Pyrmont Peninsula Place Strategy

Wind Assessment

NSW Department of Planning, Industry and Environment

19 October 2021

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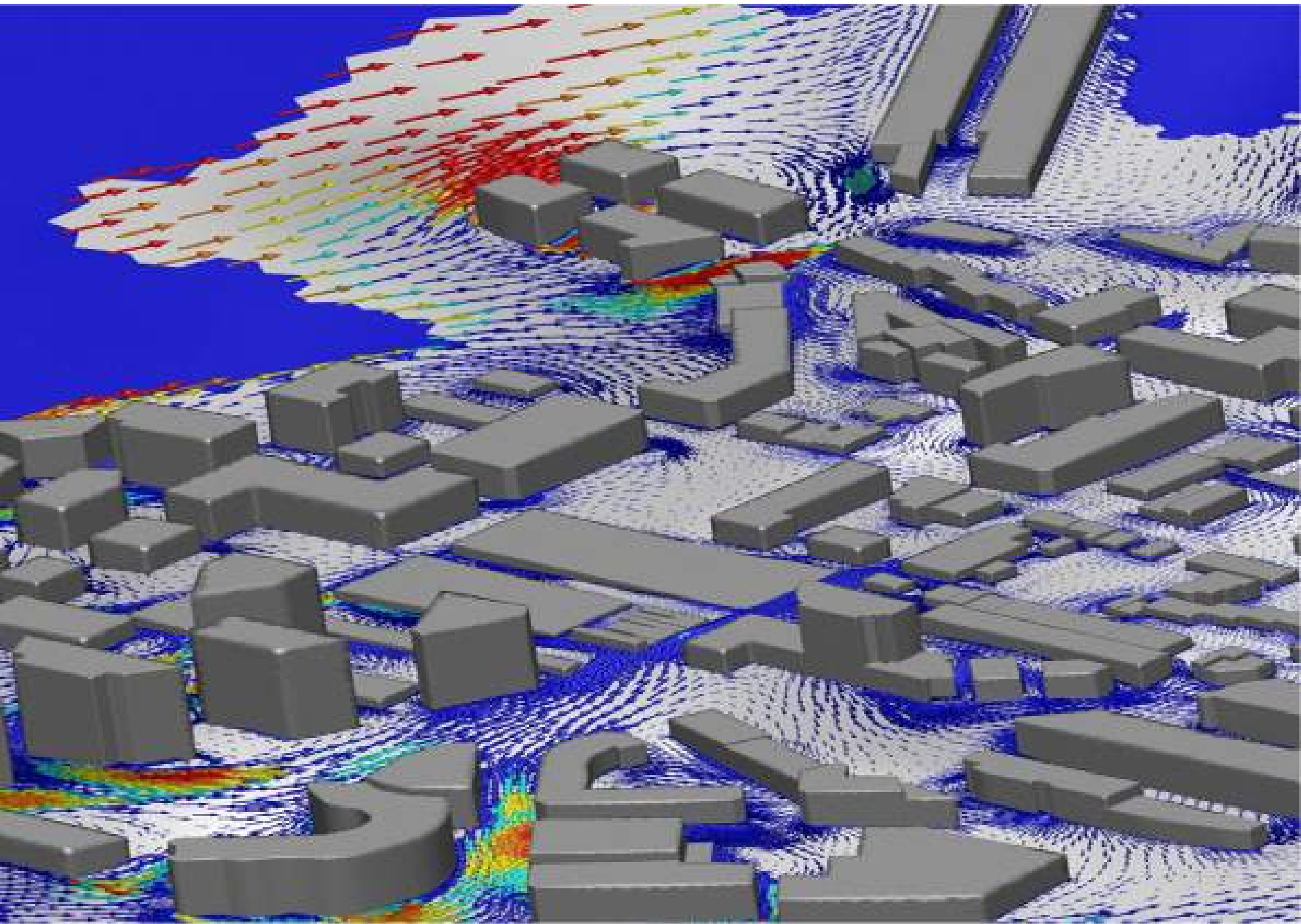

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Executive summary

This report is subject to the limitations set out in section 1.3 and the assumptions and qualifications contained throughout the report.

SJB Planning (NSW) Pty Ltd has engaged GHD to assess the wind conditions for the Pyrmont Place Peninsula area, with consideration given to the identified sites potentially subject to change. The assessment and this report have been written to inform Department of Planning, Industry and Environment (DPIE) of the updated planning controls in the Sydney Local Environment Plan (SLEP) 2012 and Development Control Plan (DCP) as part of implementing the Pyrmont Peninsula Place Strategy.

The wind assessment undertaken examined:

- Meteorology, specifically the wind climate, of the Pyrmont Peninsula area.
- Applicable wind criteria.
- A wind assessment was undertaken using computational fluid dynamics (CFD) modelling for current wind conditions for wind comfort and safety for eight (8) wind directions.

Meteorology for the site was assessed using the Bureau of Meteorology (BoM) Automatic Weather Station (AWS) at Fort Denison. Wind data from a seven-year climatology, 2014 to 2020, were used in this assessment.

On an annual all hour basis, the wind climate indicates the west sector as a preferred quadrant (>25 per cent). However, there are also several north-easterly, easterly, and southerly winds of a lesser frequency (10 to 15 per cent).

Little statistical difference was observed between all hours and day-time hours (6 am to 10 pm) wind speeds and direction. This was especially true at the high wind region of the probability distribution function of wind strength.

An assessment of climate change on wind speed and direction has found that extreme events at the high end of the scale will unlikely be affected in any measurable way by climate change for some time, i.e., short to medium term.

The DCP 2012 has numerous specific wind criteria applying to different specific sites.

For pedestrian comfort, a single criterion based on all hours and an exceedance frequency of 95th percentile should be applied across all areas of greater Sydney.

The adoption of mean wind speeds, or gust equivalent mean, of 4, 6 and 8 m/s for sitting, standing, and walking respectively is considered appropriate, consistent and straightforward with international guidance.

For pedestrian safety, a single criterion based on all hours and an exceedance frequency of once per year should be applied across all areas of greater Sydney. Using just for daytime hours is statistically ineffective and overly complicates any assessment.

Consideration should be given to applying the same averaging period as the comfort criteria, making the safety criteria based on an equivalent hourly averaged value.

As the science of pedestrian stability in wind gusts is inconclusive, the adopted 24 m/s 0.5-second gust is considered reasonable.

An assessment height above a surface should be specified in any criteria. An elevation of 1.5 m is recommended as this equates to torso wind impact, which has the most significant effect on a person's stability.

The wind assessment, undertaken using a CFD model, has found the following.

- In general, the vast majority of the assessed Pyrmont area ground level winds are acceptable for sitting based activities. Areas closest to water surfaces have the highest potential exposure to uncomfortable winds. When groups of tall buildings are clumped together near the shores of Sydney Harbour, the potential for high dis-amenity is most significant.
- Without localised mitigation, all waterfront areas can expect to have exceedances of the sitting comfort level criterion value of 4 m/s. This finding is consistent with other studies in the area.
- The northernmost areas of the peninsula are highly exposed to west and northwest winds.

– Building developments immediately northeast of the ANZAC bridge can generate significant dis-amenity between the buildings at ground level.
– There is some funnelling of winds along street canyons due to the notional NNW-SSW alignment of the streets.
– Buildings considerably higher than immediate adjacent buildings are producing higher ground level winds due to building downwash.
– The more consistent building heights through the south-central region of the Pyrmont study area give rise to lower ground level wind speeds.
– The impact of local terrain, such as harbour facing escarpments, only amplifies any potential wind comfort issues.

Concerning pedestrian safety:

– The vast majority of the assessed Pyrmont area ground level winds are considered safe based on the assessment criteria. Northernmost waterfront areas have the highest exposure to potentially unsafe winds. When groups of tall buildings are clumped together near the waterfront, the potential for unsafe conditions to be generated is greatest. The impact of local terrain, such as harbour facing escarpments, only amplifies any potential wind safety issues.
– The northernmost waterfront areas of the peninsula can be expected to have exceedances of the safety level criterion value of 24 m/s for a 0.5-second gust.
– Building developments immediately northeast of the ANZAC bridge have the greatest potential to generate unsafe wind conditions, particularly between the high-rise buildings.
– The buildings through the south-central region of the Pyrmont study area give rise to safe ground-level wind speeds, except for high buildings exposed to westerly winds immediately coming off the harbour.

Based on the results of this assessment, the following recommendations are provided.

– The wind climate for the strongest winds of Sydney does not justify a delineation of daytime hours from all hours.
– Simplify as much as possible the wind assessment criteria across both the comfort and safety requirements.
    - Apply a consistent averaging time for both comfort and safety criteria. Hourly averages are recommended due to their simplicity.
– Development height limits should be considered at the northernmost areas of the Pyrmont Peninsula but subject to an individual development wind assessment.
– With regards to wind comfort, relative building height limits should be considered, i.e., new development cannot be a certain percentage higher than the adjacent buildings but subject to an individual development wind assessment.

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1. Introduction

SJB Planning (NSW) Pty Ltd has engaged GHD to assess the wind conditions at the proposed site of Pyrmont Place Peninsula.

1.1 Purpose of this Report

This report has been written to inform the Department of Planning, Industry and Environment (DPIE) of the updated planning controls in the Sydney Local Environment Plan (SLEP) 2012 and Development Control Plan (DCP) as part of implementing the Pyrmont Peninsula Place Strategy.

1.2 Scope

The scope of this wind assessment was to:

– Undertake a meteorological assessment of the Pyrmont Peninsula area.
– Review applicable wind criteria.
– Undertake numerical computational fluid dynamics (CFD) modelling to assess current wind conditions for wind comfort and safety for eight (8) wind directions for current existing buildings and developments.
– To provide a baseline for future development assessments.

This report includes:

– A meteorological assessment based on representative measurements
  - Including an assessment of the impact of climate change on local wind speed and direction.
– A review of DCP 2012 wind criteria
– Details of the CFD study:
  - Including the assessment process, assumptions, calculations, and graphical outputs.

1.3 Limitations

GHD has prepared this report for the Department of Planning, Industry and Environment (DPIE). It may only be used and relied on by the Department of Planning, Industry and Environment (DPIE) for the purpose agreed between GHD and the Department of Planning, Industry and Environment (DPIE) as set out in section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than the Department of Planning, Industry and Environment (DPIE) arising in connection with this report. GHD also excludes implied warranties and conditions to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions, and recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring after the date that the report was prepared.

The opinions, conclusions, and recommendations in this report are based on assumptions made by GHD described throughout this report and those specifically listed in section 1.4 of this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared this report based on the Department of Planning, Industry and Environment (DPIE) information and others who provided information to GHD (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report caused by errors or omissions in that information.

1.4 Assumptions

The following assumptions were applied to this assessment.

- The assessment is for the Pyrmont-Ultimo region as a whole and not focused on one specific building/development/location.
- Data from the Bureau of Meteorology (BoM) Automatic Weather Station (AWS) at Fort Denison (station ID 066022) is representative of wind conditions that could occur at the Pyrmont site.
- The results are subject to the known limitations of CFD modelling, as described in Section 5.
- Assessed wind conditions represent hourly averaged conditions, with adjustment for gusts as detailed in Section 4.5.
- Wind directions have been examined with a resolution of approximately 45°, as described in Section 4.
- Wind speeds have been scaled to account for the difference in meteorological conditions and remain representative of the site, as described in Section 4.2.
- The CFD model has been constructed based on publicly available data sets for buildings and terrain and processed as described in Section 5.2.
- Sharp terrain has been smoothed to avoid spurious non-physical numerical effects.
- Elevated roads, such as Western Distributor and other complex urban structures, have been excluded from this assessment. Refer to Section 5.2.5.
- 'Surface friction elements' such as trees and property boundary fences have been excluded. Refer to Section 5.2.4.

2. Pyrmont Peninsula

2.1 Location

The Pyrmont Peninsula is located immediately to the west of the Sydney city central business district (CBD). It is shown in Figure 1, Figure 2 and Figure 3. The area is identified in the Sydney Local Environmental Plan (SLEP) 2012 as Ultimo-Pyrmont.

The notional centre of the peninsula area is located at 33.871°S, 151.195°E, (56H 333,065 mE, 6250655 mS).

The area of this wind assessment investigation is highlighted in Figure 1 and Figure 3. However, significant built form structures immediately adjacent to the boundary of the Ultimo-Pyrmont area were also included. One such significant structure is the Crown Towers development, shown in Figure 4.

2.2 Landscape characteristics

The landscape of the Pyrmont peninsula can be categorised as one of the most urbanised areas of Australia. Within the greater Sydney city, the height of the buildings in the Pyrmont peninsula is probably only second to that of the Sydney CBD.

Building heights greater than 50 m are regular through the assessed area.

2.3 Surrounding land

The Pyrmont peninsula is surrounded on three sides (west, north, and east) by short fetches of Sydney Harbour, with extensive development on the other side of the water.

On the east side of the area is the Sydney CBD, with numerous buildings greater than 100 m in height, including the Crown Towers development at over 270 m high.

The southern portions of the assessed Pyrmont area are bounded by highly urbanised inner-city commercial and residential developments with numerous building heights greater than 50 m.

A large portion of the western boundary south of the harbour is parkland adjacent, bounded by medium to high-density residential developments.

2.4 Terrain categorisation

The surrounding landscape, or terrain, was categorised based on the land use descriptions supplied in Australian Standard AS1170.2:2011 *Structural design actions Part 2: Wind actions* (Section 4). The wind direction-dependent terrain categories are summarised in Table 1 and shown graphically in Figure 2.

The selection of the terrain category has been based on the wind impact on the whole of the assessed area and not on a specific location.

The selected terrain categorisation is consistent with other wind assessment studies carried out for specific developments in the Pyrmont area (Vipac 2016 and Windtech 2019)[1]. These additional studies were for specific sites and, therefore, can categorise the terrain more precisely than the larger area investigated in this assessment.

Estimates of terrain surface roughness, Z_0, are summarised in Table 1, based on the AS1170.2 categorisation system.

The terrain categorisation was used to define the approaching wind velocity and turbulence vertical profiles based on AS1170.2 information.

[1] Vipac 2016. 31 Wheat Road Sydney Wind Effect Statement. Prepared by Vipac Engineers & Scientists Ltd for Grocon Group. Revision 5. 24 March 2016.
Windtech 2019. Pedestrian Wind Environment Study The New Sydney Fish Market Concept and Stage 1 And Stage 2 Main Works. Prepared for UrbanGrowth NSW Development Corporation by WINDTECH Consultants Pty Ltd. Report No. WD758-06F02(REV0)- WE. 20 May 2019.

Table 1 Terrain categorisation

Wind Direction	Wind Direction	Upwind Terrain Category (AS1170.2, sect 4.2.1)	Terrain Roughness, Z_0 (m)
338 to 22	N	tc2.5	0.06
23 to 67	NE	tc4	2.0
68 to 112	E	tc4	2.0
113 to 157	SE	tc4	2.0
158 to 202	S	tc3	0.2
203 to 247	SW	tc3	0.2
248 to 292	W	tc3	0.2
293 to 337	NW	tc3	0.2

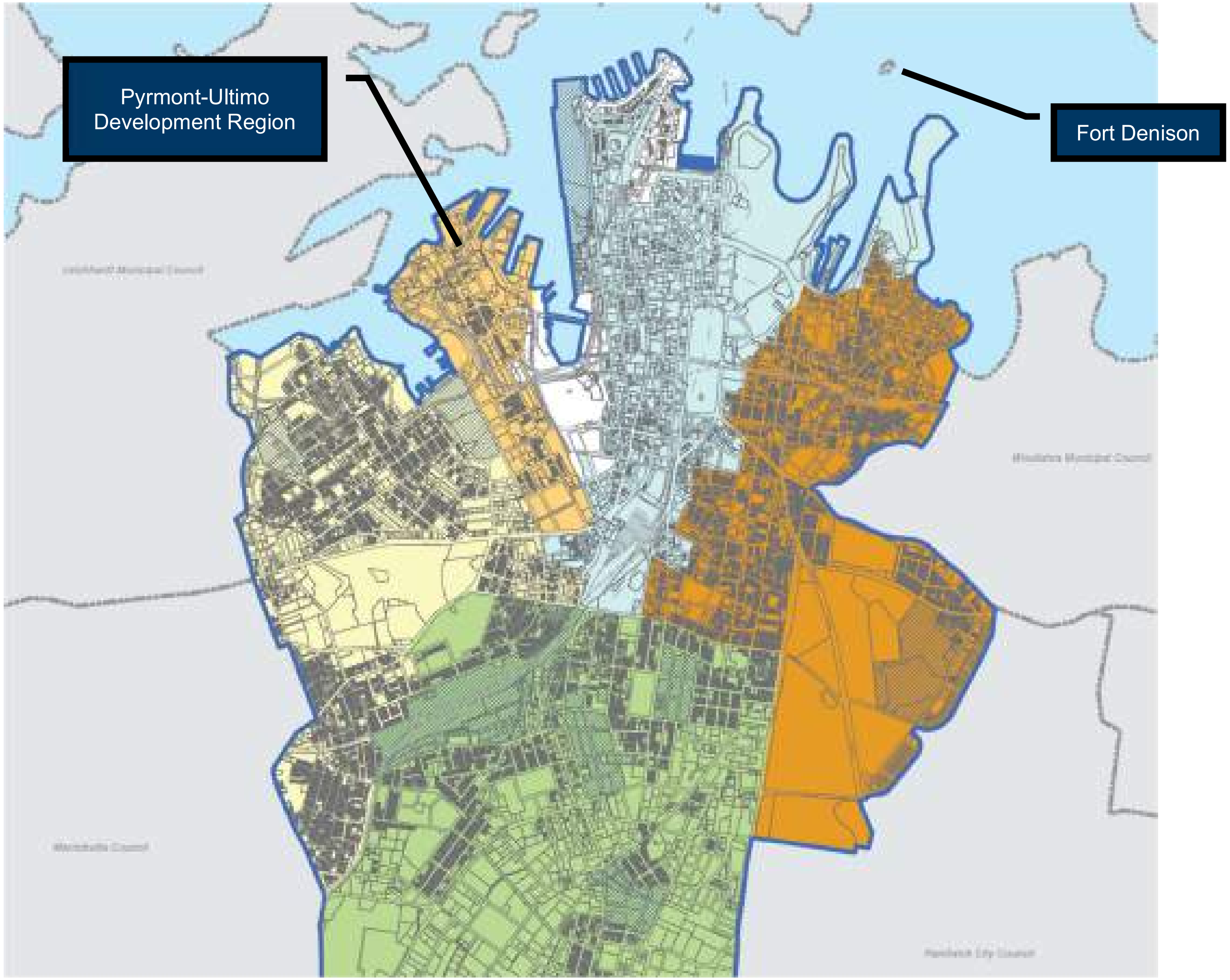

Figure 1 ***Sydney Development Control Plan 2012 Areas. Pyrmont-Ultimo Development Region shown***

Figure 2 Aerial image of Pyrmont-Ultimo Development Region and Sydney CBD. Buildings modelled in highlighted region. Applied terrain categorisation as per AS1170.2

Figure 3 Pyrmont-Ultimo Development Region.

Figure 4 Crown Barangaroo development.

3. Wind assessment criteria

Windy conditions can cause discomfort and danger to pedestrians, and downdraughts from buildings can inhibit the growth of street trees. Conversely, moderate breezes can enhance pedestrian comfort and disperse vehicle emissions and air-conditioning plant exhausts. The useability of open terraces on buildings also depends on comfortable conditions being achieved.

Assessment criteria for pedestrian wind comfort (and safety) generally have two aspects:

1. The magnitude of local airspeed
2. Frequency of occurrence.

If a very high wind speed occurs very infrequently, such a condition can be tolerated and put down to 'a windy day'. However, suppose wind speeds are high for a considerable amount of time, especially when people know it is not a 'windy day'. In that case, people are less tolerant, thus resulting in dis-amenity or poor wind comfort.

A standard resource for the selection of appropriate wind assessment criteria is Lawson (2001). The value of this resource can be inferred from the quote of Lawson (2001, p.123)[2] that for comfort (and safety) wind studies:

"*… there are almost as many sets of criteria as there are workers in the field, but differences are often small between them*."

Insofar as Lawson (2001) makes inroads into comparing some of the criteria presented by different workers, it has value in enabling us to choose an appropriate set of assessment criteria for the current work.

3.1 Sydney Development Control Plan (DCP) 2012

A review of the DCP 2012 has found several different wind assessment criteria within its contents. Some of these relate to particular development areas, while others are more general. There are some standard features of wind assessment criteria, but there are also some inconsistencies.

3.1.1 General provision

In general, the DCP only requires a wind assessment to be undertaken when a development exceeds a height of 45 m (DCP 2012 Section 3.2.6). However, the consent authority can request a wind assessment for any building at their discretion.

> **3.2.6 Wind effects**
>
> These provisions apply to all buildings over 45m high and other development where Council requires wind effects to be considered.

This general provision criteria stipulates that development must not create a ground-level environment where additionally generated wind speeds exceed:

1. 10 metres per second for active frontages as shown on the *Active frontages map*
2. 16 metres per second for all other streets.

These general criteria do not distinguish between average (1-hour) wind speed or gust wind speed, nor does it specify a frequency of occurrence. A review of this general wind effects criteria by the responsible authority is suggested.

3.1.2 Specific provisions

There are site-specific provisions in the DCP that have different requirements for the previous section's general provision.

[2] Lawson, T., 2001. Building Aerodynamics. Imperial College Press.

Numerous different site-specific wind assessment criteria have been identified in the DCP. These are summarised as follows.

– Danks Street South criteria
  DCP 2012 Section 5.9.4.15 Wind Testing
  - Development is to provide wind tunnel testing that demonstrated that all streets comply with the following wind standards:
    – Wind Safety Standards, being an annual maximum peak 0.5 seconds gust wind speed in one hour measured between 6 am and 10 pm Eastern Standard Time of 24 metres per second.
    – Wind Comfort Standard for Walking, being an hourly mean wind speed, or gust equivalent mean wind speed, whichever is greater for each wind direction, for no more than 292 hours per annum measured between 6 am and 10 pm Eastern Standard Time (i.e., 5% of those hours) of 8 metres pers second.
  - Development is to provide wind tunnel testing that demonstrates compliance.

– APDG site criteria
  DCP 2012 Section 6.1.6.3 (10)
  - New developments must not cause the ground level environment to have a mean or Gust Equivalent Mean wind speed exceeding:
    – 10 metres per second for more than 5% of the year; or
    – 15 metres per second more than once per year.

– 60 Martin Place criteria
  DCP 2012 Section 6.3.4.2 Wind
  - There will be no increase in wind impacts felt by pedestrians on the ground plane.

– 230-238 Sussex Street criterion
  DCP 2012 Section 6.3.6.7 Wind
  - There will be no increase in wind impacts felt by pedestrians on the ground plane.

– 505-523 George Street criterion
  DCP 2012 Section 6.3.7.4 Wind
  - There will be no increase in wind impacts felt by pedestrians on the ground plane.

– 4-6 Bligh Street criteria
  DCP 2012 Section 6.3.14.3 Managing Wind Impacts
  - Same as the Danks Street criteria above.

Within the DCP 2012, there are numerous more references to the mitigation of wind effects. However, they have not been documented here as no specific assessment criteria are defined.

There are no single clearly defined wind assessment criteria that apply to the whole DCP 2012. However, the criteria defined for Danks Street South (DCP 2012 Section 5.9.4.15) are considered the most representative of a default criterion where change within an acceptable limit is allowed. This conclusion is based on the Danks Street criteria being applied at multiple specific sites identified in the DCP and its acceptance when used in other wind assessments (Windtech 2019). Additionally, it is consistent with international criteria, as discussed in Section 3.2.

No part of the DCP indicates at what height above a surface the criteria wind speeds should be applied.

3.2 Comfort criterion

The adopted comfort criteria applied for this study is defined in Table 2. This applies to all 'daytime' hours.

These comfort criteria are consistent with other international criteria. In particular, the LDDC (London Docklands Development Corporation) method, as described in Lawson (2001, pp.123-135). The LDDC uses a single frequency criterion (95th percentile or 5 per cent chance of exceedance) with differing wind speeds for different acceptable activities, consistent with the descriptions provided in Table 2. These assessment criteria have been used on other international building development projects.[3]

[3] Novus Environmental. Pedestrian Wind Assessment, 121 Avenue Road, Toronto, ON, Canada. Novus Project # 13-0022. 5 February 2014. (www.novusenv.com)

The great strength of these criteria is that it is relatively simple to understand and implement. Lawson (2001) and Windtech (2019) stated that other criteria could be overly complicated to understand and explain and do not necessarily add any extra value above these applied criteria.

Day time hours

A daytime hour is defined as being between 6 am and 10 pm, representing two-thirds of the day, or 5840 hours per year.

An assessment of the meteorology (Section 4) has found little difference between daytime hours and all hours for both direction and wind speed.

Consideration of simplifying the criteria to all hours should be considered.

Wind exceedance frequency

The wind exceedance frequency of no more than 292 hours per year equates to a five per cent exceedance criterion.

Consideration of simplifying the frequency criterion definition within the DCP to five per cent should be considered.

Table 2 Wind comfort assessment criteria. Applies for daytime hours of 6 am to 10 pm.

Activity	Activity description	Upper limit mean or GEM wind speed exceeded 5% of the time (m/s)	Description of wind effects
Sitting	Outdoor areas that involve seating such as parks, cafes, dining areas and entertainment.	4.0	The light wind felt on face Leaves rustle
Standing	Short duration stationary activities (generally less than one hour) including outdoor shopping and waiting areas.	6.0	Hair is disturbed, clothes flapping Light leaves and twigs in motion Wind extends lightweight flag
Walking	For commonly used pedestrian thoroughfares.	8.0	Moderate, raises dust, loose paper Hair disarranged Small branches move

Summary

The DCP 2012 criteria for daytime hours, both velocity and exceedance frequency, are considered reasonable. However, the restriction of daytime hours (6 am to 10 pm) is considered to overly complicate any assessment, given that there is little statistical difference between daytime hours and all meteorological conditions.

Specifying the criterion as a percentile exceedance, 95^{th}, would also simplify the criteria definition.

The DCP 2012 does not specify any height above a surface plane that the criteria should be applied. A height of 1.5 m has been applied in this study, consistent with other studies (Windtech 2019).

3.3 Safety criterion

Safety or 'distress' criteria are set based on the likelihood of local wind speeds reaching levels that could potentially cause a person to become 'off balance'. They are generally based on what Lawson (2001, p.133) describes as the wind speed needed to "*upset a frail old lady*".

The DCP 2012 annual maximum 0.5-second gust wind criterion of 24 m/s was applied, as defined in Table 3. It applies to all trafficable areas such as walkways, open parks, and ground-level building fronts. These criteria were used for this assessment.

This assessment is based on an analysis of seven (7) years of meteorological data (Section 4). For an annual event frequency of once per year or one in 8760 hours, this equates to a 99.99 percentile event. This event frequency is consistent with information supplied in Lawson (2001, p.133).

Lawson (2001, p.134) defines a safety criterion wind speed of 15 m/s hourly averaged and 20 m/s hourly averaged for areas where frail people or cyclists would be unlikely to access (i.e. building rooftop plant areas). Equating this 15 m/s hourly average equates to a 0.5-second gust wind speed of 31.4 m/s (refer to Sections 4.4 and 4.5 for calculation method).

3.3.1 Other fields of study

Other fields of study have defined maximum airspeeds that are considered safe for person exposure. Underground railway systems define a maximum airspeed for egress people at about 11 m/s (average).[4] Note that the 24 m/s 0.5-second gust wind speed equates to an average hourly value of 11.5 m/s, consistent with international underground railway safety standards.

