Chapter 3: SEVERE WIND HAZARD ASSESSMENT IN METROPOLITAN PERTH

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3.1 Introduction

In this chapter a severe wind hazard assessment for metropolitan Perth is described. There were three stages to this wind hazard assessment.

- The wind data description provides information about the location of weather stations, the service periods of these stations and the maximum historical wind gust recorded at each site.
- The section on local wind effects estimates the local effect of terrain for the structure height concerned; the shielding effect provided by upwind structures and the topographic effect. These effects were numerically estimated using remote sensing techniques, digital elevation data and by using formulas given in the Australian wind loading design standard.
- The last stage was the estimation of likely severe wind speeds within a given time period. These wind speeds are commonly called return period wind speeds or return levels. The wind speed estimation for various return periods includes a sensitivity analysis. The final adopted return period wind speeds were a combination of statistical analysis, expert judgement and the satisfaction of internal consistency.

The output of this assessment is the combined (terrain/height, shielding and topographic) local wind multipliers for eight cardinal directions on a 25 m by 25 m grid across metropolitan Perth and the local return period wind speeds (called the wind hazard maps) at the same grid locations. These local wind multipliers and the wind hazard maps may be used in decision-making processes by local and state governments in disaster planning, mitigation and emergency management. They may also be useful for city and suburb planning processes.

3.2 Wind Study Area

Extreme wind is one of the major natural hazards experienced in Perth. These extreme winds are generally produced by cold fronts and not by cyclones (see for example Lin and Courtney, 2004) or thunderstorm-related downbursts. The wind study area covers Perth City and its surroundings, including Rottnest Island. The geographic extent of the area in the Universal Transverse Mercator (UTM) coordinate system lies between 354500 to 416475 longitude and 6437995 to 6498970 latitude covering an area of about 3,767 km^2. The red box in
Figure 3.1 shows the study area.

3.3 Wind Data from Weather Stations in Metropolitan Perth

Historical wind-gust datasets from ten weather stations, were provided by the Bureau of Meteorology’s (BOM) Perth Office. Eight of these are current automatic weather station (AWS) sites. Their geographic locations are shown in Figure 3.1

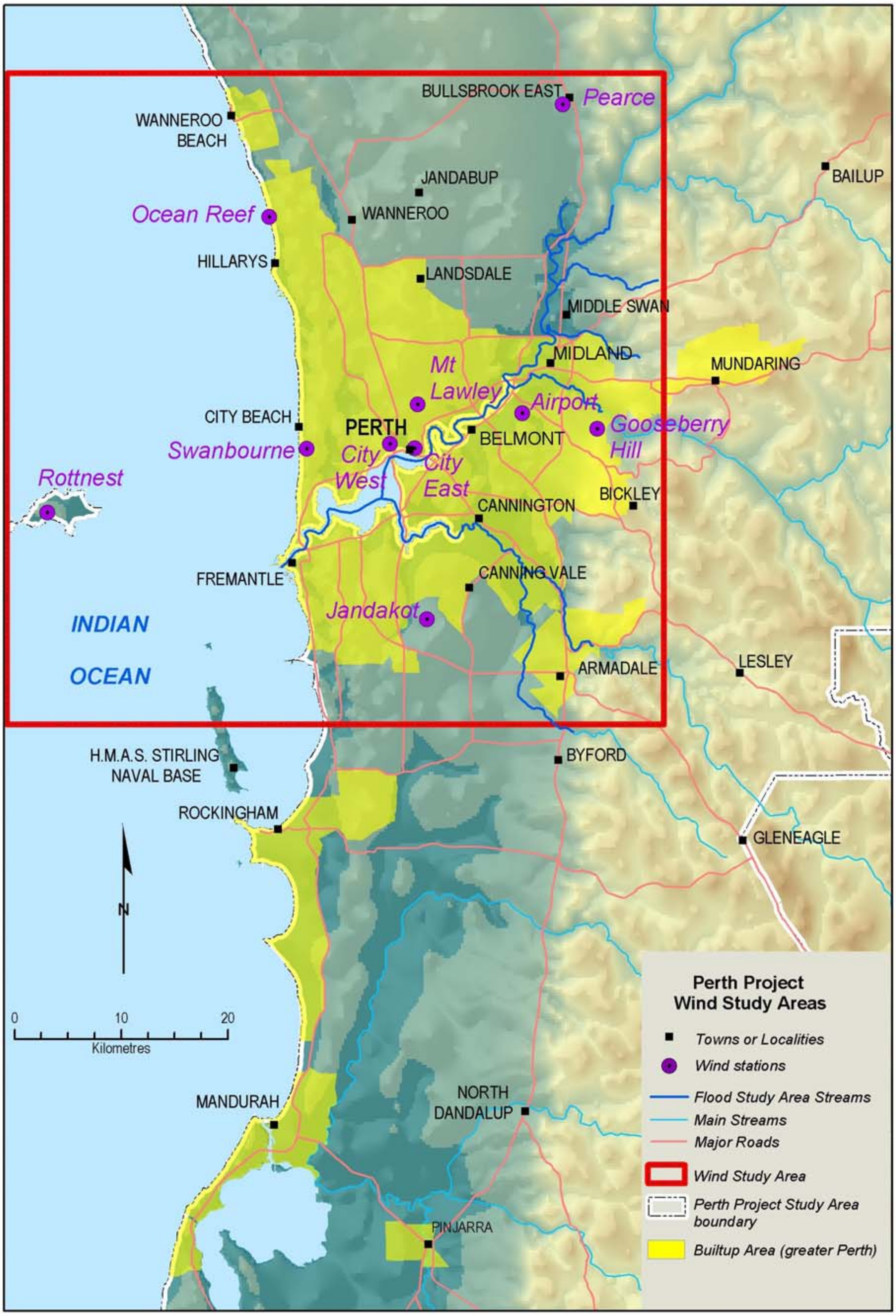

Figure 3.1: The setting of the wind study area in metropolitan Perth

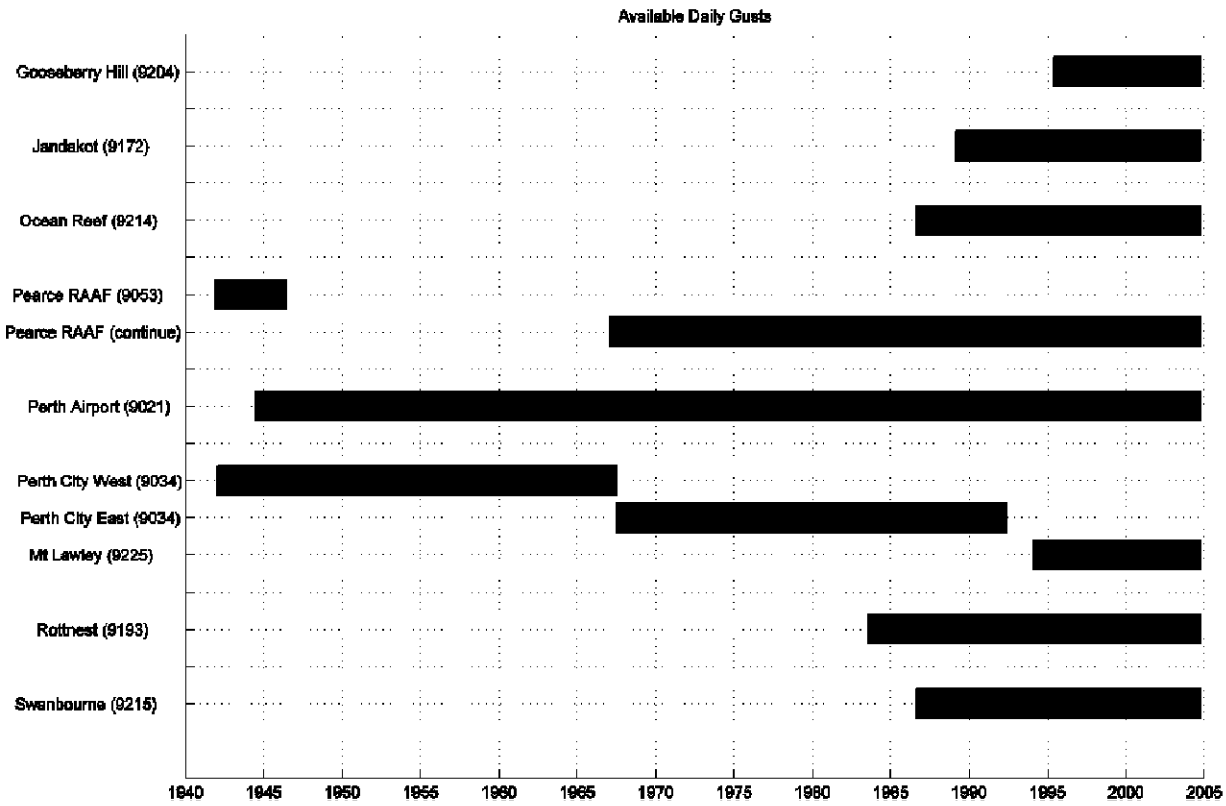

Figure 3.2: The timeline of historical and current weather stations in metropolitan Perth

Table 3.1: Weather station statistics and the historical largest gusts

Station site	**Latitude**	**Longitude**	**Station height**	**Mast height**	**Data length (years)**	**Calendar period**	**Hist max (m/s)**	**Hist max (km/h)**	**Hist max date**
City East	115.8667	-31.95	19	40	24.6	1967–1992	36	130	4/4/1978
Rottnest Is.	115.5	-32.0086	43.1	10	18.2	1983–2004	39.1	141	22/9/1988
Jandakot	115.8794	-32.1011	30.2	10	12.3	1989-2004	31.4	113	7/6/1990
Swanbourne	115.7619	-31.9558	40.96	10	17.9	1986-2004	39.6	143	23/5/1994
Mt Lawley	115.8728	-31.9192	24.9	10	10.6	1994–2004	26.2	94	17/7/1996
Perth Airport	115.9764	-31.9275	15.4	10	60.2	1944-2004	34.5	124	22/7/1990
Gooseberry Hill	116.0506	-31.9414	220	20	8.8	1995-2004	37.6	135	8/6/1995
Ocean Reef	115.7278	-31.7594	10	10	17.8	1986-2004	35	126	19/7/1989
Pearce	116.0189	-31.6669	40	10	35.0	1941-2004	36	130	28/7/1975
City West	115.8453	-31.9508	58	22	25.5	1942-1967	43.2	156	20/8/1963

The period of each station's observations is shown in Table 3.1. The latest wind data from the eight current sites was for 1 October 2004. The average wind speed over a 3-second period is referred to as a 'gust'. The majority of the wind data are daily maximum gusts. The rest of them are 1-minute maxima and 10-minute maxima which have been used to calculate daily maximum gusts for this study. As a by-product of this study, a complete set of daily maximum gusts covering the whole historical period at ten weather stations in Perth has been provided to the BOM for future research and study.

Details of the locations of weather stations and the largest wind gust at each site are listed in Table 3.1. The strongest gust recorded was 43.2 m/s (or 156 km/h) at the City West site in 1963. The longest continuous recording period was over 60 years at Perth Airport. This record was the basis for the wind hazard published in AS/NZS 1170.2 (2002). The shortest continuous recording period was only about 8 years at the Gooseberry Hill site. The current City site at Mt Lawley has also had a relatively short history (about 10 years). The strongest gust recorded at Mt Lawley was 26.2 m/s (or 94 km/h) which was the weakest amongst the ten sites in metropolitan Perth with their various operating time periods.

