Attachment A2

Environmental Wind Assessment – Waterloo Estate (South)

City of Sydney

Waterloo Precinct

Environmental Wind Assessment

Wind

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Job number 278009-00

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Executive summary

Arup have been engaged to provide a quantitative environmental wind assessment for the proposed redevelopment of the Waterloo Precinct. This report discusses the relevant results of the wind tunnel testing study conducted on the development and interpretive discussion on the impact of the proposed development on the pedestrian level wind comfort and safety.

Wind tunnel testing was conducted by Vipac in the existing and proposed configurations. Arup analysed the wind tunnel testing results for comparison with various comfort criteria and to provide greater interpretation of the comfort classifications. The comfort results presented in this report are based on Arup's analysis. The safety results presented are based on the Vipac wind tunnel report findings.

The proposed Waterloo Precinct masterplan is deemed to be appropriate from a wind comfort and safety perspective for the intended use of the various spaces.

All locations within the site are predicted to meet the walking criterion, with the majority classified as acceptable for pedestrian standing and sitting, which is considered to be the appropriate comfort criterion category for the tested locations. Where the walking criterion is exceeded in areas to the north of the site, the wind conditions are predicted to be similar to existing conditions. The proposed retained trees have been shown to improve conditions. The wind conditions in the proposed courtyards were generally classified as suitable for standing or sitting. The inclusion of a higher balustrade and porous pergola are proposed to improve comfort conditions for the mid-level terraces in the towers at the southern end of the precinct.

Almost all locations are predicted to meet the safety criterion. Only locations 4 and 5 on Raglan Street to the north of the site have slight exceedances. The measured wind conditions are similar to existing conditions and not affected by the proposed development. These exceedances would be improved with the adjacent retained trees.

Contents

1 Introduction

Arup have been engaged to provide a quantitative environmental wind assessment for the proposed redevelopment of the Waterloo Precinct. This report discusses the relevant results of the wind tunnel testing study conducted on the redevelopment and interpretive discussion on the impact of the proposed development on the pedestrian level wind comfort and safety.

2 Wind assessment

2.1 Site description

The masterplan is distributed across several blocks in Waterloo, Sydney, Figure 1. There is a mix of parkland, low-, mid-, and high-rise buildings. The tallest buildings are at the southern end of the precinct: three towers comprising 29, 30 and 27 storeys with multi-level slots at mid-level, Figure 2.

Figure 1: Masterplan

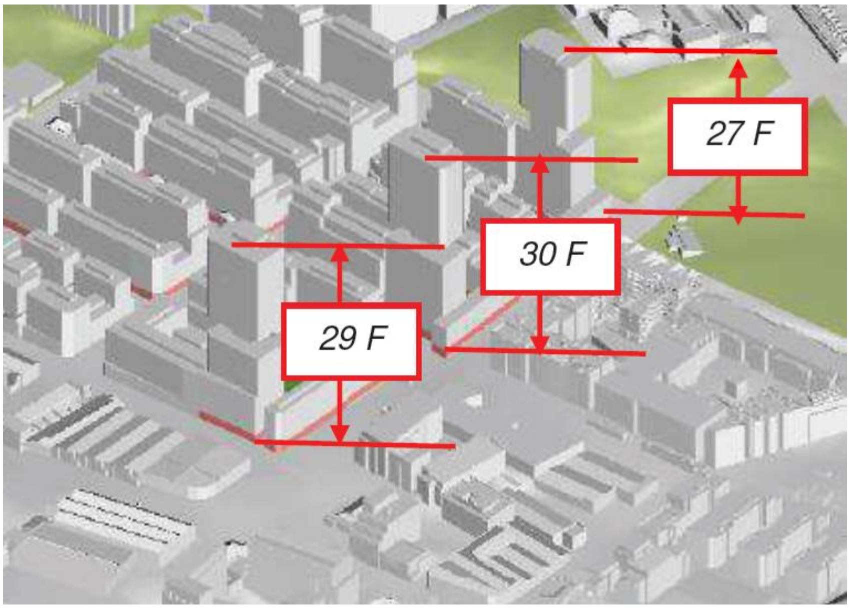


Figure 2: High-rise towers at southern end of precinct; view from the south-west

2.2 Modelling

Wind tunnel testing was conducted in the existing and proposed configurations, Figure 3.

The construction of the physical models was based on the 3d model received from the City of Sydney on 5 November 2020. No landscaping or awnings were included in the initial testing of the proposed configuration. Landscaping (existing, retained mature trees) were incorporated as part of the mitigation strategy testing.

The wind-tunnel testing programme conducted by Vipac was in accordance with the requirements of AWES (2019) and appropriate for the investigation. Appropriate wind speed and turbulence profiles, and test locations were used in the testing. In the existing and proposed configurations, measurements were taken at 128 locations, plus an additional 12 locations in the southern towers' mid-level terraces, and rooftop terraces. Testing was conducted for 36 wind directions and integrated with the Sydney wind climate.

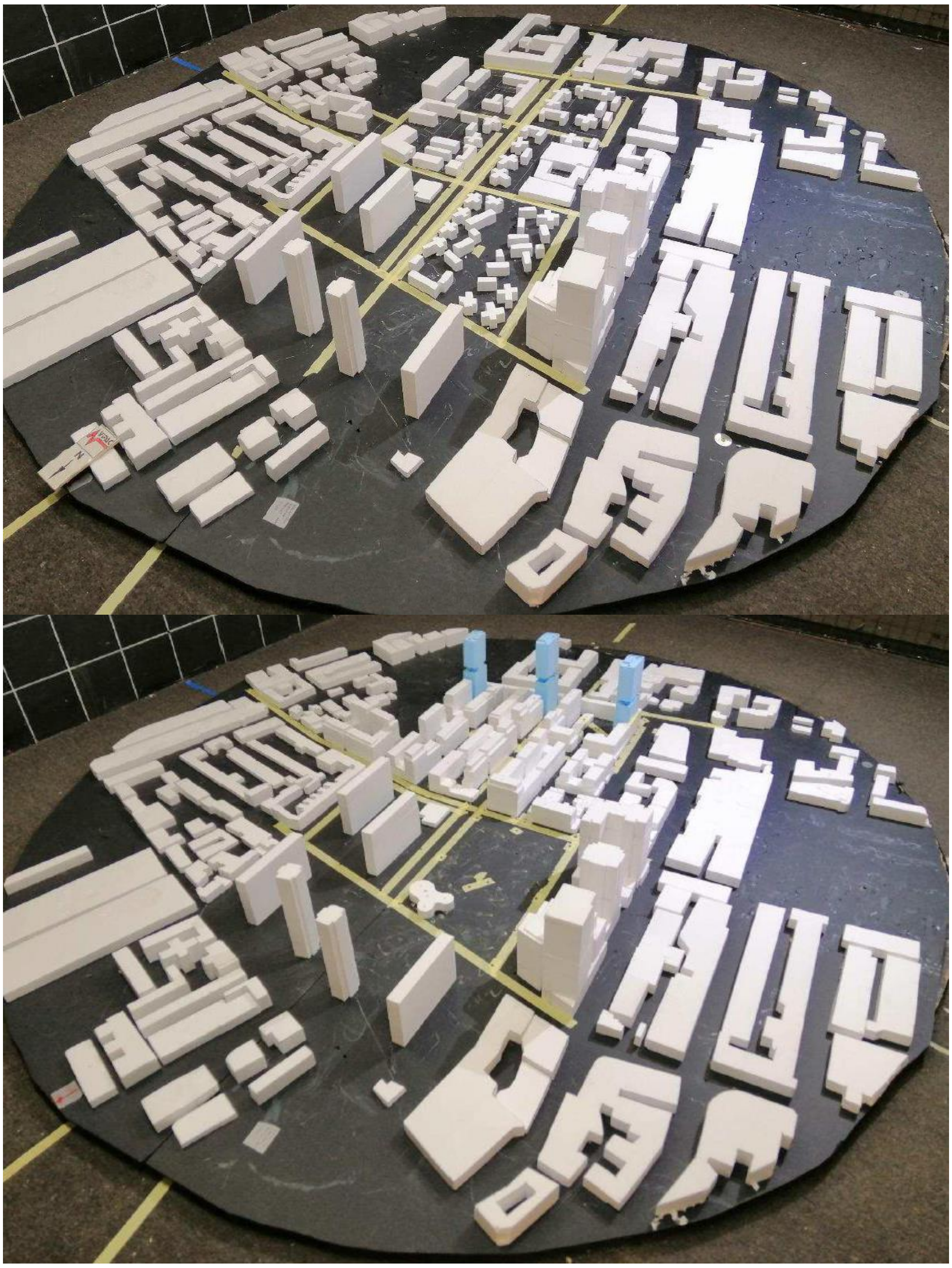


Figure 3: Photograph of the constructed model viewed from north-west

Arup analysed the wind tunnel testing results for comparison with various comfort criteria and to provide greater interpretation of the comfort classifications. Arup has analysed the results with Sydney Airport climate data (Appendix 1), for years 1995 to 2017 for hours 6 am to 10 pm in line with City of Sydney (2016) criteria (refer to Section 2.3). Strong prevailing winds for the site are from the north-east, south, and west quadrants. A general description on flow patterns around buildings is given in Appendix 2.

The comfort results presented in this report are based on Arup's analysis. The safety results presented are based on the Vipac wind tunnel report findings.

2.3 Specific wind controls

Wind comfort is generally measured in terms of wind speed and rate of change of wind speed with distance or time, where higher wind speeds are considered less comfortable. Air speeds have a large impact on thermal comfort and are generally welcome during hot summer conditions. This assessment is focused on air speeds in terms of mechanical comfort.

There have been many wind comfort criteria proposed, and a general discussion is presented in Appendix 3.