The British Rail Safety and Standards Board (2007)[5] has undertaken a considerable body of work at examining the impact of wind speed on person stability. Their assessment has found no single specific value of wind speed, either average or gust (one-second average), that is safe or unsafe. In particular, there is a whole range of issues, including a person's ability to anticipate wind impact and therefore brace for its effects.

Measurements of worker exposure near high-speed train tracks indicate gust speeds of 25 m/s can still be safe. However, wind tunnel tests have shown that gusts of 15 m/s transition from safe to unsafe. It is believed to be the nature of the gust build up – a sinusoidal ramp up due to training movement instead of a sharp rise due to rapid removal of a barrier.

3.3.2 Summary

Given that the science behind person stability in wind gusts is inconclusive regarding safe/unsafe delineation, the application of the 24 m/s 0.5-second gust is not inconsistent with the current literature. However, it appears to be on the lower end of what is considered unsafe, i.e., a conservative value. There is, therefore, some justification for it to be increased.

It would make assessment simpler if a safety criterion wind speed were in the same units as the comfort criteria, i.e., converting it to an hourly average. In this regard, the Lawson (2001, p.134) criterion of 15 m/s hourly average is simple but maybe too high in terms of an equivalent 0.5-second gust.

Applying the safety criteria to all hours should also be considered to simplify the assessment and make no statistically significant difference on the assessment.

Table 3 Wind safety assessment criteria. Applies for daytime hours of 6 am to 10 pm.

Activity	Annual maximum 0.5 s gust wind speed (m/s)	Description of wind effects
All	24.0	Off balance people

3.4 Mean and gust wind speeds

Mean wind speeds, assessed as one-hour averages, have been used to determine comfort levels. Gust equivalent mean (GEM) (Section 4.4) and mean wind speeds are considered as equivalent for this assessment.

Gust wind speeds, assessed as 0.5 second averages, have been used to determine safety levels. Refer to Section 4.5 for additional information.

3.5 Assessment planes

Wind speeds have been assessed on a plane 1.5 m above the modelled ground terrain regarding comfort and safety criteria. This is consistent with other wind studies (Windtech 2019) and represents wind impact on a person's torso while standing and head level while sitting.

[4] London Underground Standard LUL S1067 (June 2015). 11.1 m/s for emergency conditions and 15 m/s for non-public tunnel adits. NFPA 130 (2020). 11 m/s along any path of egress.
[5] Rail Safety and Standards Board, 2007. Safety of Slipstream Effects Produced by Trains. Prepared by Mott MacDonald, St Anne House, Wellesley Road, Croydon, CR2 9UL. 19 November 2007.

Wind speed contours at differing elevations are provided for reference. Specific balcony or other building-level wind speed assessment has not been undertaken. Such a detailed assessment is left to wind assessments of individual buildings.

3.6 Wind impact controls

There are numerous development design features that can be used to control or minimise local wind speeds. Some control measures in the DCP 2012 are setbacks and street walls.

A review of DCP 2012 indicates that street wall and setback strategies are based on a variety of issues, with wind only being one of many. In particular, retention of street heritage character is considered a high priority item.

Wind issues pertaining to building setbacks is highly complicated and very much site/building specific. For example, a very small setback between two large building towers may reduce wind speeds to a similar extent that a very large setback does (i.e. through air flow resistance). However, other parameters are impacted such as light, ventilation, privacy, etc.

Planning experts should balance all competing needs. With compliance to a simple overarching wind comfort criterion, development setbacks and street walls can be set on things like visual amenity or privacy.

4. Meteorology

4.1 Prevailing winds

Meteorology for the site was assessed using the Bureau of Meteorology (BoM) Automatic Weather Station (AWS) at Fort Denison, located approximately 3.3 km northeast of Pyrmont, as shown in Figure 1 and Figure 2. Meteorological observations from the Bureau of Meteorology (BoM) site Sydney – Observatory Hill (ID 066214) is immediately adjacent to the precinct. However, wind information is currently not supplied from the BoMs Observatory Hill site due to a lack of representative exposure at the site to measure wind.

Wind data from a seven-year climatology, 2014 to 2020, were used in this assessment. Some technical detail on this AWS is provided in Table 6. This study's primary wind data of interest include wind speed (anemometer) and wind direction (wind vane). Wind speed is recorded as a time average with gusts measured as the peak 3-seconds in the averaging period. The corresponding wind direction is also logged. The wind data has been studied with two different time scenarios: All hours and daytime hours (6 am – 10 pm).

Table 4 Bureau of Meteorology Melbourne (Fort Denison) AWS

Parameter	Value
BoM Site number	066022
Latitude	33.8551 ºS
Longitude	151.2254 °E
Station Height	5 m (anemometer ~10 m above sea level[6])
Data available (from)	January 2014

The averaged wind data has been divided into 45° sectors (8-point compass) (Table 6).

The long-term annual wind rose for the Fort Denison AWS has been analysed with an all directions wind speed distribution shown in Figure 5. The all directions, annual all hour average wind speed is 4.31 m/s. The wind climate on an annual all hour basis is represented by Figure 6, which indicates a west sector as a preferred quadrant. However, there are also several north-eastly, easterly and southerly winds of a lesser magnitude.

As shown in the wind roses of Figure 6, for the 'all hours' and 'daytime hours', the west component direction remains the prevailing wind direction with most wind speeds in the range between 2 to 6 m/s. It is noted that the winds from the west in the daytime hours wind rose to account for approximately 26 per cent of all incidence winds while all hours records roughly a total of 30 per cent of all incident winds.

Most of the low wind speeds (<2 m/s) are from northwest to north directions, while the strongest winds (>8 m/s) occur from both southerly and westerly directions. This strong wind preference has good exposure at Fort Denison (Figure 2) overwater fetch exceeding one kilometre to the west and 500 m to the south.

4.2 Wind speed terrain adjustment

The Fort Denison AWS is located in the middle of Sydney Harbour (Figure 2), where wind speeds experienced at this AWS are expected to be different to those experienced over the Pyrmont assessment area. A meteorological station wind speed scale factor has been adopted based Australian Standard AS1170.2 guidelines for relative wind speeds on different terrains. Recorded meteorological data at Fort Denison will be of higher velocity due to it being located over water than a meteorological station that is located on land. Concerning Table 5, AS1170.2 wind factors are based on meteorological station data being situated on land, nominally Terrain Category 2. The Fort Denison site has been defined as Terrain Category 1.5.

[6] The RM Young anemometer is "on northern arm of flag mast", of unknown height but, with good wind exposure as the station height at the base of the mast being 5 m (of rock) above sea level. BoM (2020), Basic Climatological Station Metadata. http://www.bom.gov.au/clim_data/cdio/metadata/pdf/siteinfo/IDCJMD0040.066022.SiteInfo.pdf. Accessed 31 May 2021.

The measured meteorological data is first adjusted based on the location of the Fort Denison and then adjusted based on the terrain categorisation as defined in Table 6. The final terrain wind speed adjustment factors are specified in Table 6 for each modelled wind direction.

Table 5 Meteorological data adjustment factor due to the location of Fort Denison, as per AS1170.0 guidance.

Terrain Category (AS1170.2)	Surface roughness, z_0 (m) (AS1170.2)	Terrain wind speed Multiplier @ 10 m (AS1170.2)	Meteorology station Wind speed adjustment factor
TC1	0.002	1.12	1.06
TC1.5	0.006	1.06	1
TC2	0.02	1	0.94
TC2.5	0.06	0.965	0.91
TC3	0.2	0.93	0.88
TC4	2	0.75	0.71
Fort Denison BoM station location			
TC1.5	0.006	1.06	1

Table 6 Wind direction quadrant definitions. Fort Denison defined as Terrain Category 1.5.

Wind quadrant (compass direction)	Degree start	Degree finish	Terrain category (AS1170.2)	Wind speed terrain adjustment factor (as per AS1170.2)
N	338	22	tc2.5	0.91
NE	23	67	tc4	0.71
E	68	112	tc4	0.71
SE	113	157	tc4	0.71
S	158	202	tc3	0.88
SW	203	247	tc3	0.88
W	248	292	tc3	0.88
NW	293	337	tc3	0.88

4.3 Percentile distributions

The percentile distributions of wind speed for all hours and day hours are supplied in Table 7 and Table 8, respectively, with gust wind speed data provided for all hours and daytime hours in Table A.1 and Table A.2, respectively (found in Appendix A). Table A.3 and Table A.4 of Appendix A provide information about the ratio of the gust wind speed to the average wind speed for all hours and day-time hours.

4.4 Gust Equivalent Mean

The 3-second measured gust wind speeds at Fort Denison are provided in Appendix A for the seven-year wind climatology. The ratio of gust wind speed to mean wind speed (Table A.5 and Table A.6) varies between 1.4 and 2.7.[7] By definition, the gust wind speed is higher than the one-hour mean wind speed.

[7] Excluding <10th percentile data.

The gust equivalent mean (GEM) is defined as the gust wind speed divided by 1.85. The measured meteorology indicates that this is a good relationship and will be applied for this assessment. There is some variation with wind direction. However, for the 95th percentile wind speeds, this variation is minor: 1.4 to 2.0. Of particular interest, east winds have the lowest gust factor, representing winds that have a large fetch over Sydney Harbour water. At the same time, the highest gust factor is associated with southwest winds that have first passed through the Sydney CBD high surface roughness area.

Based on the representative meteorology of Fort Denison, the measured one hour mean wind speeds are representative of the GEM wind speed.

4.5 0.5-second wind gust adjustment

The safety criterion is based on a 0.5 second gust wind speed. Meteorological gust data is measured in Australia by BoM as a 3-second average. A scale multiplication factor of 1.13 has been applied to increase the 3-second values to 0.5-second values. This equates to adjusting the transient wind speed measurement distribution from three standard deviations from the mean to 3.4 standard deviations. This approach is consistent with other wind studies of the area (Windtech 2019, Section B.1).

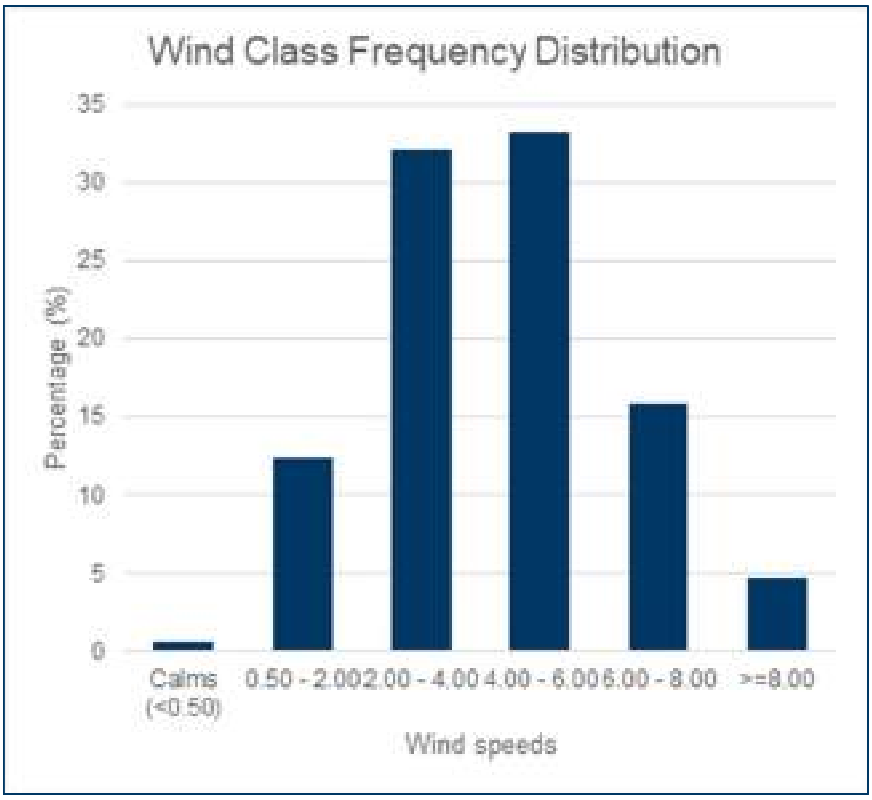

Figure 5 Wind speed distribution from For Denison (BoM Station ID: 066022) for all years

4.6 Impact of climate change

Current literature indicates that climate change may impact the wind patterns and speeds for the Sydney city area.

There are several types of weather systems that have the potential to generate extreme (damaging to destructive) winds and include:

- East Coast Lows (ECLs)
- Severe thunderstorms
- Ex-tropical cyclones
- Gales and frontal systems.

ECLs are frequently associated with significant wind speed events along the NSW coast. For example, the severe storm on 8 June 2007 produced a 3-second gust of 106 km/h at Fort Denison and the Wedding Cake site on Sydney Harbour (further east to Fort Denison) produced a 3-second gust of 135 km/h on 23 February 2013. "The overall incidence of ECLs affecting New South Wales is currently around 10 per year, with 3–5 of those systems producing severe coastal impacts with gale-force winds and flooding rains. They generally occur from autumn through to spring and are winter dominant" (Department of Environment, Climate Change and Water NSW, 2010, p.10)[8]. "Research into modern, historical and pre-European climates show us that ECLs are highly variable from year to year and decade to decade and that there is the **potential for more intense and frequent storms** than we have experienced in the recent past" (OEH, 2016, p.5, emphasis added)[9].

Bureau of Meteorology research has not detected a trend over the period where other climate change indicators are changing:

– "The Bureau has a detailed database of these lows beginning in 1973. Each year there are about ten "significant impact" maritime lows. Generally, only once per year do we see "explosive" development.
– Looking at all the lows since 1973, there is no evidence of a trend" (BoM, 2021)[10].

Moreover, "Fewer east coast lows, particularly during the cooler months of the year" (BoM, 2020)[11].

"Thunderstorms with severe winds affect all regions of the state each year with frequencies … 5 per year in the Sydney/Central Coast region" (DECCW, 2010, p.10). Small scale and short-lived damaging wind episodes due to weather events, such as severe thunderstorms, are not adequately captured in the resolution of climate models and require downscaling using regional models.

It is not known how these randomised ECL and thunderstorm events will change in a warming climate scenario.

Ex-tropical cyclones moving through south-eastern parts of Queensland and further to the Sydney region weaken as they move over cooler water, and generated gales have a low incidence (return interval). "Some modelling studies have projected an increase in categories 3 to 5 systems due to climate change, but tropical cyclone frequency is" (ibid.) more difficult to predict with the return interval likely to continue at multiple years and the BoM (2020)[11] predicting "Fewer tropical cyclones, but a greater proportion projected to be of high intensity, with ongoing large variations from year to year."

"Wind hazards derived from gales and frontal systems have a current incidence (of) low to moderate in the Sydney/Central Coast regions; There is a low level of confidence for future projections, but several models indicate a likely decline in the frequency of westerly gales as the westerly winter belt moves further south" (DECCW, 2010, p.11).

"On the annual and decadal basis, natural variability in the climate system can act to either mask or enhance any long-term human-induced trend, particularly in the next 20 years" (CSIRO 2021)[12].

In summary, the wind climate assessed here, wind speed and direction, as extreme events at the high end of the scale, will likely continue for some time and unaffected in any measurable way by climate change.

[8] DECCW, 2010. Impacts of Climate Change on Natural Hazards Profile - Statewide Overview, December 2010
[9] OEH, 2016, AdaptNSW. Eastern Seaboard Climate Change Initiative - East Coast Lows Research Program Synthesis for NRM Stakeholders
[10] BoM, 2021. East coast lows. http://www.bom.gov.au/weather-services/severe-weather-knowledge-centre/eastcoastlows.shtml. Accessed 31 May 2021.
[11] BoM 2020. State of the Climate 2020. http://www.bom.gov.au/state-of-the-climate/future-climate.shtml. Accessed 31 May 2021
[12] CSIRO, 2021. Climate Change in Australia. East Coast South (Cluster). https://www.climatechangeinaustralia.gov.au/en/projections-tools/regional-climate-change-explorer/sub-clusters/?current=ECSC&tooltip=true&popup=true. Accessed 31 May 2021.

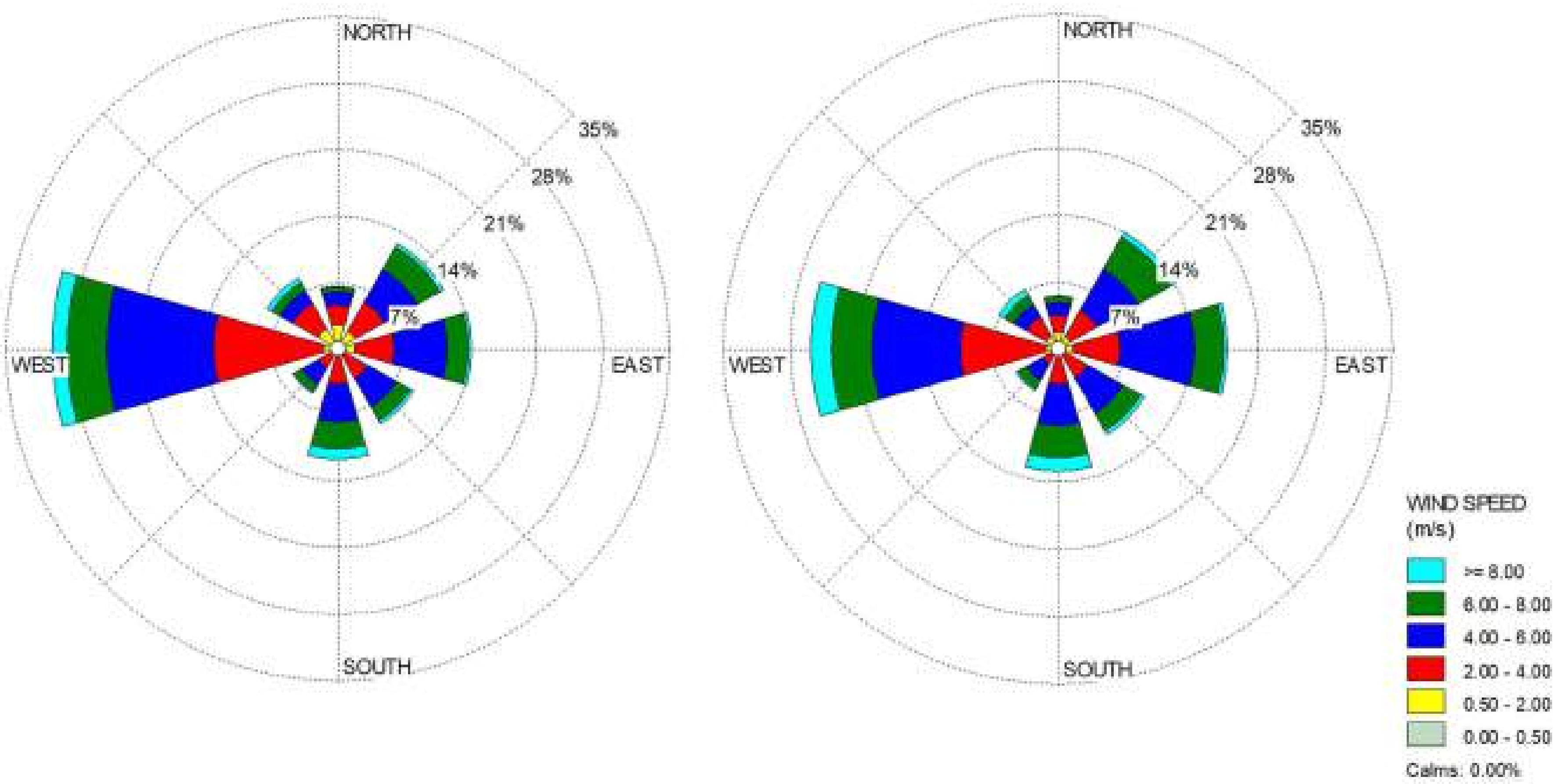

Figure 6 *Wind rose from Fort Denison BoM Station (ID: 066022). Left: 8-point compass for all hours. Right: 8-point compass for daytime hours (6 am - 10 pm)*

Table 7 Average wind statistics – Hourly average wind speed and direction percentiles and frequency – all hours 2014-2020

		Wind Speed 1-hour Avg (m/s)							
	Wind Direction (degree)	**338 to 22**	**23 to 67**	**68 to 112**	**113 to 157**	**158 to 202**	**203 to 247**	**248 to 292**	**293 to 337**
	Wind Direction (compass)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Percentile	100	10.7	14.6	18.0	16.5	14.5	10.7	17.0	13.0
	99.99 (safety criterion)	10.7	13.3	17.6	16.3	14.1	10.6	15.4	12.9
	99.9	10.0	10.2	13.4	13.5	12.6	10.2	12.4	12.3
	99	8.0	8.9	8.9	9.9	10.4	8.9	10.6	10.1
	98	7.5	8.4	8.2	9.0	9.7	8.4	9.6	9.5
	95 (comfort criterion)	6.5	7.6	7.3	7.7	8.9	7.4	8.0	8.4
	90	5.7	7.1	6.5	7.0	7.9	6.8	6.9	7.3
	80	4.6	6.3	5.8	6.1	6.9	5.9	5.9	5.7
	70	3.9	5.6	5.3	5.5	6.2	5.4	5.2	4.5
	60	3.2	4.9	4.8	4.9	5.6	4.8	4.7	3.6
	50	2.6	4.3	4.3	4.4	4.9	4.3	4.2	2.9
	30	1.4	2.9	3.2	3.4	3.8	3.2	3.4	2.0
	20	1.1	2.2	2.5	2.7	3.1	2.7	3.0	1.5
	10	0.7	1.3	1.6	1.9	2.4	2.0	2.4	1.1
	0	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.2
	Wind Direction Frequency	0.067	0.129	0.143	0.093	0.119	0.056	0.305	0.087

Table 8 Average wind statistics – Hourly average wind speed and direction percentiles and frequency – daytime hours (2014-2020)

		Wind Speed 1-hour Avg (m/s)							
	Wind Direction (degree)	**338 to 22**	**23 to 67**	**68 to 112**	**113 to 157**	**158 to 202**	**203 to 247**	**248 to 292**	**293 to 337**
	Wind Direction (compass)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Percentile	100	10.7	14.6	18.0	16.5	14.5	10.7	17.0	13.0
	99.99 (safety criterion)	10.7	13.7	17.7	16.3	14.2	10.6	15.5	13.0
	99.9	10.2	11.0	13.4	14.8	12.9	10.4	12.7	12.5
	99	8.2	9.1	8.7	9.8	10.5	9.2	11.2	10.6
	98	7.8	8.6	8.1	9.0	9.7	8.7	10.4	9.9
	95 (comfort criterion)	7.0	7.8	7.3	7.7	9.0	7.8	8.9	8.9
	90	6.1	7.3	6.7	7.0	8.0	6.9	7.6	7.9
	80	5.2	6.7	5.9	6.2	7.0	6.2	6.3	6.6
	70	4.3	6.0	5.4	5.7	6.3	5.7	5.6	5.4
	60	3.7	5.5	4.9	5.2	5.8	5.2	4.9	4.5
	50	3.0	4.9	4.6	4.7	5.3	4.6	4.4	3.6
	30	1.7	3.7	3.6	3.7	4.0	3.5	3.5	2.4
	20	1.2	2.9	2.9	3.0	3.4	2.9	3.0	1.9
	10	0.8	1.9	2.1	2.1	2.5	2.1	2.4	1.3
	0	0.0	0.2	0.2	0.2	0.2	0.2	0.3	0.3
	Wind Direction Frequency	0.056	0.142	0.180	0.105	0.130	0.052	0.261	0.073

5. Numerical Modelling

5.1 Overview

Computational Wind Engineering (CWE) is the term used to describe the use of a numerical model – using computational fluid dynamics (CFD) – to determine aspects of fluid (the atmosphere, and wind, considered as a fluid) motion around buildings and built structures. These aspects would otherwise be determined using a scale model in a wind tunnel or actual full-scale measurements. There are advantages and disadvantages to using CWE as opposed to scaling model physical testing. These are described relatively well in Cochran and Derickson (2011)[13] , and so detailed background information on all aspects of CWE will not be supplied as part of this assessment report.

The following sections are a summary of the CFD modelling.

5.2 Model geometry

A three-dimensional (3D) CFD model was constructed using ANSYS Fluent Version 21 R1.

Model geometry was constructed of the Pyrmont Peninsula and immediate surroundings, as shown in Figure 2 and Figure 3.

The 3D model of the region, shown in Figure 7, Figure 8 and Figure 9, consisted of representative buildings of the region and adjacent buildings to the area, such as Crown Towers Sydney development at Barangaroo (Figure 4).

The surface terrain was assessed and deemed that it could not be represented as a flat surface. Terrain features were included as detailed in Section 5.2.2 and Appendix B.

Building information was sourced from publicly available information, as detailed in Section 5.2.1.

5.2.1 Data source

Building and terrain elevation information for the modelling was obtained from the Foundation Spatial Data Framework's Location Information Knowledge Platform (FSDF LINK) (https://elevation.fsdf.org.au/).

Building footprint data was obtained from OpenStreetMap[14].

As defined by a horizontal plane referenced to sea level, building height was extracted for each identified building footprint. As the study examines the larger scale wind patterns around the region and not precise wind speeds associated with particular buildings, this spatial resolution was considered reasonable.

5.2.1.1 Building spatial resolution

The building footprints were manually adjusted to remove small gaps. Small 'sliver' spaces in the model would result in numerical instability or a computational grid size far more significant than computer resources would allow, for little to zero benefit to the study.

All spatial gaps less than one metre were removed, i.e., filled in. Spatial gaps between one and two metres were assessed on a case-by-case basis. Any gaps greater than two meters were retained.

For buildings with adjoining walls, height differences less than 0.3 m were removed by increasing the height of the lower building. This was done so that sliver faces and cells were not generated that would cause numerical instability.

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[13] Cochran and Derickson (2011). A physical modeler's view of Computational Wind Engineering. Journal of Wind Engineering and Industrial Aerodynamics, v.99, pp.139-153. (https://www.researchgate.net/publication/283878486_A_physical_modeler%27s_view_of_Computational_Wind_Engineering)
[14] https://www.openstreetmap.org/

Buildings were modelled as extruded prisms from their defined height to the terrain surface plane, as shown in Figure 9.

5.2.2 Terrain

Terrain surface data was extracted at a resolution of 10 m. Processing of the terrain data was undertaken to obtain a representative topography reasonable for numerical simulation and retains the large-scale features that influence the wind flow patterns around the building landscape.

The modelled terrain used a 20 m spatial resolution that was averaged over a spatial distance of 40 m. Details of the terrain processing are supplied in Appendix B.

5.2.3 Mesh resolution

The model atmosphere (domain) was modelled to an altitude of 1000 m. The CFD computational mesh is shown in Figure 8, Figure 9 and Figure 10. The modelled domain extended approximately 1500 m upwind and downwind of the assessment area.

The total computational domain for all models consisted of approximately 4.5 million cells - predominately polyhedral, with three layers of prismatic surface cells surrounding the buildings.

The modelled domain was created using a nested mesh approach with a non-conformal interface between polyhedral cells around the buildings and hexahedral cells for the up and downwind sections of the model, as can be seen in Figure 8. This method allowed for a high-resolution mesh to be applied to the complex building geometry, with efficient modelling of the upwind and downwind areas that primarily eliminate boundary proximity impacts on the building interface wind patterns.

5.2.4 Trees and fences

'Surface friction elements' such as trees and property boundary fences were not included in the modelling. These are difficult to model and generally, but not always, provide some protection from high winds. Vegetation can also change over time, with tree planting and removals possible. Therefore, the absence of these items can be considered a 'worst case' situation.

5.2.5 Elevated Roads

Elevated roads and bridges have been excluded from the model based on the following reasons.

- The study is for broad regional scale assessment, not a specific location.
- On balance, more likely to result in lower ground level wind speeds and higher wind speeds.
- Challenging to obtain representative three-dimensional geometric information. Information such as ground-level clearance and any noised wall locations and height is critical.
- A specific building adjacent to an elevated road is better assessed on an individual site-specific assessment.