3.4 Local Wind Effects

The impact of severe wind varies considerably between structures at various locations because of the geographic terrain, the height of the structures concerned, the surrounding structures and topographic factors. These site wind, exposure and speed modifications can be numerically described by so-called wind multipliers. These multipliers give quantitative measures of local wind conditions relative to the regional wind speed (defined as open terrain at 10 m height) at each location. There are three wind multipliers: the terrain/height multiplier (M_z), the shielding multiplier (M_s) and the topographic (or hill-shape) multiplier (M_h). The local site wind speed at a reference height (V_{site}) is estimated by multiplying the regional wind speed (V_R) by the local wind multipliers:

$$V_{site} = V_R \, M_z \, M_s \, M_h \qquad \textbf{Equation 3.1}$$

The local site wind speed is determined separately for each of the eight cardinal directions.

Formulas to estimate these wind multipliers for a given location are given in AS/NZS 1170.2 (2002). However, efficient and effective computational methods to estimate these wind multipliers across a larger area with higher resolution need to be developed. Satellite remote-sensing techniques, geographic information systems (GIS), image analysis software and a digital elevation dataset have been used to apply these formulas to calculate the three wind multipliers. In Figure 3.3 an overview is given of the methodology to develop terrain/height, shielding and hill-shape multipliers for eight cardinal wind directions. The process is described under separate headings below.

Terrain classification mapping

In order to estimate the terrain/height multiplier and the shielding multiplier, a terrain classification map needed to be developed. Terrain classes from AS/NZS 1170.2 Supp 1 (2002) were used to classify the Perth metropolitan area. The following classes were relevant to our wind hazard assessment.

- City buildings
- Forests
- Centres of small towns and industrial areas
- Suburban and wooded country
- Long grass with few trees
- Air fields and uncut grass
- Water
- Sandy beaches
- Cut grass

To map the terrain of the study area, Landsat Thematic Mapper data was used as input. It has 25 m spatial resolution and 6 frequency bands. (Further information about the data specifications can be obtained from the Australian Centre for Remote Sensing (ACRES) website: http://www.ga.gov.au/acres/prod_ser/landdata.htm). The satellite database of bands 432 is depicted in Figure 3.4. The terrain map development process is described in the top left hand corner of Figure 3.3 and the estimated terrain classification map using image software is shown in Figure 3.5.

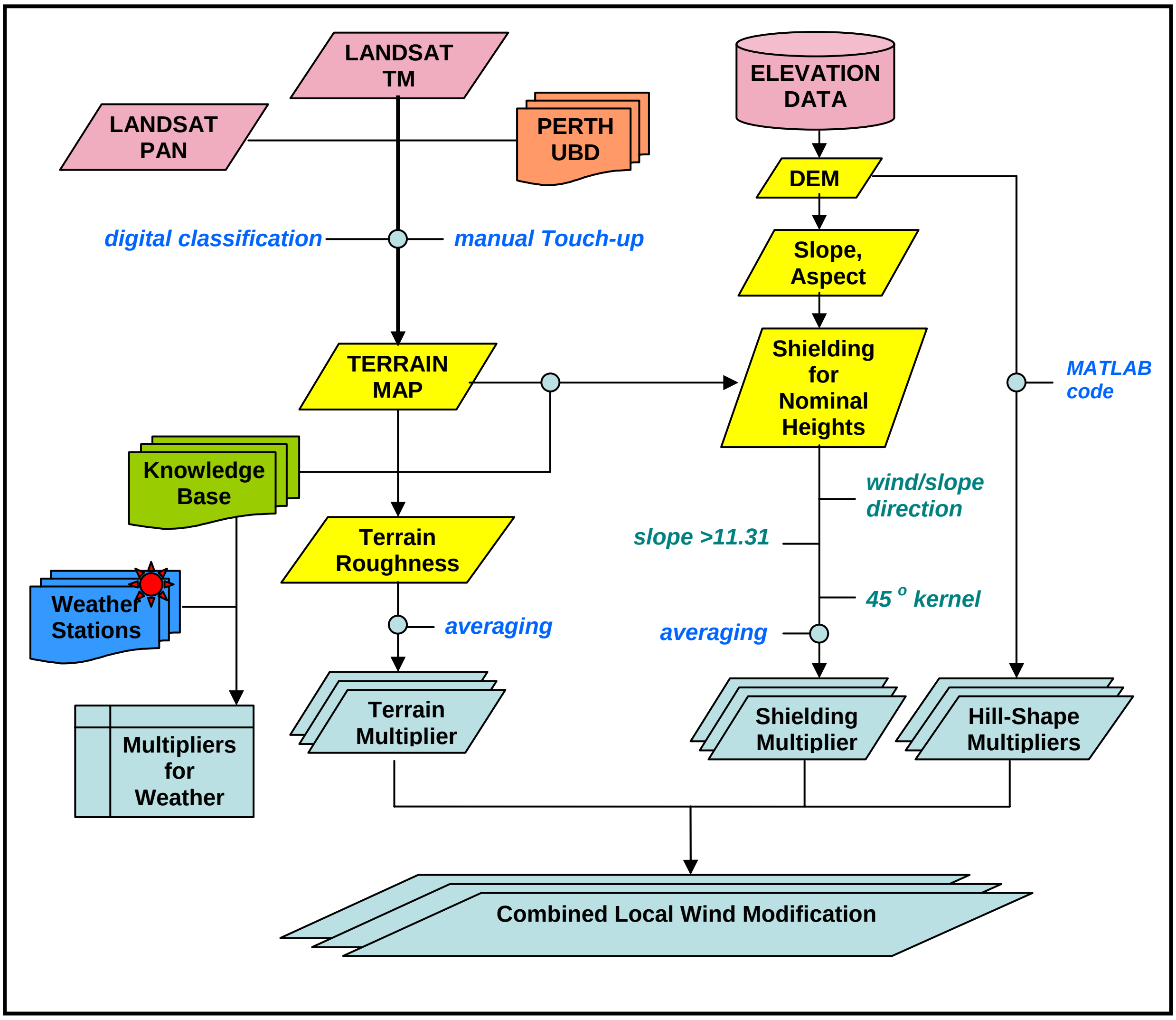

Figure 3.3: Diagram of methodology used in estimation of local wind modification multipliers

