gust at a height of 10 m in terrain with a defined roughness length. For ultimate strength design of residential buildings, the return period is normally 500 years. An ‘ultimate’ wind speed V500 has a 10% probability of being exceeded in a 50 year period (which is the average design life of residential housing). Alternatively, annual probability of exceedance is 0.002 or 0.2%.

For a 30 m high structure (tower) and a 5 m height structure (control house) situated in Terrain Category 2 in Canberra (e.g. Canberra Airport) (AS/NZS 1170.2 Region A1), the computations for the site wind speed are shown below.

The relevant heights are 30 m (tower) and 5 m (house), and we are considering north-westerly wind for the house shielded by other buildings with a shielding parameter s = 3.0. The tower has no shielding. There is no topographic effect due to the flatness of the airport location. See Table 3.7 for the calculation process.

Table 3.7 Example site wind speed calculation

Principle	Components	Tower (30 m)	House (5 m)	House (5 m in urban setting)	Standard 10 m height
Table 2.2	V_R	45 m/s	45 m/s	45 m/s	45 m/s
Table 3.1	M_d	0.95	0.95	0.95	0.95
Table 3.3 and Table 3.4 Table 3.4	$M_{z,cat}$	1.12	0.91	0.83	1.0
Table 3.5 & remove conservatism	M_s	1.0	1.0	0.77	1.0
Table 3.6	M_t	1.0	1.0	1.0	1.0
Site wind speed by Equation (1)	V_{site}	47.9 m/s	38.9 m/s	27.3 m/s	42.8 m/s

4 Conclusions

Wind multipliers are a fundamental part of local wind speed determination. They modify the broad scale wind to account for the local effects of terrain, topography and shielding. Geoscience Australia has developed a spatial methodology to compute the four wind multipliers based on the equations and tabulated information within AS/NZS 1170.2, but removing the conservatisms associated with this standard. By removing the conservatisms from shielding and topographic multipliers, at many locations combined multipliers values have reduced by 10%. The methodology incorporates a geographic information system, remote sensing information and digital elevation models with the formulae and tables defined in the Australian & New Zealand wind loading standard (AS/NZS 1170.2).

We have described the wind multipliers in a comprehensive way including the concepts, applications, as well as relevant international standards. We have also provided a detailed illustration of the computation methodology by breaking down the workflows for each of the wind multipliers.

An example of wind hazard and wind risk studies has been provided to demonstrate the use of the wind multiplier computation methodology in the Appendix A. The wind multipliers are also applied for other applications by Geoscience Australia such as bushfire spread and impact assessment.

Acknowledgements

The authors would like to thank a number of people who assisted with the formulation, planning and the development of the software which has enabled this body of underpinning information to be available for the user community. In particular we would like to thank Dr John Holmes and Mark Edwards for their early stewardship of the activity and specifically for their valuable advice and engineering judgement. We would like to thank our past colleagues at Geoscience Australia, Xun Guo Lin, Chris Thomas, Babu Divi, Matthew Driessen and Alan Forghani, who contributed to the development of both the methodology and the code. In addition, we would also like to thank present colleagues, Martin Wehner, Mark Edwards, Craig Arthur, Duncan Moore and Martine Woolf for their advice and assistance with the development of the computer code, and also with the preparation and review of this document.

Glossary

Atmospheric Boundary Layer:

- Also called friction layer or planetary boundary layer. It refers to the air layer adjacent to the earth's surface. Because of the intense turbulent mixing that occurs in it, its properties are determined primarily by the thermal and dynamic influence of the underlying surface. The thickness of the layer ranges from 300 m to 2 km, which increases with increasing wind speed and decreasing thermal stability of the atmosphere. Up to an altitude of 100 m wind speed within the layer increases approximately in proportion to the logarithm of the altitude; above 100 m it increases more slowly (Laikhtman, 1970).

Design Event:

- A design event corresponds to a totally fictitious "engineering design event" that results in the same peak gust wind speed that covers all of the area of interest (i.e. the event domain). A design event has the same maximum wind speed over the spatial extent of the event whereas a real-world extreme wind speed event (i.e. tropical cyclone, thunderstorm or tornado) has a maximum wind speed that reduces as we move to the spatial extremes of the event domain.

Design Wind Speed:

- Refers to the gust wind speed classification for structural design for a building site or domestic home site. To identify the Wind Classification (design gust wind speed) for the proposed site there are four variables that initially require identification. They are the Wind Region, Terrain Category, Shielding Factor and Topographic Classification. These and then the Wind Classification can be determined using Tables in the Australian Wind Loadings Standard (AS/NZS1170.2:2011).

Digital Elevation Models (DEM):

- A digital model or 3D representation of a terrain's surface created from terrain elevation data. The elevation of a geographic location is its height above a reference geodetic datum.

Directional Filter:

- A numerical filter used for producing the terrain and shielding multiplier for each cardinal direction in this document. For the terrain multiplier, it is implemented as a weighted average value of terrain multipliers over a specific averaging distance (considering the structure's height) upwind of the structure of interest to smooth changes from one terrain class to the other. For the shielding multiplier, to derive the shielding factor that is appropriate to a particular direction, the directional filter is implemented as the weighted average value of shielding factors within the shielding zone upwind of the structure.

Normalised Difference Vegetation Index (NDVI):

- A numerical indicator that uses the visible and near-infrared bands of the electromagnetic spectrum to analyse remote sensing measurements and quantify the amount of green vegetative cover on the land surface over wide areas, as well as identify water and ice.

Return Period:

- The average time period between exceedances of a given intensity threshold. It is the inverse of the complementary cumulative distribution of the extremes, i.e. probability of exceeding a threshold within a given time period. For design wind speeds, return periods are generally given in years. For example, a 100-year return period wind speed has a probability of exceedence of 0.01 in any one year. Return period is interchangeable with average recurrence interval (ARI) (Mason and Haynes, 2010).

Roughness Length:

- Used in numerical models to express the roughness of the surface. It represents the size of eddies produced from the wind moving over a rough surface; the larger the eddies the larger roughness length and vice versa. A higher roughness length implies more exchange of air between the surface and the atmosphere and thus lowering the wind speed near the ground.

Terrain Classes:

- A terrain class is a type of terrain with a unique roughness length. To compute the terrain multiplier, the terrain classes are used to account for the roughness length. To compute the shielding multiplier, the terrain classes are used to define the location of shielding objects. Terrain classes are classified from satellite images. AS/NZS 1170.2 Supp 1 (2002) defines a number of terrain classes relevant to the wind hazard assessment.