5.3 Numerical modelling

A steady-state Reynolds Average Naiver-Stokes (RANS) method was used to model the wind around the building structures. This is a 'time independent' solution that provides 'average' conditions, subject to the applied turbulence model. A RANS approach to computational wind assessments is considered an effective method of modelling steady-state conditions.

The numerical modelling schemes applied to the modelling are summarised in Table 9.

Table 9 CFD model settings summary

Parameter	Value
CFD Package	ANSYS Fluent Version 21 R1
Computational Cells	4.45 million – polyhedral, hexahedral, and prismatic
Numerical Solution Schemes	Steady State SIMPLE Pressure-Velocity Solver Gradient: Least Squares Cell Based Pressure: Standard Momentum: Third-Order MUSCL Turbulent kinetic energy: QUICK Turbulent dissipation rate: QUICK
Turbulence Model	Realisable k-ε
Wall Functions	Standard
Material Models	Constant density and material property air. $\rho = 1.2\ kg/m^3$ $\mu = 1.8e\text{-}05\ Pa.s$

Figure 7 Modelled numerical domain

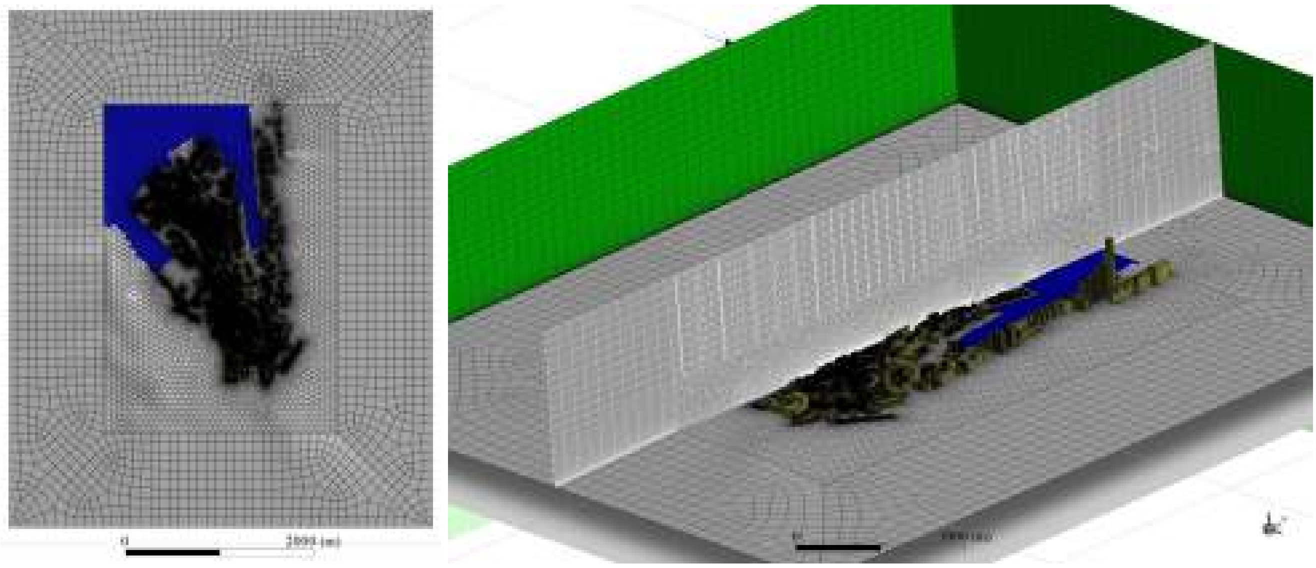

Figure 8 ***CFD mesh***

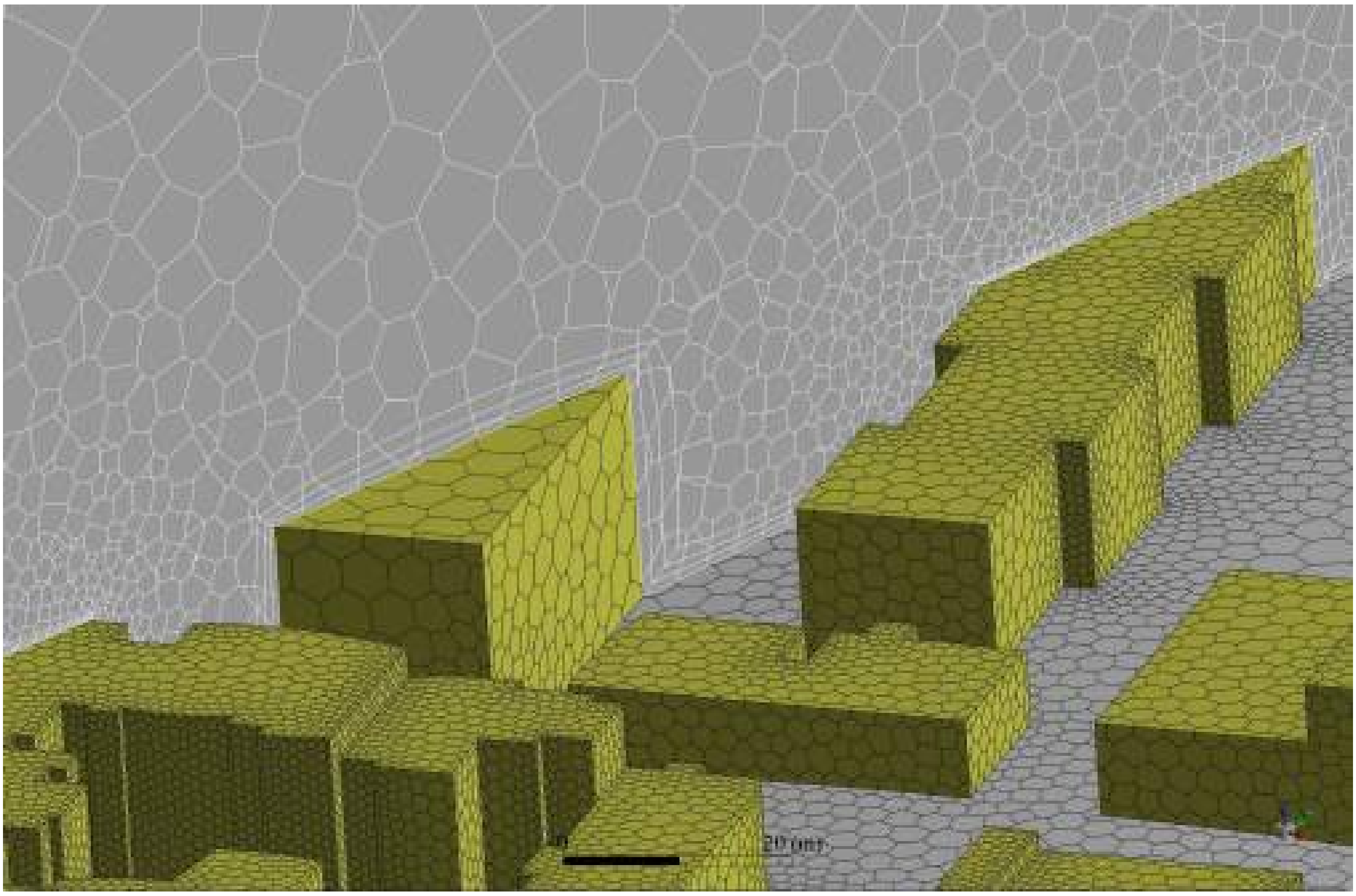

Figure 9 ***CFD building mesh***

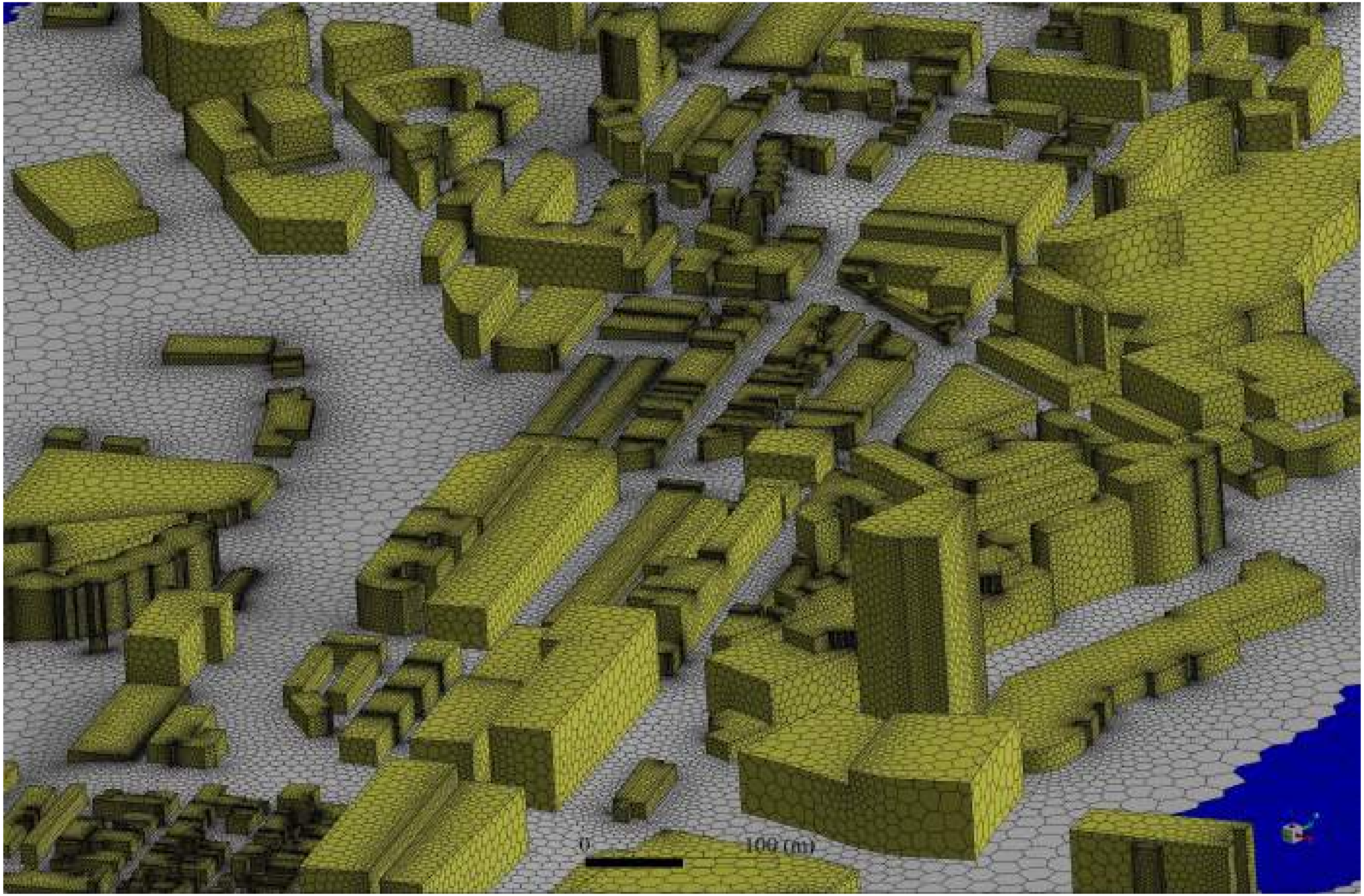

Figure 10 CFD building mesh

5.4 Wind velocity

The wind velocity profile was modelled as described in AS1170.2. A power law regression function was developed from the information supplied in Table 4.1 of AS1170.2 that related reference wind speed and terrain category to the velocity profile with respect to altitude. The adopted wind profiles for a 10 m/s reference wind speed are shown in Figure 12.

The adopted wind profiles were terminated at an altitude of 200 m, with wind speeds at higher elevations assumed to be equal to that at 200 m. This was done as AS1170.2 does not extend higher than 200 m, and all buildings in the Pyrmont assessment area are shorter than 200 m. Crown Towers is higher than 200 m but is only included in the model for its massing impact on winds.

An example of how the model velocity profile evolves as it passes through the domain is shown in Appendix F. Model boundary inlet profile, profile immediately upstream of the assessment area and profile immediately downstream of the assessment area are shown for a west 7.8 m/s wind condition (ID 027).

5.5 Turbulence modelling

A realisable k-ε turbulence model was applied with model settings of turbulent kinetic energy, k, and turbulent dissipation rate, ε, set to those described by Richards and Hoxley (1993). This approach does not discriminate between vertical or horizontal turbulence.

AS1170.2 provides information regarding turbulence intensity concerning the terrain category and altitude. A review of the relationship between turbulence intensity and turbulent kinetic energy found that the vertical variation of turbulent kinetic energy was negligible concerning that defined at a reference height of 10 m. Given this, the approximation that turbulent kinetic energy was constant throughout the atmosphere was applied.

The calculation procedure for turbulence parameters is described in Figure 11. AS1170.2 is used to define the terrain category and turbulence intensity. The Richards and Hoxley (1993) k-ε turbulence model was used to define k and ε values, using model constants $C\mu$ (0.09) and κ (0.42, von Karman constant) and the intermediate calculation of the friction velocity, U^*.

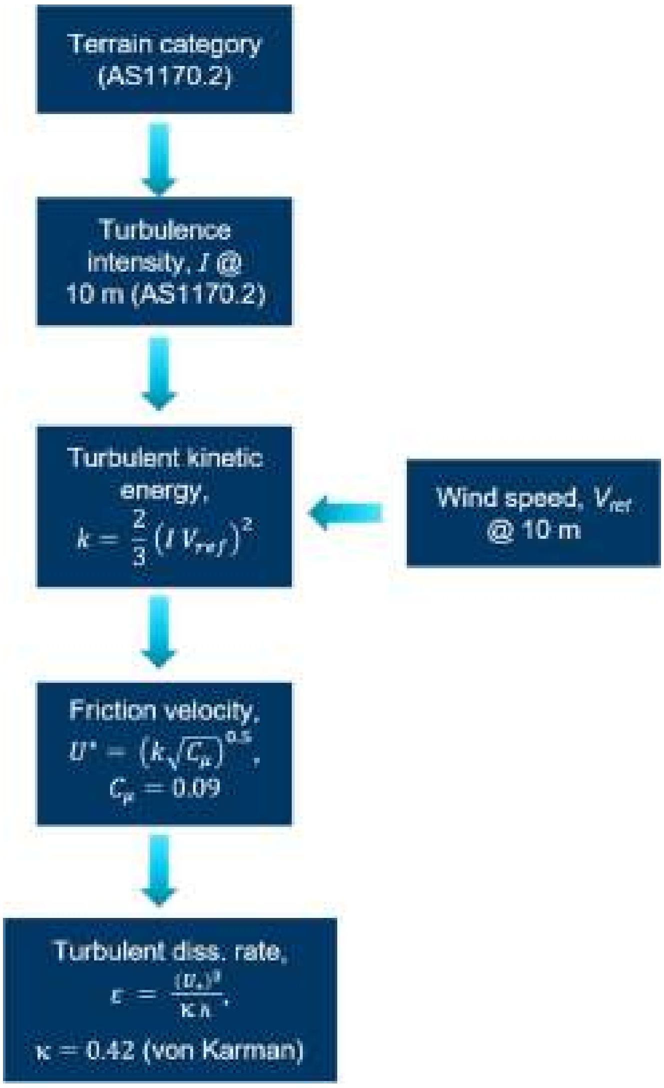

Figure 11 ***Turbulence parameter calculation procedure***

The applied turbulent kinetic energy at the modelled domain wind inlet for different reference wind speeds due to the upstream terrain categorisation is tabulated in Table 10.

The turbulent dissipation rate ε decreases with altitude, as shown in Figure 13, for a 10 m/s reference wind speed and different terrain categories.

Table 10 Applied turbulence kinetic energy, k, values (m²/s²)

Wind speed (m/s)	Terrain category TC2.5	Terrain category TC3.0	Terrain category TC4.0
5	0.7	1.0	2.0
10	2.8	3.9	7.8
15	6.4	8.8	17.5
20	11.4	15.6	31.2

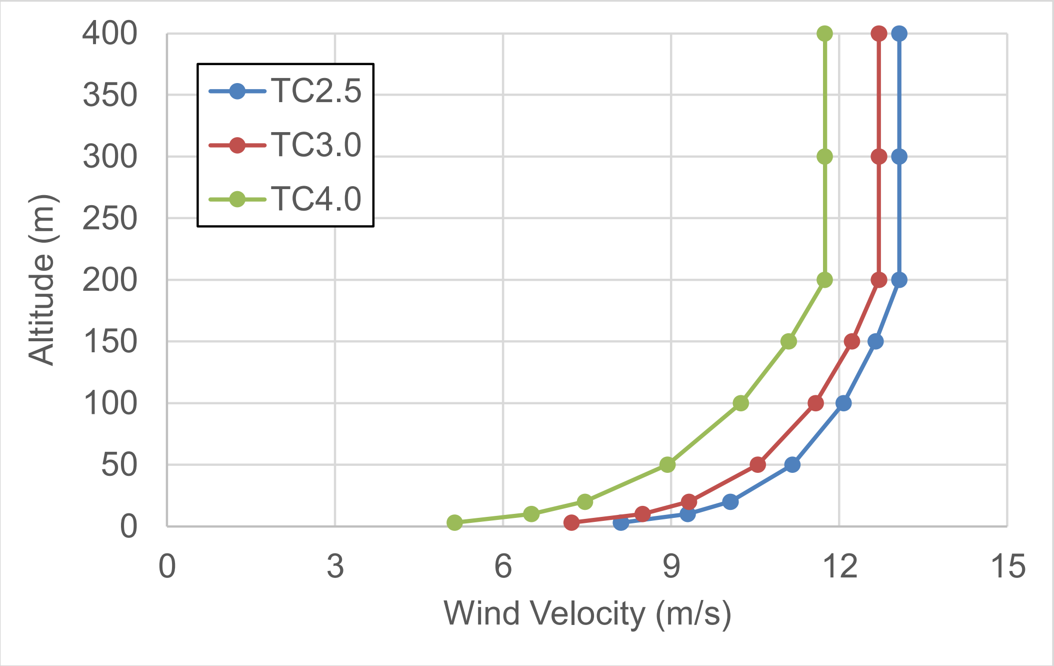

Figure 12 Applied inlet velocity profile for nominal 10 m/s wind speed for different terrain categories. Profiles based on AS1170.2 (Table 4.1) terrain wind speed multiplier

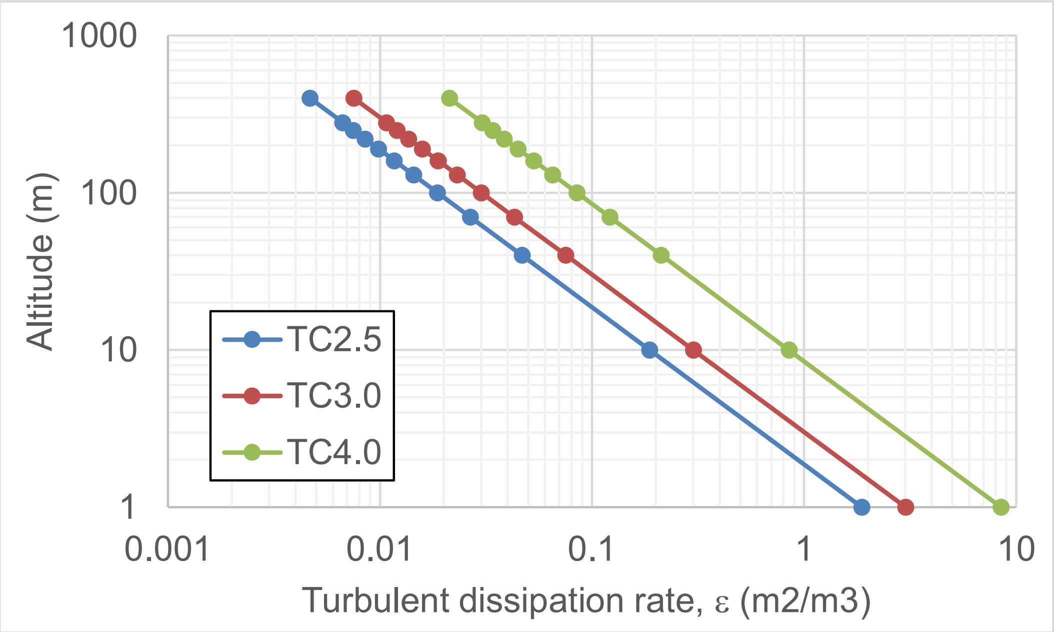

Figure 13 Applied inlet turbulence dissipation rate for model boundary conditions, ε, profile for 10 m/s wind condition for different terrain categories

5.6 Modelled wind conditions

Based on the assessment of the meteorology occurring at the site-representative Fort Denison AWS (section 4) and adjusting for terrain differences between the assessment region and the meteorological station location (being in the middle of Sydney Harbour), the wind conditions listed in Table 11 were modelled using the constructed CFD model. These conditions, wind speed and wind direction combination, were selected to assess for pedestrian comfort and safety reasons detailed in section 3.

Table 11 Summary of CFD modelled wind conditions

Reference ID	Wind Direction (degree)	Terrain category (AS1170.2)	Meteorology wind speed (95th %ile daytime avg)	Terrain adjustment wind speed (m/s)	Reason for simulation
021	0 (N)	TC2.5	7.0	6.3	Comfort assessment
022	45 (NE)	TC4.0	7.8	5.5	Comfort assessment
023	90 (E)	TC4.0	7.3	5.1	Comfort assessment
024	135 (SE)	TC4.0	7.7	5.5	Comfort assessment
025	180 (S)	TC3.0	9.0	7.9	Comfort assessment
026	225 (SW)	TC3.0	7.8	6.8	Comfort assessment
027	270 (W)	TC3.0	8.9	7.8	Comfort assessment
028	315 (NW)	TC3.0	8.9	7.8	Comfort assessment
			Meteorology wind speed (99.99th %ile daytime avg)	**Terrain and 0.5 s gust adjustment speed (m/s)**	
031	0 (N)	TC2.5	10.7	20.3	Safety assessment
032	45 (NE)	TC4.0	13.7	20.2	Safety assessment
033	90 (E)	TC4.0	17.7	26.2	Safety assessment
034	135 (SE)	TC4.0	16.3	24.2	Safety assessment
035	180 (S)	TC3.0	14.2	26.0	Safety assessment
036	225 (SW)	TC3.0	10.6	19.5	Safety assessment
037	270 (W)	TC3.0	15.5	28.4	Safety assessment
038	315 (NW)	TC3.0	13.0	23.8	Safety assessment

6. Comfort assessment results

Contours of local ground level (1.5 m) wind speed for the 95th percentile daytime wind conditions are shown in Appendix C for the pedestrian comfort assessment.

Estimates of the ground level area exceeding each of the three comfort level criteria values of 4, 6 and 8 m/s are provided in Table 12.

The two assessed wind conditions with the largest estimated area of local winds above 4 m/s are shown in Figure 14 and Figure 15.

Based on a review of the comfort level contour plots, the following observations are made:

- Without localised mitigation, all waterfront areas can expect to have exceedances of the sitting comfort level criterion value of 4 m/s (Figure 16 and Figure 17). This result is consistent with the findings of the Windtech (2019) study, "*Most areas will experience strong winds which will exceed the relevant criteria for comfort, some which also exceed the safety criteria.*"
- The northernmost areas of the peninsula are highly exposed to west and northwest winds.
- Building developments immediately northeast of the ANZAC bridge can generate significant dis-amenity between the buildings at ground level, as shown in Figure 15 and Figure 17.
- There is some funnelling of winds along street canyons due to the notional NNW-SSW alignment of the streets, as shown in Appendix C (Figure 25 and Figure 26).
- Buildings considerably higher than immediate adjacent buildings produce higher ground level winds due to building downwash, as shown in Figure 16.
- The more consistent building heights through the south-central region of the Pyrmont study area, give rise to lower ground level wind speeds.
- It must be noted that this assessment does not consider the protection that vegetation (trees) and other small scale wind screening measures, such as property boundary fences or noise barriers along roads in the area, have on wind speed estimates.
- The impact of local terrain, such as harbour facing escarpments, only amplifies potential wind comfort issues. Note that the modelling approach tended to smooth out sharp escarpments so that some local terrain influences, especially near the coast, could be considerably higher than estimated from this modelling. Refer to Section 5.2.2 and Appendix B.

Contours of wind velocity at different elevations are shown in Appendix D.

In general, the vast majority of the assessed Pyrmont area ground level winds are acceptable for sitting based activities, primarily due to the built-up nature of the region. Coastal areas, as expected, have the highest potential exposure to uncomfortable winds. When groups of tall buildings are clumped together near the coast, as shown in Figure 17, the potential for high dis-amenity is most significant.