The current draft Central Sydney Planning Strategy 2016-2036 wind controls, applicable to this project, are based on the work of Lawson (1990), described in Figure 33 and Table 1. The safety criterion in the Central Sydney Planning Strategy 2016-2036 is based on a 0.5 s gust wind speed of 24 m/s occurring once per annum during daylight hours. The comfort criteria are based on a 5% of the time exceedance during daylight hours.

Table 1: Pedestrian comfort criteria for various activities

Comfort (max. of mean or GEM wind speed exceeded 5% of the time)	
<2 m/s	Dining
2-4 m/s	Sitting
4-6 m/s	Standing
6-8 m/s	Walking
8-10 m/s	Objective walking or cycling
>10 m/s	Uncomfortable
Safety (max. of mean or GEM wind speed exceeded 0.022% of the time)	
<15 m/s	General access
<20 m/s	Able-bodied people (less mobile or cyclists not expected)

Transferring the 5% of the measured wind speed to ground level would result in a wind speed of about 6 m/s, which would be on the boundary of the classification between pedestrian standing and walking.

2.4 Results discussion

Almost all test locations meet both the safety and comfort walking criteria. In terms of comfort, the majority of locations are classified as suitable for pedestrian standing or sitting, Figure 4. No location was classified as suitable for outdoor dining and additional amelioration would be required for such a level of comfort.

There are a few exceptions and these are discussed below; mitigation strategies have been identified in order to meet the criteria, Table 2.

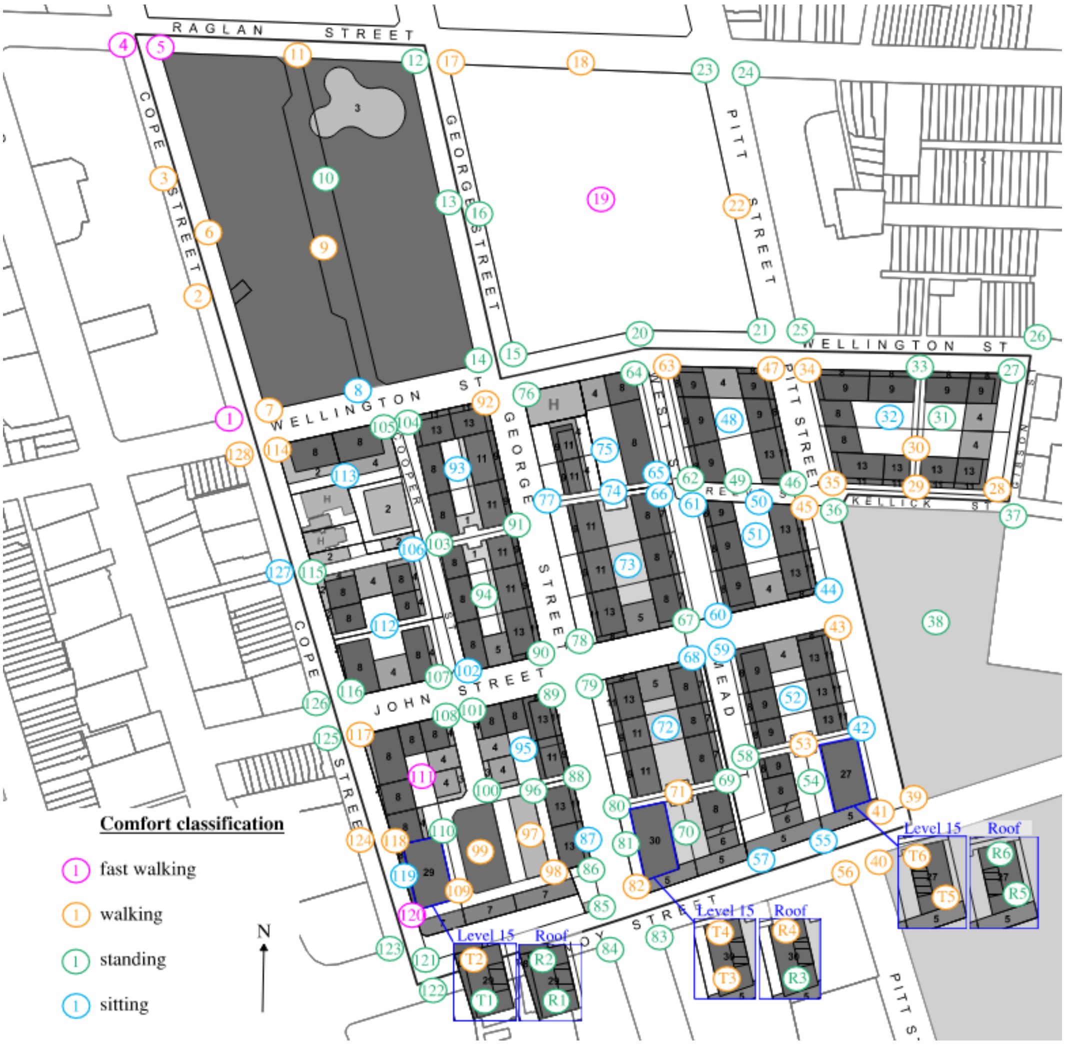


Figure 4: Summary of test locations and comfort classification

Table 2: Results Summary

Description / Test Location		Test configuration / criterion						Mitigation strategy to meet safety/comfort criteria
		Safety			Comfort – walking criterion			
		Existing	Proposed	Proposed with mitigation	Existing	Proposed	Proposed with mitigation	
Ground Plane	5	Y	N	Y	Y	N	N	Retained trees, as proposed [1]
Tower terraces (Level 15)	T1	N/A	N	Y	N/A	Y	Y (suitable for sitting 81% of the time)	≥ 2.4m balustrade or safety management plan
	T3	N/A	Y	Y	N/A	Y	Y (suitable for sitting 78% of the time)	≥ 2.4m balustrade or safety management plan
	T5	N/A	N	Y	N/A	Y	Y (suitable for sitting 65% of the time)	≥ 2.4m balustrade & pergola with porous roof or safety management plan

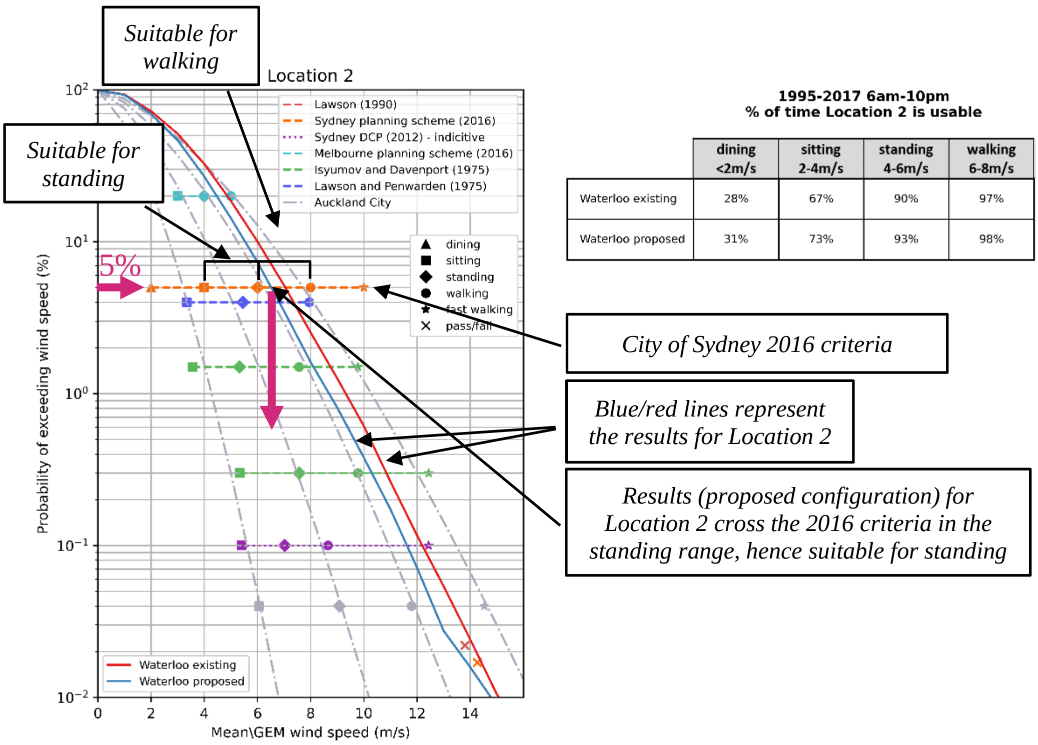
NOTES:

1. The inclusion of retained mature trees improved wind comfort conditions, but are classified as suitable for fast walking. Refer to discussion in Section in 2.4.1.

These critical results highlighted in Table 2 are discussed below and comparative results at each location against various criteria are included. As an example, the results for Location 2, Figure 4, are presented in Figure 5. The chart is a plot of the probability of exceeding a particular wind speed against wind speed. This graph clearly illustrates the expected probability distribution of wind speed at a specific location: for example, the mean wind speed exceeded for 5% of time would be about 6.5 m/s as illustrated in Figure 5. The 3 s gust wind speed can be estimated by multiplying this value by 1.85. The blue line shows the results for the proposed configuration and crosses the 5% probability level to the left of the circle symbol for the Sydney planning scheme (2016) criteria, and therefore, would be classified as suitable for pedestrian walking.

On Figure 5, various internationally recognised wind comfort criteria for assessing the wind climate are presented, with the various symbols indicating the comfort category targets for specific activities. The results for each location are plotted in the solid coloured curves.

The applicable City of Sydney criteria are the *Sydney planning scheme (2016)*, as per Section 2.3. The table to the right of Figure 5 gives the percentage of time that the wind speed would be less than that associated with the various intent of use categories, for example Location 2 in the proposed configuration would be less than the wind speed associated with the dining and sitting criteria for 31% and 73% of the time respectively.