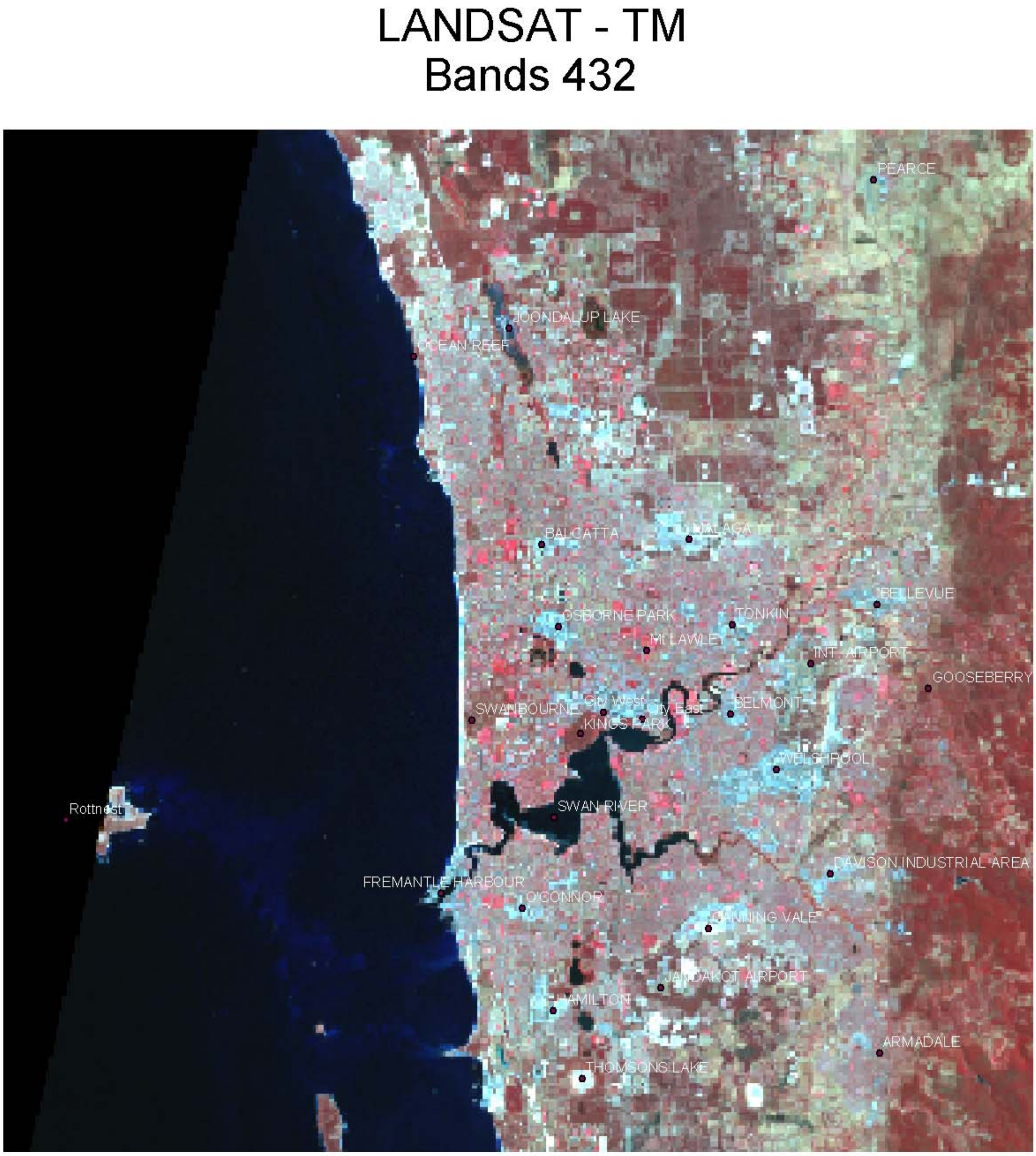

Figure 3.4: LANDSAT satellite database of Bands 432 of metropolitan Perth

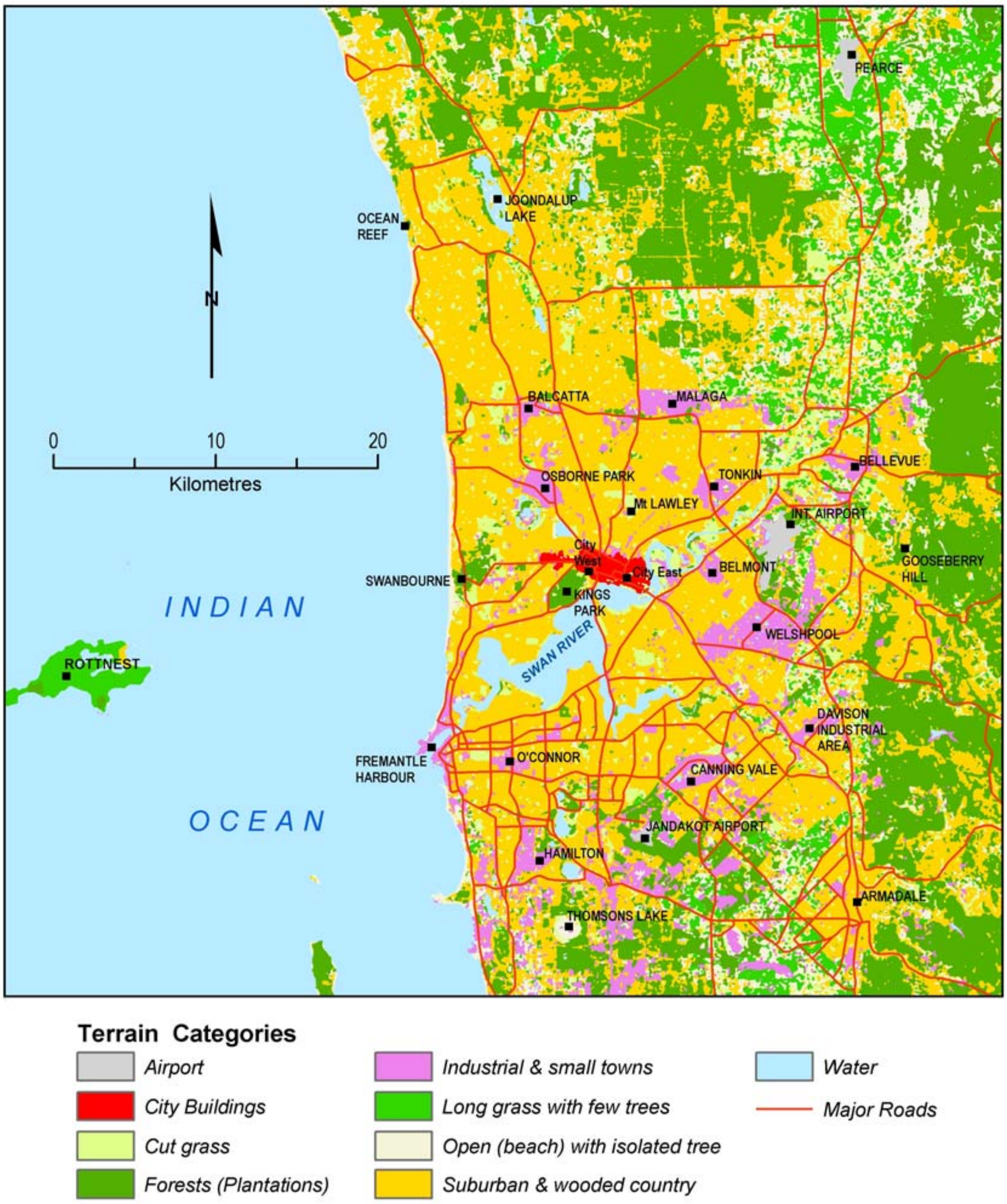

Figure 3.5: Terrain map of Perth wind study area

Table 3.2: The nominated height in each terrain category

Terrain category	Terrain classification	Nominated height (m)	M_z
4	City	50	0.9
	Forest	20	0.794
	Town centre/Industrial	20	0.92
3	Suburb buildings	3–10	0.83
	Trees	<5	0.89
2	Water/Airport	<3	0.91
	Cut grass	<3	0.92

When there are different terrain classifications upwind of a structure of primary interest, the method of averaging described in AS/NZS 1170.2 (2002) was applied. The distance for averaging depends on the height of the structure. However, since the nominated heights for various terrain classifications in the Perth wind study area are all less than 50 m, an averaging distance of 1 km was adopted, following Table 4.2(A) of AS/NZS 1170.2 (2002). Using the averaging method, the terrain/height multipliers were estimated. The process is shown in the bottom left hand side of Figure 3.3 and Figure 3.6 shows the study region M_z values for the wind direction from west to east.

The M_z for AWS sites are listed in Table 3.3. Note that, since we know the exact mast heights of the AWS, these heights were used in the calculation of M_z rather than using the nominated building height for the terrain categories in which they are situated. Also, note that as the City West site was (and is) surrounded by town-centre-like buildings rather than urban city high-rises, the M_z estimated using the current city terrain classification may overestimate the actual terrain effect. After consulting with meteorologists in the BOM Perth Office, a 15% reduction of the M_z derived using the current terrain was adopted for adjusting wind speeds to appropriate terrain category. The M_z values for the City West AWS listed in the last row of Table 3.3 are the adjusted values.

Table 3.3: Terrain/height multipliers M_z for AWS locations

Name	North	NE	East	SE	South	SW	West	NW
City East	0.85	0.94	0.85	0.85	1.02	0.99	0.85	0.85
Rottnest Is.	0.96	0.97	0.96	0.96	0.97	0.96	0.96	0.96
Jandakot	0.93	1.00	0.91	0.92	0.87	0.86	0.95	0.91
Swanbourne	0.80	0.80	0.82	0.86	0.80	0.89	0.89	0.84
Mt Lawley	1.03	0.92	0.88	0.88	0.91	0.84	0.83	0.91
Perth Airport	0.82	0.82	0.94	0.97	0.97	1.00	1.00	0.93
Gooseberry Hill	0.93	0.87	0.91	0.92	0.90	0.86	0.89	0.88
Ocean Reef	0.90	0.84	0.87	0.84	1.00	1.00	1.00	1.00
Pearce	1.00	0.88	0.90	0.96	1.00	1.00	0.99	1.00
City West	0.92	0.87	0.91	0.93	1.06	0.98	0.94	0.87

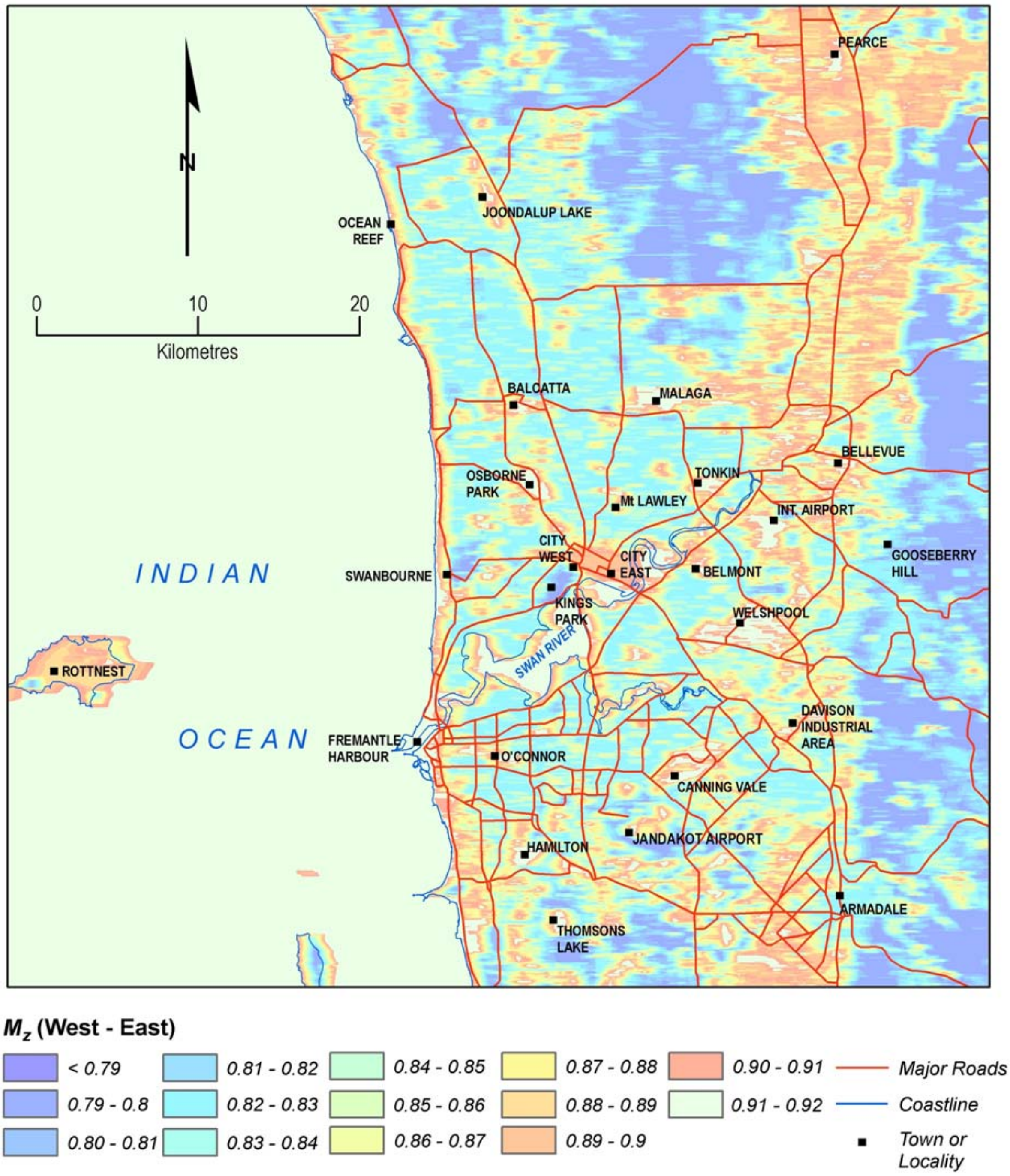

Figure 3.6: Terrain/height multipliers M_z for the wind direction from west to east

Shielding multipliers

The shielding multiplier (M_s) of a structure depends on the number of buildings upwind in a shielding zone with at least the same height as the structure concerned. The shielding zone is defined as a 45 degrees upwind sector area with a radius of 20 times the building height and centred on the building concerned. A formula is provided in AS/NZS 1170.2 (2002) to calculate the shielding multiplier, given the average building height, the number of buildings in the shielding zone and the width of those buildings. Figure 3.7 shows the estimated shielding multipliers for winds from west to east in the study area. For each of the ten weather station sites, manual study of aerial photographs has been carried out for all directions within its shielding zone. It was found that the only shielding multipliers less than unity are for the City East site in several wind directions. Using the formula given in AS/NZS 1170.2 (2002), these M_s have been calculated and checked with meteorologists in the BOM's Perth Office. Table 3.4 lists the M_s for AWS locations.