Table 12 Area (%) exceedance estimates at 1.5 m

Wind direction	Wind speed (m/s)	WS > 4.0 m/s (%)	WS > 6.0 m/s (%)	WS > 8.0 m/s (%)
0 (N)	6.3	1.41	0.10	0.00
45 (NE)	5.5	0.21	0.00	0.00
90 (E)	5.1	0.04	0.00	0.00
135 (SE)	5.5	0.05	0.00	0.00
180 (S)	7.9	2.28	0.11	0.00
225 (SW)	6.8	1.88	0.04	0.00
270 (W)	7.8	3.73	0.25	0.01
315 (NW)	7.8	4.11	0.51	0.04

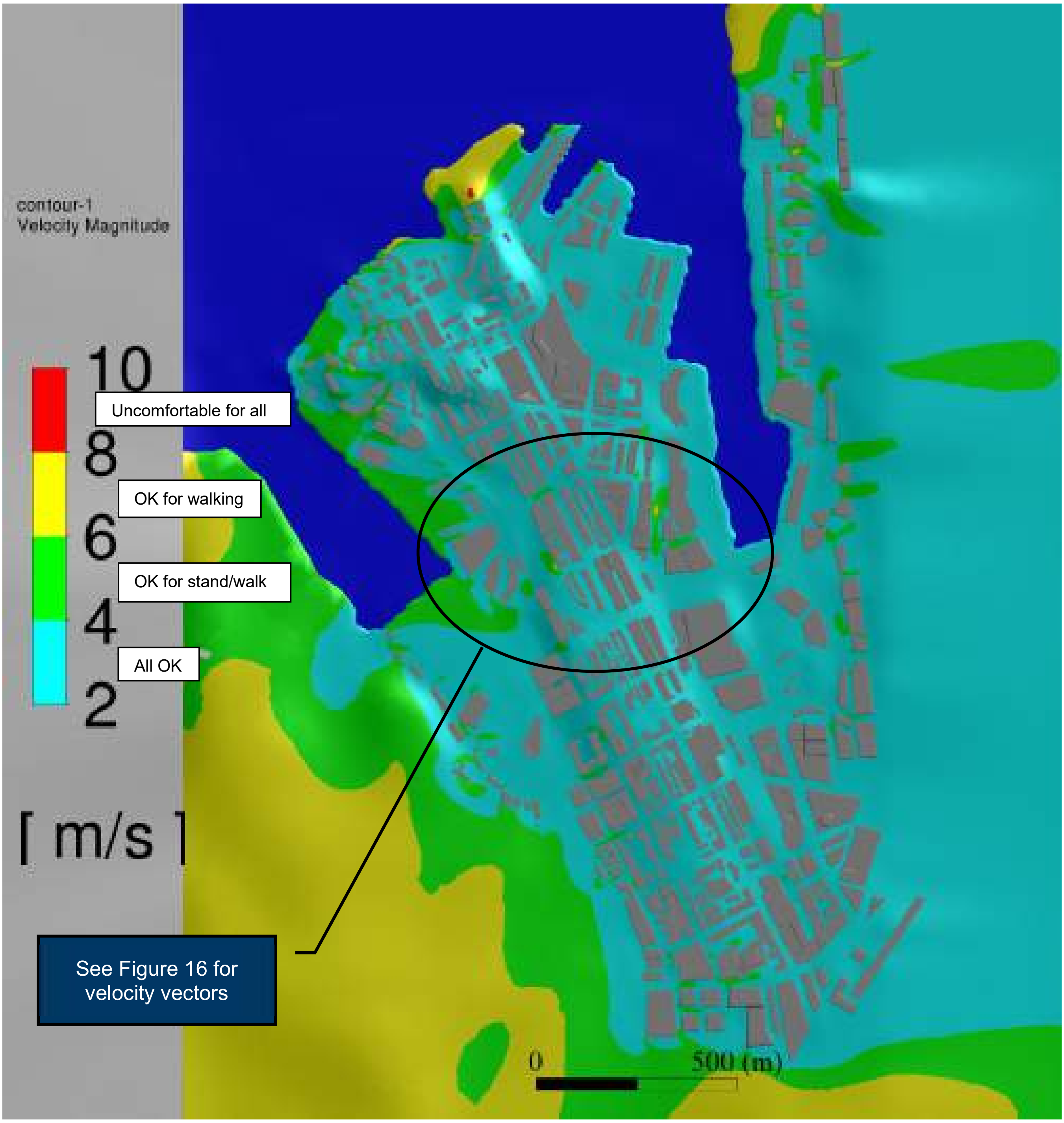

Figure 14 Pedestrian comfort assessment – 7.8 m/s @ 270° (ID 027). Contours of local wind speed @ 1.5 m

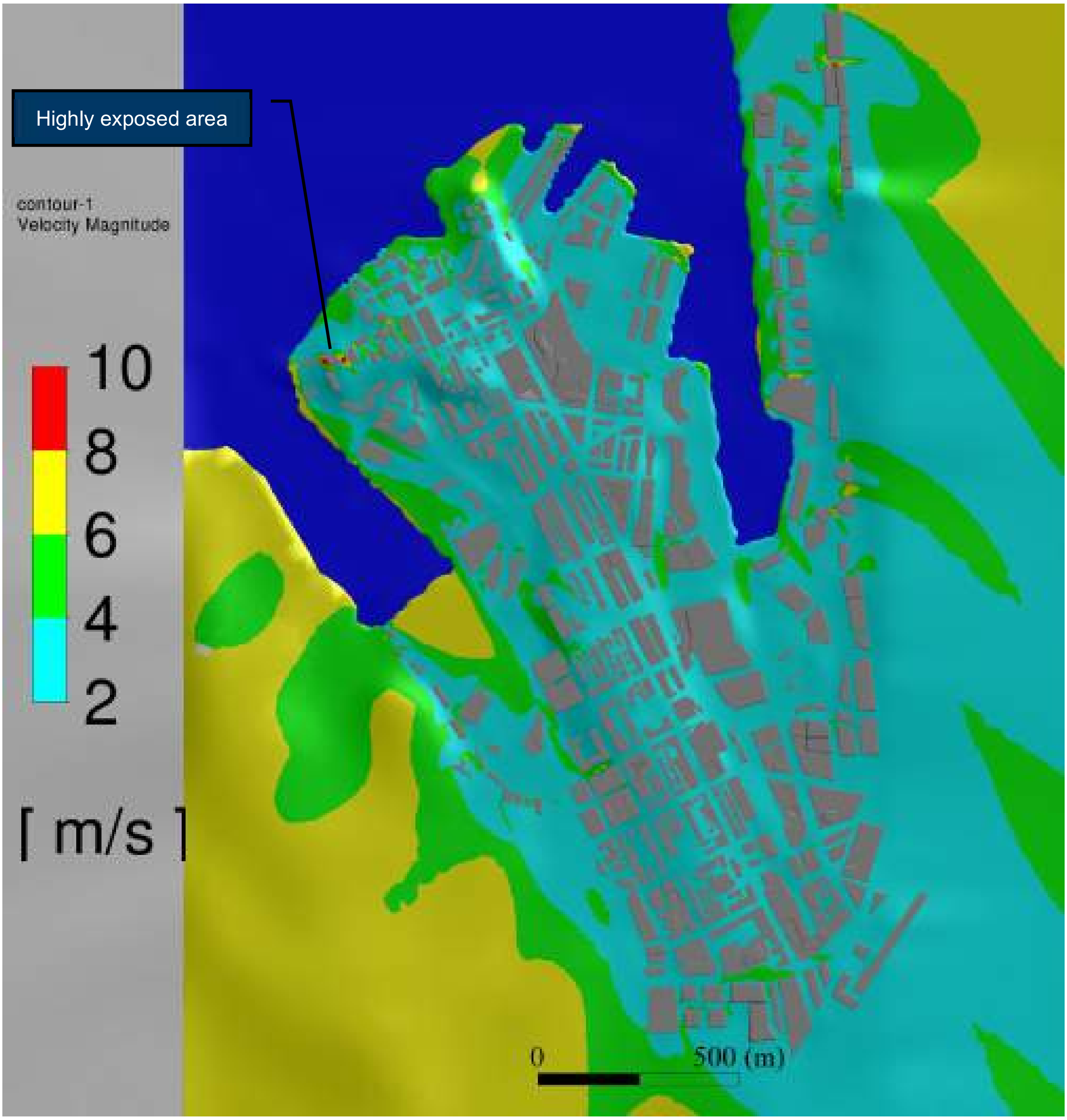

Figure 15 *Pedestrian comfort assessment – 7.8 m/s @ 315° (ID 028). Contours of local wind speed @ 1.5 m*

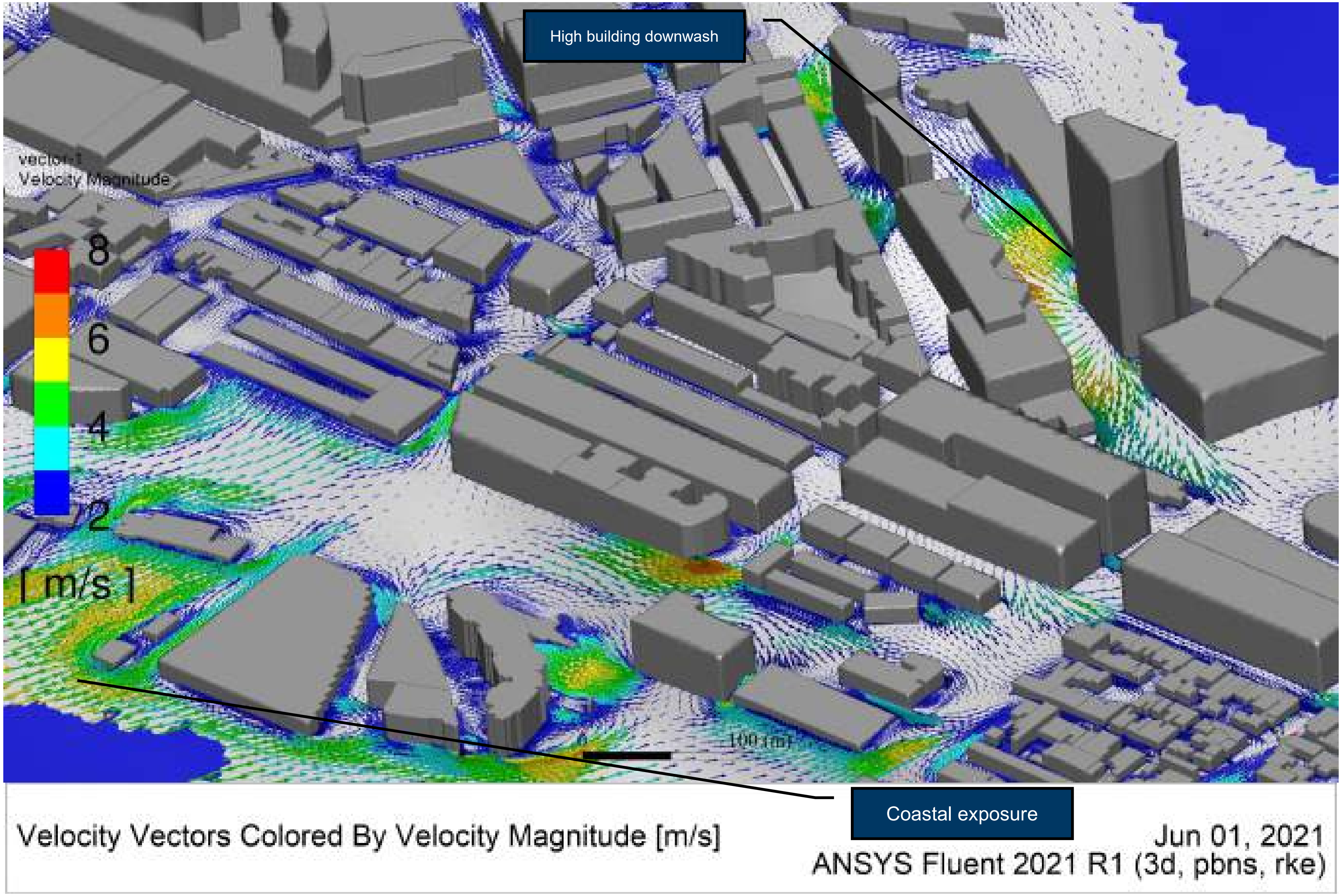

Figure 16 *Pedestrian comfort assessment – 7.8 m/s @ 270° (ID 027). Local wind velocity vectors @ 1.5 m*

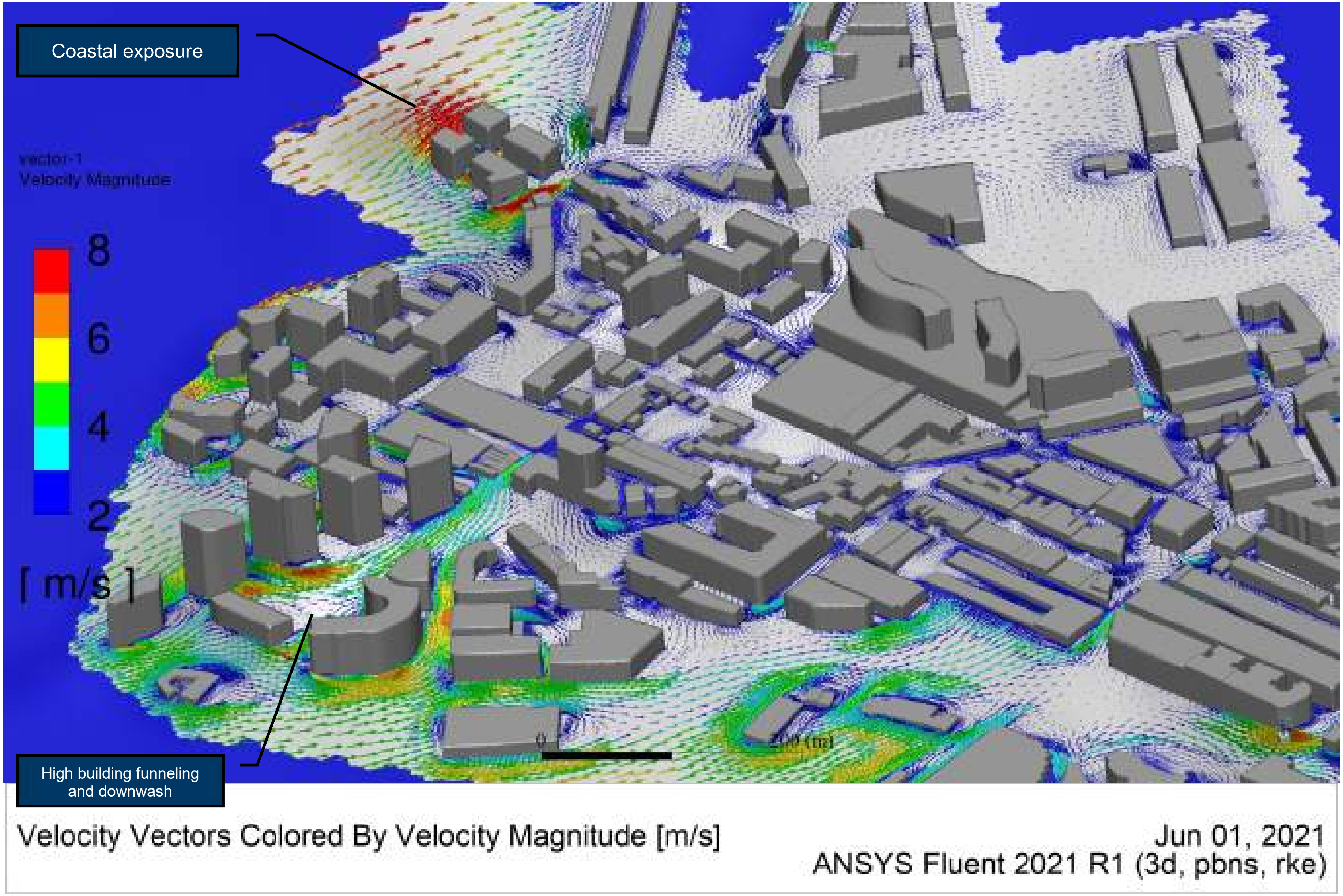

Figure 17 ***Pedestrian comfort assessment – 7.8 m/s @ 315° (ID 028). Local wind velocity vectors @ 1.5 m***

7. Safety assessment results

Contours of local ground level (1.5 m) 0.5-second gust wind speed for an annual exceedance (99.99th percentile) daytime wind conditions are shown in Appendix E for the pedestrian safety assessment.

Estimates of the ground level area exceeding the annual safety level criterion of 24 m/s for a 0.5-second gust are provided in Table 13. It is clear from the result in Table 13 that west and northwest winds result in the most significant areas of potential pedestrian safety. These two assessed wind conditions are shown in Figure 18 and Figure 19, focusing on the northern area of the assessment region.

Based on a review of the safety level contour plots, the following observations are made.

– The northernmost waterfront areas of the peninsula can be expected to have exceedances of the safety level criterion value of 24 m/s for a 0.5-second gust (Figure 18).
– Building developments immediately northeast of the ANZAC bridge have the greatest potential to generate unsafe wind conditions, particularly between the buildings, as shown in Figure 18 and Figure 19.
– The buildings through the south-central region of the Pyrmont study area give rise to safe ground level wind speeds, except high buildings exposed to westerly winds immediately coming off the harbour, as indicated in Figure 20.
– It must be noted that this assessment does not consider the protection that vegetation (trees) and other small scale wind screening measures, such as property boundary fences or noise barriers along roads in the area, have on wind speed estimates.

In general, the vast majority of the assessed Pyrmont area ground level winds are considered safe based on the assessment criteria, primarily due to the built-up nature of the region. Northernmost coastal areas, as expected, have the highest exposure to potentially unsafe winds. When groups of tall buildings are clumped together near the coast, as shown in Figure 17 and Figure 20, the potential for unsafe conditions to be generated is most significant. The impact of local terrains, such as harbour facing escarpments, only amplifies potential wind safety issues.

Table 13 Safety criterion exceedance estimates at ground level (1.5 m)

Wind direction	Wind speed (99.99th %ile) (m/s)	0.5-second gust wind speed (m/s)	% area > 24 m/s gust	Number of CFD cells > 24 m/s gust	Maximum gust (m/s)
0 (N)	9.7	20.3	0.001	3	26.9
45 (NE)	9.7	20.2	0.000	0	21.2
90 (E)	12.5	26.2	0.003	10	26.9
135 (SE)	11.6	24.2	0.002	6	26.7
180 (S)	12.4	26.0	0.001	4	25.6
225 (SW)	9.3	19.5	0.000	0	20.7
270 (W)	13.6	28.4	0.107	334	33.9
315 (NW)	11.4	23.8	0.049	153	28.8

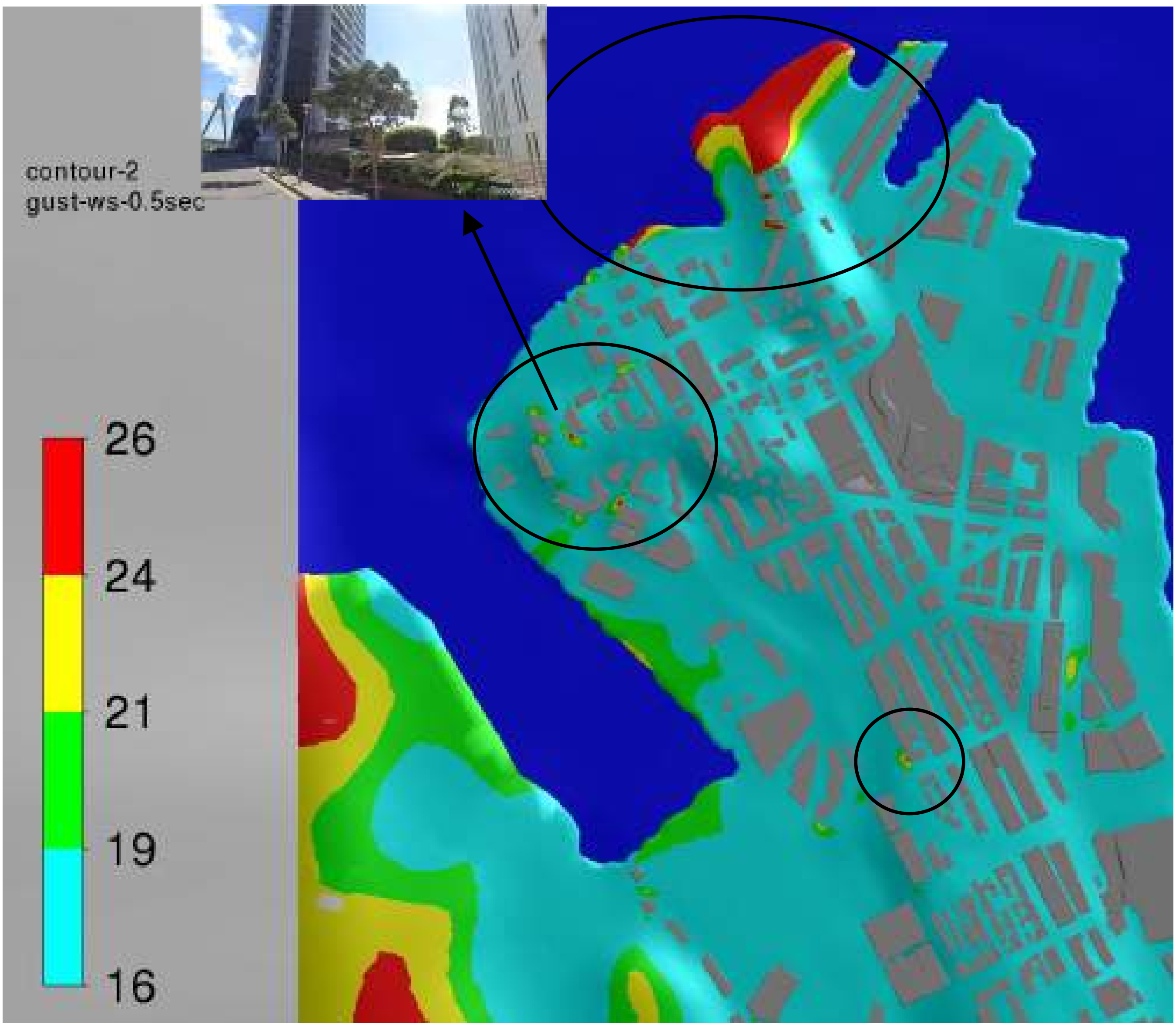

Figure 18 ***Pedestrian safety assessment – 13.6 m/s @ 270° (ID 037). Contours of local wind speed @ 1.5 m. Exceedances circled—inset image of ground level at identified safety exceedance area***

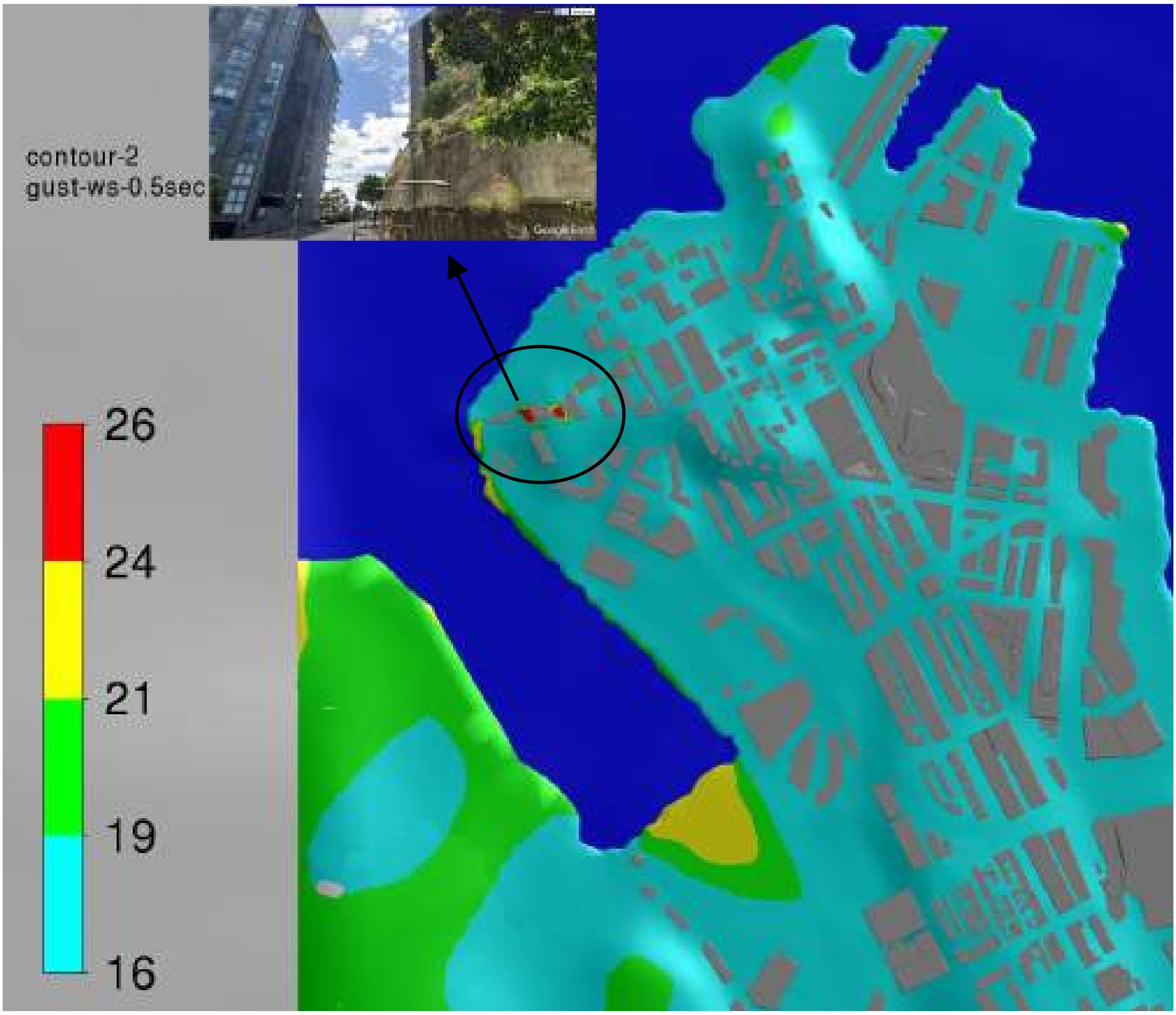

Figure 19 ***Pedestrian safety assessment – 11.4 m/s @ 315° (ID 038). Contours of local wind speed @ 1.5 m. Exceedances circled. Inset image of ground level at identified safety exceedance area***

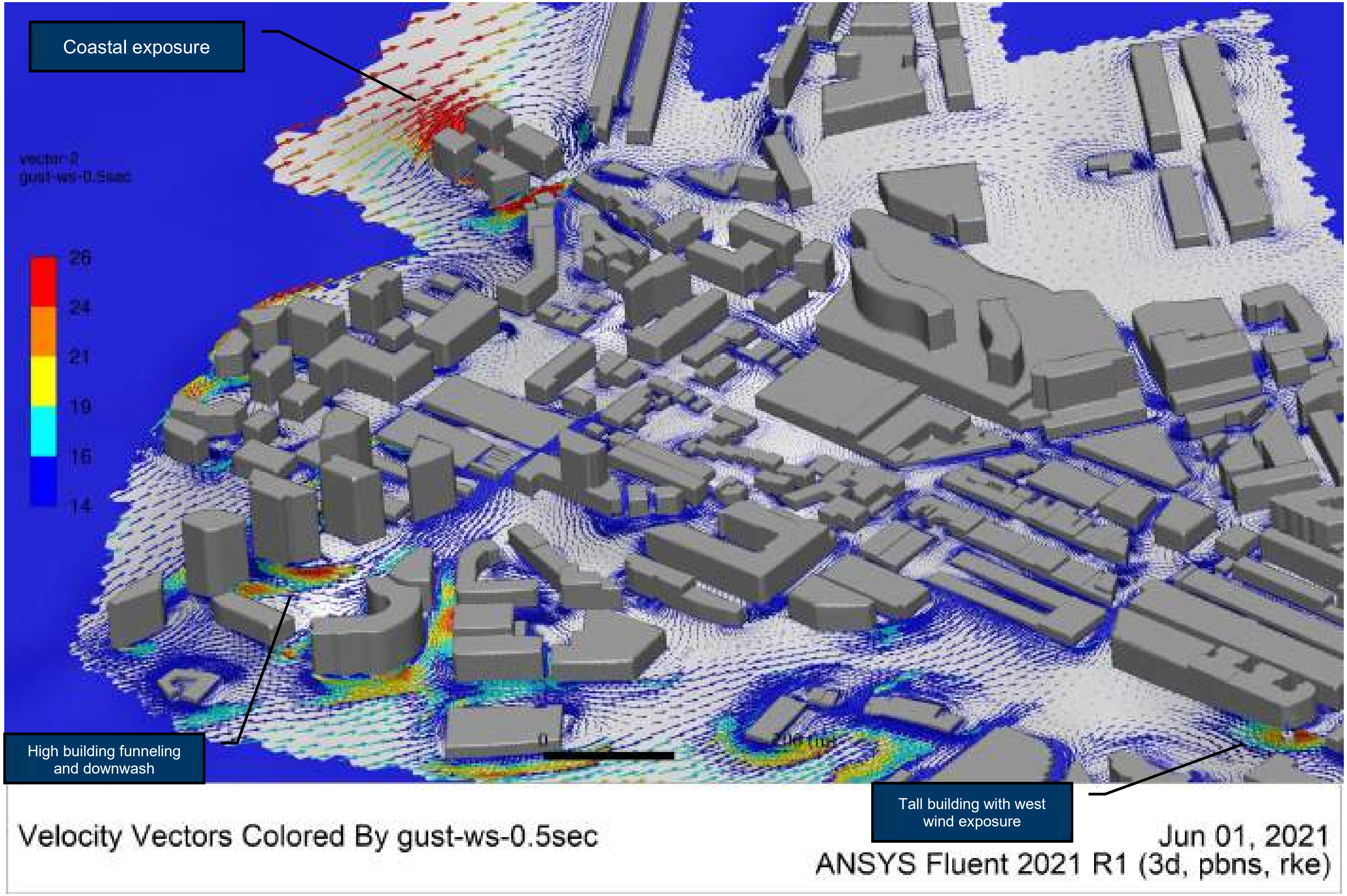

Figure 20 *Pedestrian safety assessment – 13.6 m/s @ 270° (ID 037). Local wind velocity vectors @ 1.5 m*

8. Conclusions

8.1 Meteorology

Meteorology for the site was assessed using the Bureau of Meteorology (BoM) Automatic Weather Station (AWS) at Fort Denison, located approximately 3.3 km northeast of Pyrmont. Wind data from a seven-year climatology, 2014 to 2020, were used in this assessment.