1995-2017 6am-10pm
% of time Location 2 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	28%	67%	90%	97%
Waterloo proposed	31%	73%	93%	98%

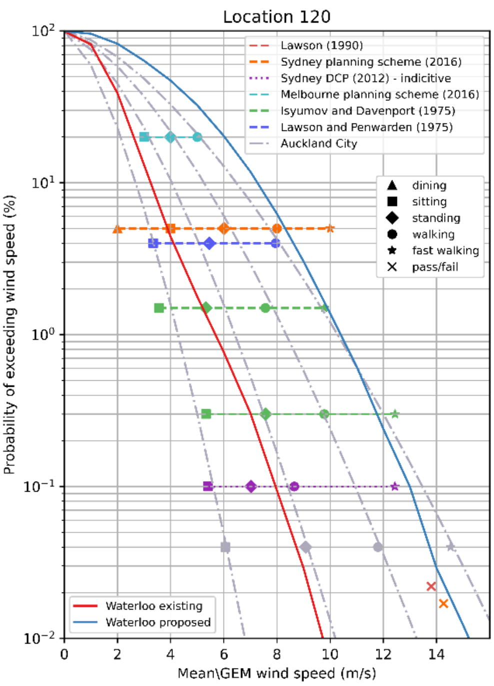
Figure 5: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 2

2.4.1 Ground plane

In terms of pedestrian comfort, wind conditions at ground plane are expected to meet their intended use at all locations, with exception of a couple of points requiring mitigation strategies in order to do so.

The safety criterion is met at all locations, except for locations 4 and 5 (although it is also not met in the existing configurations for both locations). These exceedances are caused by winds from the north-west quadrant and are generated by the large development to the west of Cope Street.

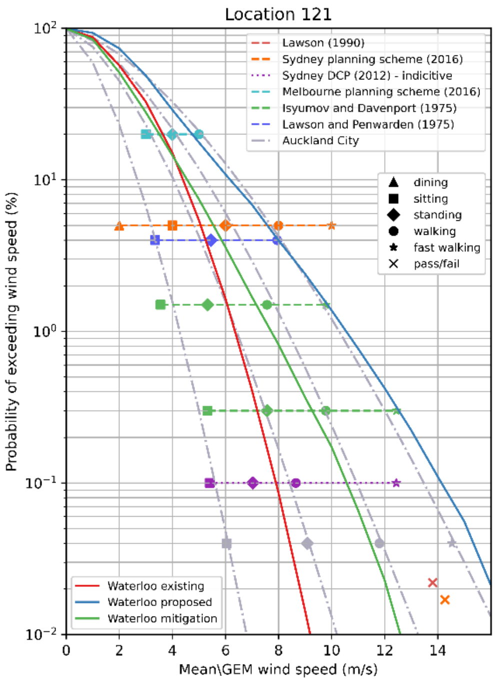
Location 120, located to the south-west corner of the site, just exceeds the walking criterion in the proposed configuration. The wind directions creating strong wind conditions at this location are from the north-east and west inducing downwash from the 29-storey building. With the inclusion of retained trees, as proposed for the masterplan (Figure 20), and the proposed awning along the laneway, Figure 23, the walking criterion would be expected to be met. The inclusion of retained mature trees was tested for Location 121, which saw a marked improvement, Figure 7.



1995-2017 6am-10pm
% of time Location 120 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	61%	96%	99%	100%
Waterloo proposed	18%	53%	80%	94%

Figure 6: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 120

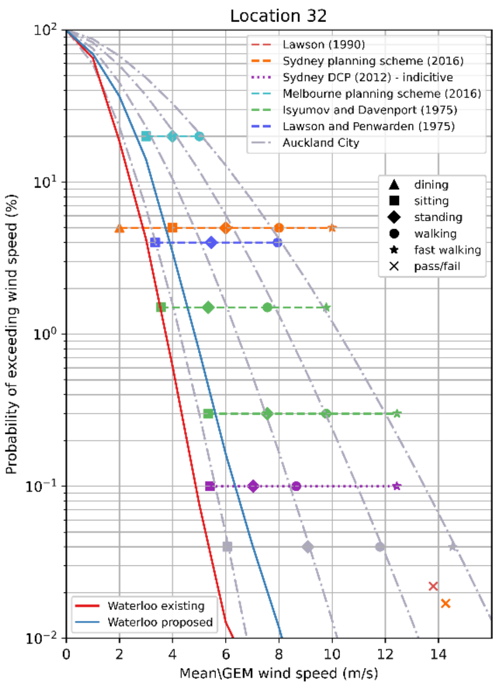


1995-2017 6am-10pm
% of time Location 121 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	43%	85%	98%	100%
Waterloo proposed	26%	71%	89%	96%
Waterloo mitigation	49%	86%	96%	99%

Figure 7: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 121

There are a number of courtyards throughout the site (Locations 31, 32, 48, 51, 52, 54, 75, 93, 94, 95, 99, 111 and 112). Almost all of these locations meet either the sitting or standing criteria, which are considered appropriate for a courtyard. As an example, the results for Location 32 are provided in Figure 8.

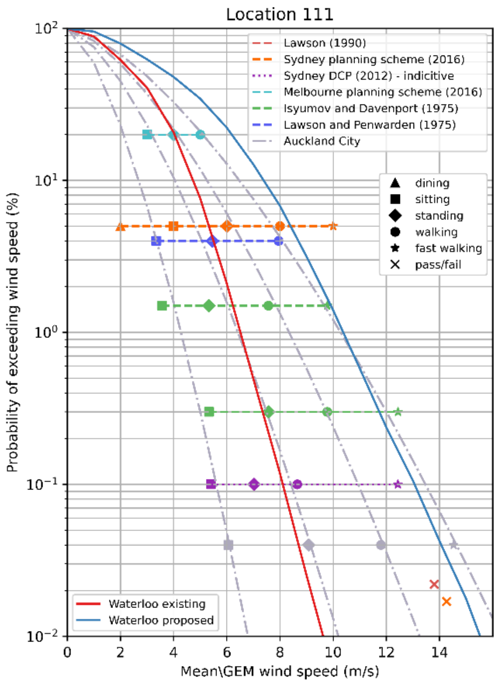


1995-2017 6am-10pm
% of time Location 32 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	82%	99%	100%	100%
Waterloo proposed	63%	97%	100%	100%

Figure 8: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 32

One of the courtyards, location 111, is classified as fast walking. It is dominated by winds from the south and the north-east causing recirculation across the courtyard. However, the results only slightly exceed the walking criterion, Figure 9, with the estimated 5% of the time mean wind speed predicted to be approximately 8.3 m/s. The courtyard would unlikely be used extensively during strong winds from the south, due to the temperature. Reducing the height of the buildings to the north of the courtyard and increasing the height buildings to the east would be expected to reduce the level of recirculation across this courtyard for the wind directions of interest. This has since been incorporated into the masterplan, increasing the building to the north of the courtyard from 4 to 8 storeys and the building to the east, from 4 to 6 storeys, Figure 10.



1995-2017 6am-10pm
% of time Location 111 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	38%	79%	98%	100%
Waterloo proposed	21%	52%	78%	93%

Figure 9: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 111

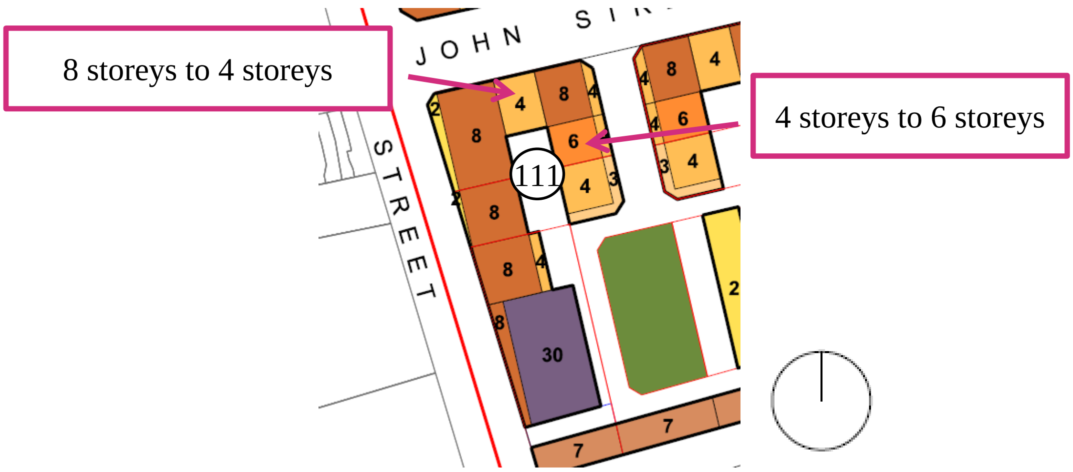
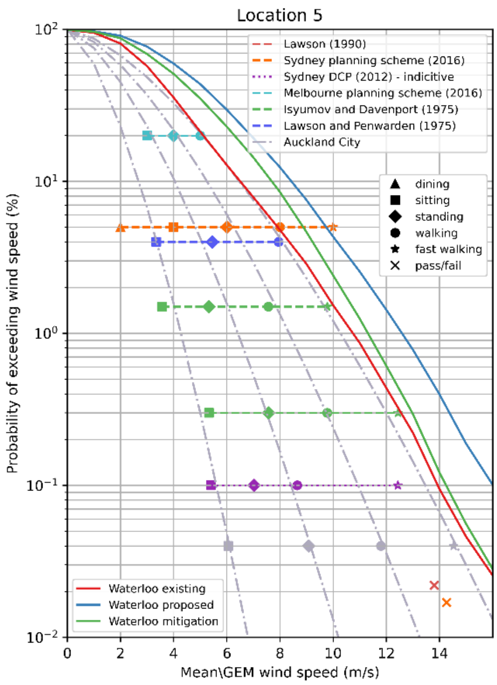


Figure 10: Proposed changes to the building heights around Location 111

Four locations (1, 4, 5, and 19) to the north of the main development did not meet the walking comfort criterion . Location 5 is on the walking criterion threshold for the existing configuration and close to the fast walking criterion for the proposed configuration, Figure 11. This is primarily caused by the reduction in shielding from the existing smaller buildings on the site. Retained trees were included as part of mitigation (Figure 20) and the wind conditions improved, while still exceeding the walking criterion, Figure 11. In terms of safety, there is a slight exceedance for winds from the west, but is similar between the existing and proposed configurations, primarily caused by the large development to the west, and the reduction in blockage with the removal of the low-rise existing structures. The inclusion of retained mature trees meant that the safety criterion is met for all wind directions for Location 5.