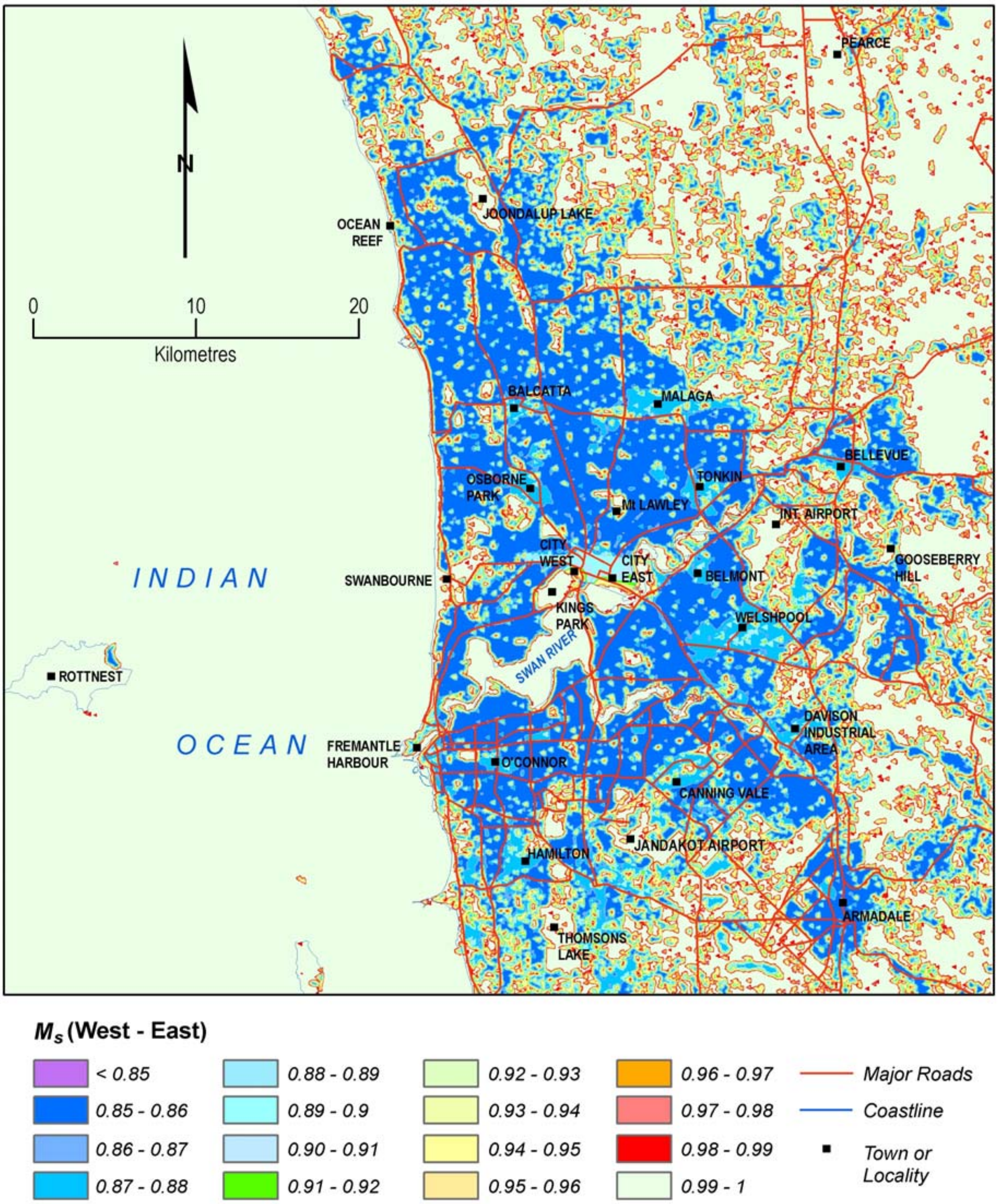

Figure 3.7: Shielding multipliers M_s for the study area

Table 3.4: Shielding multipliers M_s for AWS locations

Name	North	NE	East	SE	South	SW	West	NW
City East	1	1	1	0.91	1	0.86	0.84	0.93
Rottnest Is.	1	1	1	1	1	1	1	1
Jandakot	1	1	1	1	1	1	1	1
Swanbourne	1	1	1	1	1	1	1	1
Mt Lawley	1	1	1	1	1	1	1	1
Perth Airport	1	1	1	1	1	1	1	1
Gooseberry Hill	1	1	1	1	1	1	1	1
Ocean Reef	1	1	1	1	1	1	1	1
Pearce	1	1	1	1	1	1	1	1
City West	1	1	1	1	1	1	1	1

Topographic features of metropolitan Perth

The topographic features of metropolitan Perth have been captured by a digital elevation model (DEM) generated from spot height data at a spacing of 1 minute UTM. The DEM of metropolitan Perth in a 25 m by 25 m grid is shown in Figure 3.8. It can be seen that the majority of metropolitan Perth is gently undulating, except the Darling Range Scarp which is more than 200 m above mean sea level. Note that the Gooseberry Hill weather station was built on the Darling Range Scarp with the purpose of catching the easterly winds.

Topographic wind multipliers

Standing on an uphill slope will normally feel windy comparing to standing on a flat area. This is called the topographic (or hill-shape) wind effect. In wind engineering, it is calculated by multiplying the regional wind speed, V_R, by the topographic (or hill-shape) multiplier M_h. The methodology that uses a DEM to produce the M_h multiplier is shown on the far right of Figure 3.3.

AS/NZS 1170.2:2002 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 defined in the Standard. For the slopes between 5% and 45%, the formula in AS/NZS 1170.2:2002 will provide values for M_h. Table 3.5 gives M_h values for some different 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 or greater than 45% (or 24.2 degrees).

Table 3.5: Hill-shape multiplier at crest ($|x| = 0$) when $z = 0$, from Table 4.4 of AS/NZS 1170.2 (2002)

Hill slope (%)	Hill slope (degrees)	M_h
< 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

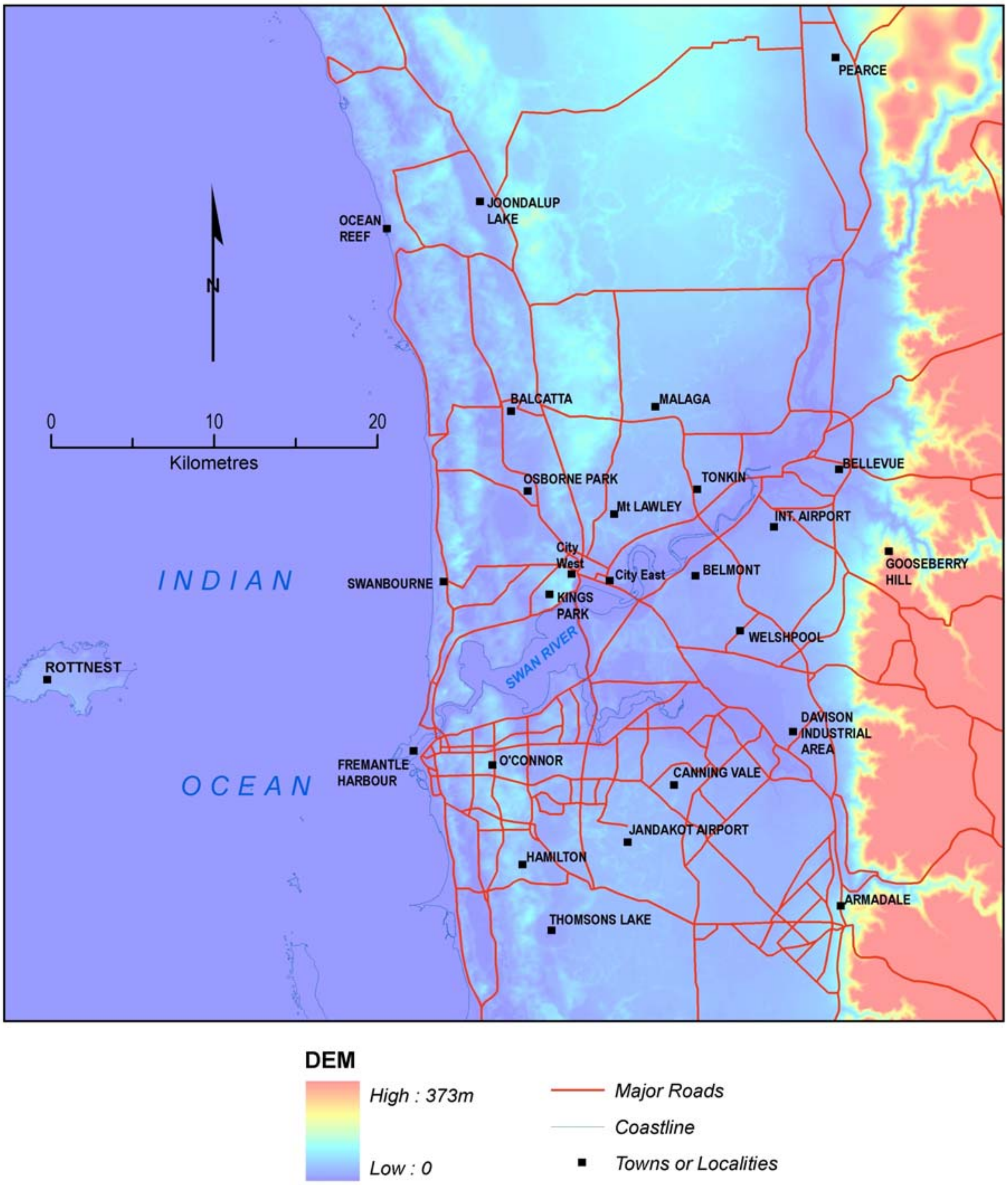

Figure 3.8: The elevation (m) of metropolitan Perth in a 25 m by 25 m grid

In calculating M_h for metropolitan Perth, the height of the structure above the local ground level was set to zero. There were three reasons to do this. First, the estimate of a hill-shape multiplier is required for every point within the study area of metropolitan Perth, whether it currently has a building on it or not. So a building height may not currently exist. Secondly, even in the case of an existing building, in general we do not know the height of the building without a physical building survey having been done. Thirdly, the M_h value has been found to be insensitive to the height of the building.

The 8-directional topographic wind multipliers for metropolitan Perth on a 25 m by 25 m grid have been estimated. Among them, the M_h for west to east is shown in Figure 3.9. The M_h values of AWS sites have been estimated using the DEM on grids. Note that for each site, the nearest grid point has been used to represent the true AWS location. Table 3.6 shows the values of M_h for each AWS site in each direction.

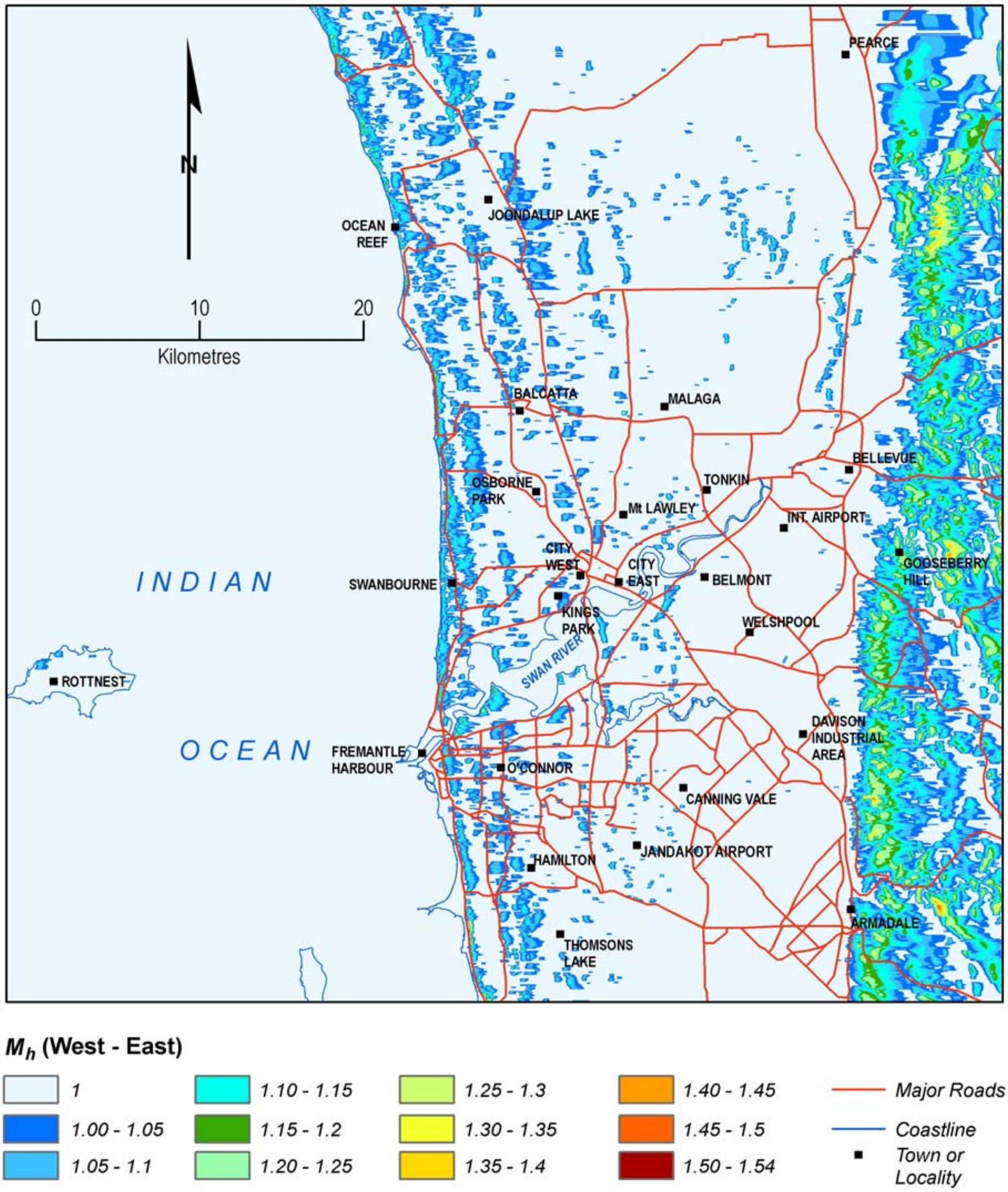

Figure 3.9: the M_h of metropolitan Perth from west to east

Table 3.6: Hill-shape multiplier M_h for AWS locations

Name	North	NE	East	SE	South	SW	West	NW
City East	1.00	1.00	1.04	1.00	1.00	1.00	1.00	1.00
Rottnest Is.	1.11	1.14	1.13	1.10	1.09	1.11	1.09	1.07
Jandakot	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Swanbourne	1.06	1.08	1.09	1.08	1.00	1.09	1.12	1.14
Mt Lawley	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Perth Airport	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gooseberry Hill	1.25	1.35	1.30	1.03	1.31	1.42	1.27	1.29
Ocean Reef	1.00	1.00	1.00	1.00	1.00	1.08	1.01	1.02
Pearce	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
City West	1.09	1.12	1.17	1.18	1.00	1.00	1.00	1.00