On an annual all hour basis, the wind climate indicates a west sector as a preferred quadrant (>25 per cent). However, several north-easterly, easterly and southerly winds of a lesser frequency (10 to 15 per cent).

Little statistical difference was observed between all hours and daytime hours (6 am to 10 pm) wind speeds and direction.

An assessment of climate change on wind speed and direction has found that extreme events at the high end of the scale will unlikely be affected in any measurable way by climate change for some time, i.e., short to medium term.

8.2 Criteria

The DCP has numerous specific wind criteria applying to different specific sites. This is not ideal for any future developments and assessors, including DPIE, of any development applications.

8.2.1 Pedestrian comfort

For pedestrian comfort, a single criterion based on all hours and an exceedance frequency of 95th percentile should be applied across all areas of greater Sydney. Applying just for daytime hours is statistically ineffective and overly complicates any assessment.

The adoption of mean wind speeds, or gust equivalent mean, of 4, 6 and 8 m/s for sitting, standing and walking, respectively, is considered appropriate, consistent and straightforward with international guidance.

An assessment height above a surface should be applied. A height of 1.5 m is recommended.

8.2.2 Pedestrian safety

For pedestrian safety, a single criterion based on all hours and an exceedance frequency of once per year, nominally 99.99th percentile, should be applied across all areas of greater Sydney. Applying just for daytime hours is statistically ineffective and overly complicates any assessment.

Consideration should be given to applying the same averaging period as the comfort criteria, making the safety criteria based on an equivalent hourly averaged value.

As the science of pedestrian stability in wind gusts is inconclusive, the adopted 24 m/s 0.5-second gust is consistent with known studies.

An assessment height above a surface should be applied. A height of 1.5 m is recommended as this equates to torso wind impact, which has the most significant effect on person stability.

8.2.3 Suggested criteria

A suggested simplified wind comfort criteria is provided in Table 14.

A suggested change to the safety criteria is more difficult to prescribe due to the uncertainties in the science. However, replacing the existing 24 m/s 0.5-second gust magnitude with a one-hour averaged 15 m/s magnitude should be considered. The time scales of the comfort and safety criteria would be consistent. A frequency of once per year should be retained.

Suggested safety criterion: 15 m/s one-hour averaged, 99.99th percentile.

Table 14 Wind comfort assessment criteria. Applies for all hours at a plane 1.5 m above the local ground level

Activity	Activity description	Upper limit 1 hour mean wind speed exceeded 5% of the time (m/s)	Description of wind effects
Sitting	Outdoor areas that involve seating such as parks, cafes, dining areas and entertainment.	4.0	The light wind felt on face Leaves rustle
Standing	Short duration stationary activities (generally less than one hour) including outdoor shopping and waiting areas.	6.0	Hair is disturbed, clothes flapping Light leaves and twigs in motion Wind extends lightweight flag
Walking	For commonly used pedestrian thoroughfares.	8.0	Moderate, raises dust, loose paper Hair disarranged Small branches move

8.3 Wind Assessment

The wind assessment, undertaken using a CFD model, has found the following.

8.3.1 Pedestrian comfort

In general, the vast majority of the assessed Pyrmont area ground level winds are acceptable for sitting based activities. Waterfront areas, as expected, have the highest potential exposure to uncomfortable winds. When groups of tall buildings are clumped together near the waterfront, the potential for high dis-amenity is most significant.

Specifically:

– All waterfront areas can expect to have exceedances of the sitting comfort level criterion value of 4 m/s.
– The northernmost areas of the peninsula are highly exposed to west and northwest winds.
– Building developments immediately northeast of the ANZAC bridge have the potential to generate significant dis-amenity between the buildings at ground level.
– There is some funnelling of winds along street canyons due to the notional NNW-SSW alignment of the streets.
– Buildings considerably higher than immediate adjacent buildings are producing higher ground level winds due to building downwash.
– The more consistent building heights through the south-central region of the Pyrmont study area give rise to lower ground level wind speeds.
– It must be noted that this assessment does not consider the protection that vegetation (trees) and other small scale wind screening measures, such as property boundary fences or noise barriers along roads in the area, have on wind speed estimates.
– The impact of local terrain, such as harbour facing escarpments, only amplifies any potential wind comfort issues.

8.3.2 Pedestrian safety

The vast majority of the assessed Pyrmont area ground level winds are considered safe based on the assessment criteria. Northernmost coastal areas, as expected, have the highest exposure to potentially unsafe winds. When groups of tall buildings are clumped together near the waterfront, the potential for unsafe conditions to be generated is greatest. The impact of local terrains, such as harbour facing escarpments, only amplifies any potential wind safety issues.

Specifically:

– The northernmost waterfront areas of the peninsula can be expected to have exceedances of the safety level criterion value of 24 m/s for a 0.5-second gust.
– Building developments immediately northeast of the ANZAC bridge have the greatest potential to generate unsafe wind conditions, particularly between the high-rise buildings.
– The buildings through the south-central region of the Pyrmont study area give rise to safe ground-level wind speeds, except for high buildings exposed to westerly winds immediately coming off the harbour.

8.4 Recommendations

Based on the results of this assessment, the following recommendations are provided.

– The meteorology of Sydney does not justify a delineation of daytime hours from all hours.
– Consider opportunities to simplify as much as possible the wind assessment criteria across both the comfort and safety requirements.
– Apply a consistent averaging time for both comfort and safety criteria. Hourly averages are recommended due to their simplicity.
– Development height limits should be considered at the northernmost areas of the Pyrmont Peninsula but subject to an individual development wind assessment.
– With regards to wind comfort, relative building height limits should be considered, i.e., a new development cannot be a certain percentage higher than the adjacent buildings but subject to an individual development wind assessment. However, it is recognised that a balanced approach must consider all aspects of a development.

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Appendix A

Average wind statistics

Table A.1 Hourly average wind speed and direction percentiles and frequency – all hours 2014-2020

		Wind Speed 1 hour Avg (m/s)							
	Wind Direction (degree)	**338 to 22**	**23 to 67**	**68 to 112**	**113 to 157**	**158 to 202**	**203 to 247**	**248 to 292**	**293 to 337**
	Wind Direction (compass)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Percentile	100	10.7	14.6	18.0	16.5	14.5	10.7	17.0	13.0
	99.99	10.7	13.3	17.6	16.3	14.1	10.6	15.4	12.9
	99.9	10.0	10.2	13.4	13.5	12.6	10.2	12.4	12.3
	99	8.0	8.9	8.9	9.9	10.4	8.9	10.6	10.1
	98	7.5	8.4	8.2	9.0	9.7	8.4	9.6	9.5
	95	6.5	7.6	7.3	7.7	8.9	7.4	8.0	8.4
	90	5.7	7.1	6.5	7.0	7.9	6.8	6.9	7.3
	80	4.6	6.3	5.8	6.1	6.9	5.9	5.9	5.7
	70	3.9	5.6	5.3	5.5	6.2	5.4	5.2	4.5
	60	3.2	4.9	4.8	4.9	5.6	4.8	4.7	3.6
	50	2.6	4.3	4.3	4.4	4.9	4.3	4.2	2.9
	30	1.4	2.9	3.2	3.4	3.8	3.2	3.4	2.0
	20	1.1	2.2	2.5	2.7	3.1	2.7	3.0	1.5
	10	0.7	1.3	1.6	1.9	2.4	2.0	2.4	1.1
	0	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.2
	Wind Direction Frequency	0.067	0.129	0.143	0.093	0.119	0.056	0.305	0.087

Table A.2 Average wind statistics – Hourly average wind speed and direction percentiles and frequency – daytime hours (2014-2020)

		Wind Speed 1 hour Avg (m/s)							
	Wind Direction (degree)	**338 to 22**	**23 to 67**	**68 to 112**	**113 to 157**	**158 to 202**	**203 to 247**	**248 to 292**	**293 to 337**
	Wind Direction (compass)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Percentile	100	10.7	14.6	18.0	16.5	14.5	10.7	17.0	13.0
	99.99	10.7	13.7	17.7	16.3	14.2	10.6	15.5	13.0
	99.9	10.2	11.0	13.4	14.8	12.9	10.4	12.7	12.5
	99	8.2	9.1	8.7	9.8	10.5	9.2	11.2	10.6
	98	7.8	8.6	8.1	9.0	9.7	8.7	10.4	9.9
	95	7.0	7.8	7.3	7.7	9.0	7.8	8.9	8.9
	90	6.1	7.3	6.7	7.0	8.0	6.9	7.6	7.9
	80	5.2	6.7	5.9	6.2	7.0	6.2	6.3	6.6
	70	4.3	6.0	5.4	5.7	6.3	5.7	5.6	5.4
	60	3.7	5.5	4.9	5.2	5.8	5.2	4.9	4.5
	50	3.0	4.9	4.6	4.7	5.3	4.6	4.4	3.6
	30	1.7	3.7	3.6	3.7	4.0	3.5	3.5	2.4
	20	1.2	2.9	2.9	3.0	3.4	2.9	3.0	1.9
	10	0.8	1.9	2.1	2.1	2.5	2.1	2.4	1.3
	0	0.0	0.2	0.2	0.2	0.2	0.2	0.3	0.3
	Wind Direction Frequency	0.056	0.142	0.180	0.105	0.130	0.052	0.261	0.073

Table A.3 *Gust wind statistics – Gust wind speed and direction percentiles and frequency – all hours (2014 -2020)*

		Wind Speed Gust (m/s)							
	Wind Direction (degree)	338 to 22	23 to 67	68 to 112	113 to 157	158 to 202	203 to 247	248 to 292	293 to 337
	Wind Direction (compass)	N	NE	E	SE	S	SW	W	NW
Percentile	100	28.9	24.7	28.4	24.7	24.2	21.1	26.8	29.4
	99.99	28.9	24.0	27.9	24.7	24.2	21.1	25.3	27.2
	99.9	19.0	19.6	22.0	22.6	22.6	19.9	21.1	22.4
	99	13.4	15.0	13.4	16.5	19.0	17.6	18.0	18.0
	98	12.3	14.4	12.3	15.0	17.5	16.5	16.5	17.0
	95	10.8	12.9	10.3	12.9	15.9	15.0	13.4	15.0
	90	9.3	11.8	9.3	11.3	14.4	13.4	11.3	12.9
	80	7.7	10.8	8.2	10.3	12.3	11.8	8.7	10.3
	70	6.7	9.8	7.7	9.3	11.3	10.3	7.7	8.2
	60	5.7	8.7	6.7	8.2	10.3	9.3	6.7	6.7
	50	4.6	7.7	6.2	7.2	9.3	8.2	6.2	5.1
	30	3.1	5.7	5.1	5.7	7.2	6.7	5.1	3.6
	20	2.6	4.6	4.1	4.6	6.2	5.1	4.6	3.1
	10	1.5	3.1	3.1	3.6	4.6	4.1	3.6	2.6
	0	0.0	0.5	0.5	1.0	1.0	0.5	0.5	0.5
	Wind Direction Frequency	0.067	0.129	0.143	0.093	0.119	0.056	0.305	0.087

Table A.4 Gust wind statistics – Gust wind speed and direction percentiles and frequency – daytime hours (2014 -2020)

		Wind Speed Gust (m/s)							
	Wind Direction (degree)	**338 to 22**	**23 to 67**	**68 to 112**	**113 to 157**	**158 to 202**	**203 to 247**	**248 to 292**	**293 to 337**
	Wind Direction (compass)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Percentile	100	28.9	23.8	28.4	24.7	24.2	21.1	26.8	29.4
	99.99	27.3	23.8	28.0	24.7	24.2	21.1	25.7	28.2
	99.9	20.6	20.2	23.0	23.0	22.6	20.5	22.2	23.8
	99	14.4	15.4	13.4	16.5	19.0	18.6	18.6	19.0
	98	13.4	14.4	11.8	15.0	17.5	17.1	17.5	17.5
	95	11.8	13.4	10.3	12.9	15.9	15.9	15.0	15.9
	90	10.3	12.3	9.3	11.3	14.4	14.4	12.9	13.9
	80	8.7	11.3	8.2	10.3	12.9	12.3	10.3	11.3
	70	7.2	10.3	7.7	9.3	11.3	10.8	8.7	9.8
	60	6.7	9.3	7.2	8.7	10.3	10.3	7.2	8.2
	50	5.7	8.7	6.7	7.7	9.3	9.0	6.7	6.7
	30	3.6	6.7	5.7	6.2	7.2	6.7	5.1	4.6
	20	2.6	5.7	4.6	5.1	6.2	5.7	4.6	3.6
	10	1.5	4.1	3.6	4.1	5.1	4.4	4.1	2.6
	0	0.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0
	Wind Direction Frequency	0.056	0.142	0.180	0.105	0.130	0.052	0.261	0.073

Table A.5 Gust wind statistics – Ratio of gust to average wind speed – all hours (2014 -2020)

		Wind Speed Gust Ratio (-)							
	Wind Direction (degree)	**338 to 22**	**23 to 67**	**68 to 112**	**113 to 157**	**158 to 202**	**203 to 247**	**248 to 292**	**293 to 337**
	Wind Direction (compass)	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Percentile	100	2.7	1.7	1.6	1.5	1.7	2.0	1.6	2.3
	99.99	2.7	1.8	1.6	1.5	1.7	2.0	1.6	2.1
	99.9	1.9	1.9	1.6	1.7	1.8	1.9	1.7	1.8
	99	1.7	1.7	1.5	1.7	1.8	2.0	1.7	1.8
	98	1.6	1.7	1.5	1.7	1.8	2.0	1.7	1.8
	95	1.7	1.7	1.4	1.7	1.8	2.0	1.7	1.8
	90	1.6	1.7	1.4	1.6	1.8	2.0	1.6	1.8
	80	1.7	1.7	1.4	1.7	1.8	2.0	1.5	1.8
	70	1.7	1.8	1.5	1.7	1.8	1.9	1.5	1.8
	60	1.8	1.8	1.4	1.7	1.9	1.9	1.4	1.9
	50	1.8	1.8	1.4	1.6	1.9	1.9	1.5	1.7
	30	2.1	1.9	1.6	1.7	1.9	2.1	1.5	1.8
	20	2.4	2.1	1.7	1.7	2.0	1.9	1.5	2.0
	10	2.1	2.3	1.9	1.9	1.9	2.1	1.5	2.3
	0	0.0	5.0	5.0	19.0	4.8	10.0	5.0	3.3
	Wind Direction Frequency	0.067	0.129	0.143	0.093	0.119	0.056	0.305	0.087

Table A.6 Gust wind statistics – Ratio of gust to average wind speed – daytime hours (2014 -2020)

		Wind Speed Gust Ratio (-)							
	Wind Direction (degree)	338 to 22	23 to 67	68 to 112	113 to 157	158 to 202	203 to 247	248 to 292	293 to 337
	Wind Direction (compass)	N	NE	E	SE	S	SW	W	NW
Percentile	100	2.7	1.6	1.6	1.5	1.7	2.0	1.6	2.3
	99.99	2.6	1.7	1.6	1.5	1.7	2.0	1.7	2.2
	99.9	2.0	1.8	1.7	1.6	1.8	2.0	1.7	1.9
	99	1.8	1.7	1.5	1.7	1.8	2.0	1.7	1.8
	98	1.7	1.7	1.5	1.7	1.8	2.0	1.7	1.8
	95	1.7	1.7	1.4	1.7	1.8	2.0	1.7	1.8
	90	1.7	1.7	1.4	1.6	1.8	2.1	1.7	1.8
	80	1.7	1.7	1.4	1.7	1.8	2.0	1.6	1.7
	70	1.7	1.7	1.4	1.6	1.8	1.9	1.6	1.8
	60	1.8	1.7	1.5	1.7	1.8	2.0	1.5	1.8
	50	1.9	1.8	1.5	1.6	1.8	2.0	1.5	1.9
	30	2.1	1.8	1.6	1.7	1.8	1.9	1.5	1.9
	20	2.2	1.9	1.6	1.7	1.9	1.9	1.5	1.9
	10	1.9	2.2	1.8	2.0	2.0	2.1	1.7	2.0
	0	0.0	3.3	4.8	4.8	4.8	6.3	3.8	3.8
	Wind Direction Frequency	0.056	0.142	0.180	0.105	0.130	0.052	0.261	0.073

Appendix B

Terrain Processing

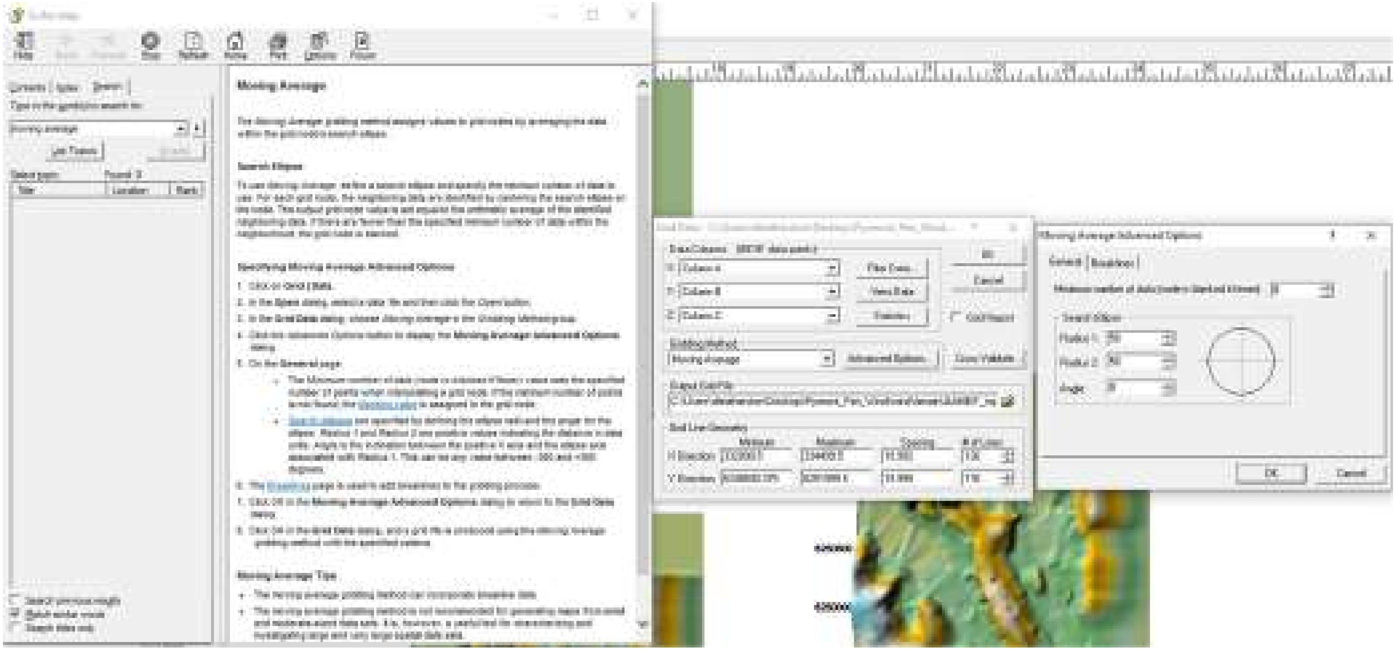
Terrain at 20 m grid point resolution – taken from 10 m resolution original data

Problem: 10 m resolution terrain in geometry model very complex and results in complex NURB surface that takes a lot of time to calculate normal for meshing.
Baseline terrain has curvature on steep terrain that appears to be unrealistic.

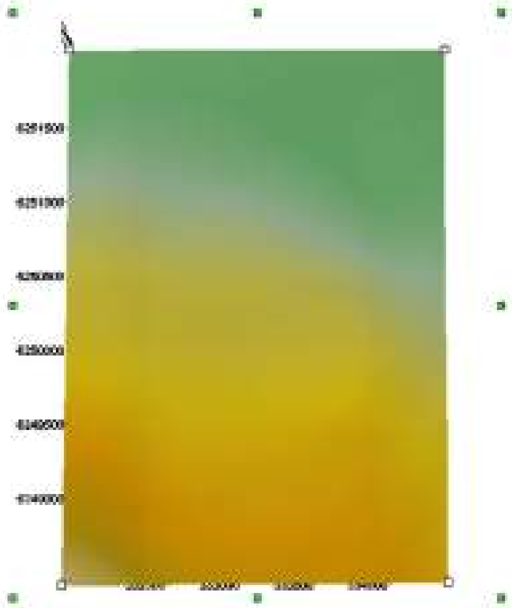
Purpose of Study: Smooth terrain to remove unrealistic curvatures and reduce complexity for meshing and geometry manipulation. Maintain sufficient detail to preserve terrain impact on winds.

Result: Apply a 40 m averaging value with terrain defined at 20 m spacings.

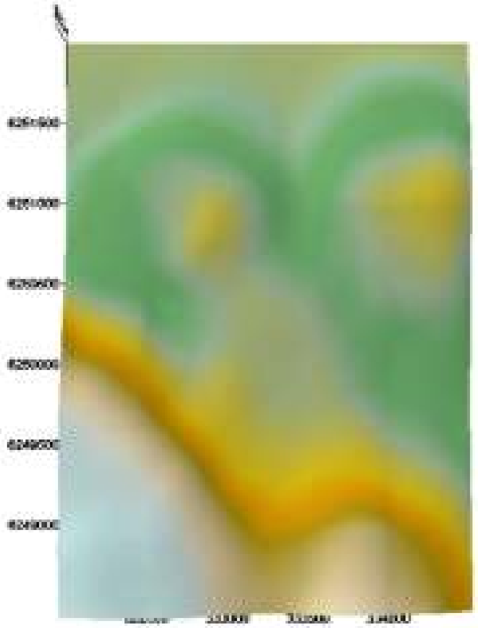
Software: Surfer Version 8.



Search Radius = 2000

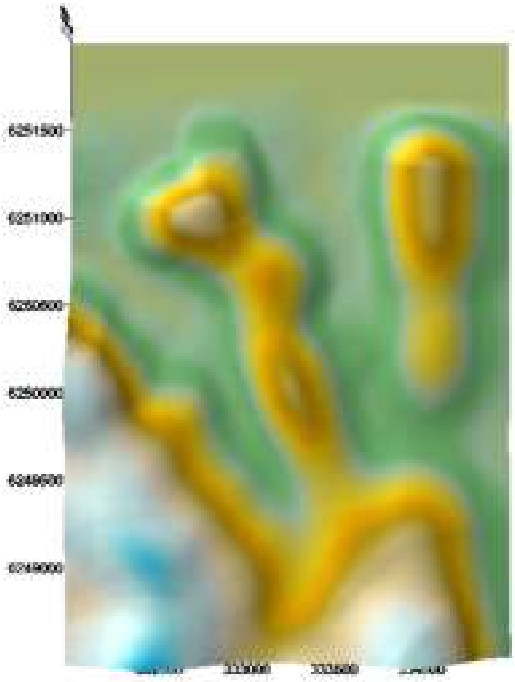


500

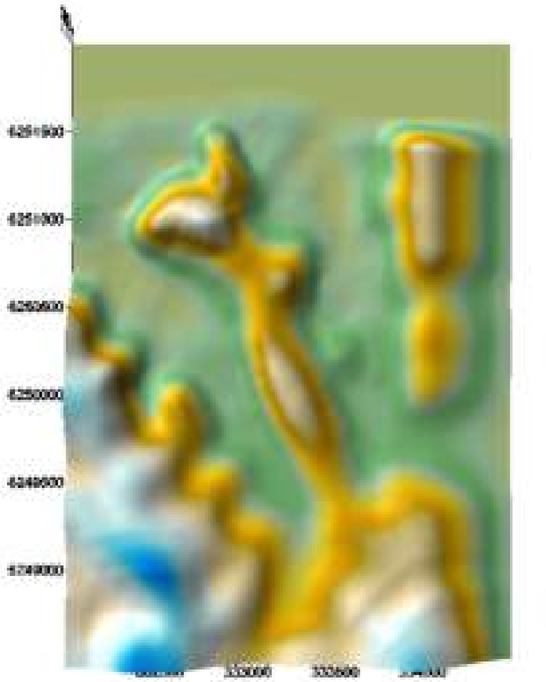


1000

200



100



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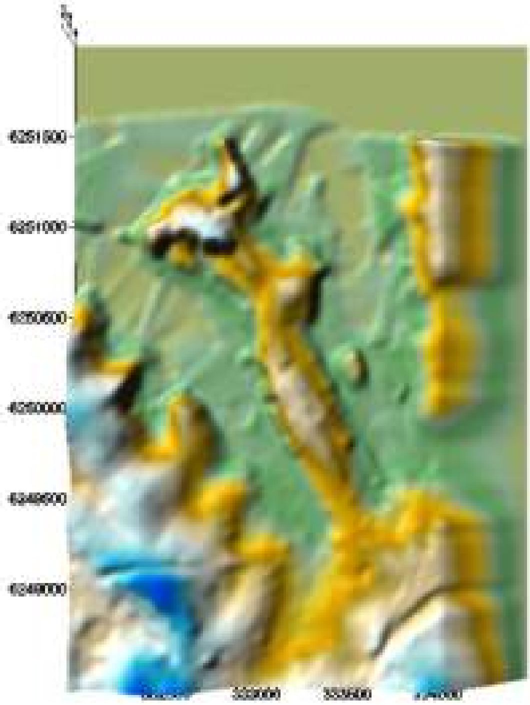

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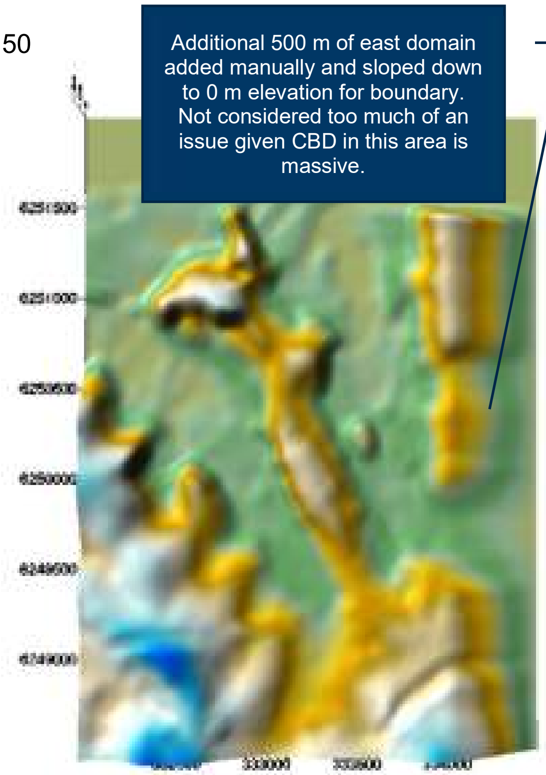
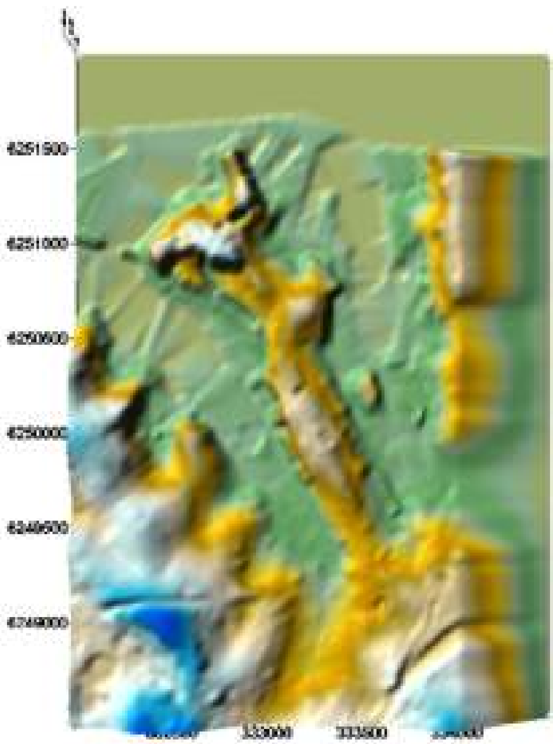
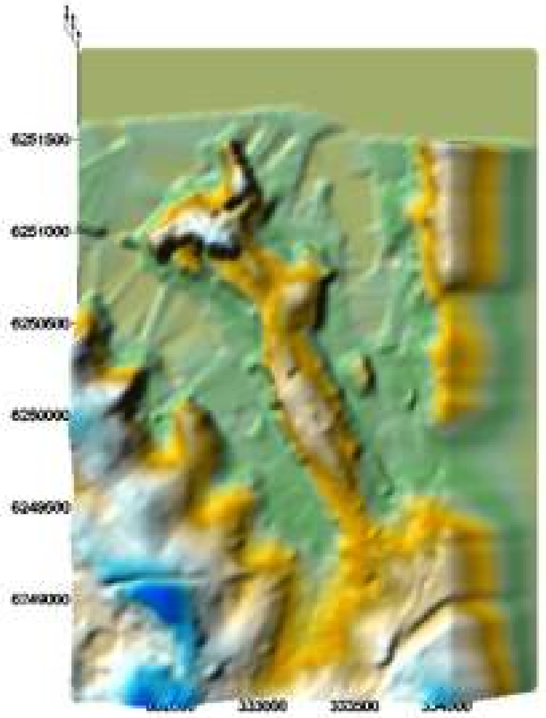

Additional 500 m of east domain added manually and sloped down to 0 m elevation for boundary. Not considered too much of an issue given CBD in this area is massive.