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Appendix A An example of application of the wind multipliers for wind risk assessment

A review commissioned by the Council of Australian Government (COAG) in 2001, *Natural Disasters in Australia: reforming mitigation, relief and recovery arrangements* (COAG, 2002) recommended a new approach to natural disasters in Australia, which involved a fundamental shift in focus beyond relief and recovery towards cost-effective, evidence-based disaster mitigation to achieve safer, more sustainable Australian communities from future natural disasters. Consequently, the management and mitigation of natural hazards and the response to disasters have become increasingly important for local and national authorities.

Because of the tendency of people moving to coastal areas that are inherently at risk from severe weather-related events, severe winds generated by tropical cyclones, thunderstorms and tornadoes may be occurring more frequently and have definitely caused significant economic loss in Australia. Severe winds have caused approximately 23 percent of natural hazard related building damage in Australia during the period 1900 to 2003 (Chen, 2004), and the damage bill in individual cases has exceeded one billion dollars (Crompton and McAneney. 2008). Cyclone Larry in 2006 caused over $1 billion in damages and the total losses from Cyclone Yasi in 2011 reached $3.5 billion. Li and Stewart (2011) predicted that if the cyclone intensity were to increase by 25% by 2050 due to climate change, the cumulative damage costs over 50 years in North Queensland will jump from $690 million (without climate change) to $2.0 billion.

Options are available to manage the risk from peak wind gusts ranging from improving the quality of Australian structures, through stricter building design and construction practices and improved materials and fasteners. However as a fundamental part of the natural disaster relief and mitigation arrangements, it is essential that the risk from peak wind gusts be accurately quantified if informed and practical risk management strategies are to be implemented. It is important to evaluate the impact of the severe wind risks on the Australian communities, converting hazard and exposure information into likely consequences for a particular area (a suburb, a city etc.) in terms of damages and replacement costs, casualties, disruption and number of people affected. Over the past decade, Geoscience Australia has undertaken research and development on the individual aspects of wind risk assessment as well as developing a wind risk assessment framework, which has been applied in several wind risk assessment projects nationally and at state level. The recent application is the National Wind Risk Assessment (NWRA) for then Department of Climate Change and Energy Efficiency (Arthur et al., 2011), now a part of Department of the Environment.

The developed wind risk assessment model consists of several integral components, and can be expressed as

wind hazard → exposure → vulnerability → risk

(as utilised in studies by Nadimpalli *et al*., 2007; Cechet *et al*., 2010).

The quantification of the wind hazard is the first step towards the assessment of wind gust risk posed to a number of Australian communities. Exposure is represented as spatial databases developed to record community profiles including people and property characteristics under threat of natural disasters (Nadimpalli, 2009). Applying a wind hazard to an exposure, the impact and risk can be predicted in terms of economic loss and community losses, based on vulnerability models. A suite of vulnerability models have been developed in Geoscience Australia, which are used to derive the building damages for given gust wind speeds for a variety of building types (Wehner *et al*., 2010).

Geoscience Australia, in collaboration with the Department of the Environment, has conducted a preliminary study to investigate the risk posed to Australian communities by severe winds, both in the current climate and under a range of future climate scenarios. This National Wind Risk Assessment (NWRA) represents the first national-scale assessment of severe wind risk, using consistent information on residential buildings and severe wind hazard.

The NWRA has produced an understanding of severe wind hazard for the whole Australian continent, including extreme winds caused by tropical cyclones, thunderstorm downbursts and synoptic storms. New modelling and analysis techniques have been applied to the results of Intergovernmental Panel on Climate Change (IPCC) climate modelling efforts to enable assessment of regional wind hazard to the end of the 21st century for four case study regions: Cairns, southeast Queensland, Hobart and Perth.

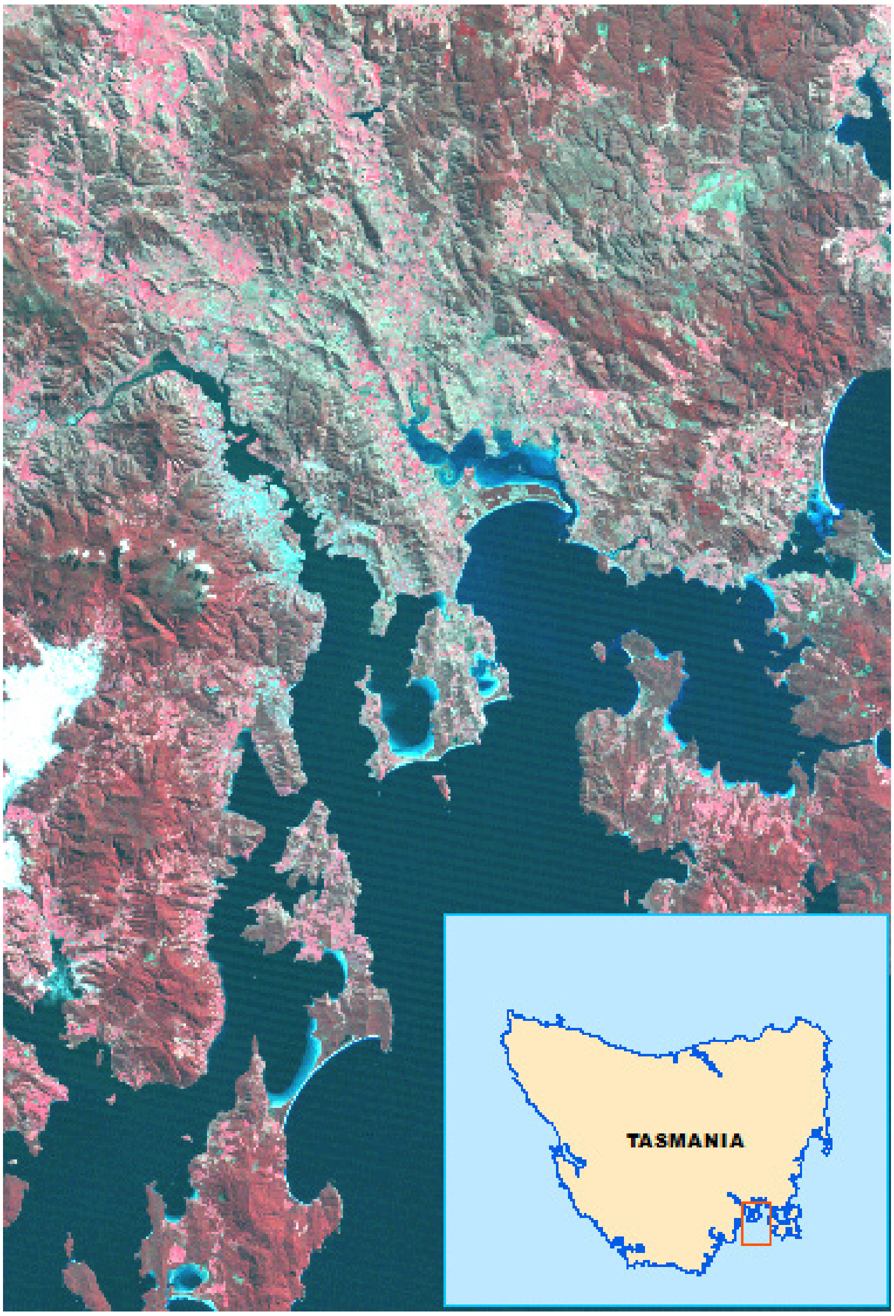
The NWRA presents methods by which the effectiveness of adaptation to improve residential building resilience may be assessed in economic terms. In developing adaptation options, it is essential to have an understanding of the existing risk, and the risk at future times if no action is taken. Adaptation options can then be assessed on their cost versus benefit (i.e. reduction in risk).