Combined local wind effects

The combined local wind effect multiplier (named *M3*) was obtained by multiplying the three individual multipliers M_z, M_s and M_h together for each wind direction. Figure 3.10 displays the *M3* of the study area with the wind direction from west to east.

Table 3.7 lists *M3* for all AWS sites for each wind direction. Using this table, the speed of each recorded gust has been adjusted by dividing by the corresponding *M3* according to the wind direction the gust was coming from. Equation 3.1 has been solved for V_R using the observed weather station wind speed V_{site}. This converts historically recorded wind speeds to the standard condition of open level terrain and a 10 m observation height. When the station mast height (see Table 3.1) was not at the standard height of 10 m, a speed–height conversion was also made using the following relationship (Whittingham, 1964):

$$V_{10m} = V_h \left(\frac{10}{h} \right)^{\frac{1}{8}}$$ **Equation 3.2**

By using Equations 3.1 and 3.2, a new set of adjusted daily gusts has been generated for each AWS site. It was used for the return period analysis discussed in the next section.

It should be pointed out that the gust that was strongest before adjustment may differ from the gust that was strongest after adjustment. For instance, at Pearce, a 20 m/s gust from the north would give an adjusted speed of 20 m/s, because *M3*=1.00, but an 18 m/s gust from the NE would give an adjusted speed of 18/0.88 = 20.45 m/s.

Table 3.7: Combined local wind multipliers (*M3*) for AWS locations for eight wind directions

Name	North	NE	East	SE	South	SW	West	NW
City East	0.85	0.94	0.88	0.77	1.02	0.86	0.71	0.79
Rottnest Is.	1.07	1.11	1.09	1.06	1.06	1.07	1.05	1.03
Jandakot	0.93	1.00	0.91	0.92	0.87	0.86	0.95	0.91
Swanbourne	0.85	0.86	0.89	0.93	0.80	0.98	1.00	0.95
Mt Lawley	1.03	0.92	0.88	0.88	0.91	0.84	0.83	0.91
Perth Airport	0.82	0.82	0.94	0.97	0.97	1.00	1.00	0.93
Gooseberry Hill	1.16	1.17	1.18	0.95	1.17	1.22	1.13	1.13
Ocean Reef	0.90	0.84	0.87	0.84	1.00	1.08	1.01	1.02
Pearce	1.00	0.88	0.90	0.96	1.00	1.00	0.99	1.00
City West	1.00	0.98	1.06	1.10	1.06	0.98	0.94	0.87

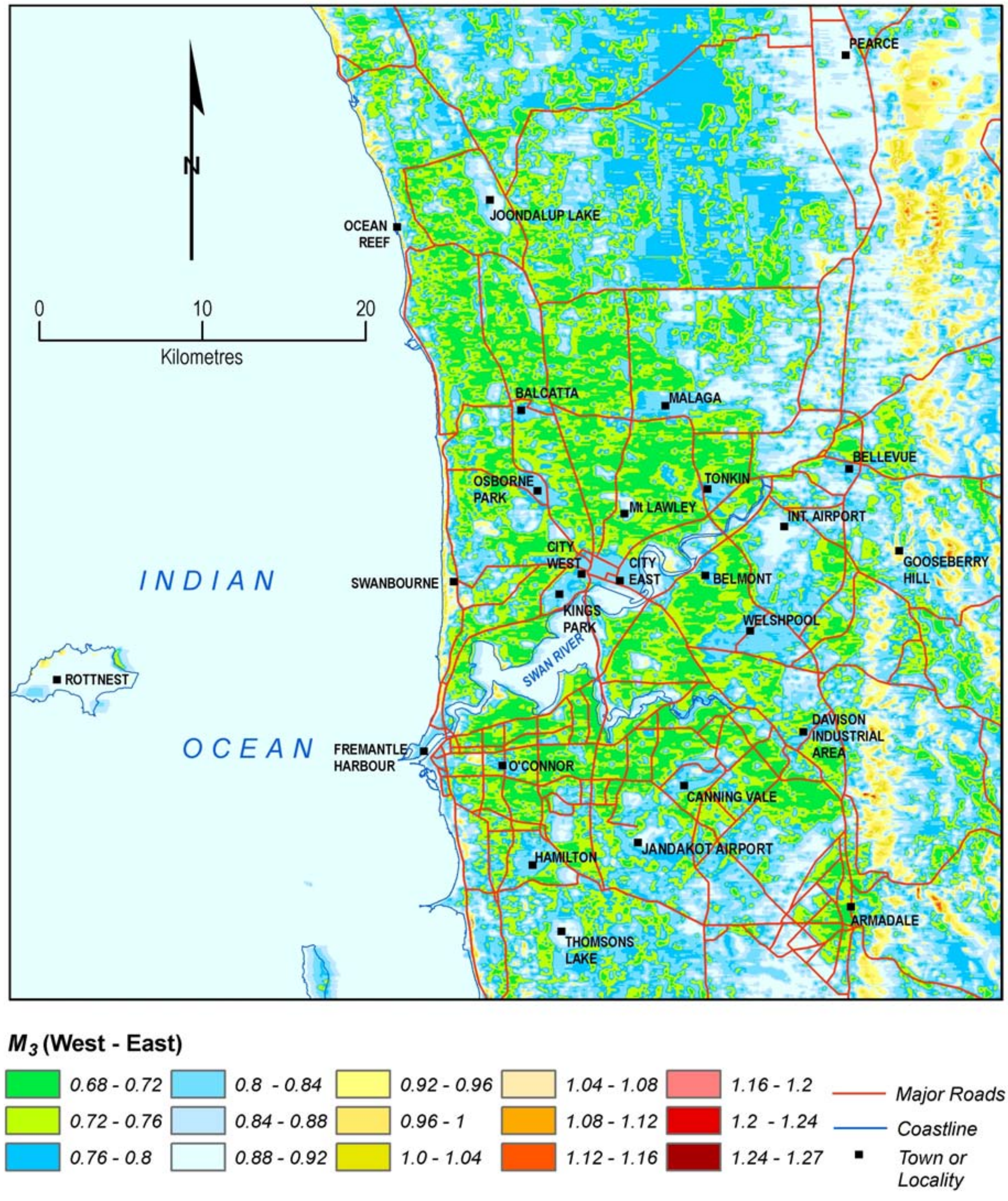

Figure 3.10: Multiplier *M3* for wind from west to east for the study area

3.5 Return Period Wind Speed Estimation

Extreme value theory is a statistical technique for describing one tail of the distribution of unusual (extreme) events rather than the usual events. It includes data fitting (or model parameter estimation) and quantile estimation. Sensitivity analysis is also carried out to examine the uncertainty of these speed estimates.

Extreme value analysis

Classical extreme value theory is based on the analysis of the largest (or smallest) value in an epoch. In wind engineering, an epoch is assumed to be a calendar year. The yearly maximum wind gust is usually used as data input for classical extreme value analysis. However, if the amount of data recorded is too small, monthly maxima may also be used.

Classical extreme value theory is based on three asymptotic extreme value distributions identified by Fisher and Tippett (1928). The generalized extreme value (GEV) distribution introduced by Jenkinson (1955) combines the three distributions into a single mathematical form. A brief description of GEV is given in the appendix.

In the past 20 years a new body of extreme value theory has been developed, called ‘peaks over threshold’ (POT) modelling. This theory allows for the use of all available data exceeding a sufficiently high threshold. A brief introduction to POT is given in Lin (2003).

An attempt was made to apply the POT method to the Perth wind dataset, but the results were not satisfactory. Return period wind speeds seemed to be underestimated by about 10–20%. There are two possible reasons for this. First, the POT method assumed independent events. However, a storm may continue for up to two or three days at a time, generating 2–3 large daily maximum gusts. Such data are not independent of each other. A technique called ‘de-clustering’ was developed to extract the largest gust within a given time window (e.g. three days). However, after this was done, return period wind speeds still seemed to be underestimated.

The second reason is the difficulty in choosing the threshold value. Using a smaller threshold value might allow the model to fit normal events well, but fail to fit the extreme ones. However, using a higher threshold value might leave insufficient data points to fit the model. Available techniques such as the sample mean excess function have been applied to the dataset, but it did not show a clear linear trend. This suggests that the dataset is not suitable for the POT method. This may need further investigation.

The technique of GEV has therefore been adopted in this study to estimate the return period wind speeds.

An introduction to extreme value theory can be found in Embrechts *et al.* (2001) and Colse (2001). A review of methods for calculating extreme wind speeds using extreme value techniques can be found in Palutikof *et al.* (1999).

Fitting Perth wind dataset to a GEV

Yearly and monthly maximum gusts have been recalculated from the adjusted daily gusts. When the lengths of datasets were shorter than ten years, only the monthly maximum gusts were fitted since there were too few points in the yearly data to compute a reliable estimate. These maxima were then fitted to a GEV and its parameters estimated. (See Appendix A for information on data fitting methods and the general function of GEV.)

After a GEV distribution has been fitted, the return period wind speeds were then calculated for given time periods with the results given in the next section.

There are a few issues that require discussion here. Firstly, there are three city weather station sites in Perth City: City West, City East and Mt Lawley. The first two sites have about 25 years of data each, while Mt Lawley has only about 10 years. Also, the strongest daily gust in Mt Lawley was only 94 km/h comparing to 156 km/h in City West and 130 km/h in City East. If we fit these three sites separately, they will have quite different return period wind speeds but they are physically located close to each other. Another important point about these three sites is that they were never operated in parallel. Rather, they have been used one after another, because one replaced another. One logical way to handle this issue is to combine the adjusted daily gusts for these three sites together to form a 'super city' site with about 60 years of data. This approach was adopted with the 'super city' weather station site nominally placed at the geometric centre of these three sites. Extreme value analysis was then performed on adjusted data contributed from three cities sites.