1995-2017 6am-10pm
% of time Location 5 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	19%	64%	87%	95%
Waterloo proposed	9%	40%	70%	88%
Waterloo mitigation	13%	49%	77%	91%

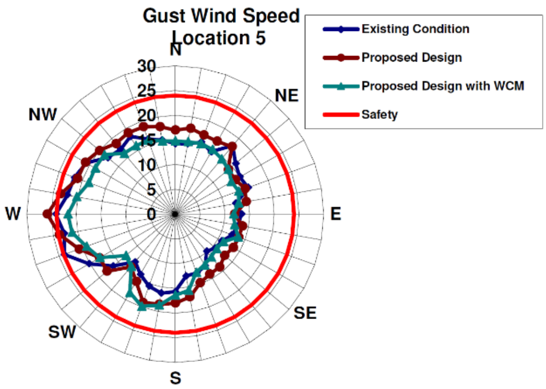
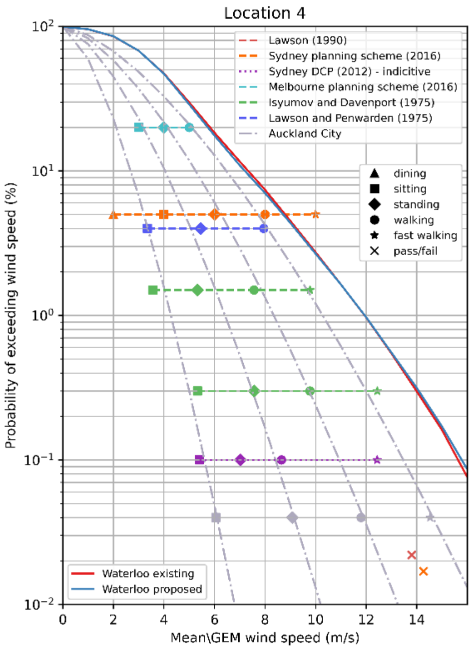


Figure 11: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 5

The results for Location 4, Figure 4, were similar, however, for comfort, both the existing and proposed results are classified as fast walking. Retained trees are expected to improve the comfort results and the walking criterion met. From a safety perspective, there is a slight exceedance for winds for the west for both the existing and proposed configurations. Once again, retained mature trees would likely mean that the safety criterion is met. Wind conditions are similar in both configurations.

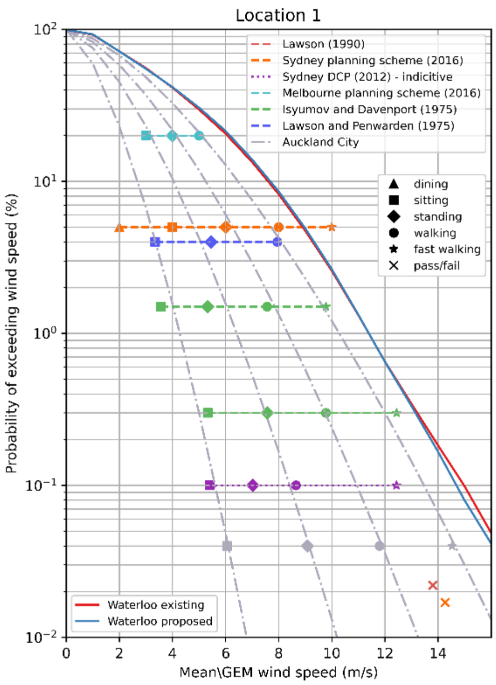


1995-2017 6am-10pm
% of time Location 4 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	15%	53%	82%	93%
Waterloo proposed	14%	53%	82%	93%

Figure 12: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 4

Location 1 is classified as fast walking for the existing and proposed configurations, Figure 13, indicating that the removal of the existing buildings and the development of the site is not expected to measurably change the local wind conditions.

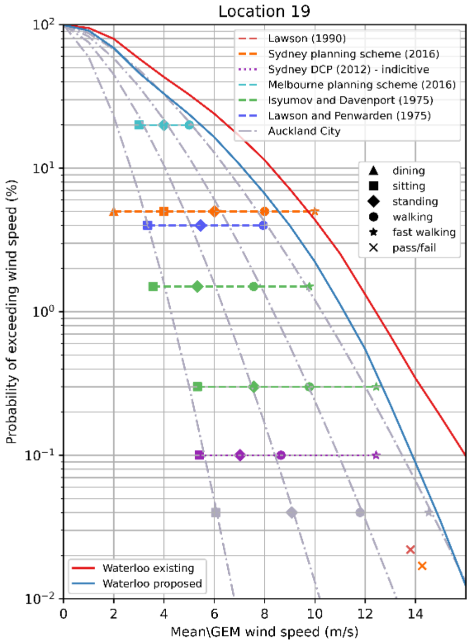


1995-2017 6am-10pm
% of time Location 1 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	28%	59%	79%	92%
Waterloo proposed	28%	58%	79%	91%

Figure 13: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 1

Similarly, Location 19 is classified as suitable for fast walking activities for the existing and proposed configurations, Figure 14, with the proposed configuration improving conditions.



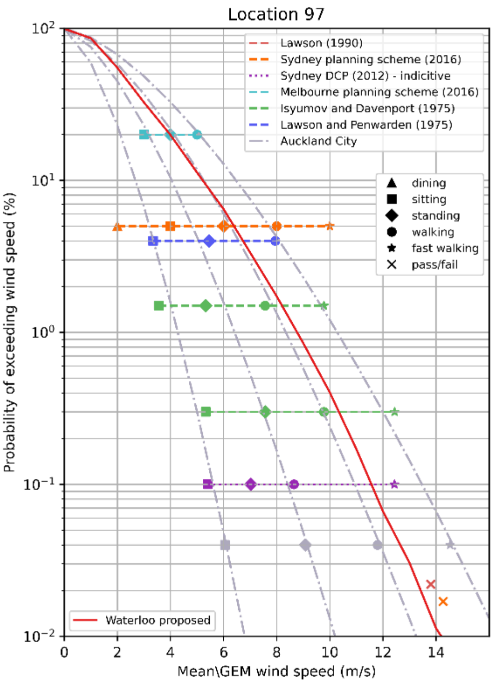
1995-2017 6am-10pm
% of time Location 19 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo existing	20%	57%	76%	89%
Waterloo proposed	31%	67%	84%	93%

Figure 14: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 19

2.4.2 Low-rise rooftops

There are a number of low-rise one- and two-storey rooftops throughout the site which have the potential to be used as rooftop terraces (locations 70, 72, 73 and 97). With the exception of point 97, all of these locations meet either the sitting or standing criteria. Location 97 meets the walking criterion and is just above the standing criterion, Figure 15, meeting the wind speed associated with the sitting criterion for 80% of the time, which is considered good for a rooftop terrace in Sydney.



1995-2017 6am-10pm
% of time Location 97 is usable

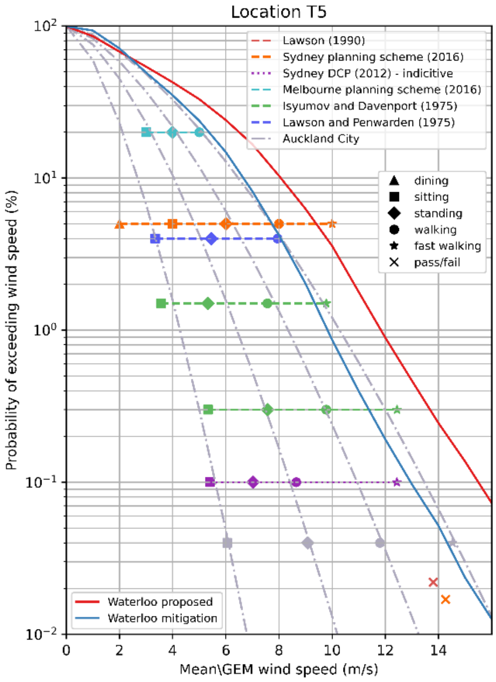
	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo proposed	45%	80%	94%	98%

Figure 15: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 97

2.4.3 Tower terraces (Level 15)

Although not intended to be trafficable, the Level 15 terraces in the towers located at the southern end of the site were assessed. They were tested with no mitigation and with high screens and a pergola. From a comfort perspective, location T5 required mitigation measures (pergola with a porous roof and balustrade of at least 2.4 m high) to meet the walking criterion (Figure 16 and Figure 22). Mitigation measures were also tested for the other terrace locations (T1-T4, T6). For T1 and T3, a balustrade at least 2.4 m in height assisted with improving conditions. With the inclusion of the higher balustrade, the results for location T1 went from just meeting the walking criterion to meeting the standing criterion, Figure 22.