This Appendix utilises the Hobart area of the Tasmanian region to provide a graphical representation of the outputs for each stage of the risk assessment. These information layers include:

A1. Satellite image of the Hobart region
A2. Map of the Hobart region
A3. Terrain classification
A4. Terrain wind multiplier
A5. Digital Elevation Model (DEM) of the Hobart region
A6. Shielding wind multiplier
A7. Topographic wind multiplier
A8. Combined (M_4) wind multipliers (terrain, topography, shielding and direction)
A9. 500-year return period wind hazard
A10. 500-year return period impact/loss
A11. Annualised Loss

The wind multipliers are essential in the determination of the local wind hazard. Further information can be obtained from Arthur *et al.* (2011).

The regional gust wind speeds for 500-year return period are shown in the main body of the report (see Table 2.2).

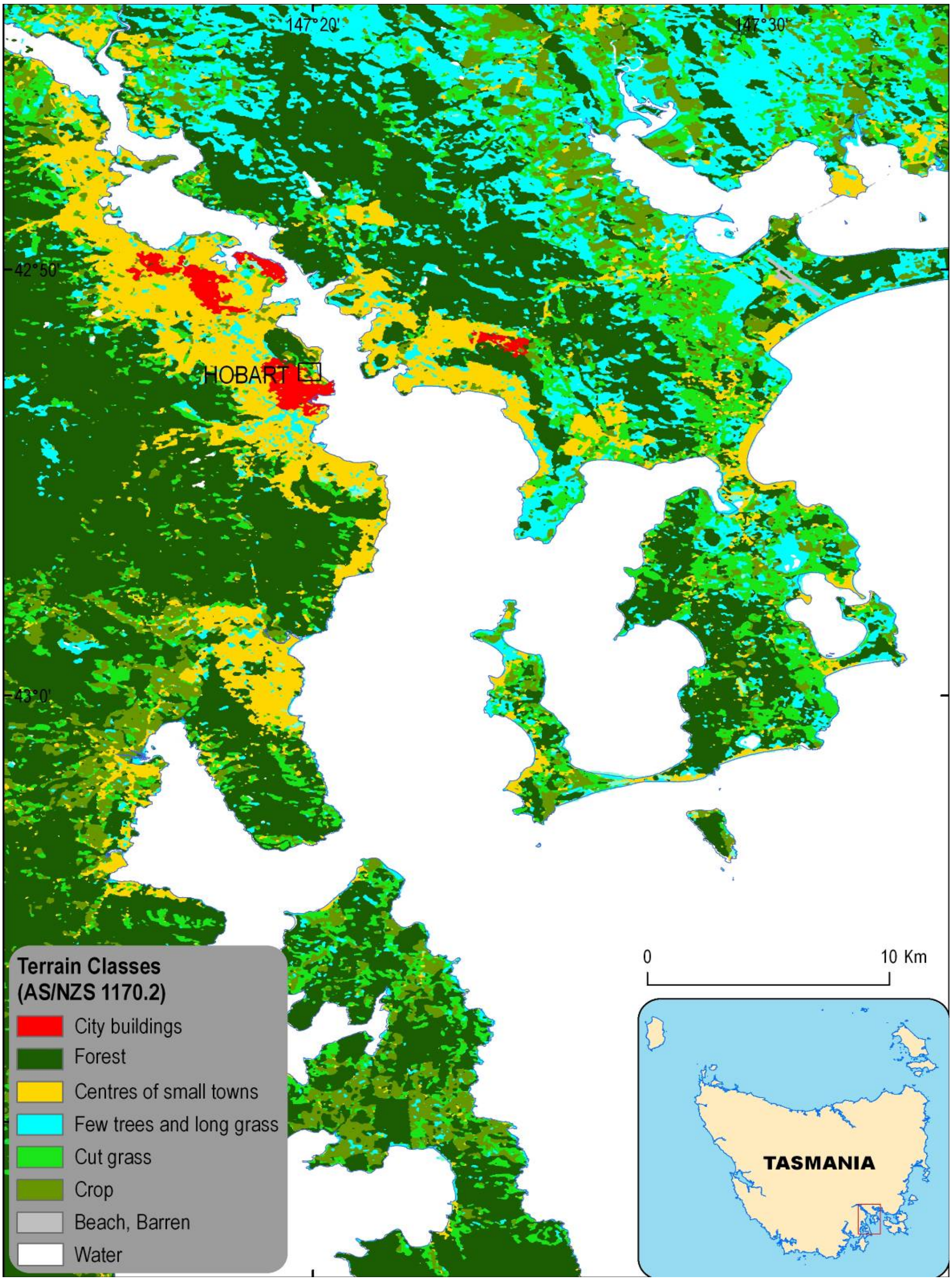


Appendix Figure A.1 LANDSAT Satellite image of Bands 432 of the Hobart region.

Appendix Figure A.1 is the Landsat satellite image of the Hobart region. The combination of the band is 432, where dark red represents forest, brighter red represents crops and younger vegetation, blue or grey stands for cities.