Secondly, it should be pointed out that return period wind speed estimation is based on fitting historical wind gusts with extreme value distributions. Hence, it is subject to uncertainties within the data and the nature of wind gusts. The recorded daily maximum gusts at each site represent a very localised phenomenon. Each one only indicates an instantaneous wind speed at a particular location at a particular time. It may only be used with some uncertainty to represent other locations (even locations nearby) or other time periods (either before or afterwards). For example, the largest historical gust was 156 km/h at the City West site recorded in 1963. It was under the historical terrain condition prevailing more than 40 years ago. The current wind environment characteristics, including surrounding buildings and terrain (vegetation), may be quite different to those of 40 years ago.

Thirdly, the estimates are subject to data fitting errors. Particularly, when the data periods are smaller than 20 years, the fitting error and uncertainty can be quite large. A number of techniques have been applied to reduce/contain the fitting error and to estimate the uncertainty. Several fitting methods have been used and the maximum value of return period wind speed derived from different methods has been adopted. Furthermore, statistical hypothesis tests have been performed to make certain the statistical basis of choosing the underline extreme value distribution is statistically sound. Finally, sensitivity analysis has been carried out at selected sites by removing/replacing the historical largest gusts, by adding artificial large gusts and by halving the datasets.

Fourthly, predictions based on historical data are somewhat uncertain because of the effect of long-term weather variation and global warming. In particular, recent research (Li *et al.*, 2005) has shown a change point in weather patterns around 1965 in southwest Western Australia, including metropolitan Perth. It claims that the mean sea level pressure (MSLP) had increased in the mid-latitudes while rainfall had decreased after 1965. With the increased MSLP, the westerly winds are expected to have decreased.

Estimated return period wind speeds

The 50, 100, 500 and 1000-year return period regional wind speeds (in m/s) are listed in Table 3.8, together with the historical largest gusts at each site for comparison.

Return period wind speeds are also given in Australian wind loading standard (AS/NZS 1170.2, 2002). In the standard, Perth is located in Region A which has the return period wind speeds listed in Table 3.9. We understand that the wind data used in the analysis were from Perth Airport. We have therefore included our estimates for the airport in Table 3.9 for comparison purposes. It can be seen that they are very similar. However, looking at Table 3.8, the return period speeds at coastal sites and the city site (which is closer to the coast than the airport site) are much greater than those for the airport. This suggests that return period speeds may be underestimated if the speeds estimated for the airport are applied to the whole of metropolitan Perth.

Table 3.8: Historical largest gusts and return period wind speed estimations (m/s) for open terrain at 10 m height

AWS site	Data length (years)	Record period	Hist max (m/s)	Hist max (km/h)	50y V	100y V	500y V	1000y V	50y V (90–04)
Super City	60.7	1942–2004	43.2	156	44	47	53	56	
Rottnest Is.	18.2	1983–2004	39.1	141	39	40	41	42	38
Jandakot	12.3	1989–2004	31.4	113	36	37	39	40	36
Swanbourne	17.9	1986–2004	39.6	143	45	47	54	56	45
Perth Airport	60.2	1944–2004	34.5	124	38	40	45	47	42
Gooseberry Hill	8.8	1995–2004	37.6	135	31	32	33	33	
Ocean Reef	17.8	1986–2004	35	126	44	46	53	55	44
Pearce	35.0	1941–2004	36	130	38	40	45	47	34

The last column in Table 3.8 shows the regional 50-year return speeds estimated using the data for 1990–2004. There are two uses for these figures. First, they show the estimated return speeds for a consistent time period. The fact that they are quite different indicates that the windfield does differ from location to location. Secondly, comparison may be made to the 50-year return speeds (as shown in the sixth column of Table 3.8) using all available data. Two locations show differences; the airport site (38 m/s vs 42 m/s) and Pearce (38 m/s vs 34 m/s).

Table 3.9: Comparison of estimated return period wind speeds with those given in the Australian Wind Standard

Estimated return period wind speed	50y V (m/s)	100y V (m/s)	500y V (m/s)	1000y V (m/s)
Region A, Australian Wind Standard	39	41	45	46
Perth Airport	38	40	45	47

Model validation

An important question when considering any numerical model of a complex physical process is the reliability and appropriateness of the chosen model. Graphical methods are commonly used in model validation. Two popular methods involve plotting cumulative distribution functions (CDF) and quantile–quantile plot (QQ-plot). Both of these methods have been used to validate the statistical models generated.

Sensitivity analysis

Sensitivity analysis is a way of quantifying the uncertainty in the estimates. The form of sensitivity analysis conducted was to investigate the effects of omitting the largest gusts and of changing the length of the data period. To simplify this task, the sensitivity analysis was done using the original gust dataset rather than the adjusted dataset.

It was suspected that the single data record of 156 km/h at City West has played a significant role in the return period wind speed estimation at the site. To test the effect of this large gust record, it was removed from the City West dataset and the extreme value analysis was conducted again. The resulting estimates are listed as the second row in Table 3.10. It can be seen that the 50-year and 100-year return wind speeds have been reduced from 46 m/s and 49 m/s to 45 m/s and 48 m/s, respectively. The effect of a single large data point is not as significant as was expected.

Next, instead of removing this data point, it was added into the dataset for the City East, Mt Lawley and Perth Airport sites. Table 3.10 shows that the effect of adding this larger gust is about 2–5 m/s (or 7.2–18 km/h) speed difference. A 5 m/s effect was obtained at Mt Lawley site, where the original largest wind gust was only 26.2 m/s (94 km/h), much smaller than the 156 km/h point added. The short data period at Mt Lawley has probably also contributed to a larger difference (with and without the 156 km/h gust) than at the other two sites (City East and Perth Airport).

The second series of sensitivity analysis has been done in order to examine the effects of the length of datasets. The longest dataset (the airport site) has been divided into 2 subsets of about 30 years each. From Table 3.10, it can been seen that the earlier 30-year period gives estimates of 35 m/s and 36 m/s as the 50-year and 100-year return winds, about 2 m/s smaller than the original estimates arrived at using the full 60 years of data. The second 30 years of data gives the same result as the whole dataset for 50-year return speed: a slightly larger estimated 100-year return period speed (40 m/s versus 38 m/s). This is not surprising since the strongest gust (124 km/h) is in this second 30-year period.

Finally, the airport dataset has been divided into four smaller sets, each of about 15 years of wind gust records. The results from this sensitivity analysis can be seen in Table 3.10 and are not particularly surprising. Two datasets have 50-year and 100-year return period estimates of 35 and 36 m/s each, the same as the for first 30 years of data but 2 m/s slower than the original dataset. The other two datasets have higher value of estimates (39 and 41 m/s), possibly due to the occurrences of a larger wind gust in the relatively short period (15 years).

Table 3.10: Results from the sensitivity analysis

Based on original data	Sensitivity analysis	50y V (m/s)	100y V (m/s)
City West		46	49
	City West (remove 156 km/h)	45	48
City East		42	45
	City East (add 156 km/h)	44	47
Mt Lawley		27	29
	Mt Lawley (add 156 km/h)	32	34
Perth Airport		37	38
	Airport (add 156 km/h)	39	40
	Airport (earlier 30 years)	35	36
	Airport (later 30 years)	37	40
	Airport (1st 15 years)	35	36
	Airport (2nd 15 years)	39	41
	Airport (3rd 15 years)	35	36
	Airport (4th 15 years)	39	41

Some general conclusions from the sensitivity analysis are as follows:

- Single large data points have some influence on the estimated return period speeds, but such influence is not excessive. In other words, higher estimates of return period speeds come from a number of large events, not just one.
- Estimating return period speeds from a short dataset are highly sensitive to its largest gusts. If the largest gusts were not very much bigger in value, it may lead to a smaller (underestimated) return period speed. Mt Lawley may be such a case: it only has about 10 years of records with the largest gust only 26.2 m/s. Hence, its estimated 50-year and 100-year return wind speeds are only 27 and 29 m/s, and are quite possibly underestimated. On the other hand, if there are several bigger gusts in a relative short period, the estimates tend to give larger (overestimated) return wind speeds. Swanbourne may be an example of this.
- This may partially answer the question of why these three coastal sites (Swanbourne, Ocean Reef and Rottnest Island) have similar wind conditions and similar operating periods, but their estimates were quite different. Swanbourne's estimates are higher than the other two coastal sites (see Table 3.8). This was probably due to the concentration of bigger gusts in a short period. This is also reflecting the uncertainty (or estimate errors) associated with a short time period. These three coastal sites may warrant further investigation.

Interpolation of estimated return period wind speeds to all of metropolitan Perth

Using the return period wind speeds at the eight AWS sites (Table 3.8), several interpolation methods were used to estimate return period wind speeds at grid points. However, the results were not consistent with accepted meteorological knowledge. After consulting with meteorologists in BOM Perth office, a wind spatial profile suitable for metropolitan Perth was developed. It includes a series of north–south strips starting from the coastline and stepping down towards the interior. This follows the principle of gradually decreasing wind energy as wind travels further away from the water with surface/terrain friction having a significant effect. The estimated return speed values at the eight AWS sites (see Table 3.8) have been used in setting up the heights (speed values) of these strips. Minor speed adjustments have also been made to satisfy the principle that wind speed decreases with distance from the coast. Figure 3.11 shows the interpolation of 50-year return period speeds in open terrain at 10 m height. The speeds in brackets are the AWS estimates given in Table 3.8 for comparison with the colour strips (indicating the interpolated return speeds) in which they are located.

Directional return period wind speeds

The return period wind speeds estimated in the previous section are not directional. The available data were not adequate to support estimation of directional return period wind speeds, essentially because the available daily maximum gusts are one record per day, not one direction per day.

A practical way of estimating directional return period wind speeds is to use the direction multipliers M_d published in Table 3.2 of the Australian wind loading standard (AS/NZS 1170.2, 2002). The column for Region A1, which includes Perth, is reproduced in Table 3.11.

Table 3.11: Wind direction multiplier (M_d) from AS/NZS 1170.2 (2002)

	North	NE	East	SE	South	SW	West	NW
M_d for Region A1	0.90	0.80	0.80	0.80	0.85	0.95	1.00	0.95

These may then be multiplied by the combined local wind multipliers (*M3*) which were calculated earlier. Hence the overall procedure for finding local directional return period wind speeds is to multiply the grid return period speed (from interpolation) by the wind direction multiplier and the combined local wind multiplier:

$$V_{site,d} = V_{10m} \; M_d \; M3 \qquad \textbf{Equation 3.3}$$

Using this equation, the return period speed at each grid in each direction can be estimated. Figure 3.12 displays the grid 50-year return speeds for westerly winds.