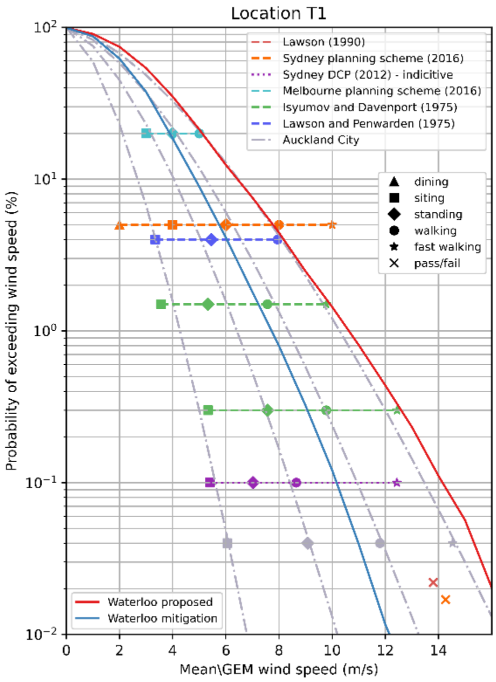
There were slight safety exceedances for locations T1 and T5, for winds from the west and winds from the south, respectively. The safety criterion was met with the mitigation measures noted above.



1995-2017 6am-10pm
% of time Location T5 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo proposed	32%	57%	76%	90%
Waterloo mitigation	29%	65%	85%	96%

Figure 16: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location T5



1995-2017 6am-10pm
% of time Location T1 is usable

	dining <2m/s	sitting 2-4m/s	standing 4-6m/s	walking 6-8m/s
Waterloo proposed	26%	65%	88%	96%
Waterloo mitigation	38%	81%	96%	99%

Figure 17: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location T1

2.4.4 Additional Comments

The Level 15 terraces, or ‘slots’, in the three towers at the southern end of the precinct have been incorporated mainly to benefit ground level conditions. While there is some benefit to pedestrian comfort conditions, the benefit of the slots is more critical to safety conditions. While the proposed retained trees also assist with greatly improving comfort and safety conditions, if the retained trees were to be removed in the future, the inclusion of the slots for safety conditions would be of great benefit.

There are a number of mid-rise rooftop terraces that are proposed for the rooftops of the 8- to 13-storey buildings. Although not tested as part of the wind tunnel testing, conditions would be expected to meet walking criteria with no mitigation and meet the safety criterion, which is typical of mid-rise rooftop conditions. In order to improve comfort conditions so that some areas are suitable for standing, it is recommended that at least 3 sides of the terrace are enclosed. This could be achieved by high screens (i.e. at least 2.4 m high) and/or dense landscaping, Figure 18.

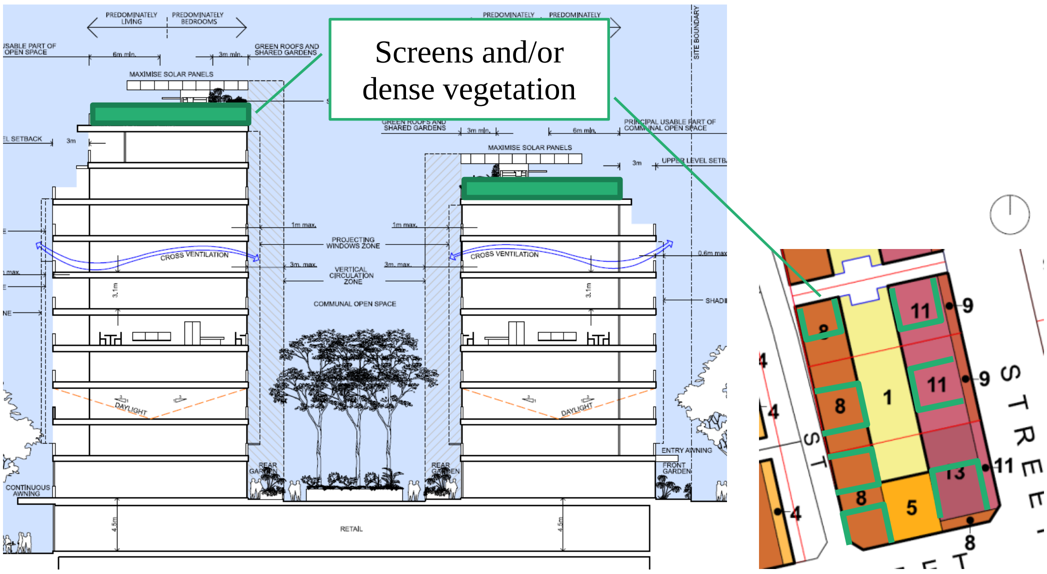


Figure 18: Recommended indicative rooftop terraces screens/dense vegetation in green: section (L) and plan (right)

Since the wind tunnel testing was conducted, a few changes have been made to the masterplan, Figure 19:

1. Increase from 2 to 4 storeys
2. Increase from 2 to 4 storeys
3. Decrease from 8 to 4 storeys
4. Increase from 4 to 6 storeys
5. Decrease from 8 to 4 storeys
6. Increase from 4 to 6 storeys
7. Decrease from 13 to 11 storeys

8. Removal of the building in the north-west corner of the northern park

Changes 3 and 4 have already been discussed in Section 2.4.1 and are as per recommendations to improve ground plane conditions. In the context of the precinct and the scale of the changes, the rest of the changes are expected to have negligible impact on the wind conditions.

Figure 19: Proposed changes to the masterplan since wind tunnel testing was conducted

2.4.5 Summary of mitigation measures

In summary, the following mitigation measures are required to meet the comfort and/or safety criteria:

- balustrade heights of at least 1.2 m for rooftop terraces,
- if the Level 15 tower terraces are to become trafficable (currently proposed to not be trafficable), balustrade of at least 2.4 m high(Figure 21 and Figure 22),

- pergola with porous roof at level 15 in the eastern most tower (Figure 22),
- incorporate high screens (at least 2.4 m) and/or dense vegetation to at least 3 sides of the rooftop terraces of the mid-rise (8- to 13-storey) buildings, Figure 18,
- proposed retained mature trees (Figure 22), and
- an additional awning in the south-west laneway (Figure 23).

Figure 20: ground plane wind mitigation strategies for Locations 5 and 121

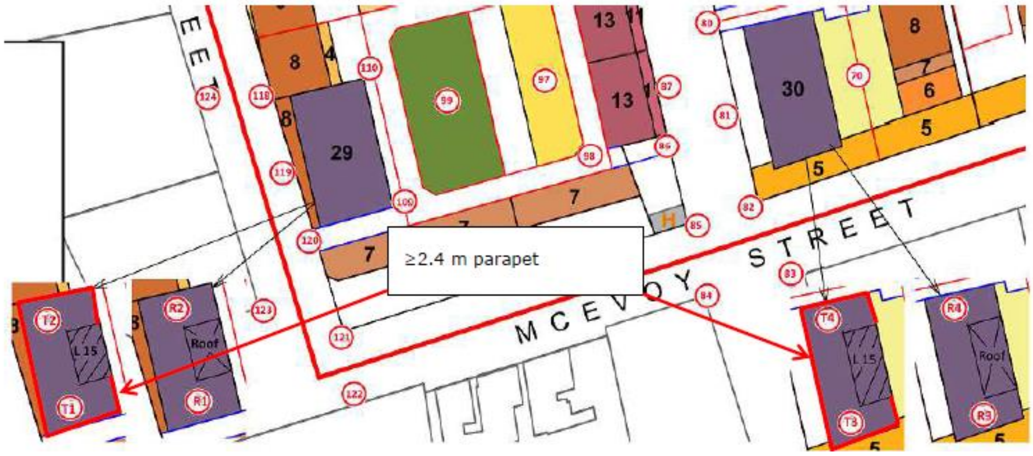


Figure 21: Terrace (Level 15) wind mitigation strategies for locations T1 and T3

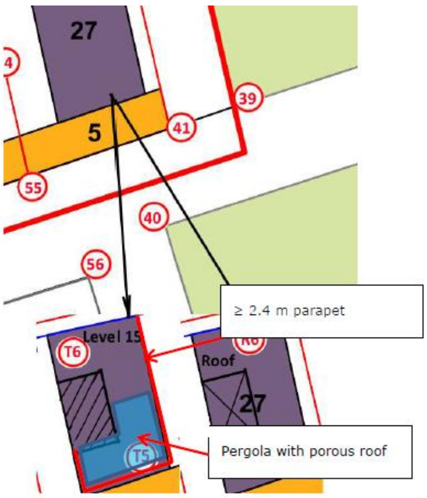


Figure 22: Terrace (Level 15) wind mitigation strategies for locations T5

Although not tested, there are a number of proposed awnings and colonnades that are expected to further improve conditions, Figure 23. An additional awning is recommended for one of the laneways in the south-west corner of the site.

Figure 23: Proposed awnings and colonnades

2.5 Summary

The proposed Waterloo Precinct masterplan is deemed to be appropriate from a wind comfort and safety perspective.

Almost all locations are predicted to meet the walking criterion, which is considered to be the appropriate comfort criterion category for the tested locations. Where the walking criterion is not met, conditions are similar to existing conditions. The proposed retained mature trees are expected to improve local conditions. The proposed courtyards were generally classified as suitable for pedestrian standing or sitting. For the mid-level terraces in the high-rise towers, the inclusion of a higher perimeter balustrade and porous pergola improved the wind comfort conditions.

Almost all locations are predicted to meet the safety criterion. Only Locations 4 and 5 have slight exceedances and these are similar to existing conditions. Wind conditions at these locations expected to be improved with the adjacent retained mature trees.