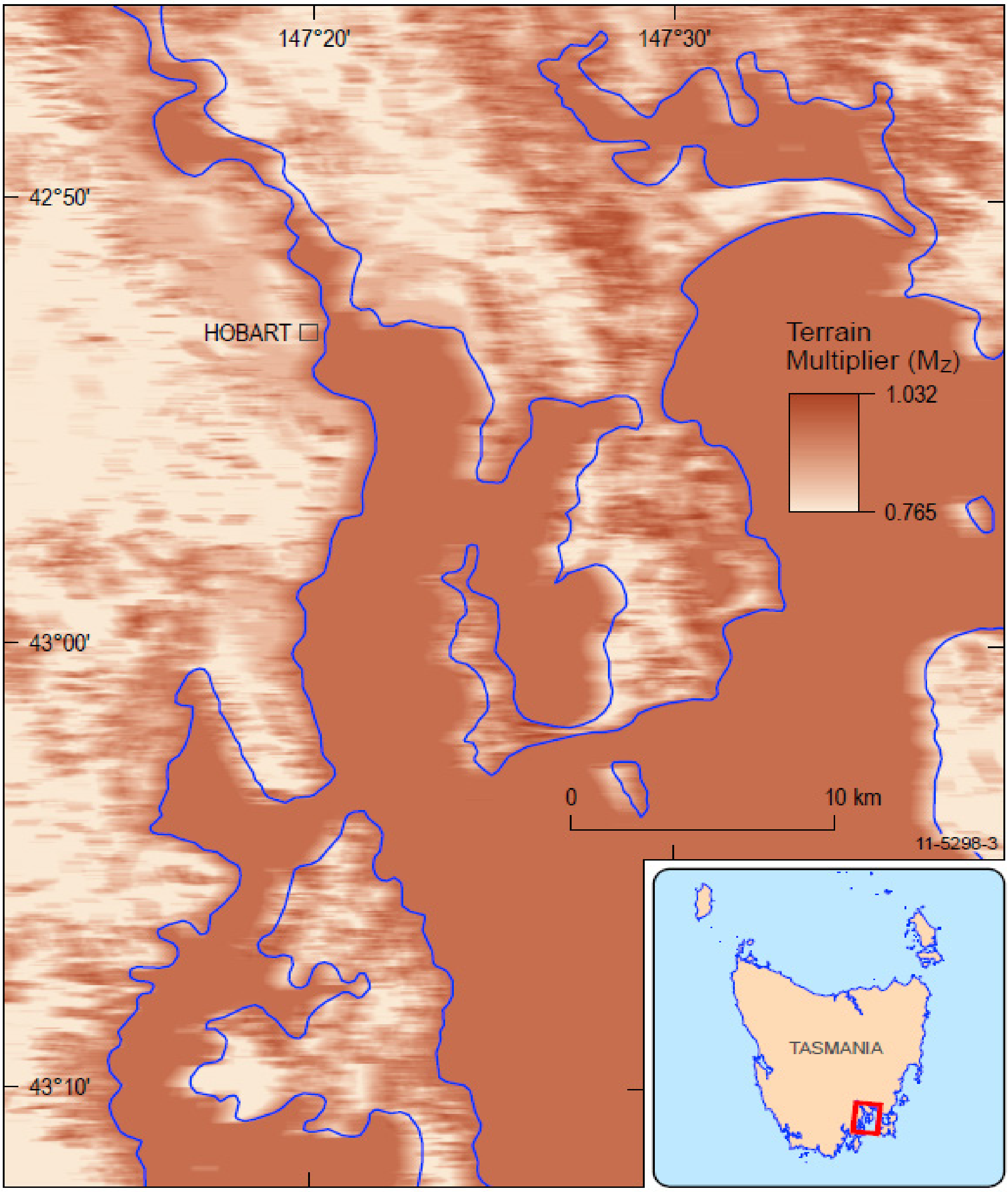
Appendix Figure A.2 Map of the Hobart region.

Appendix Figure A.2 is a map view of the Hobart region, where the pink colour represents urban regions (built-up areas).



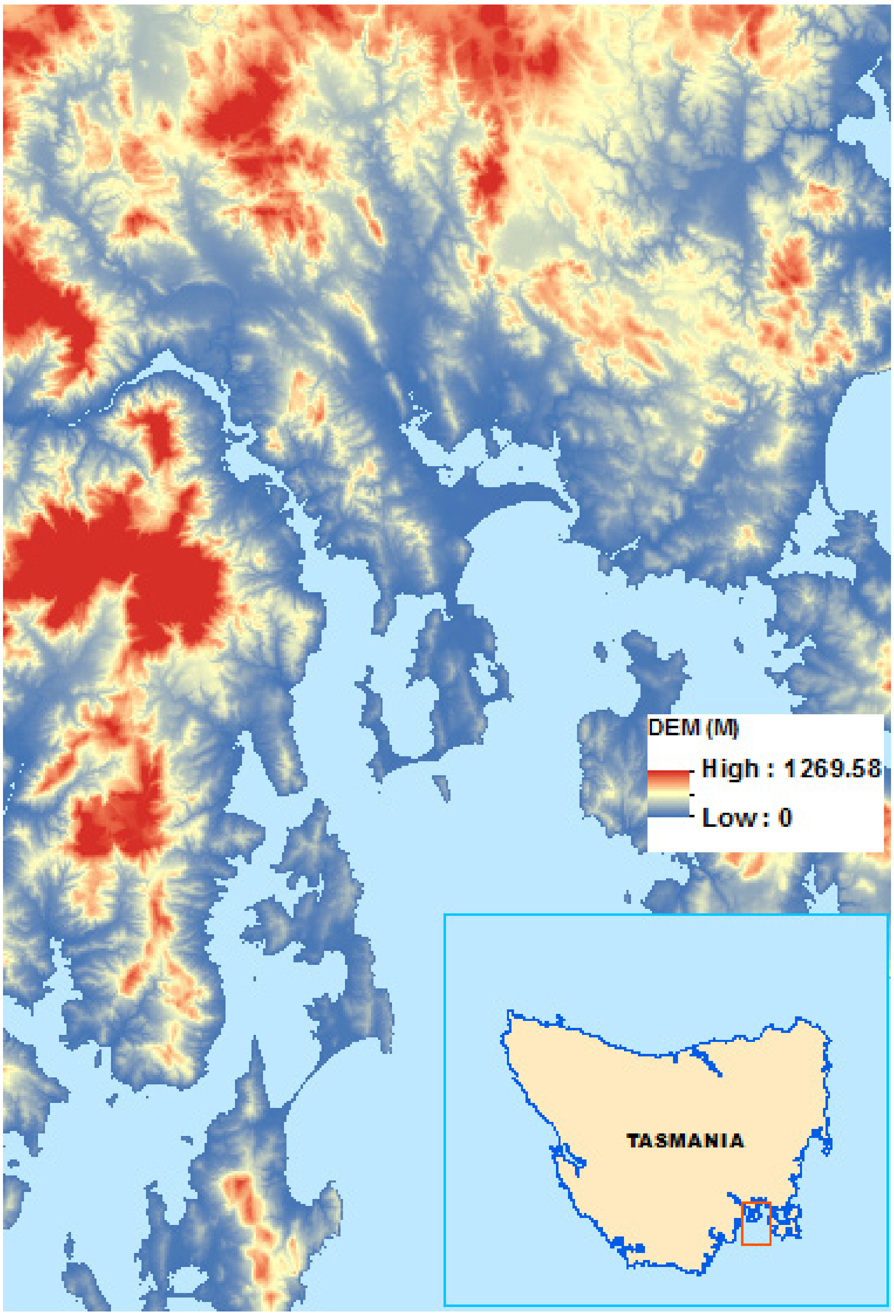
Appendix Figure A.3 Terrain classification map of the Hobart region.