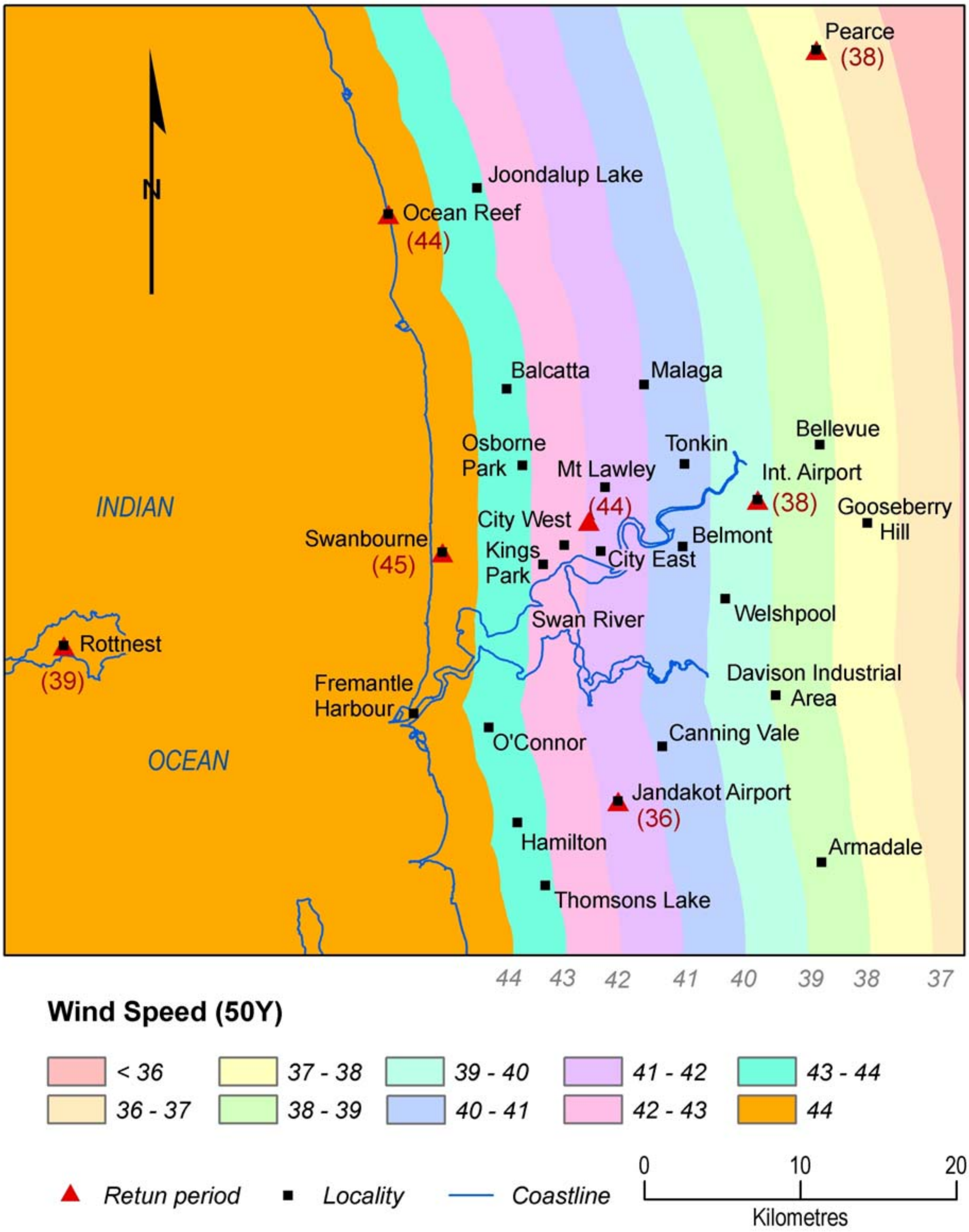

Figure 3.11: The interpolation of 50-year return period speeds for open terrain at 10 m height

Maximum non-directional return period speeds

Since we do not know the orientation of buildings other than those surveyed, directional return period speeds will be difficult to use quantitatively. The purpose of wind risk assessment is to quantitatively estimate the cost of replacing and repairing structures after a return period wind has blown. A maximum non-directional speed may be used to assess possible building damage within a return period. This maximum return period wind speed in every direction at each grid point was calculated using the following equation:

$$V_{site,\max} = \max_{d} V_{site,d} \qquad \textbf{Equation 3.4}$$

Figures 3.13 – 3.16 show the calculated maximum non-directional 50, 100, 500 and 1,000-year return period speeds, respectively. These are the estimated wind hazard maps for metropolitan Perth. They provide valuable wind hazard information for city planning, risk management, emergency management and the like. When building damage models appropriate for Perth construction become available and combined with the building cost models, a quantitative wind risk assessment can be achieved.

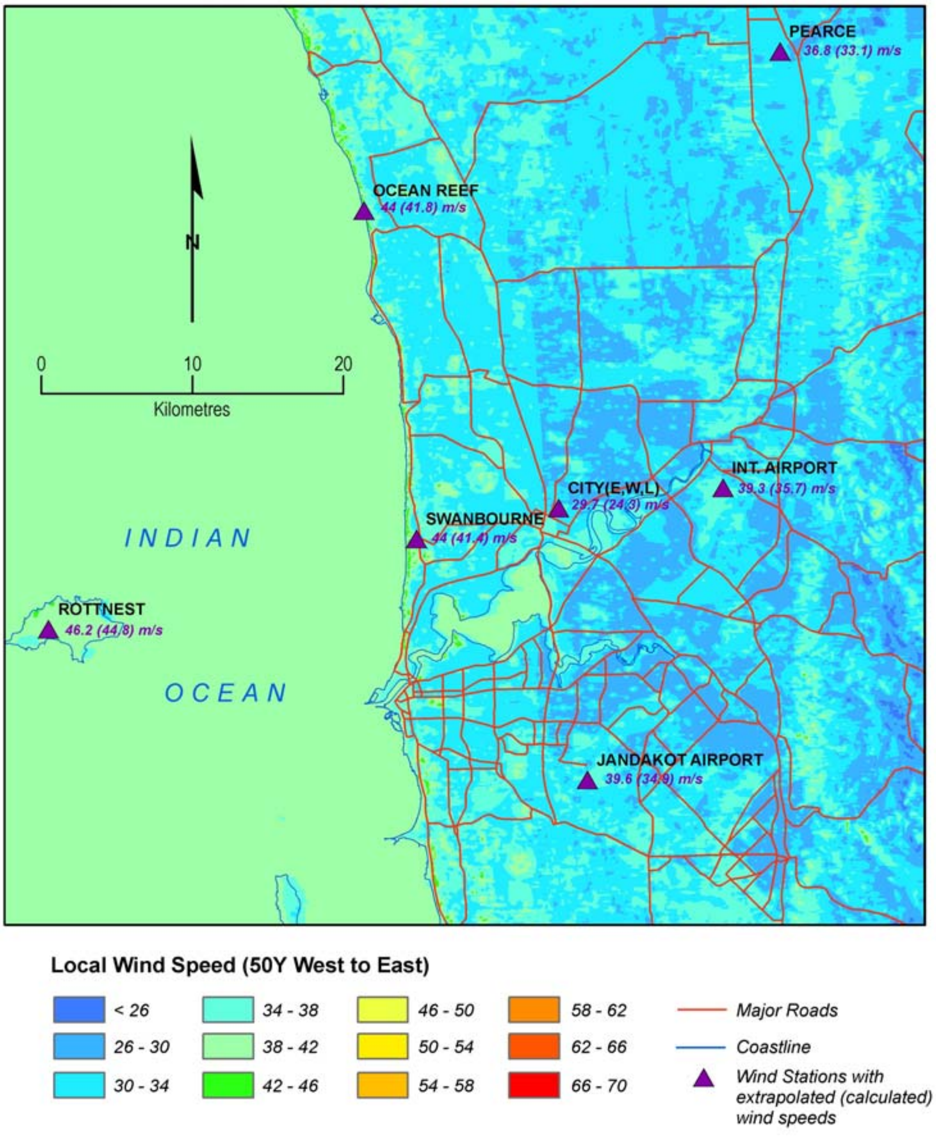

Figure 3.12: Estimated local 50-year return period speed for wind from west to east