3 References

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Appendix 1: Wind climate

The wind frequency and direction information measured by the Bureau of Meteorology anemometer at a standard height of 10 m at Sydney Airport from 1995 to 2017 have been used in this analysis, Figure 24. The arms of the wind rose point in the direction from where the wind is coming from. The anemometer is located about 6.3 km to the south-west of the site. The directional wind speeds measured here are considered representative of the wind conditions at the site.

It is evident from Figure 24 that strong prevailing winds are organised into three main groups which centre at about the north-east, south, and west quadrants.

Strong summer winds occur mainly from the south quadrant and the north-east. Winds from the south are associated with large synoptic frontal systems and generally provide the strongest gusts during summer. Moderate intensity winds from the north-east tend to bring cooling relief on hot summer afternoons typically lasting from noon to dusk. These are small-scale temperature driven effects; the larger the temperature differential between land and sea, the stronger the wind.

Winter and early spring strong winds typically occur from the south-west, and west quadrants. West quadrant winds provide the strongest winds affecting the area throughout the year and tend to be associated with large scale synoptic events that can be hot or cold depending on inland conditions.

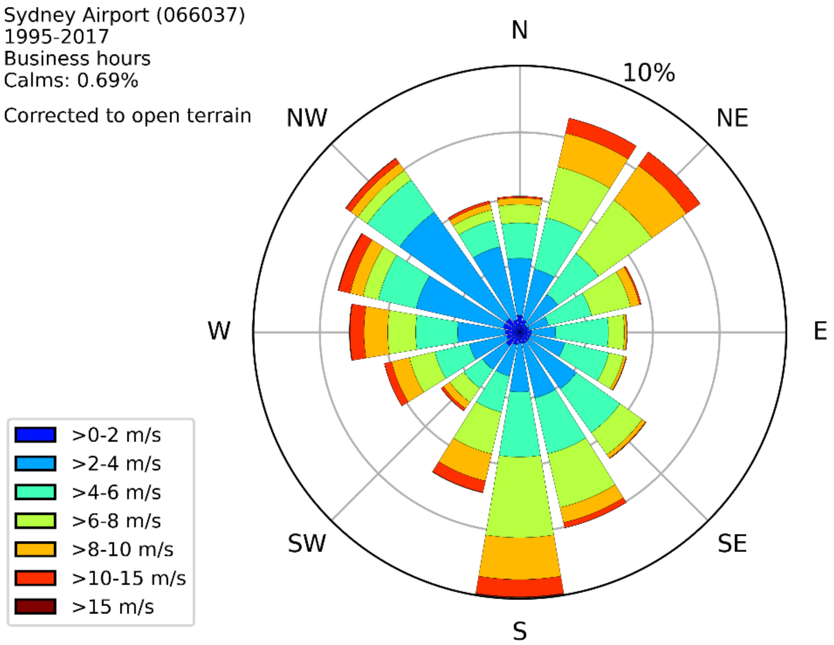

Figure 24 Wind rose showing probability of time of wind direction and speed

Appendix 2: Wind flow mechanisms

An urban environment generates a complex wind flow pattern around closely spaced structures, hence it is exceptionally difficult to generalise the flow mechanisms and impact of specific buildings as the flow is generated by the entire surrounds. However, it is best to start with an understanding of the basic flow mechanisms around an isolated structure.

Isolated building

When the wind hits an isolated building, the wind is decelerated on the windward face generating an area of high pressure, Figure 25, with the highest pressure at the stagnation point at about two thirds of the height of the building. The higher pressure bubble extends a distance from the building face of about half the building height or width, whichever is lower. The flow is then accelerated down and around the windward corners to areas of lower pressure, Figure 25. This flow mechanism is called **downwash** and causes the windiest conditions at ground level on the windward corners and along the sides of the building.

Rounding the building corners or chamfering the edges reduces downwash by encouraging the flow to go around the building at higher levels. However, concave curving of the windward face can increase the amount of downwash. Depending on the orientation and isolation of the building, uncomfortable downwash can be experienced on buildings of greater than about 6 storeys.

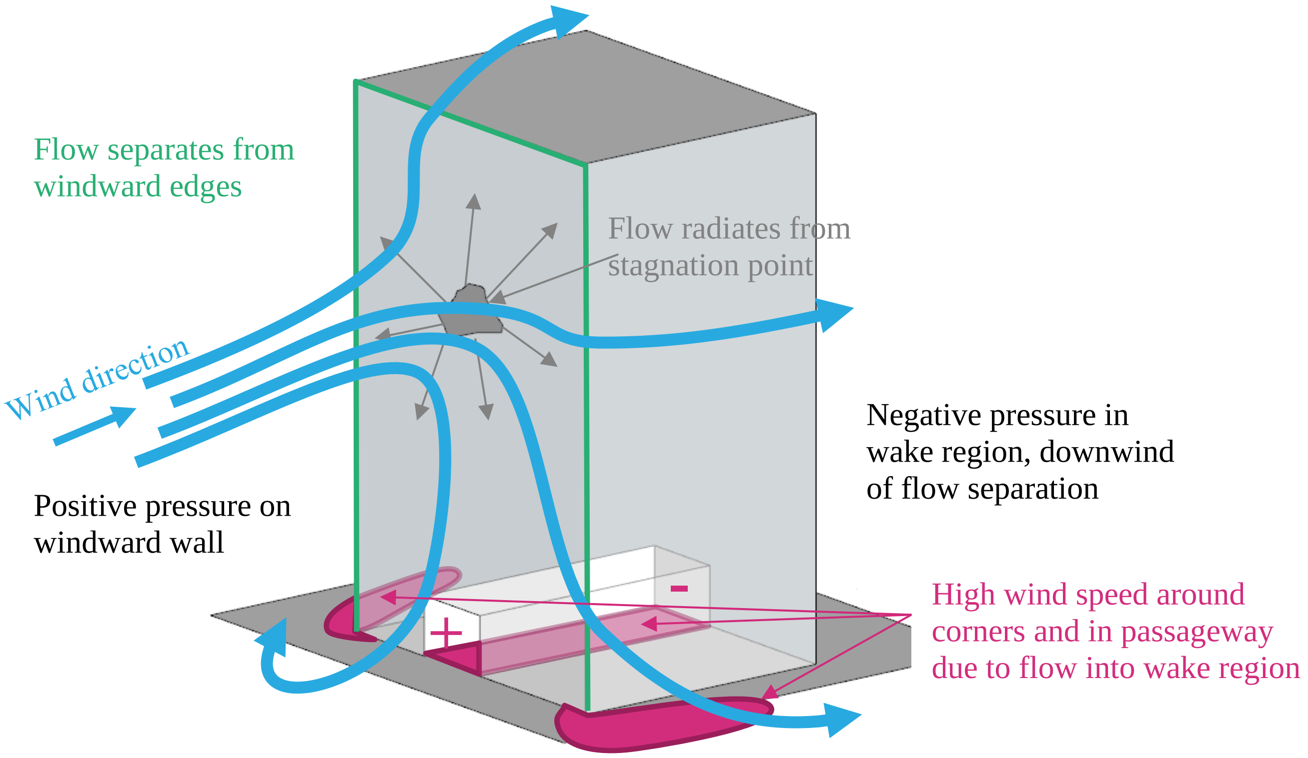

Figure 25 Schematic wind flow around tall isolated building

Techniques to mitigate the effects of downwash winds at ground level include the provision of horizontal elements, the most effective being a podium to divert the downward flow away from pavements and building entrances, but this will generate windy conditions on the podium roof, Figure 11. Generally, the lower the podium roof and deeper the setback from the podium edge to the tower improves the ground level wind conditions. The provision of an 8 m setback on an isolated building is generally sufficient to improve ground level conditions, but is highly dependent on the building isolation, orientation to prevailing wind directions, shape and width of the building, and any plan form changes at higher level.

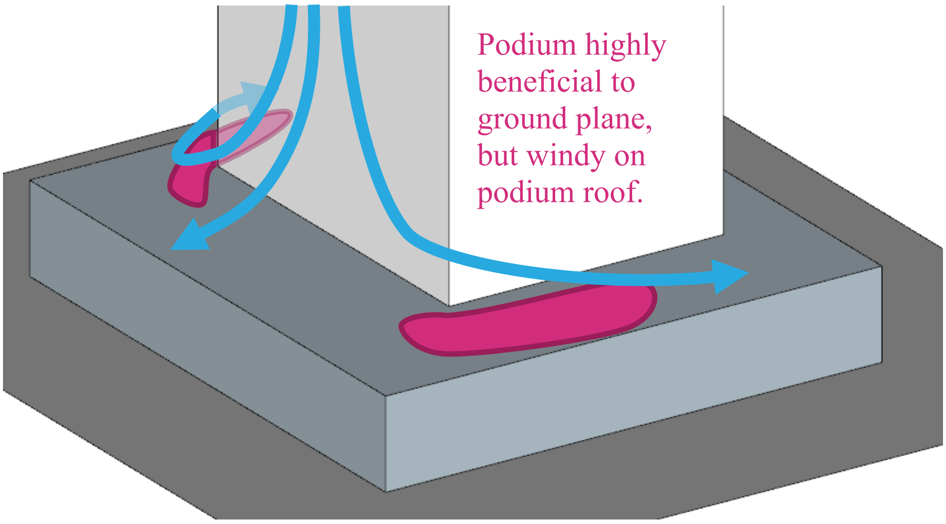

Figure 26 Schematic flow pattern around building with podium

Awnings along street frontages perform a similar function as a podium, and generally the larger the horizontal projection from the façade, the more effective it will be in diverting downwash flow, Figure 27. Awnings become less effective if they are not continuous along the entire façade, or on wide buildings as the positive pressure bubble extends beyond the awning resulting in horizontal flow under the awning.