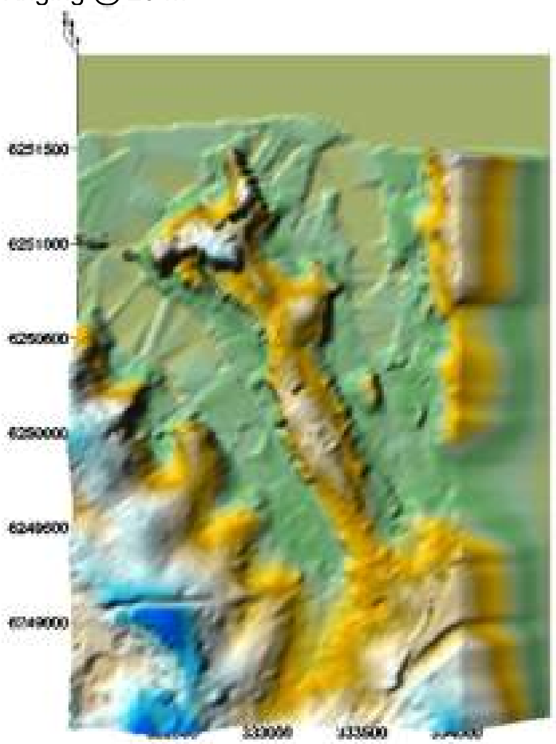
20



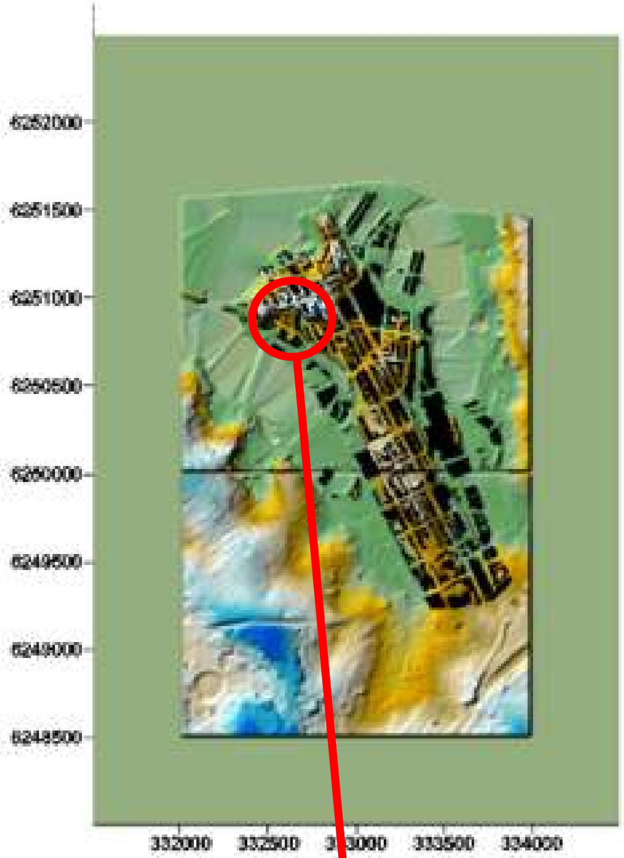
10



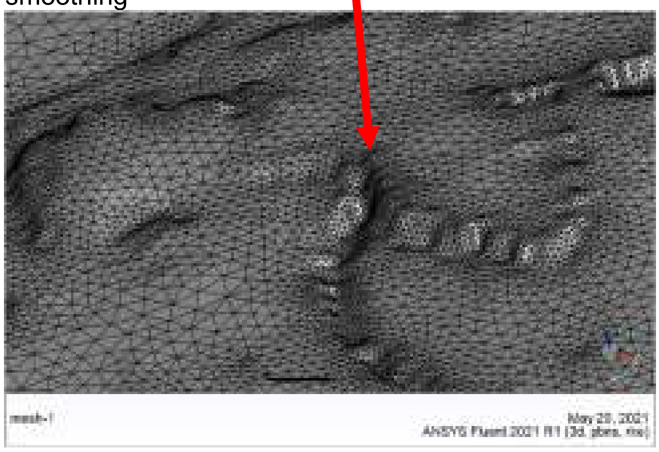
Kriging @ 20 m



With Buildings overlaid



Mesh of terrain alone – 2 m defeature with 5 m curvature resolution – 10 m resolution terrain – no smoothing



Appendix C

Comfort Level Wind Contours – Ground Level

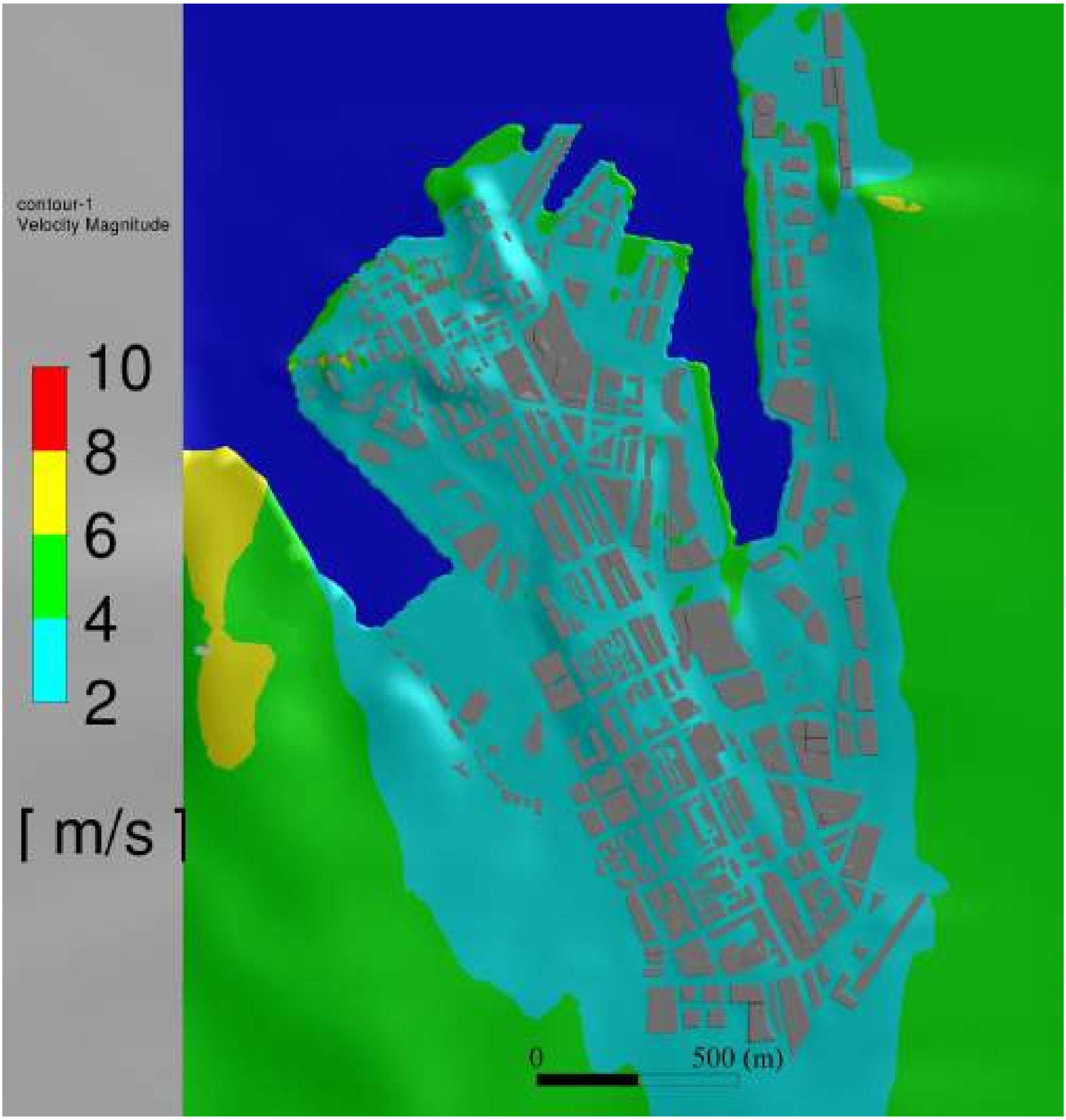


Figure 21 Pedestrian comfort assessment – 6.3 m/s @ 0°. Contours of local wind speed @ 1.5 m

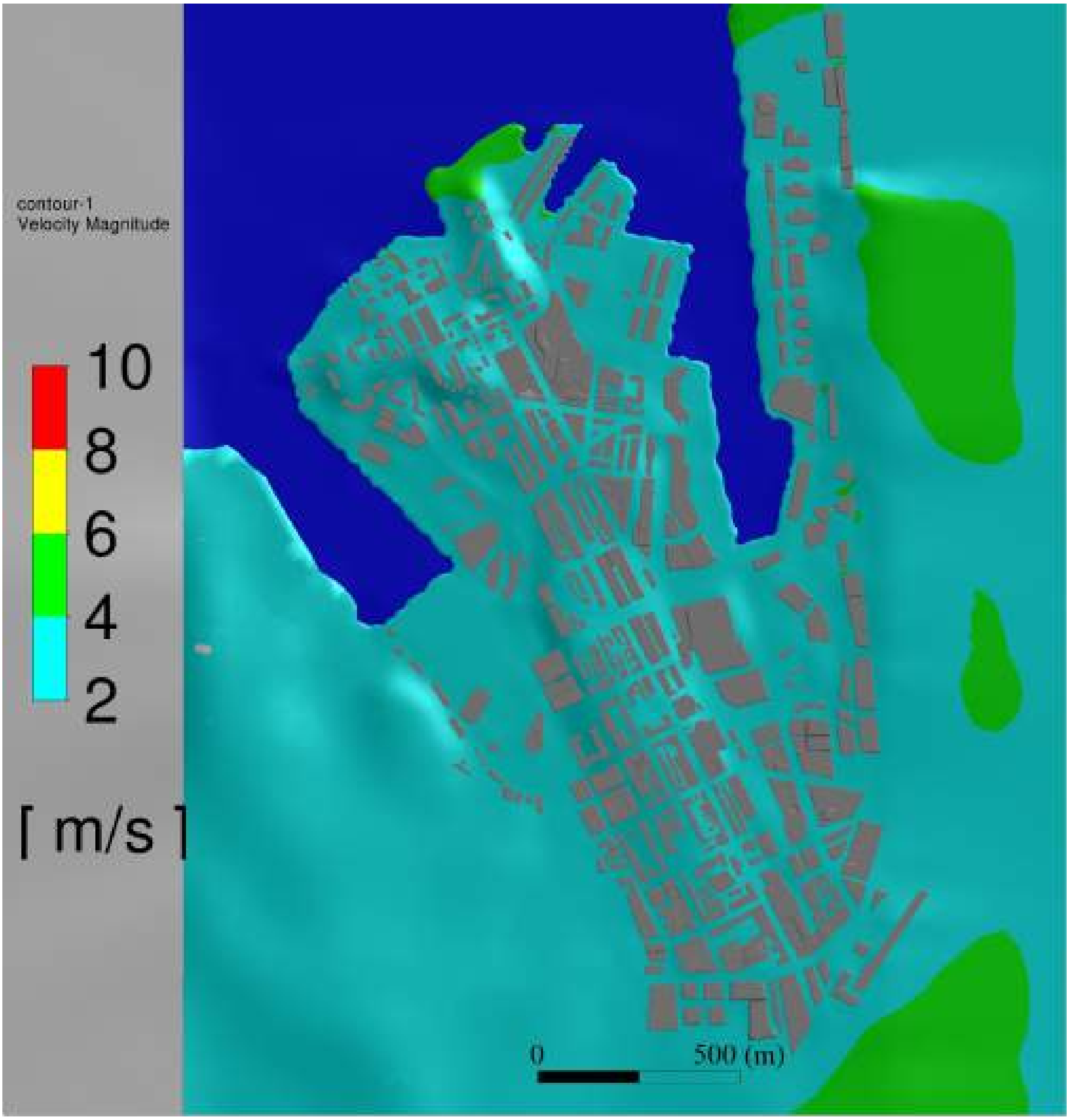


Figure 22 Pedestrian comfort assessment – 5.5 m/s @ 45°. Contours of local wind speed @ 1.5 m

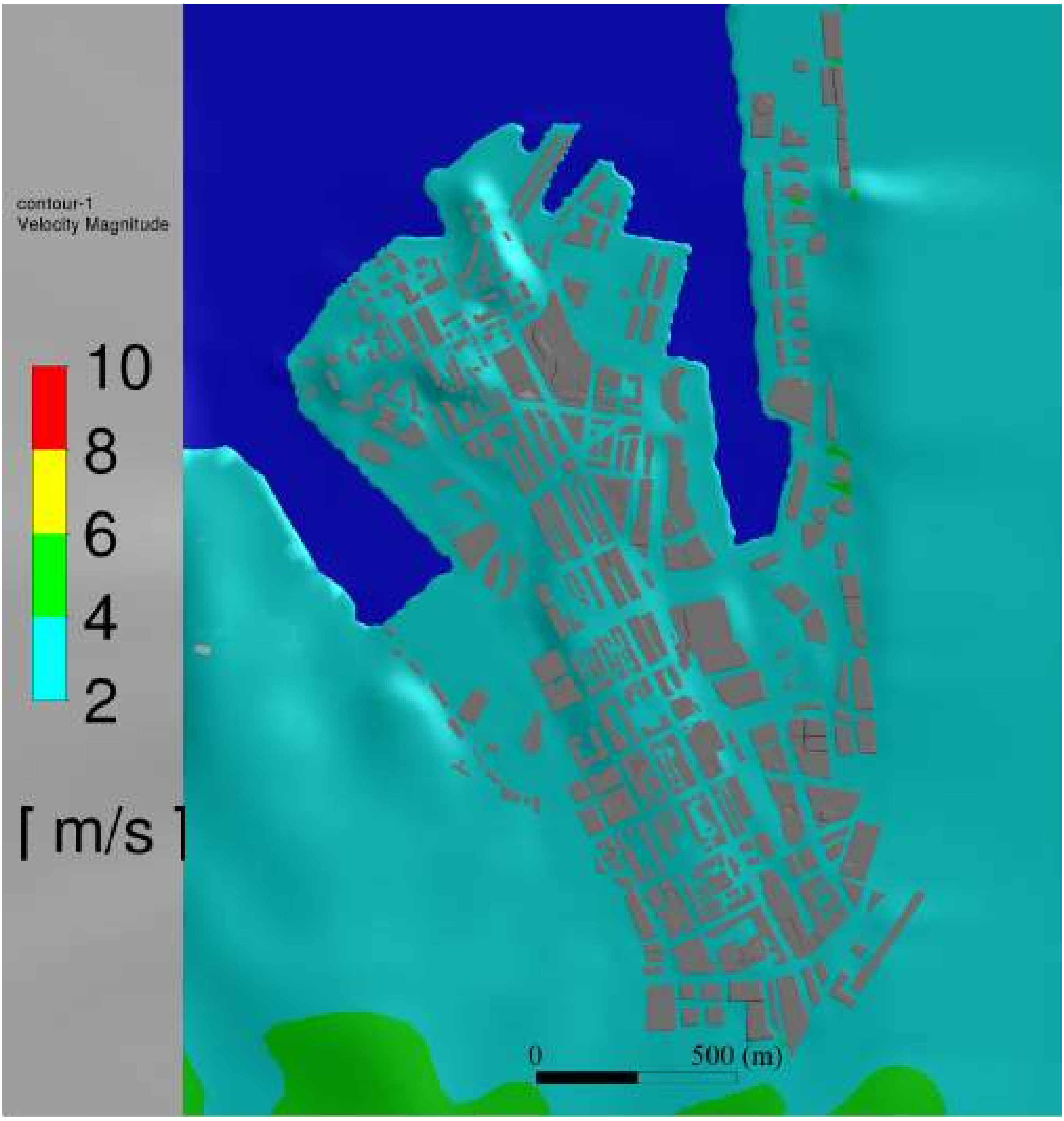


Figure 23 *Pedestrian comfort assessment – 5.1 m/s @ 90°. Contours of local wind speed @ 1.5 m*

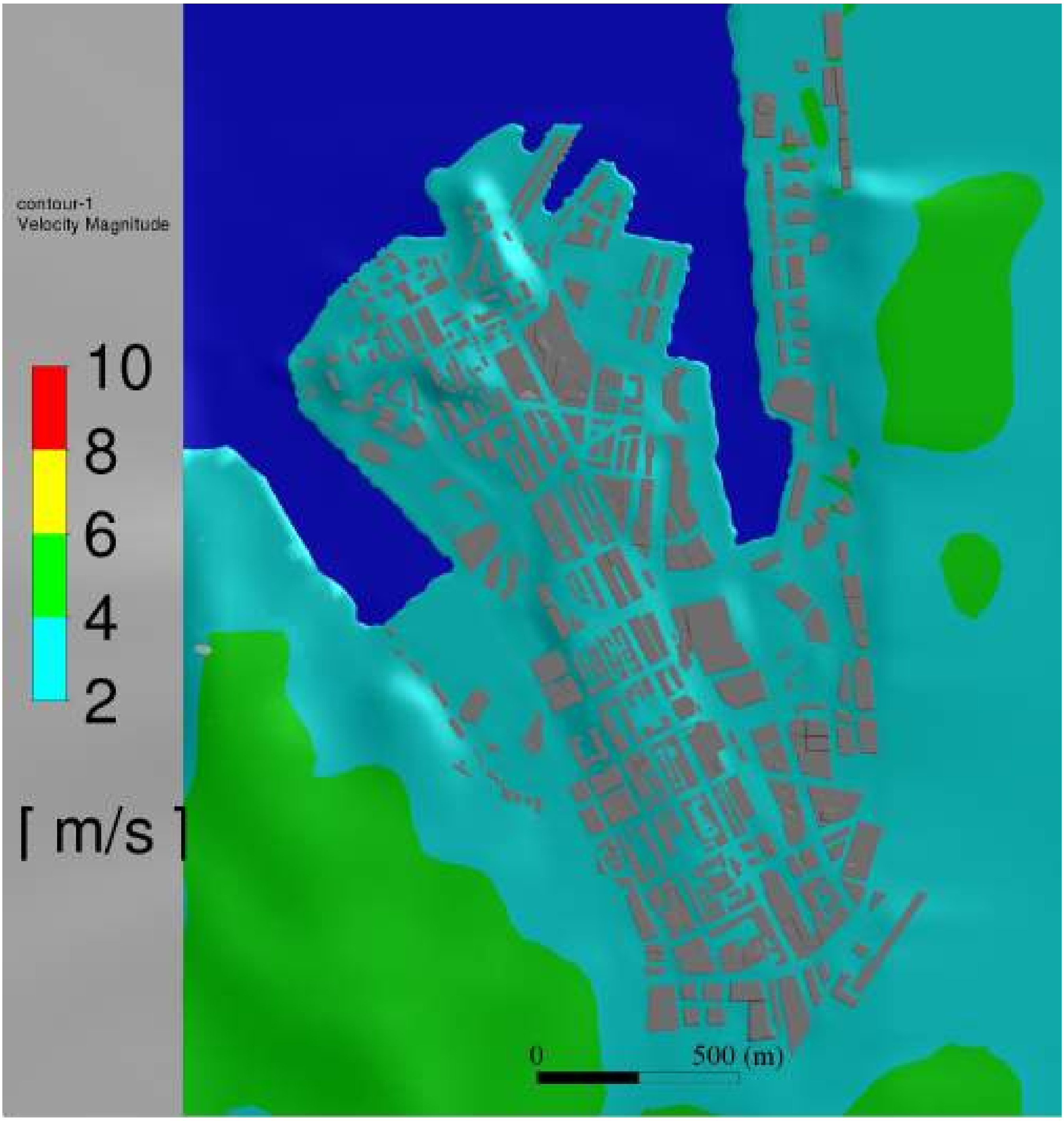


Figure 24 *Pedestrian comfort assessment – 5.5 m/s @ 135°. Contours of local wind speed @ 1.5 m*

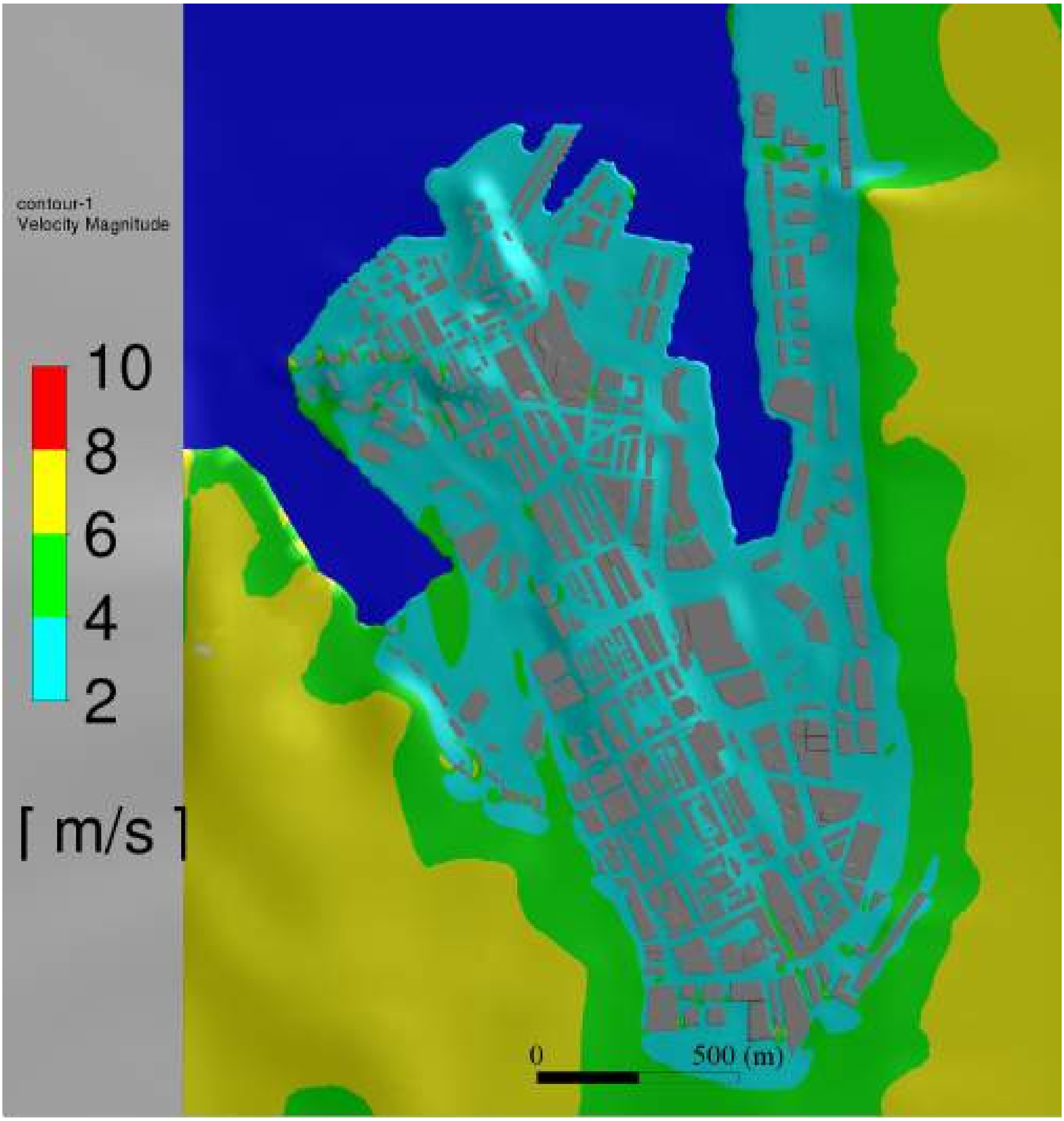


Figure 25 *Pedestrian comfort assessment – 7.9 m/s @ 180°. Contours of local wind speed @ 1.5 m*

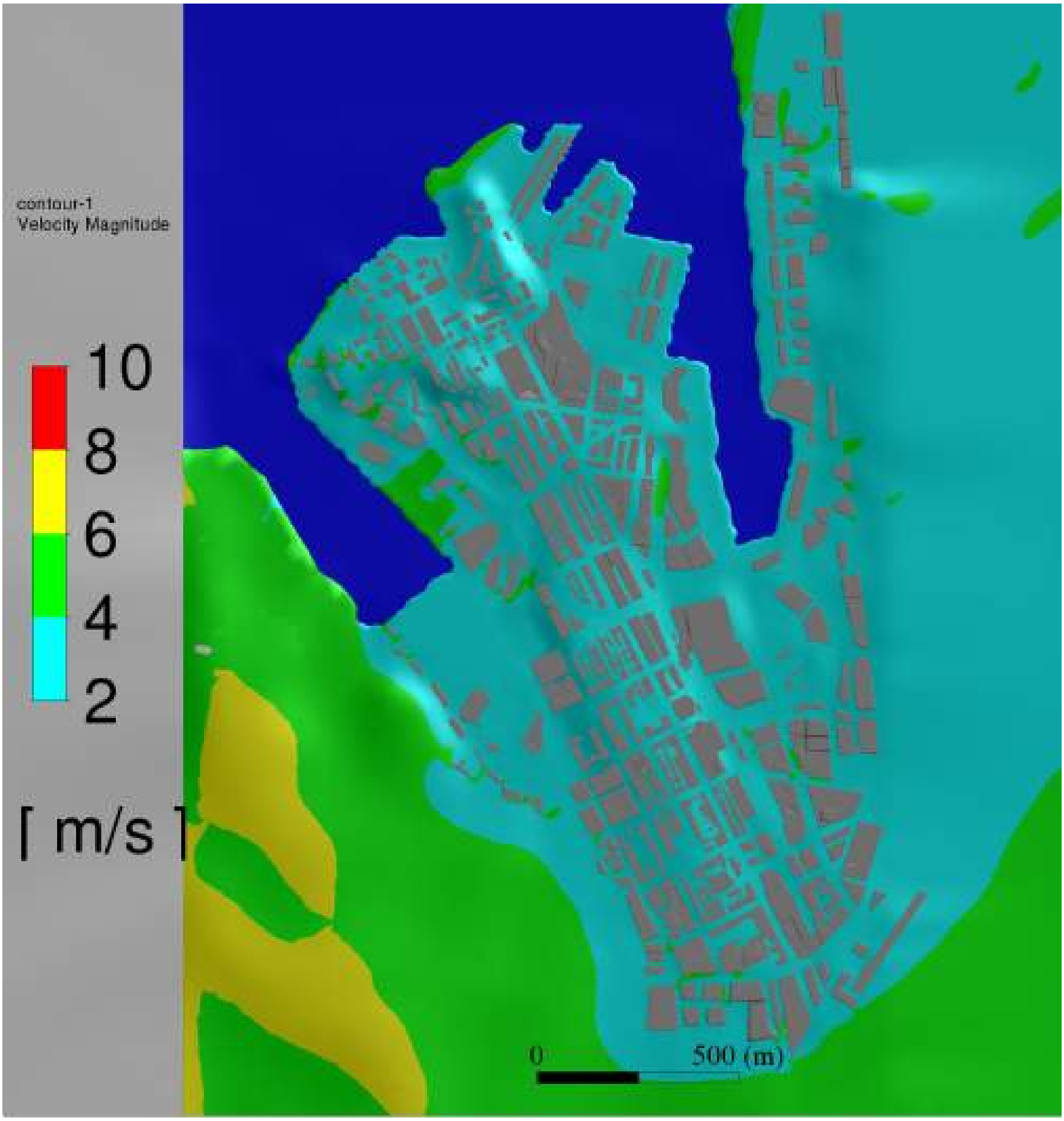


Figure 26 Pedestrian comfort assessment – 6.8 m/s @ 225°. Contours of local wind speed @ 1.5 m