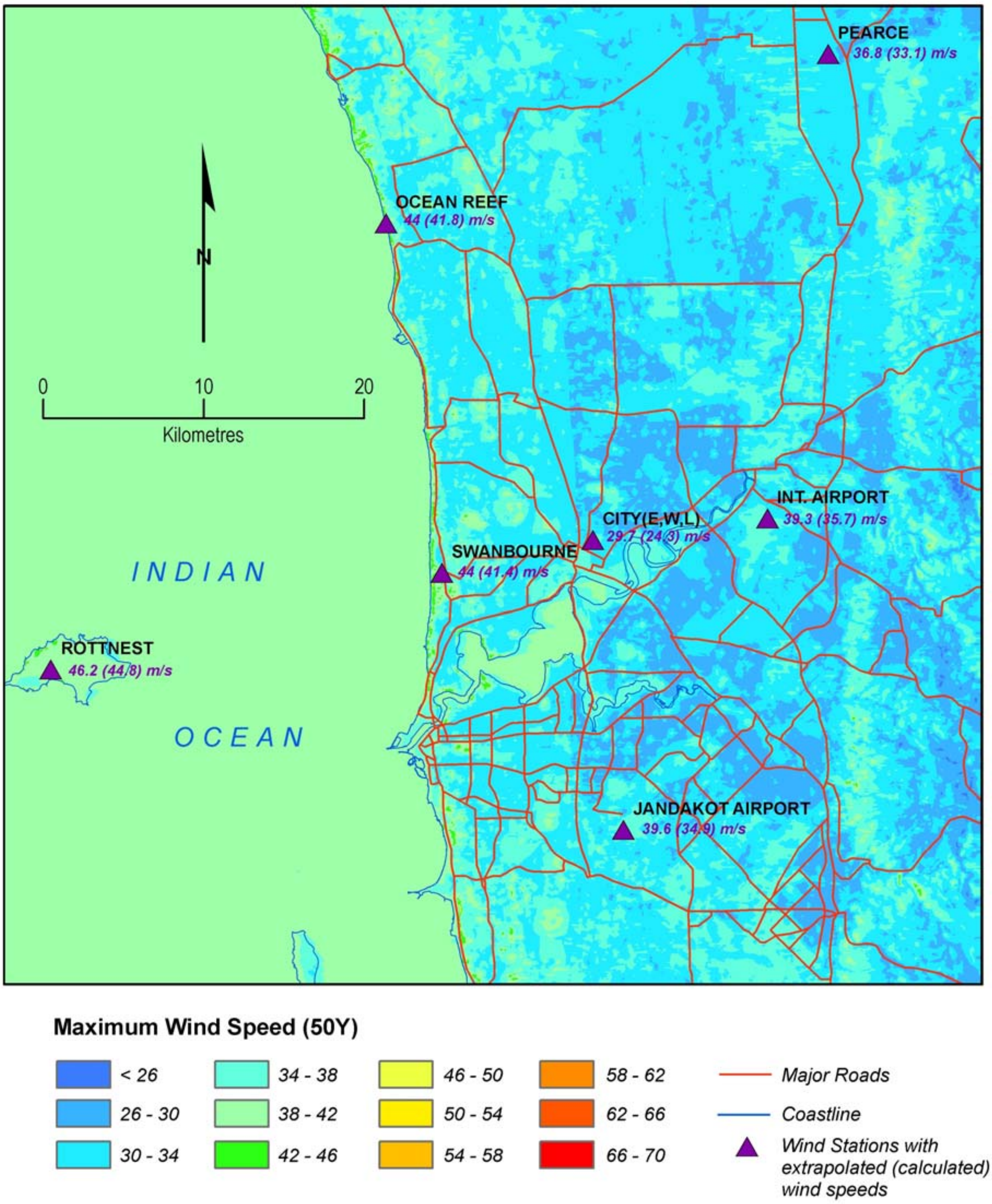

Figure 3.13: Maximum non-directional 50-year return period speeds

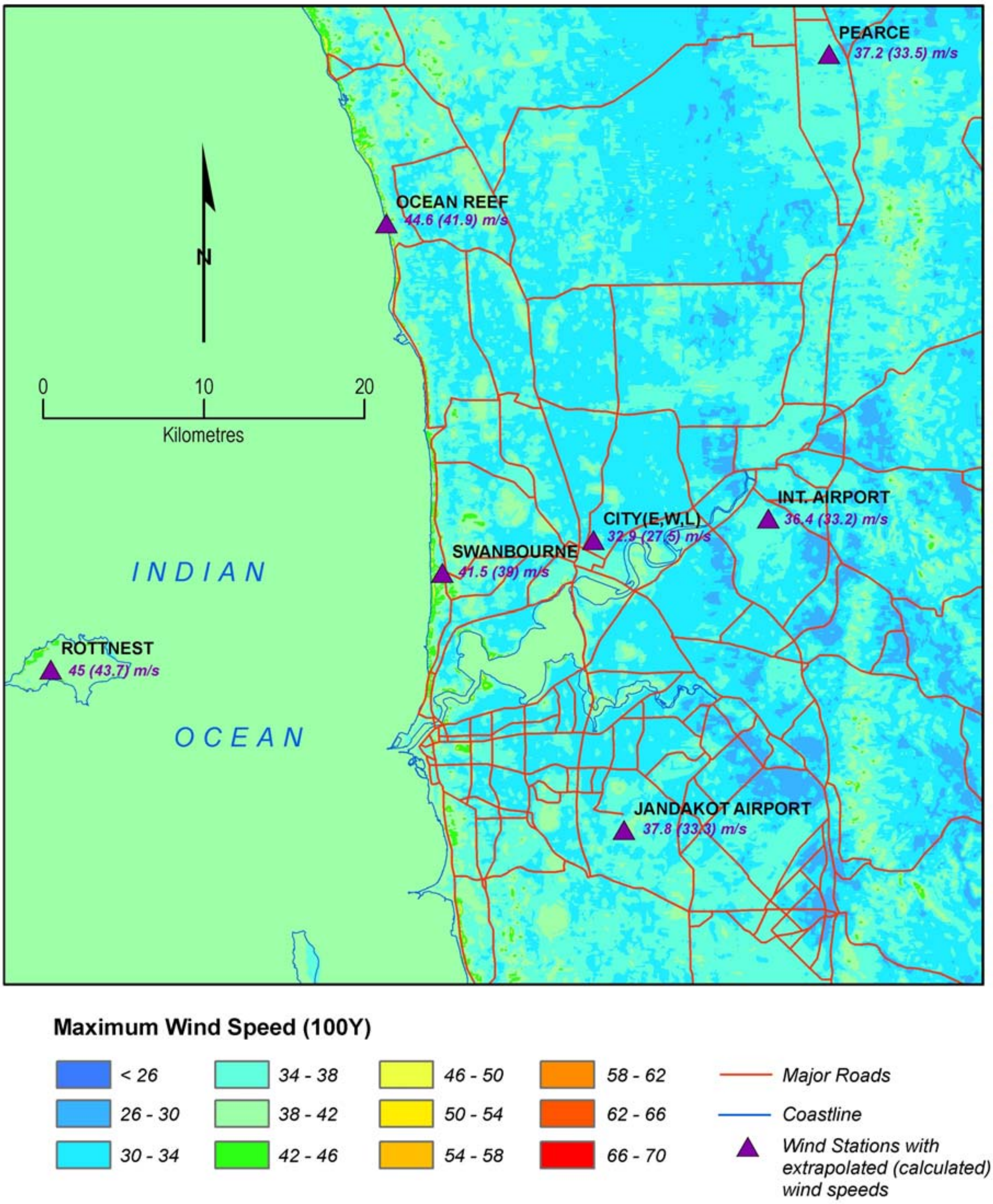

Figure 3.14: Maximum non-directional 100-year return period speeds

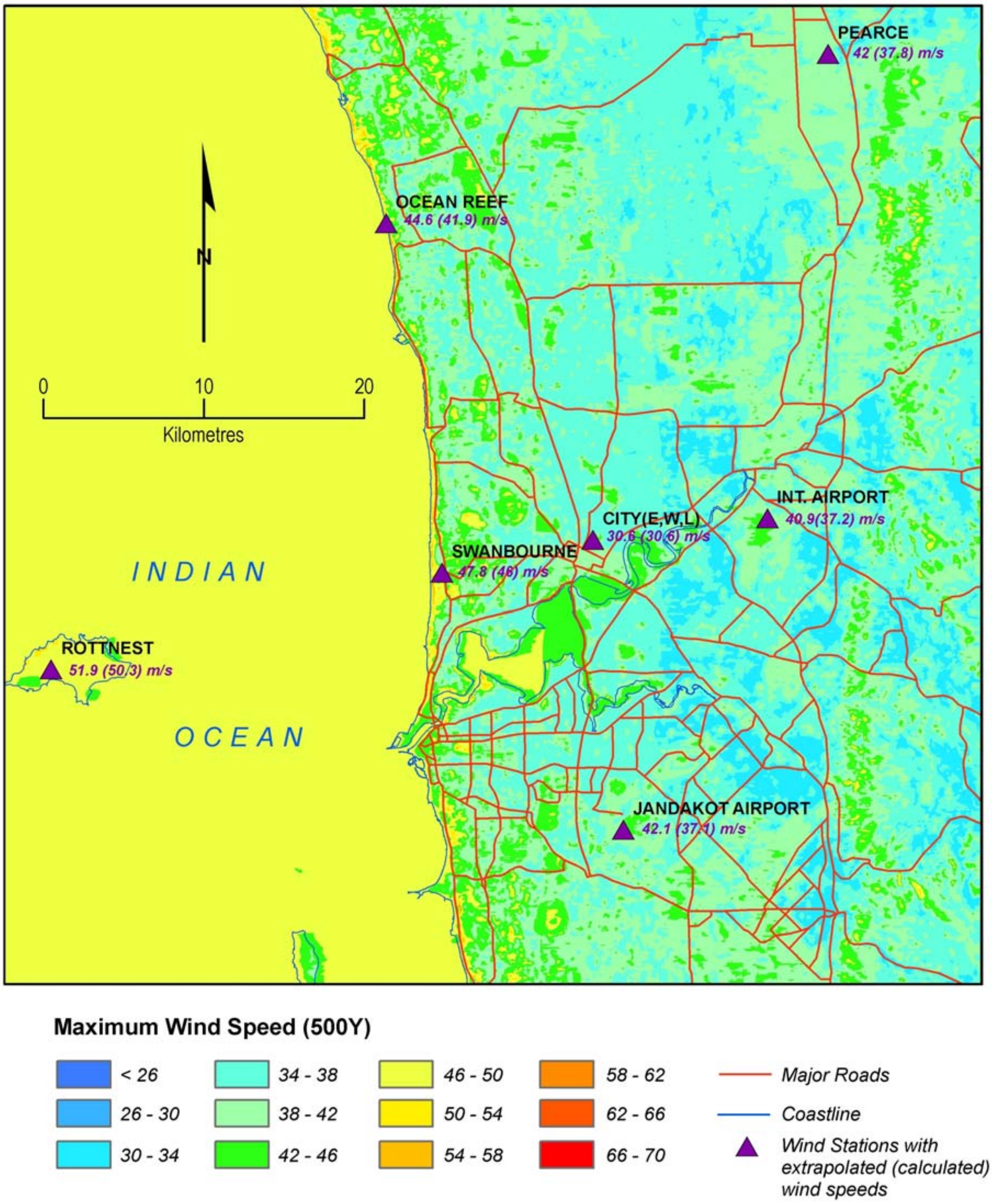

Figure 3.15: Maximum non-directional 500-year return period speeds

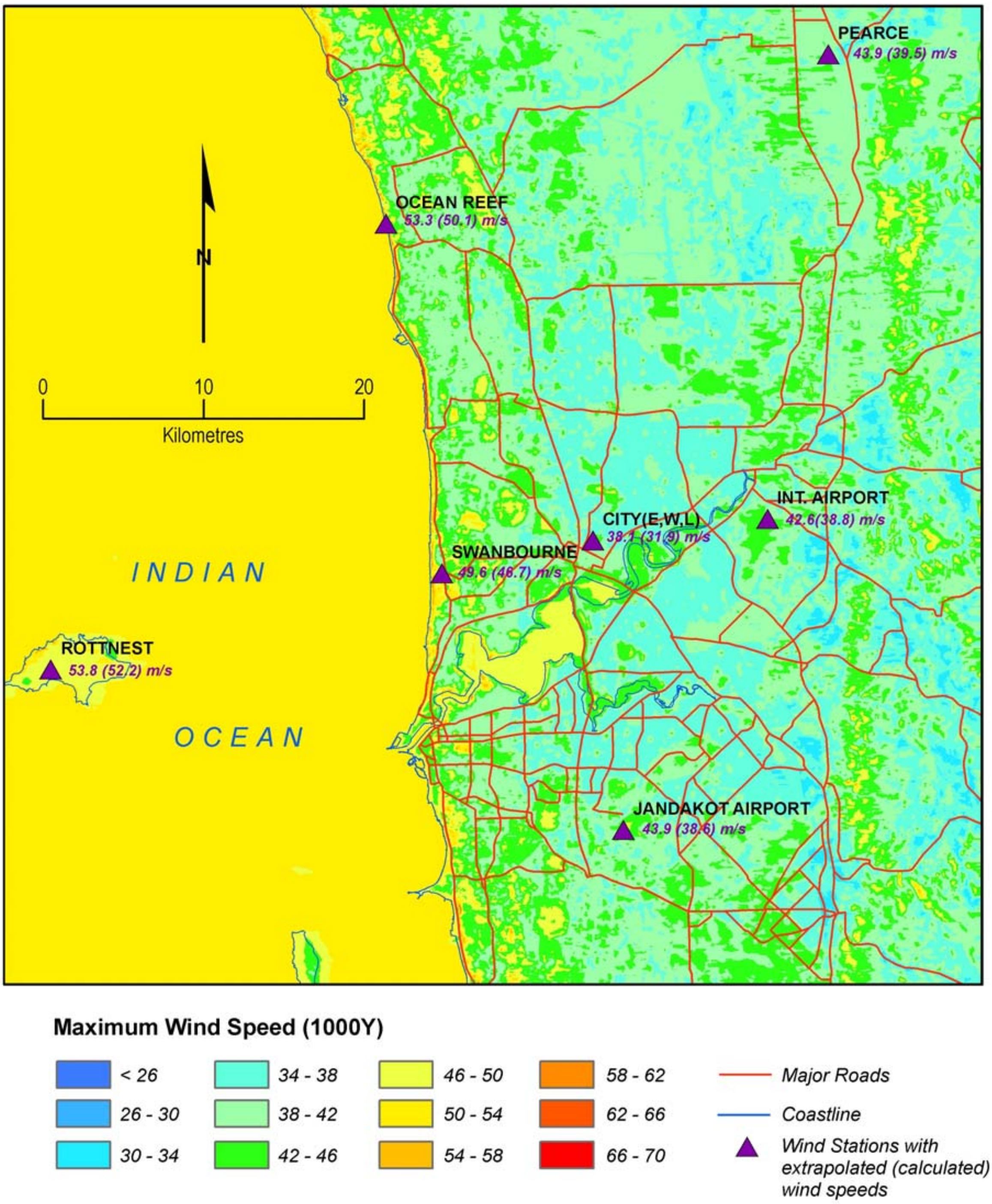

Figure 3.16: Maximum non-directional 1000-year return period speeds

3.6 Conclusions

Assessment of severe wind hazard for metropolitan Perth has been carried out using statistical data analysis, remote sensing and GIS techniques. Return period wind speeds for 50-, 100-, 500- and 1000-year return periods have been estimated for weather station sites using extreme value analysis. These point estimates have been interpolated to the entire study area of metropolitan Perth on a 25 by 25 m grid using a simplified windfield decay model. Finally, wind hazard maps of the study area have been generated. They are in the form of maximum non-directional return period speeds. These maps provide valuable wind hazard information for city planning, risk management, emergency management and the like. Combined with building damage models and building cost models, these maps can be used for quantitative wind risk assessment.

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