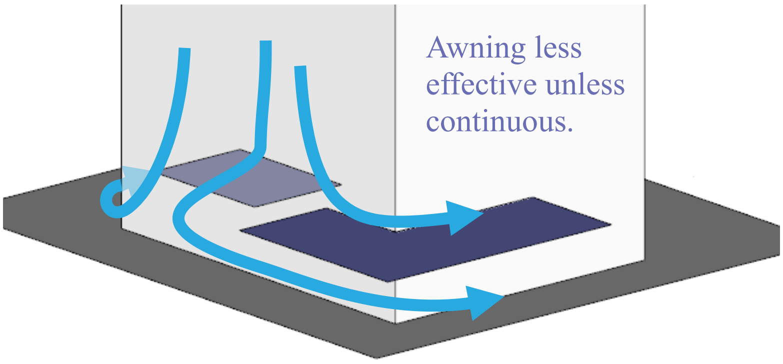

Figure 27 Schematic flow pattern around building with awning

It should be noted that colonnades at the base of a building with no podium generally create augmented windy conditions at the corners due to an increase in the pressure differential, Figure 28. Similarly, open through-site links through a building cause wind issues as the environment tries to equilibrate the pressure generated at the entrances to the link, Figure 25. If the link is blocked, wind conditions will be calm unless there is a flow path through the building, Figure 29. This area is in a region of high pressure and therefore the is the potential for internal flow issues. A ground level recessed corner has a similar effect as an undercroft, resulting in windier conditions, Figure 29.

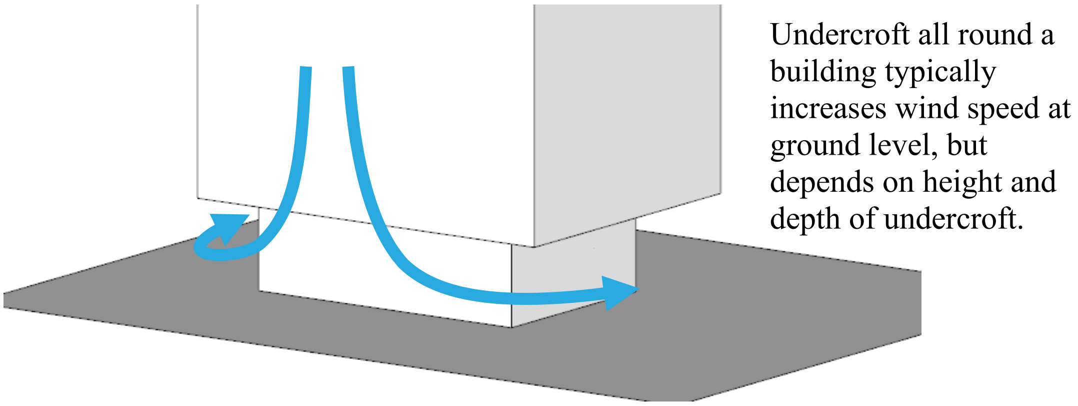

Figure 28 Schematic of flow patterns around isolated building with undercroft

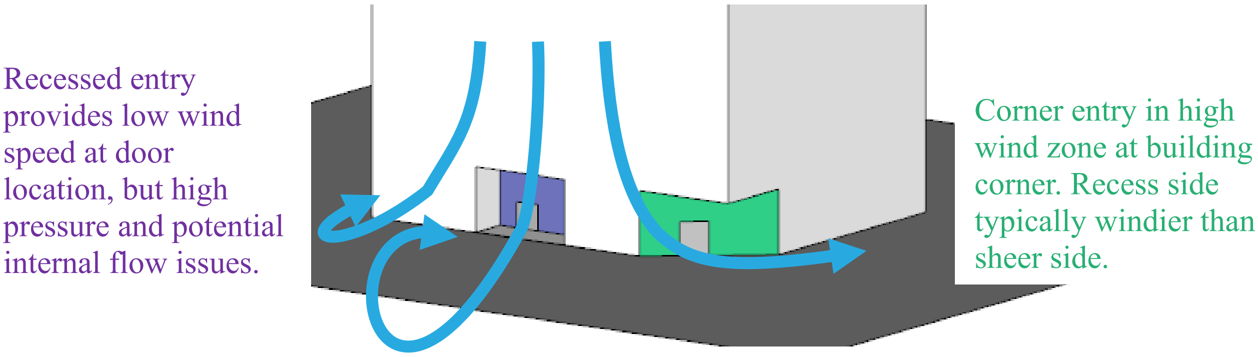

Figure 29 Schematic of flow patterns around isolated building with ground articulation

Multiple buildings

When a building is located in a city environment, depending on upwind buildings, the interference effects may be positive or negative, Figure 30. If the building is taller, more of the wind impacting on the exposed section of the building is likely to be drawn to ground level by the increase in height of the stagnation point, and the additional negative pressure induced at the base. If the upwind buildings are of similar height then the pressure around the building will be more uniform hence downwash is typically reduced with the flow passing over the buildings.

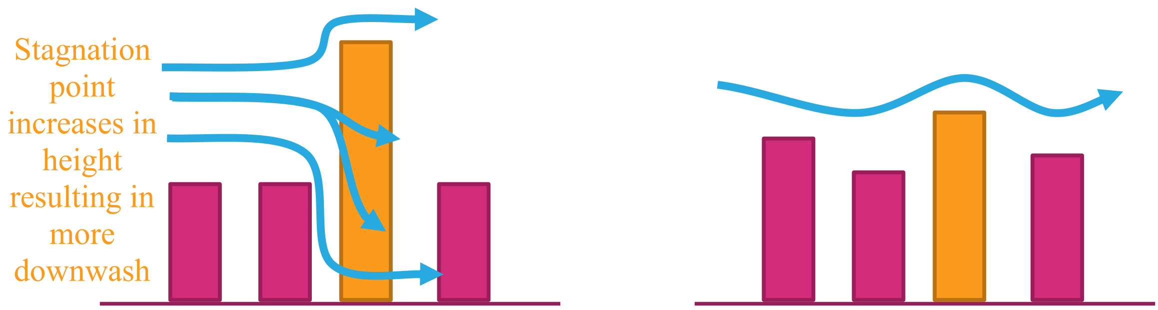

Figure 30 Schematic of flow pattern interference from surrounding buildings

The above discussion becomes more complex when three-dimensional effects are considered, both with orientation and staggering of buildings, and incident wind direction, Figure 31.

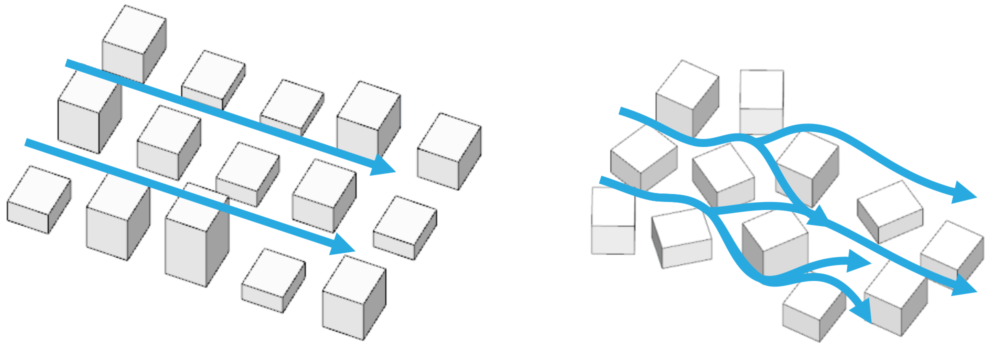

Figure 31 Schematic of flow patterns through a grid and random street layout

Channelling occurs when the wind is accelerated between two buildings, or along straight streets with buildings on either side, Figure 31(L), particularly on the edge of built-up areas where the approaching flow is diverted around the city massing and channelled along the fringe by a relatively continuous wall of building facades. This is generally the primary mechanism driving the wind conditions for this perimeter of a built-up area, particularly on corners, which are exposed to multiple wind directions. The perimeter edge zone in a built-up area is typically about two blocks deep. Downwash is more important flow mechanism for the edge zone of a built-up area with buildings of similar height.

As the city expands, the central section of the city typically becomes calmer, particularly if the grid pattern of the streets is discontinued, Figure 31(R). When buildings are located on the corner of a central city block, the geometry becomes slightly more important with respect to the local wind environment.

Single barriers and screens

The wind flow pattern over a vertical barrier is illustrated in Figure 32, showing there will be recirculation zones near the windward wall and in the immediate lee of the barrier. The typical extent of these recirculation zones relative to the height of the barrier, h, is illustrated in Figure 32. These regions are not fixed but fluctuate in time. The mean wind speed in the wake areas drops significantly compared with the incident flow. With increasing distance from the barrier the flow pattern will resort to the undisturbed state. Typically the mean velocity and turbulence intensity at barrier height would be expected to be within 10% of the free stream conditions at 10 times the height of the structure downwind from the barrier.

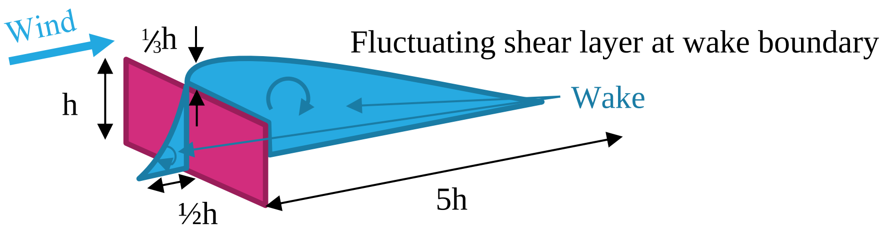

Figure 32: Sketch of the flow pattern over an isolated structure

Appendix 3: Wind speed criteria

General discussion

Primary controls that are used in the assessment of how wind affects pedestrians are the wind speed, and rate of change of wind speed. A description of the effect of a specific wind speed on pedestrians is provided in Table 3. It should be noted that the turbulence, or rate of change of wind speed, will affect human response to wind and the descriptions are more associated with response to mean wind speed.