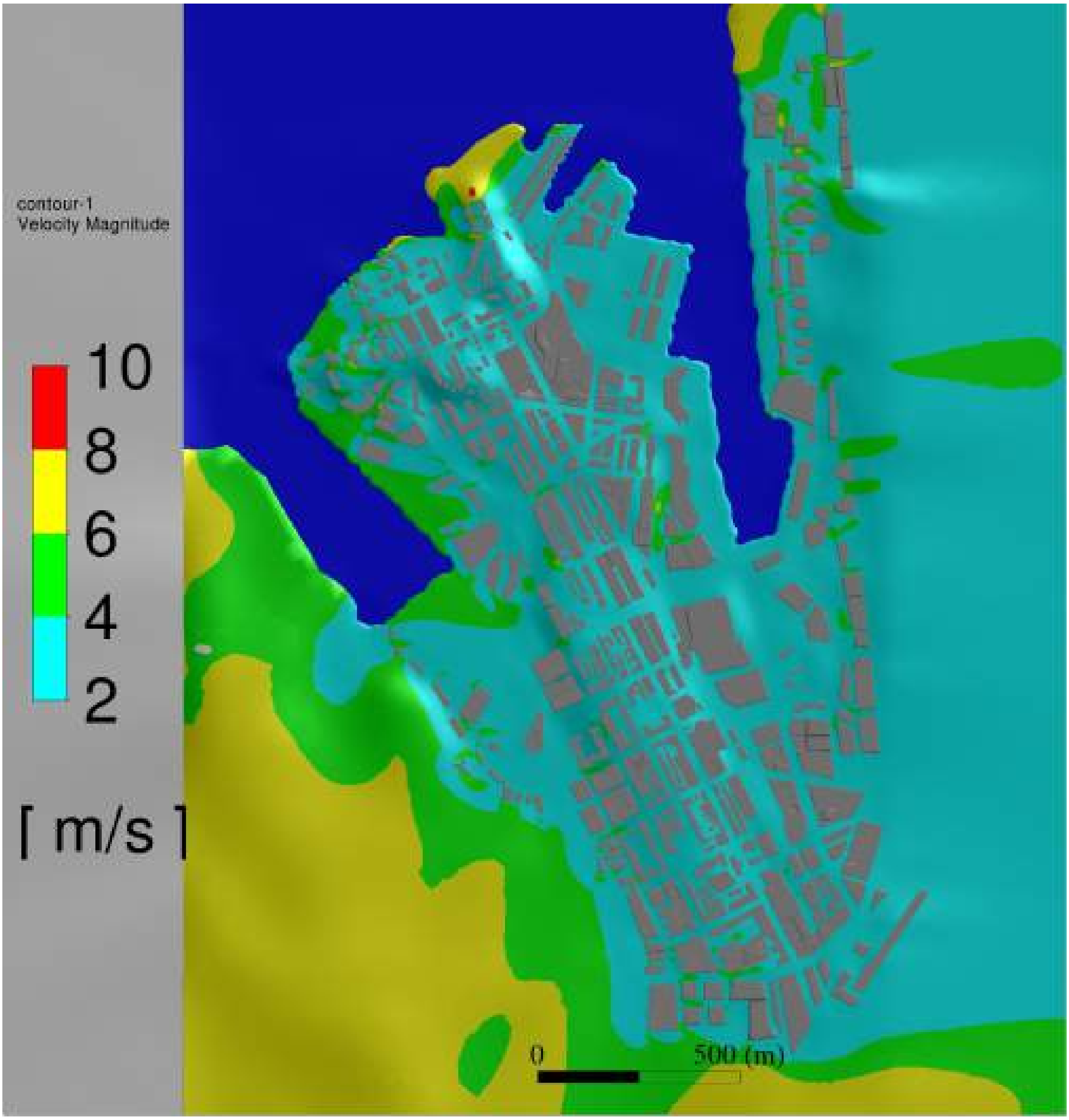


Figure 27 *Pedestrian comfort assessment – 7.8 m/s @ 270°. Contours of local wind speed @ 1.5 m*

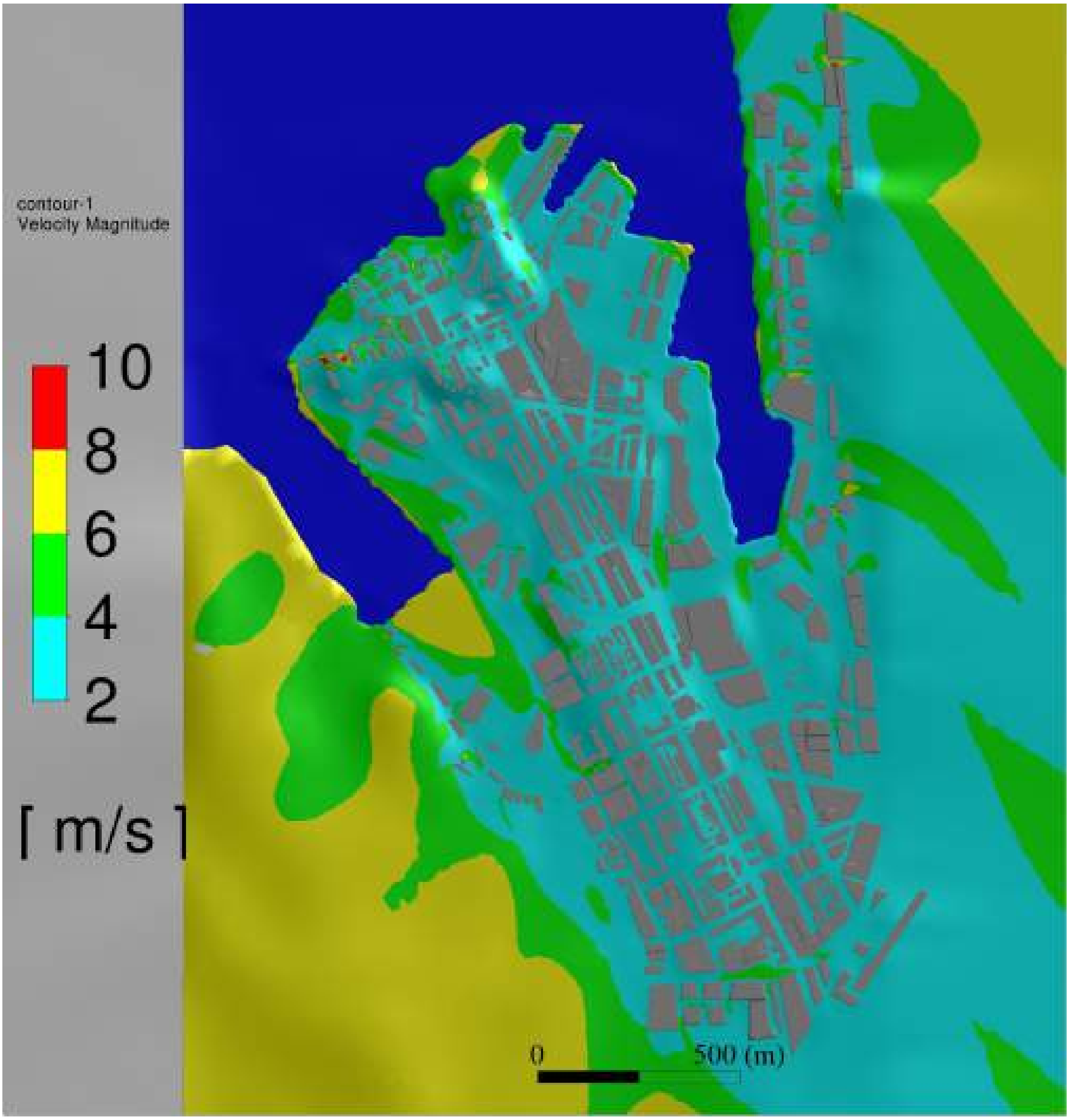


Figure 28 Pedestrian comfort assessment – 7.8 m/s @ 315°. Contours of local wind speed @ 1.5 m

Appendix D

Comfort Level Contours – Above Ground Level

Table 1 ID 021. WD = 000, WS = 6.3 m/s

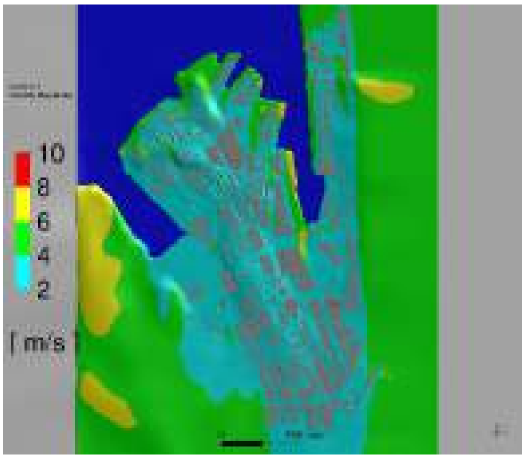
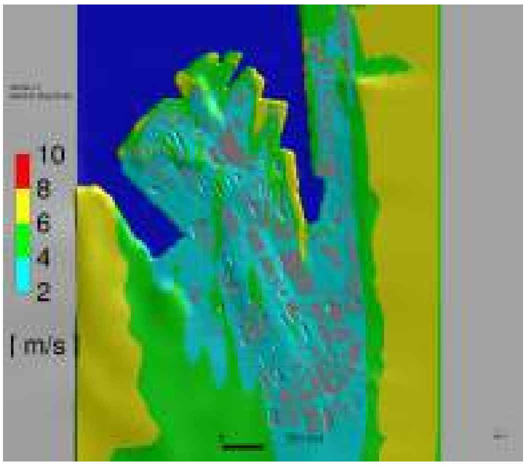
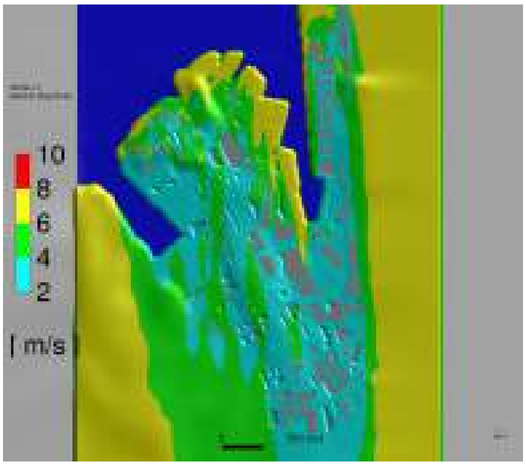
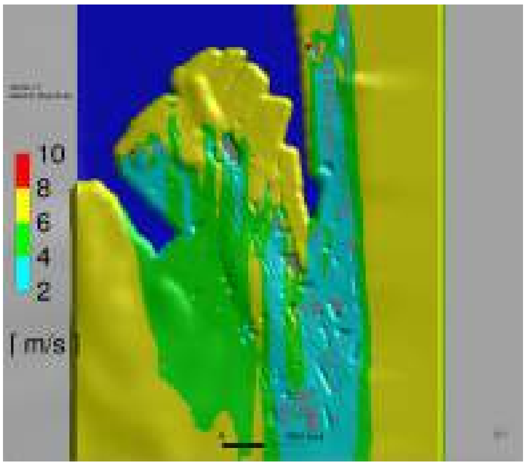
Elevation (m)	95th %ile wind speed contour plot
10	
20	
30	
50	

Table 2 *ID 022. WD = 045, WS = 5.5 m/s*

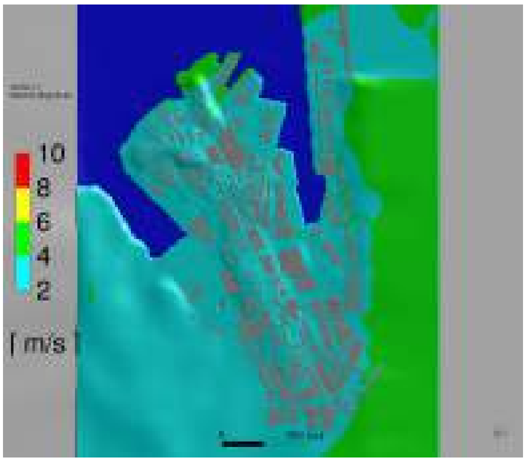
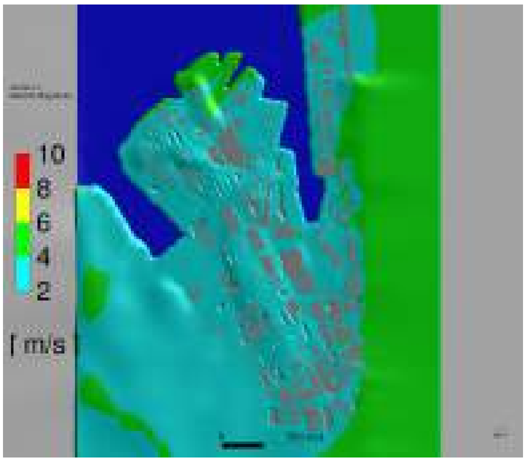
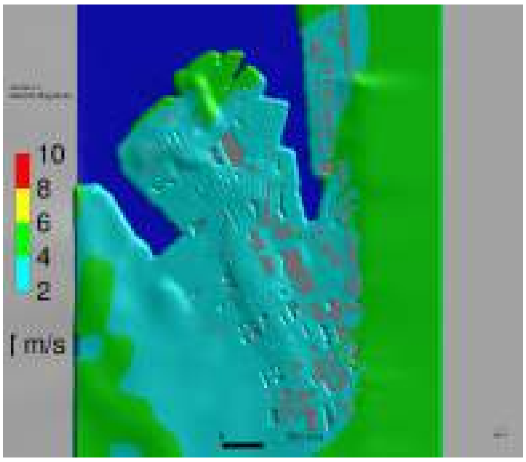
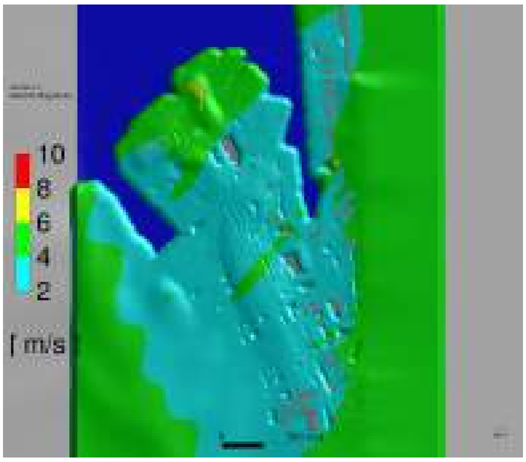
Elevation (m)	95th %ile wind speed contour plot
10	
20	
30	
50	

Table 3 *ID 023. WD = 090, WS = 5.1 m/s*

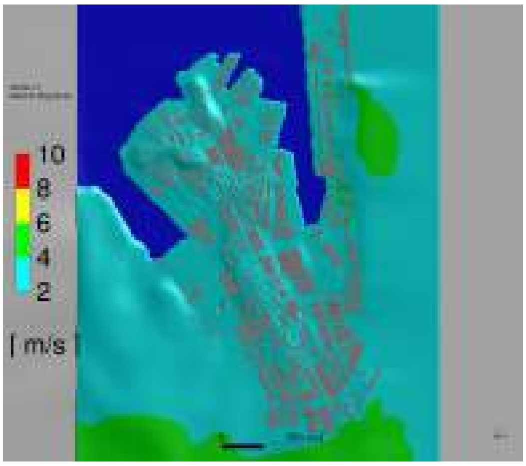
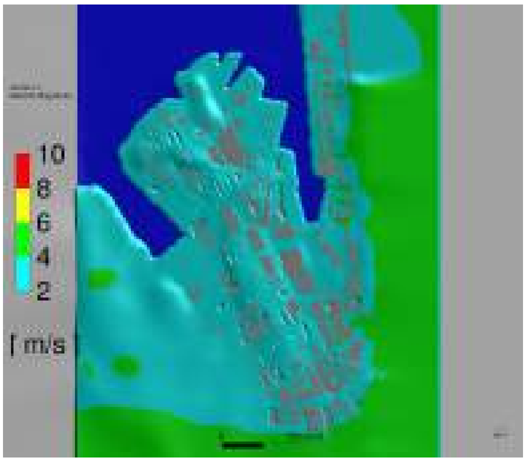
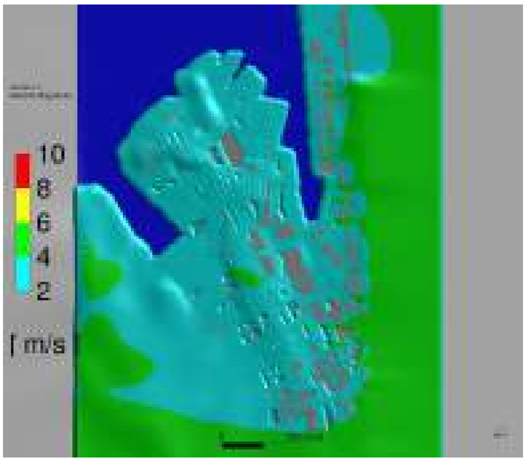
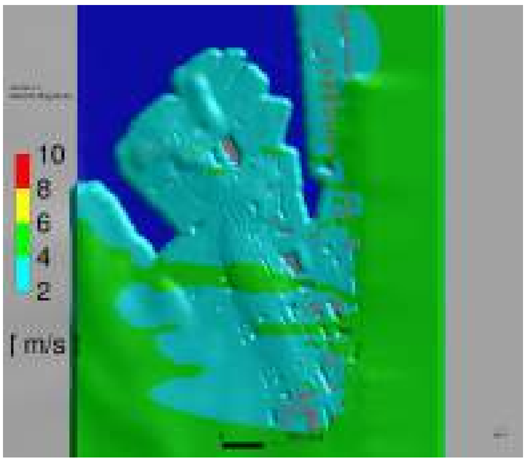
Elevation (m)	95^{th} %ile wind speed contour plot
10	
20	
30	
50	

Table 4 *ID 024. WD = 135, WS = 5.5 m/s*

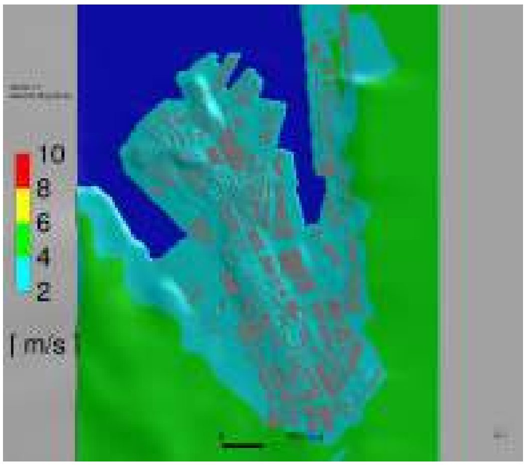
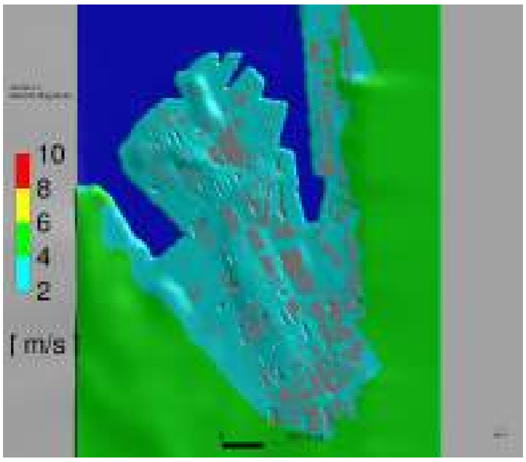
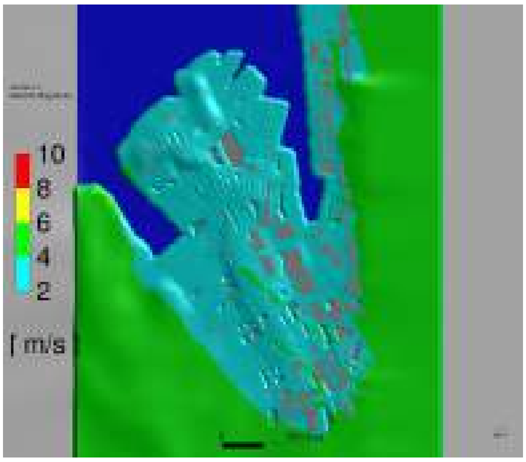
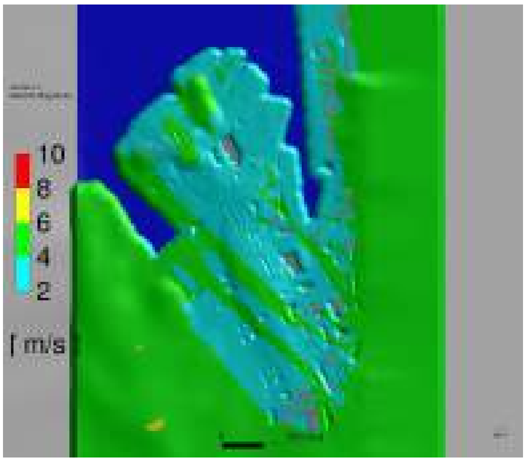
Elevation (m)	95th %ile wind speed contour plot
10	
20	
30	
50	

Table 5 *ID 025. WD = 180, WS = 7.9 m/s*

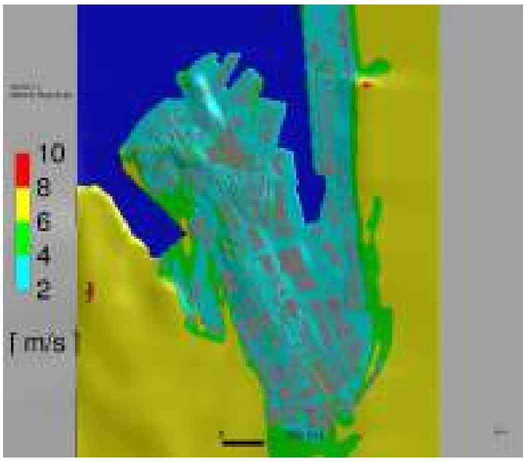
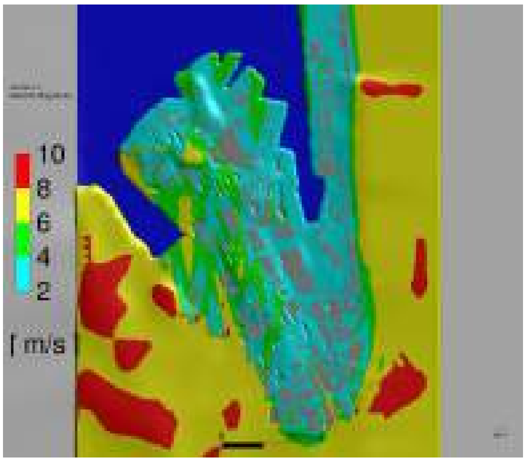
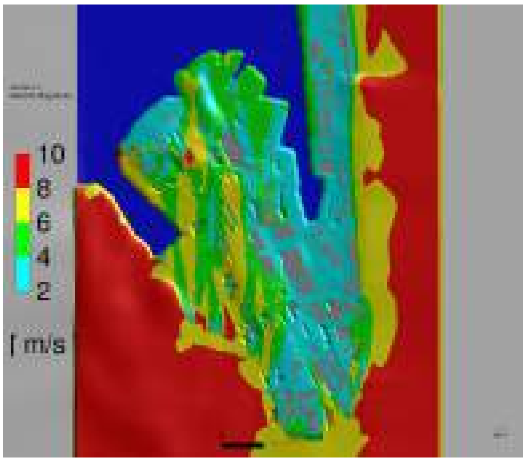
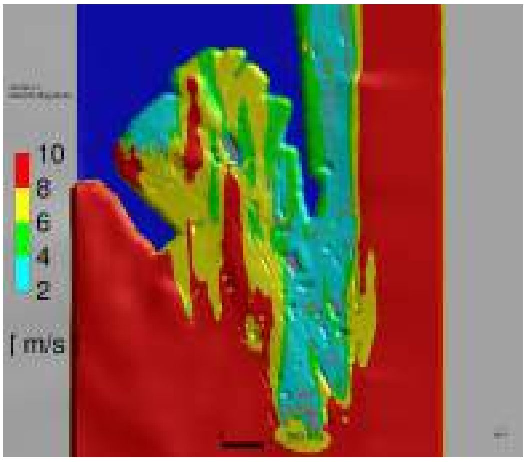
Elevation (m)	95th %ile wind speed contour plot
10	
20	
30	
50	

Table 6 *ID 026. WD = 225, WS = 6.8 m/s*

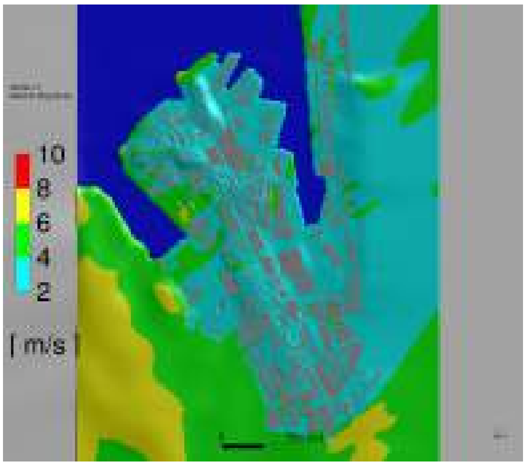
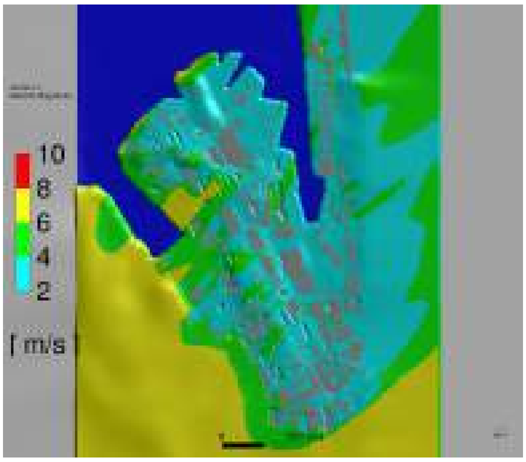
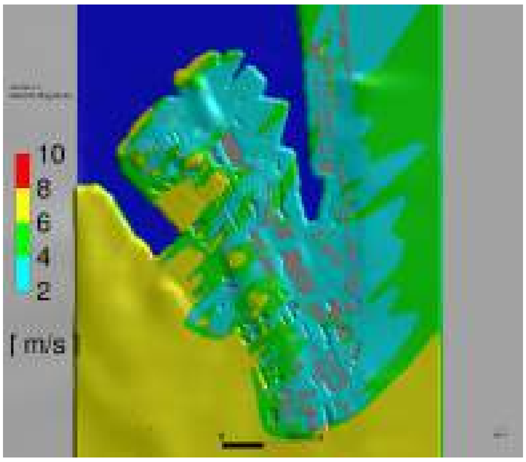
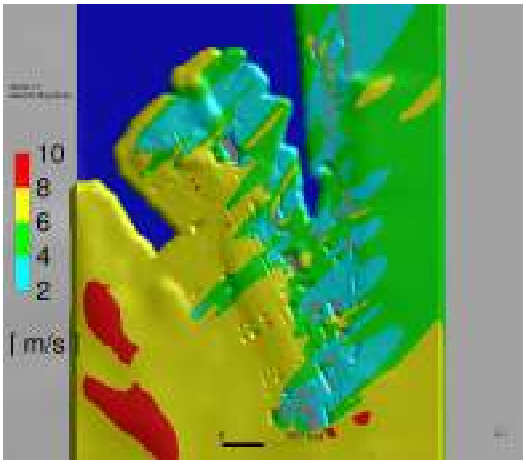
Elevation (m)	95th %ile wind speed contour plot
10	
20	
30	
50	