Appendix Figure A.3 is the land cover map derived from the satellite image (shown in Appendix Figure A.1). It shows the distribution of the terrain classes defined in the AS/NZS 1170.2.



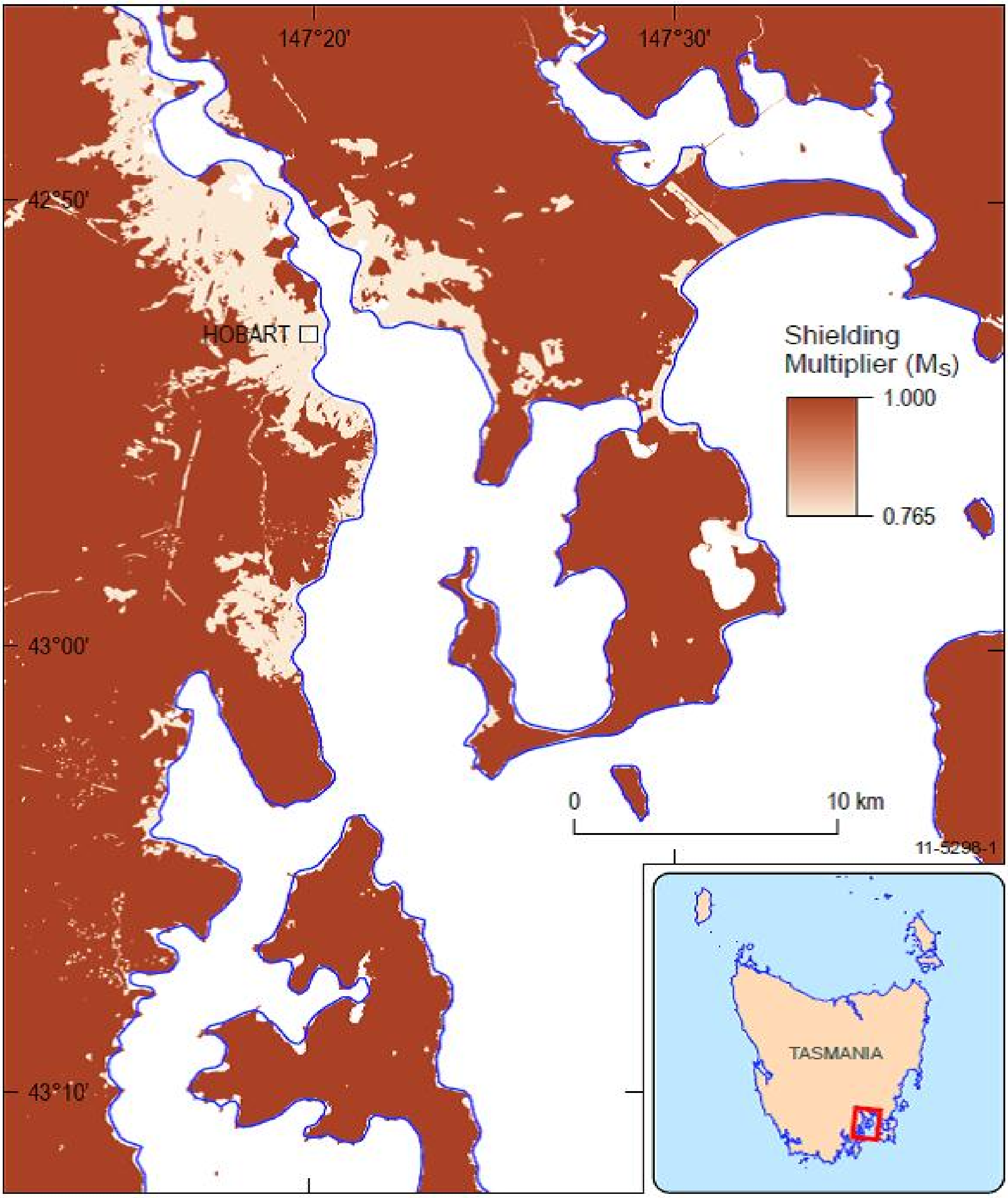
Appendix Figure A.4 Terrain wind multiplier (the Hobart region) – westerly direction.

Appendix Figure A.4 is a map of the terrain multiplier of the Hobart region (computed based on terrain classes in Appendix Figure A.3) at westerly direction. It shows that the terrain multiplier values vary spatially due to different land cover on the ground. In forest area the terrain multiplier values are relatively low due to the high roughness length.