Table 3 Summary of wind effects on pedestrians

Description	**Speed (m/s)**	**Effects**
Calm, light air	0–2	Human perception to wind speed at about 0.2 m/s. Napkins blown away and newspapers flutter at about 1 m/s.
Light breeze	2–3	Wind felt on face. Light clothing disturbed. Cappuccino froth blown off at about 2.5 m/s.
Gentle breeze	3–5	Wind extends light flag. Hair is disturbed. Clothing flaps.
Moderate breeze	5–8	Raises dust, dry soil. Hair disarranged. Sand on beach saltates at about 5 m/s. Full paper coffee cup blown over at about 5.5 m/s.
Fresh breeze	8–11	Force felt on body. Limit of agreeable wind on land. Umbrellas used with difficulty. Wind sock fully extended at about 8 m/s.
Strong breeze	11–14	Hair blown straight. Difficult to walk steadily. Wind noise on ears unpleasant. Windborne snow above head height (blizzard).
Near gale	14–17	Inconvenience felt when walking.
Gale	17–21	Generally impedes progress. Difficulty with balance in gusts.
Strong gale	21–24	People blown over by gusts.

Local wind effects can be assessed with respect to a number of environmental wind speed criteria established by various researchers. These have all generally been developed around a 3 s gust, or 1 hour mean wind speed. During strong events, a pedestrian would react to a significantly shorter duration gust than a 3 s, and historic weather data is normally presented as a 10 minute mean.

Despite the apparent differences in numerical values and assumptions made in their development, it has been found that when these are compared on a probabilistic basis, there is some agreement between the various criteria. However, a number of studies have shown that over a wider range of flow conditions, such as smooth flow across water bodies, to turbulent flow in city centres, there is less general agreement among. The downside of these criteria is that they have seldom been benchmarked, or confirmed through long-term measurements in the field, particularly for comfort conditions. The wind criteria were all developed in temperate climates and are unfortunately not the only environmental factor that affects pedestrian comfort.

For assessing the effects of wind on pedestrians, neither the random peak gust wind speed (3 s or otherwise), nor the mean wind speed in isolation are adequate. The gust wind speed gives a measure of the extreme nature of the wind, but the mean wind speed indicates the longer duration impact on pedestrians. The extreme gust wind speed is considered to be suitable for safety considerations, but not necessarily for serviceability comfort issues such as outdoor dining. This is because the instantaneous gust velocity does not always correlate well with mean wind speed, and is not necessarily representative of the parent distribution. Hence, the perceived 'windiness' of a location can either be dictated by strong steady flows, or gusty turbulent flow with a smaller mean wind speed.

To measure the effect of turbulent wind conditions on pedestrians, a statistical procedure is required to combine the effects of both mean and gust. This has been conducted by various researchers to develop an equivalent mean wind speed to represent the perceived effect of a gust event. This is called the 'gust equivalent mean' or 'effective wind speed' and the relationship between the mean and 3 s gust wind speed is defined within the criteria, but two typical conversions are:

$$U_{GEM} = \frac{(U_{mean} + 3 \cdot \sigma_u)}{1.85} \text{ and } U_{GEM} = \frac{1.3 \cdot (U_{mean} + 2 \cdot \sigma_u)}{1.85}$$

It is evident that a standard description of the relationship between the mean and impact of the gust would vary considerably depending on the approach turbulence, and use of the space.

A comparison between the mean and 3 s gust wind speed criteria from a probabilistic basis are presented in Figure 33 and Figure 35. The grey lines are typical results from modelling and show how the various criteria would classify a single location. City of Auckland has control mechanisms for accessing usability of spaces from a wind perspective as illustrated in Figure 33 with definitions of the intended use of the space categories defined in Figure 34.

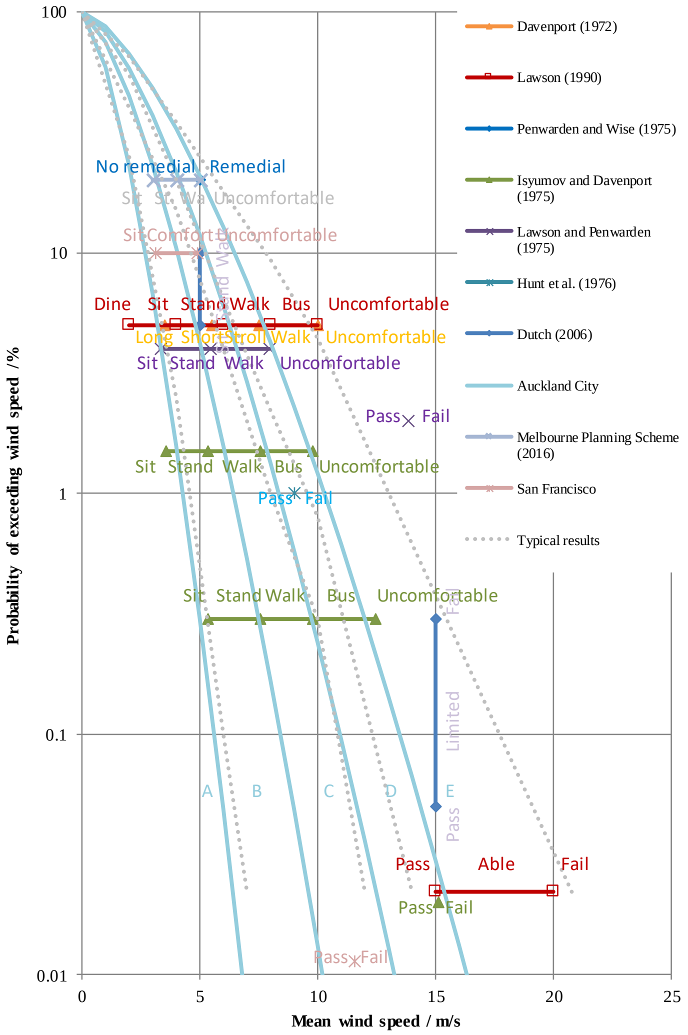

Figure 33 Probabilistic comparison between wind criteria based on mean wind speed

Category A	Areas of pedestrian use or adjacent dwellings containing significant formal elements and features intended to encourage longer term recreational or relaxation use i.e. public open space and adjacent outdoor living space
Category B	Areas of pedestrian use or adjacent dwellings containing minor elements and features intended to encourage short term recreation or relaxation, including adjacent private residential properties
Category C	Areas of formed footpath or open space pedestrian linkages, used primarily for pedestrian transit and devoid of significant or repeated recreational or relaxational features, such as footpaths not covered in categories A or B above
Category D	Areas of road, carriage way, or vehicular routes, used primarily for vehicular transit and open storage, such as roads generally where devoid of any features or form which would include the spaces in categories A - C above.
Category E	Category E represents conditions which are dangerous to the elderly and infants and of considerable cumulative discomfort to others, including residents in adjacent sites. Category E

Figure 34: Auckland Utility Plan (2016) wind categories

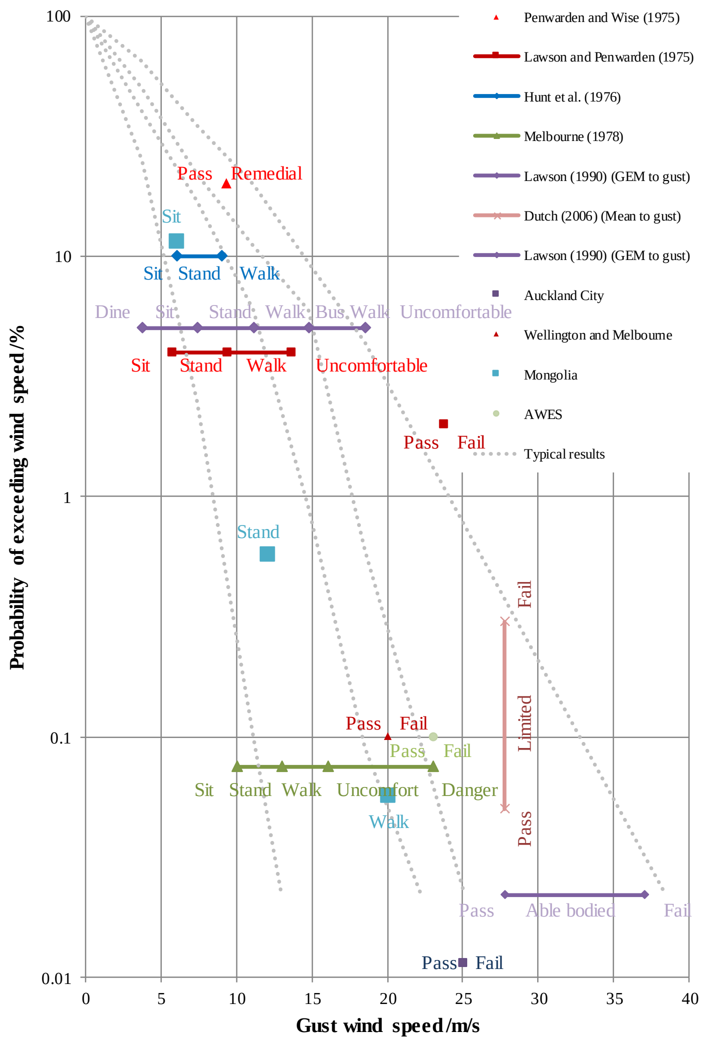

Figure 35 Probabilistic comparison between wind criteria based on 3 s gust wind speed