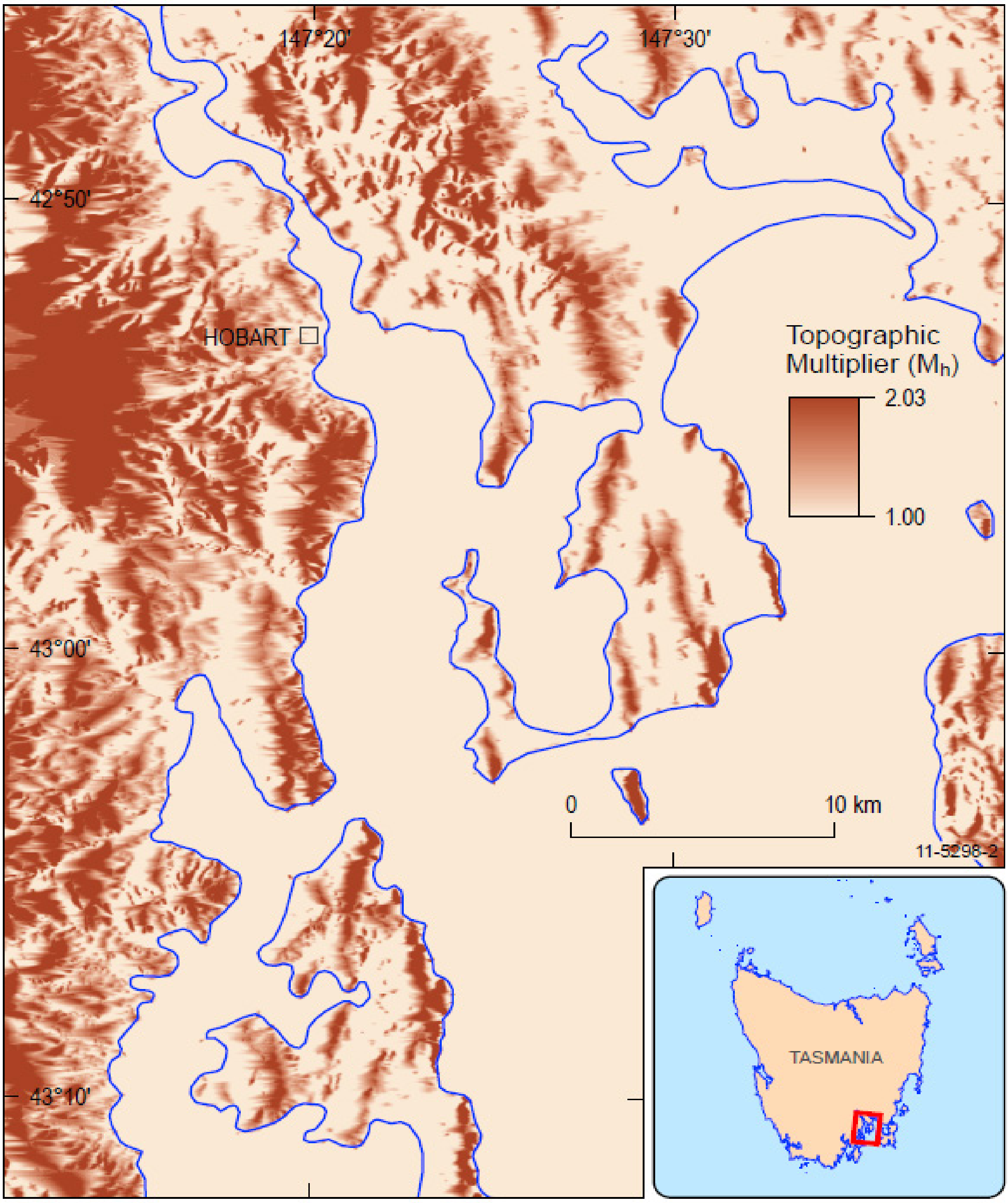
Appendix Figure A.5 Digital Elevation Model (DEM) of the Hobart region.

Appendix Figure A.5 shows the DEM of the Hobart. The colour extends from blue to red as the elevation increases. The DEM is used to compute the shielding multiplier and topographic multiplier.



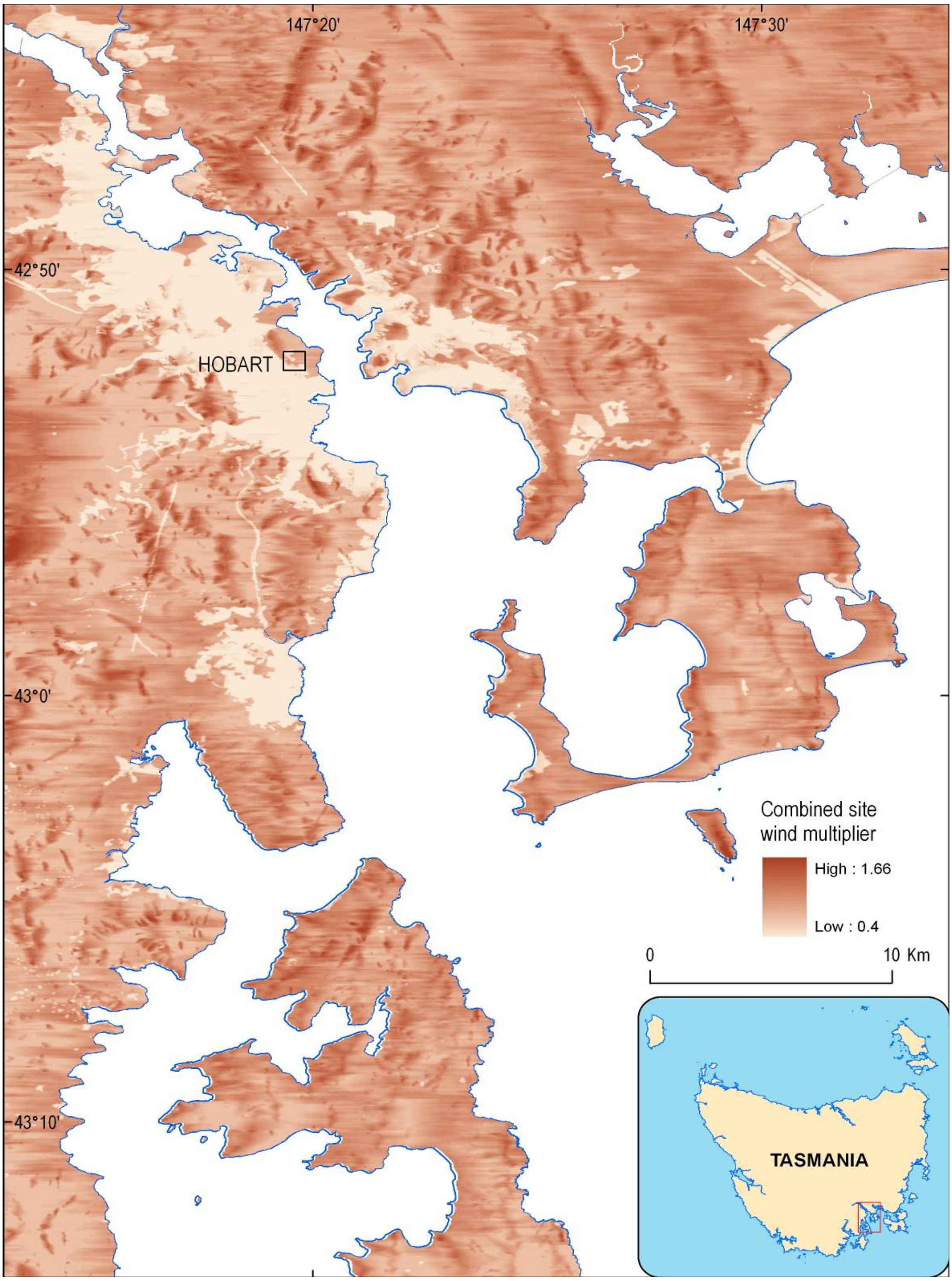
Appendix Figure A.6 Shielding wind multiplier (the Hobart region) – westerly direction.

Appendix Figure A.6 is a map of the shielding multiplier of the Hobart region (computed based on terrain classes in Appendix Figure A.3 and DEM in Appendix Figure A.5) at westerly direction. It shows that the shielding multiplier only applies to the built-up areas with values less than 1, while other non-built-up areas have the default shielding multiplier value of 1.



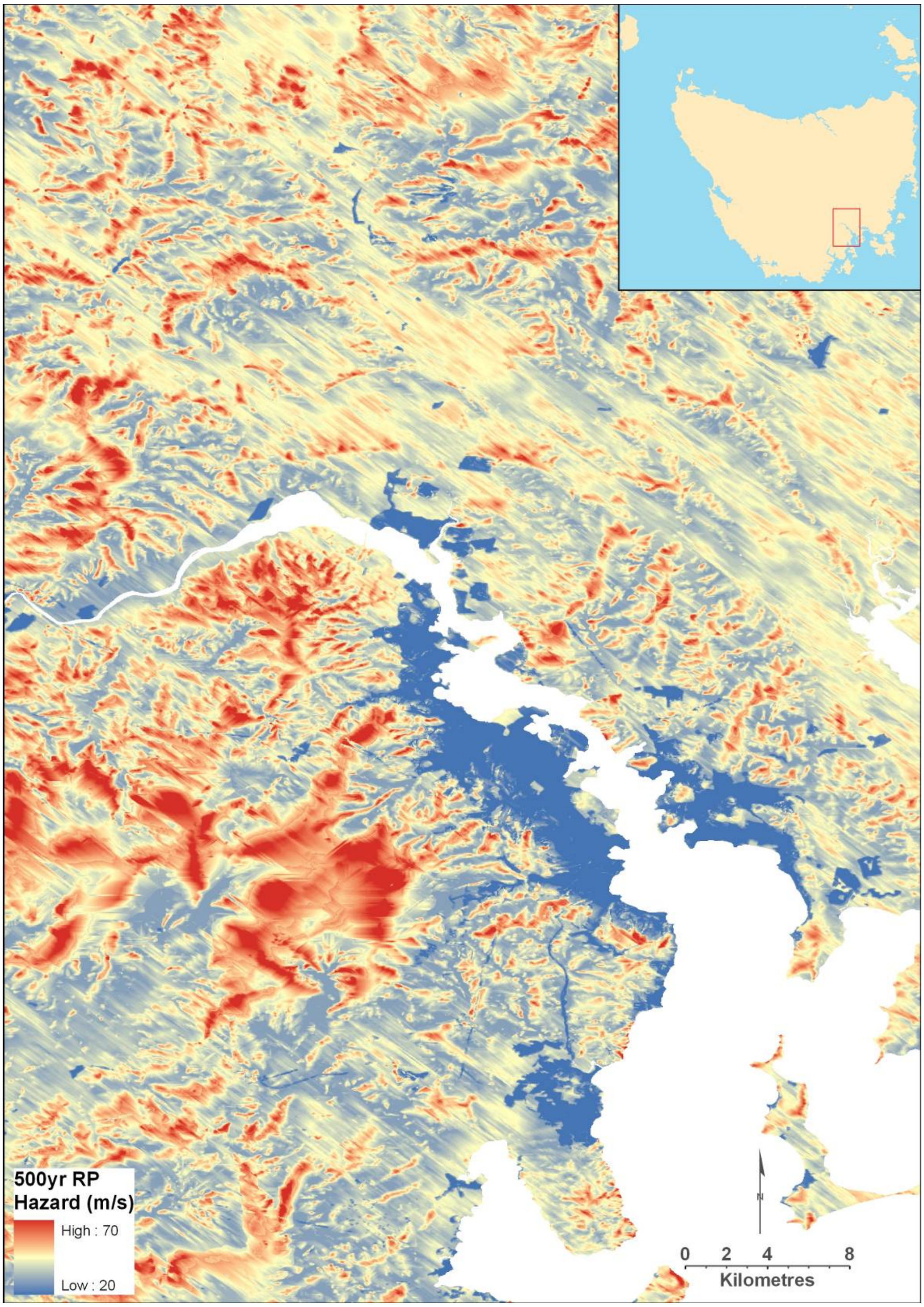
Appendix Figure A.7 Topographic wind multiplier (the Hobart region) - westerly direction.

Appendix Figure A.7 is a map of the topographic multiplier of the Hobart region (computed based on DEM in Appendix Figure A.5) at westerly direction. It shows that the topographic multiplier is higher in the mountain areas (with slopes) than the flat areas.



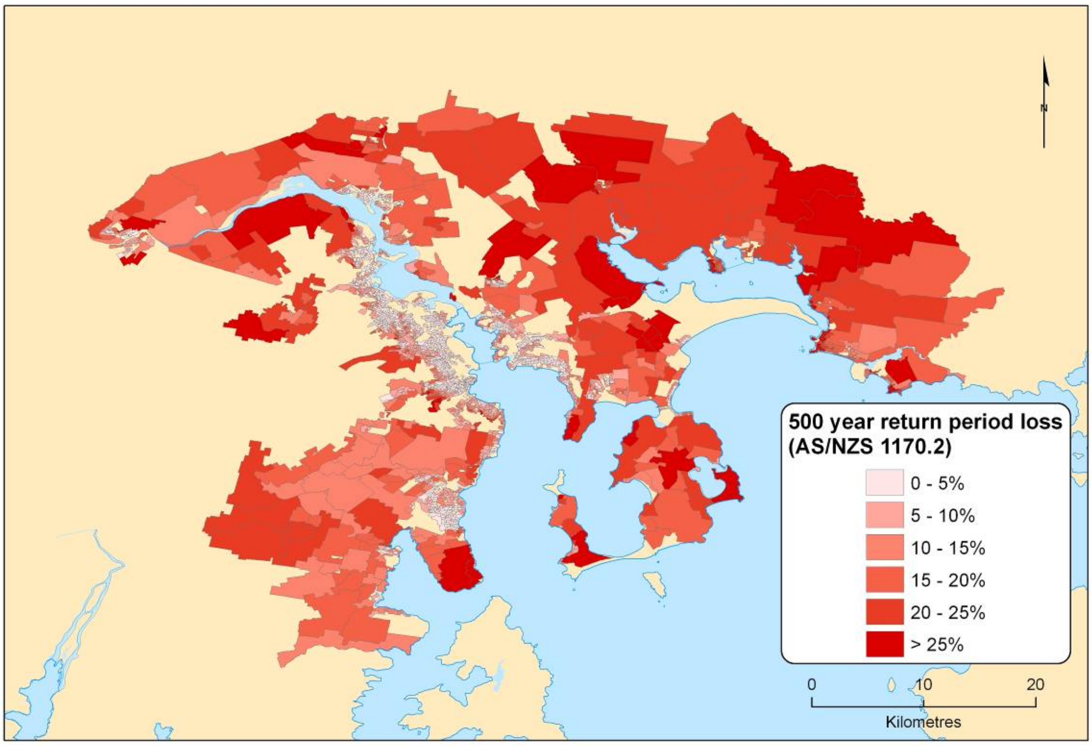
Appendix Figure A.8 Combined (M_4) wind multipliers (the Hobart region) – westerly direction.

Appendix Figure A.8 is a map of the combined multiplier of the Hobart region (M_4) at westerly direction, which is product of terrain multiplier (shown in Appendix Figure A.4), shielding multiplier (shown in Appendix Figure A.6), topographic multiplier (shown in Appendix Figure A.7) and direction multiplier (taken from AS/NZS 1170.2).



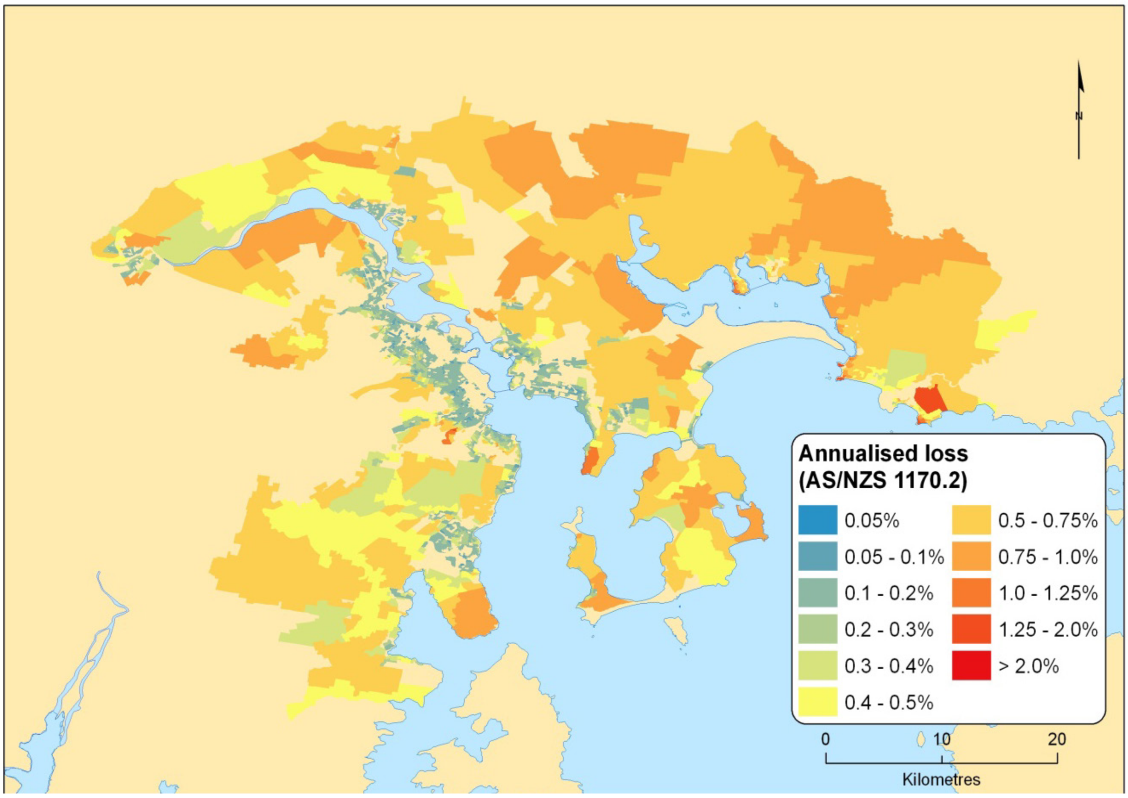
Appendix Figure A.9 500-year return period local design-wind hazard map (the Hobart region)

Appendix Figure A.9 is a map of local wind hazard of 500-year return period of the Hobart region, derived by multiplying the regional wind speed of 500-year return period (45 m/s) taken from AS/NZS 1170.2 with the maximum M_4 of the eight cardinal directions. It shows the relatively high local wind hazard in the mountain area (displayed in red colour) due to the higher local wind multiplier values.



Appendix Figure A.10 500-year return period loss of the Hobart region.

The hazard depicted in Appendix Figure A.9 has been used in the wind risk assessment. Combining the wind hazard, residential exposure and vulnerability information of the Hobart region, the 500-year return period loss has been computed, shown in the Appendix Figure A.10, where the building-scale risk has been aggregated to Australian Bureau of Statistics (ABS) mesh block level.



Appendix Figure A.11 Annualised loss of the Hobart region.

The annualised loss based on 10-year to 2000-year return period hazard events has been computed for the Hobart region and is shown in Appendix Figure A.11, where the loss was computed at the building-scale, and then further aggregated to Australian Bureau of Statistics (ABS) mesh block level.