Table 7 *ID 027. WD = 270, WS = 7.8 m/s*

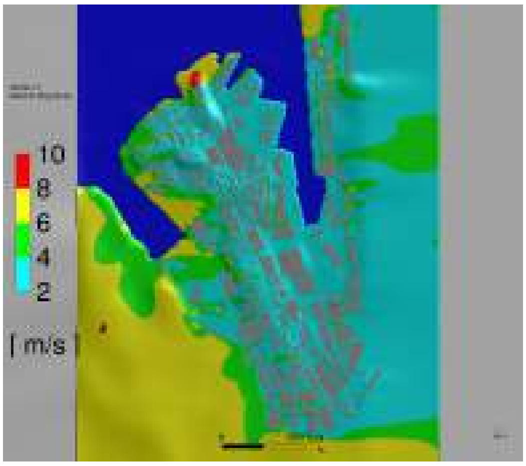
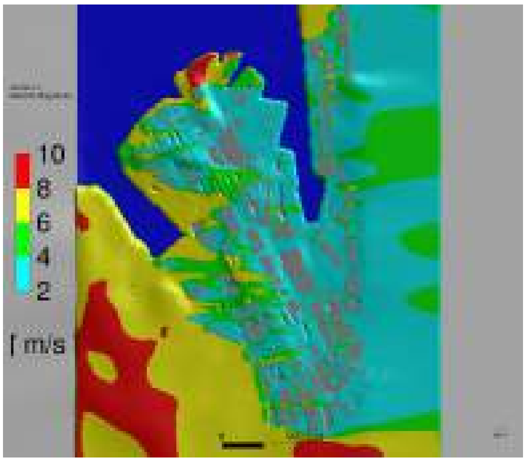
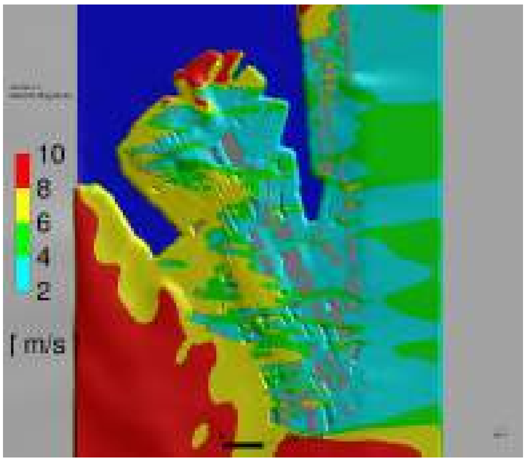
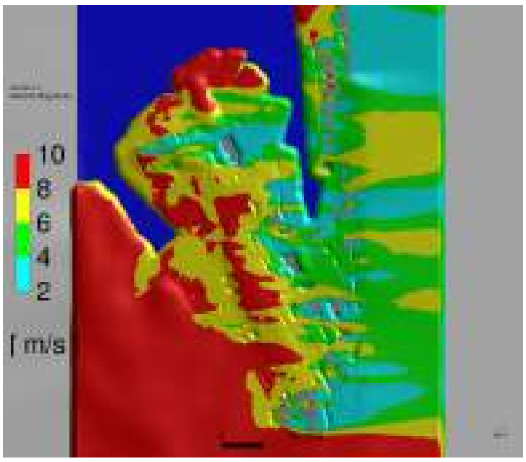
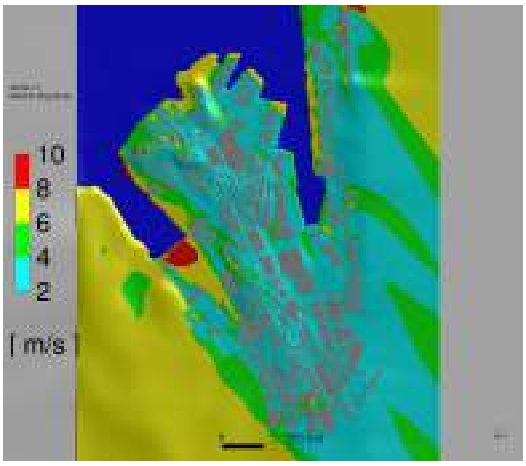
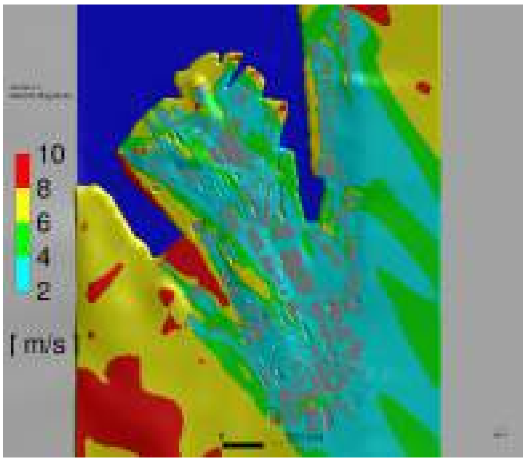
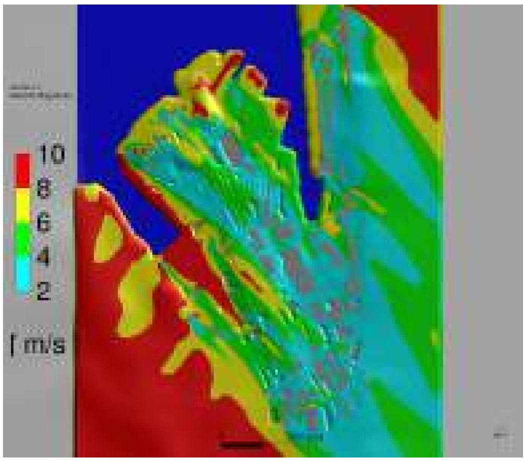
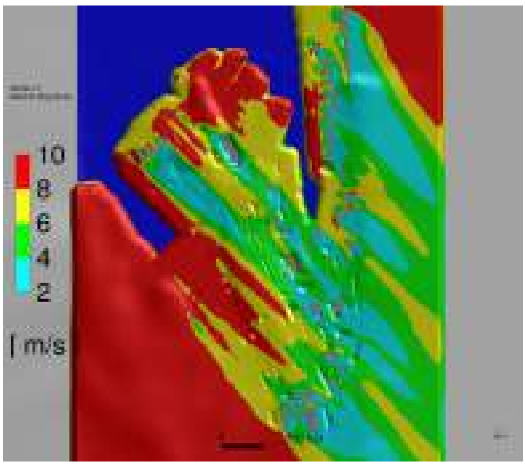
Elevation (m)	95th %ile wind speed contour plot
10	
20	
30	
50	

Table 8 *ID 028. WD = 315, WS = 7.8 m/s*

Elevation (m)	95th %ile wind speed contour plot
10	
20	
30	
50	

Appendix E

Safety Level Wind Contours – Ground Level

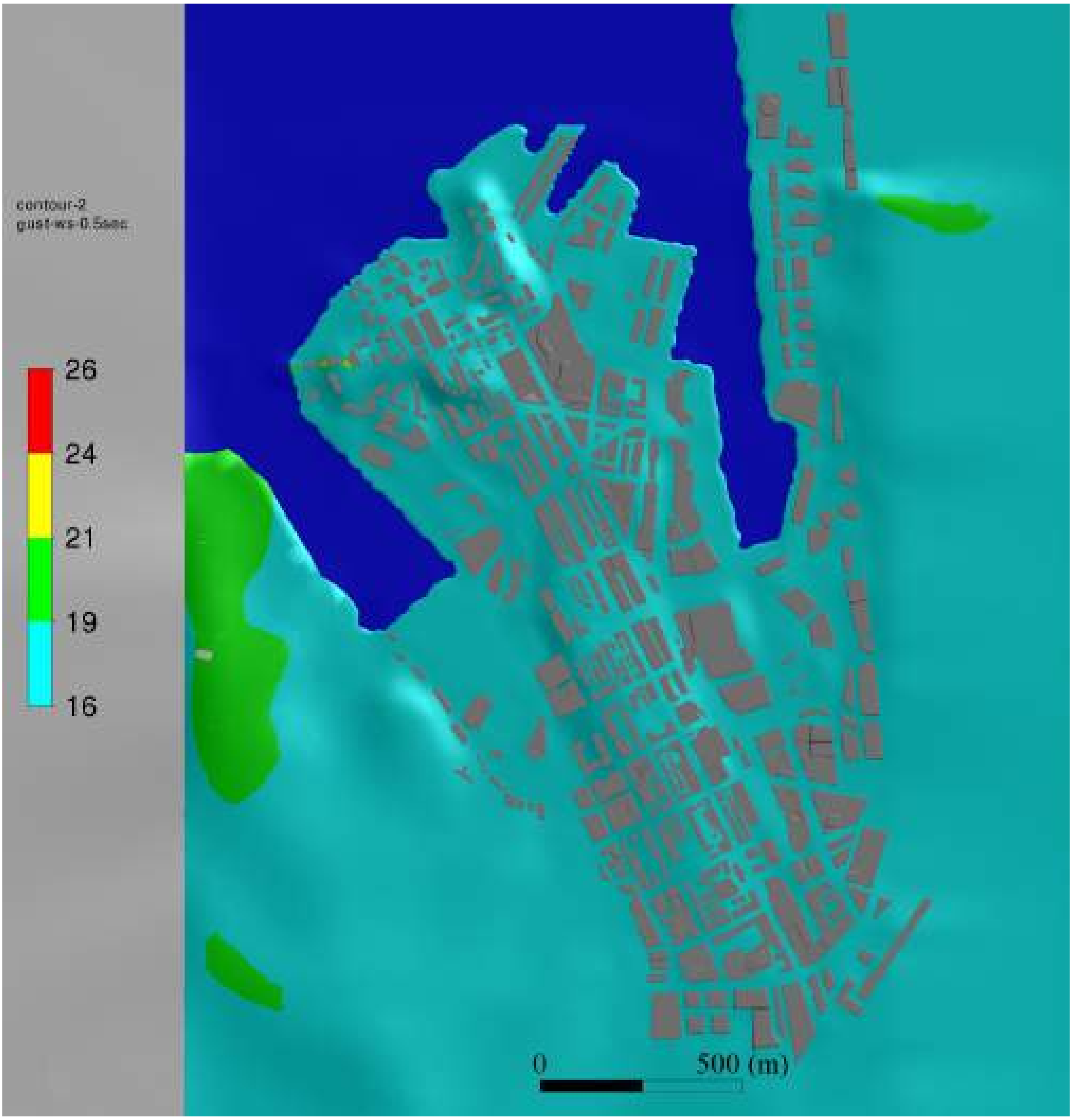


Figure 29 ***Pedestrian safety assessment – 9.7 m/s @ 0°. Contours of local 0.5 s gust wind speed @ 1.5 m***

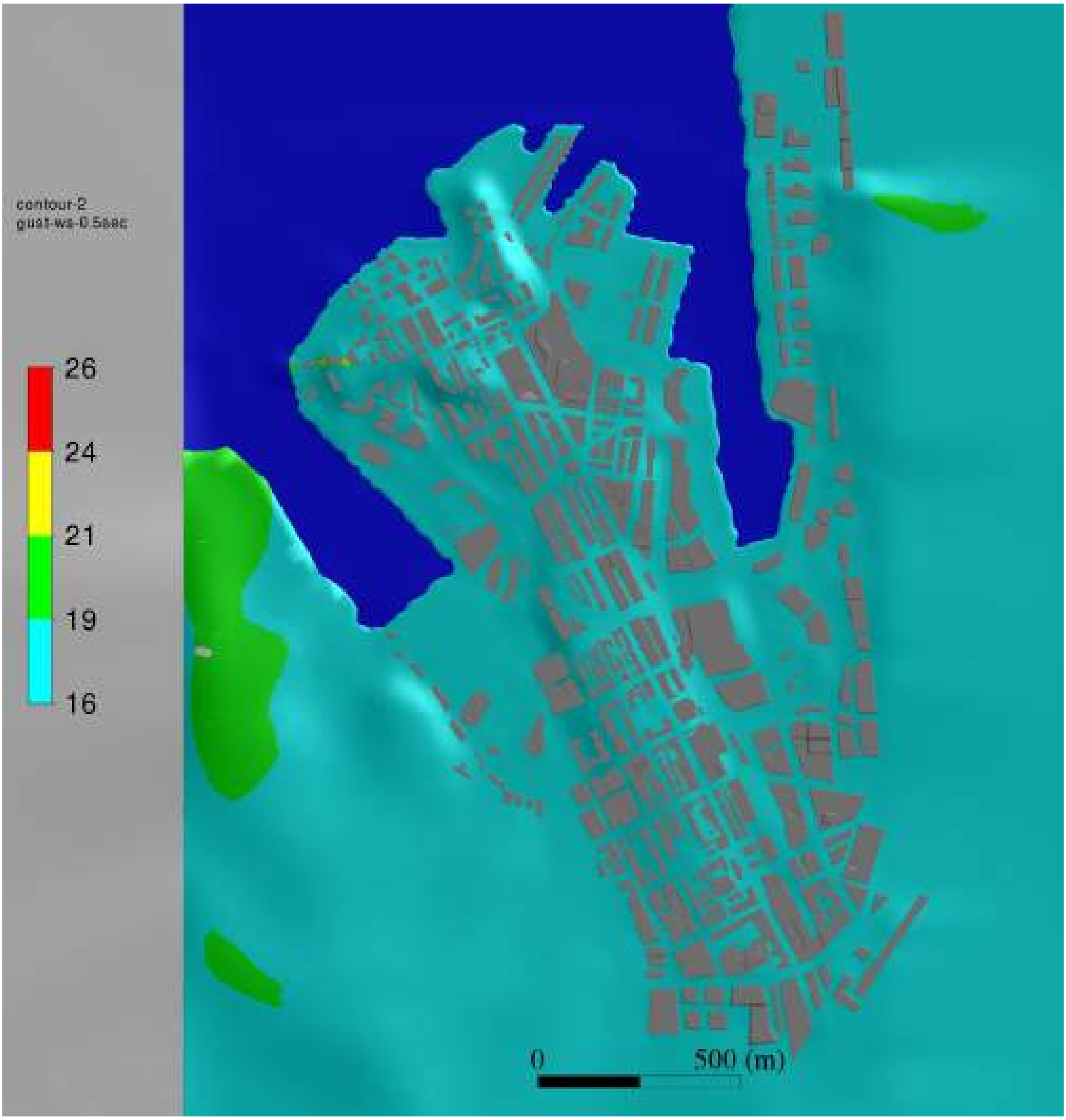


Figure 30 ***Pedestrian safety assessment – 9.7 m/s @ 45°. Contours of local 0.5 s gust wind speed @ 1.5 m***

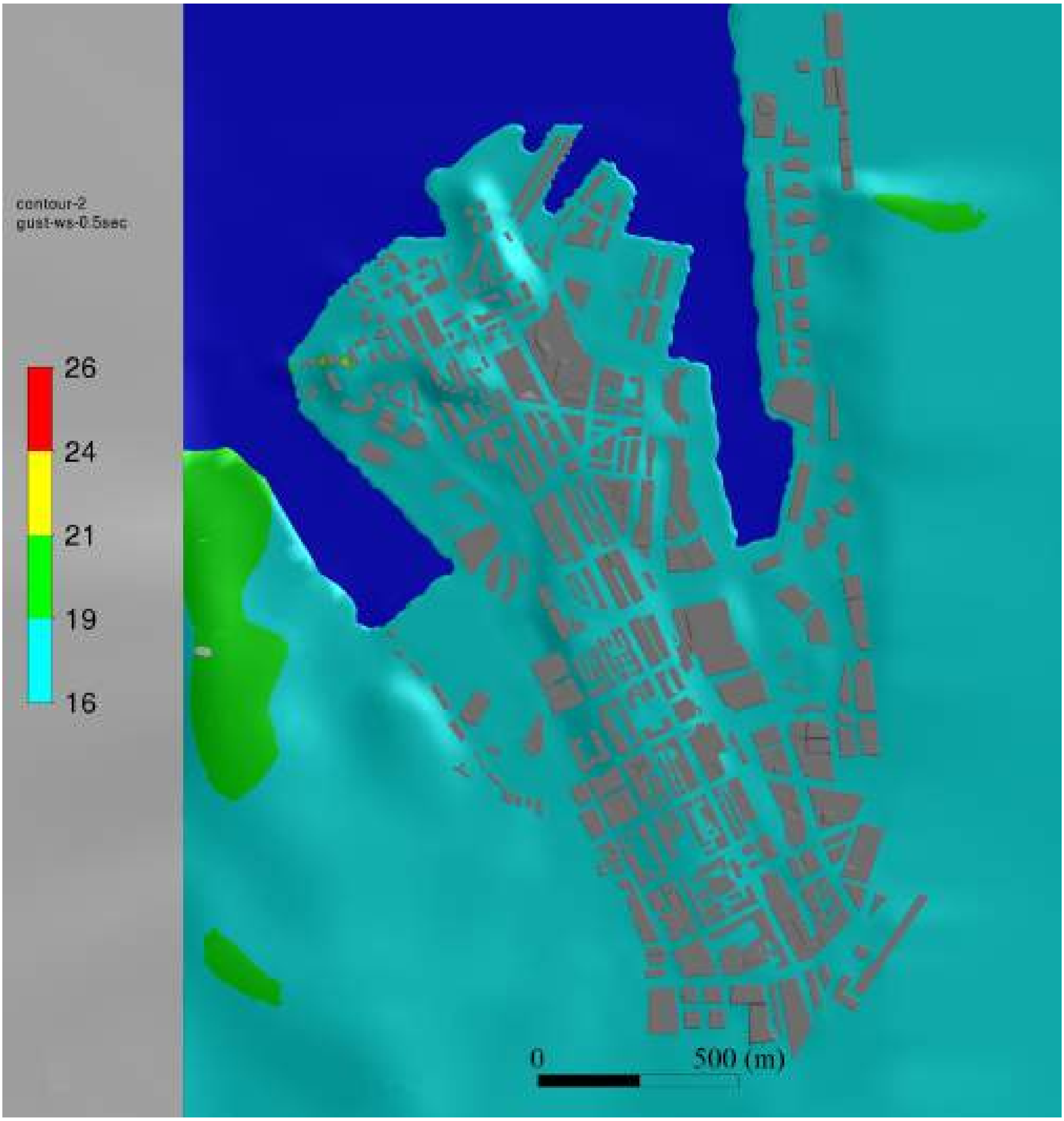


Figure 31 Pedestrian safety assessment – 12.5 m/s @ 90°. Contours of local 0.5 s gust wind speed @ 1.5 m

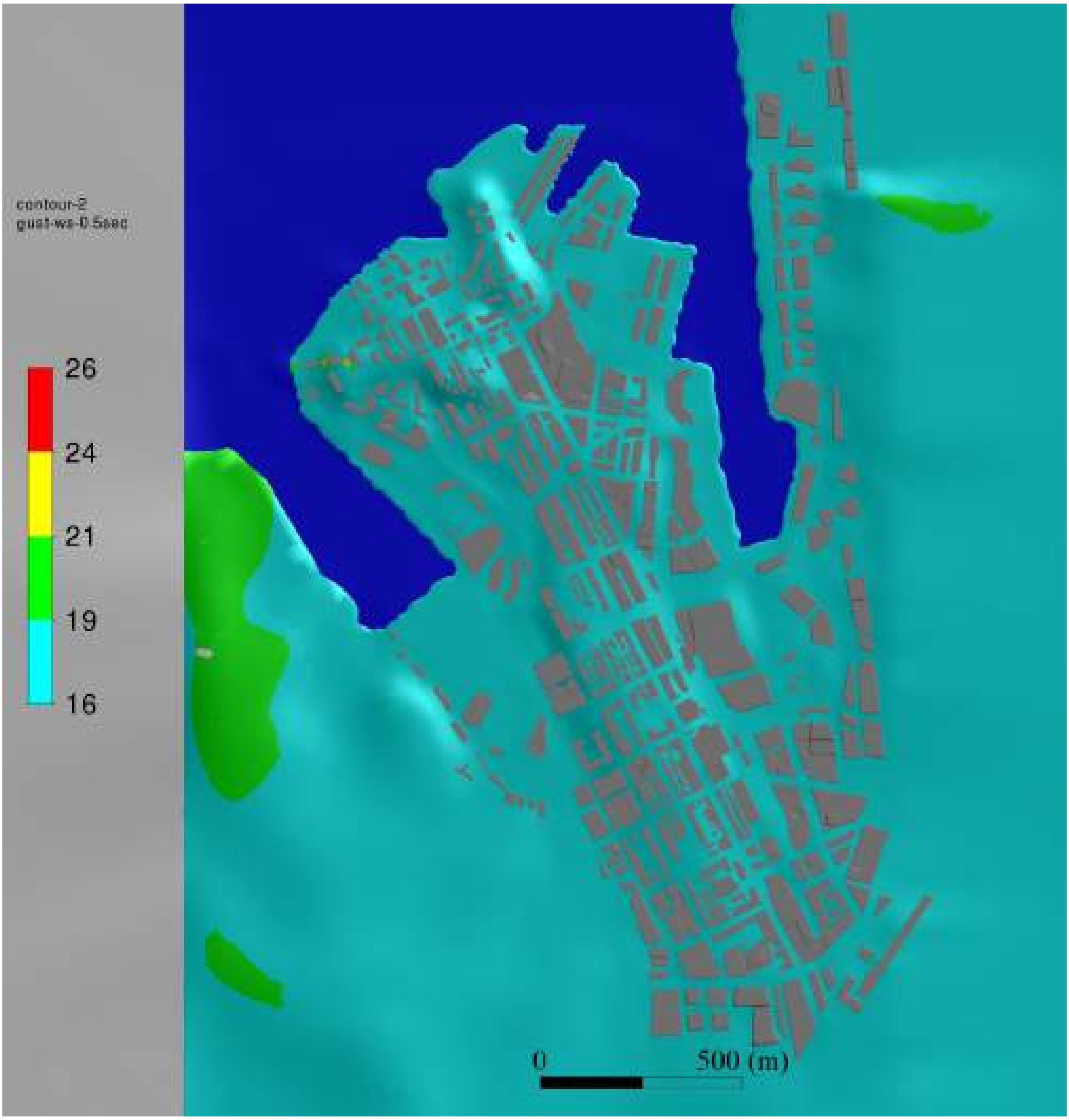


Figure 32 Pedestrian safety assessment – 11.6 m/s @ 135°. Contours of local 0.5 s gust wind speed @ 1.5 m

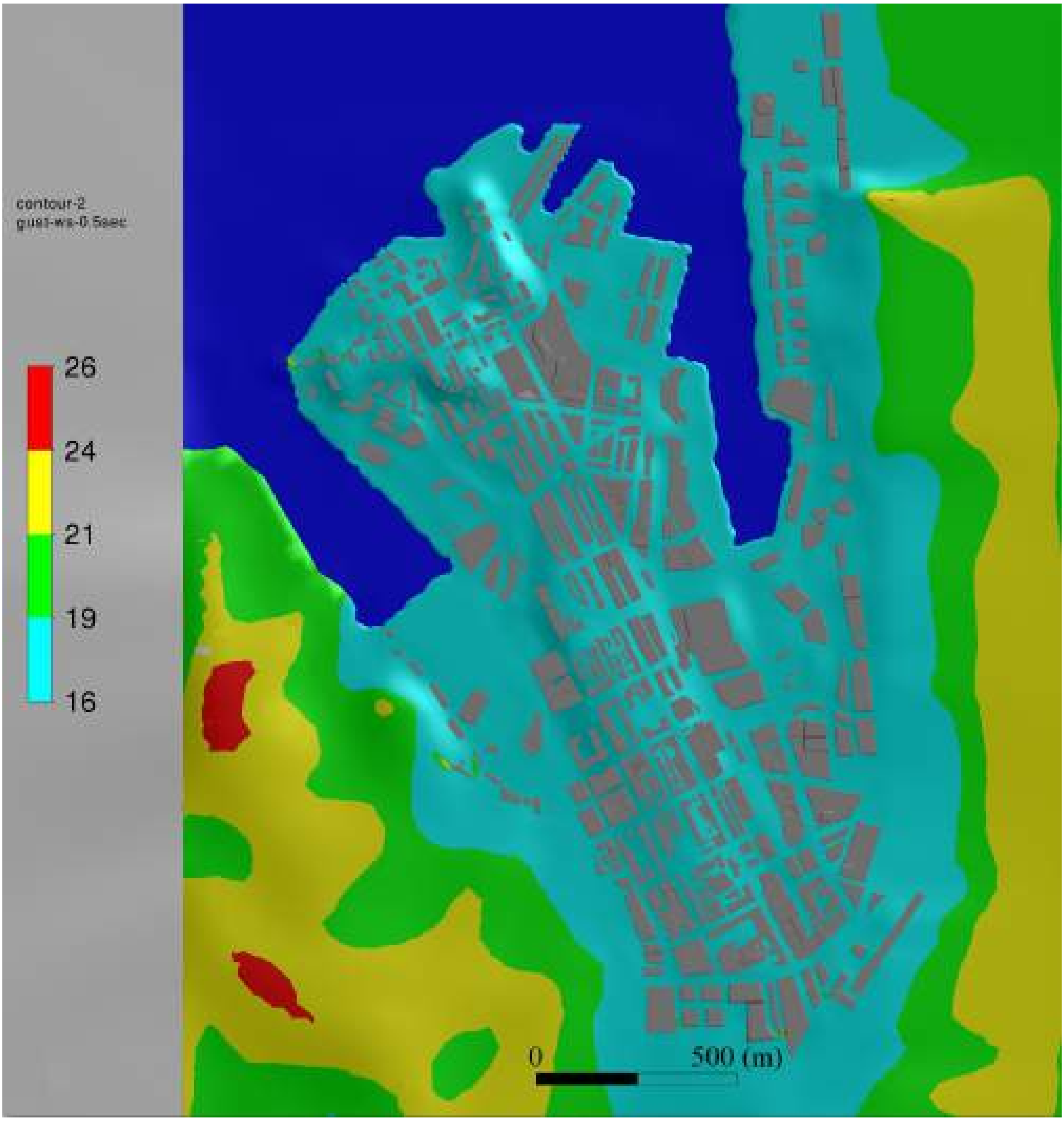


Figure 33 ***Pedestrian safety assessment – 12.4 m/s @ 180°. Contours of local 0.5 s gust wind speed @ 1.5 m***

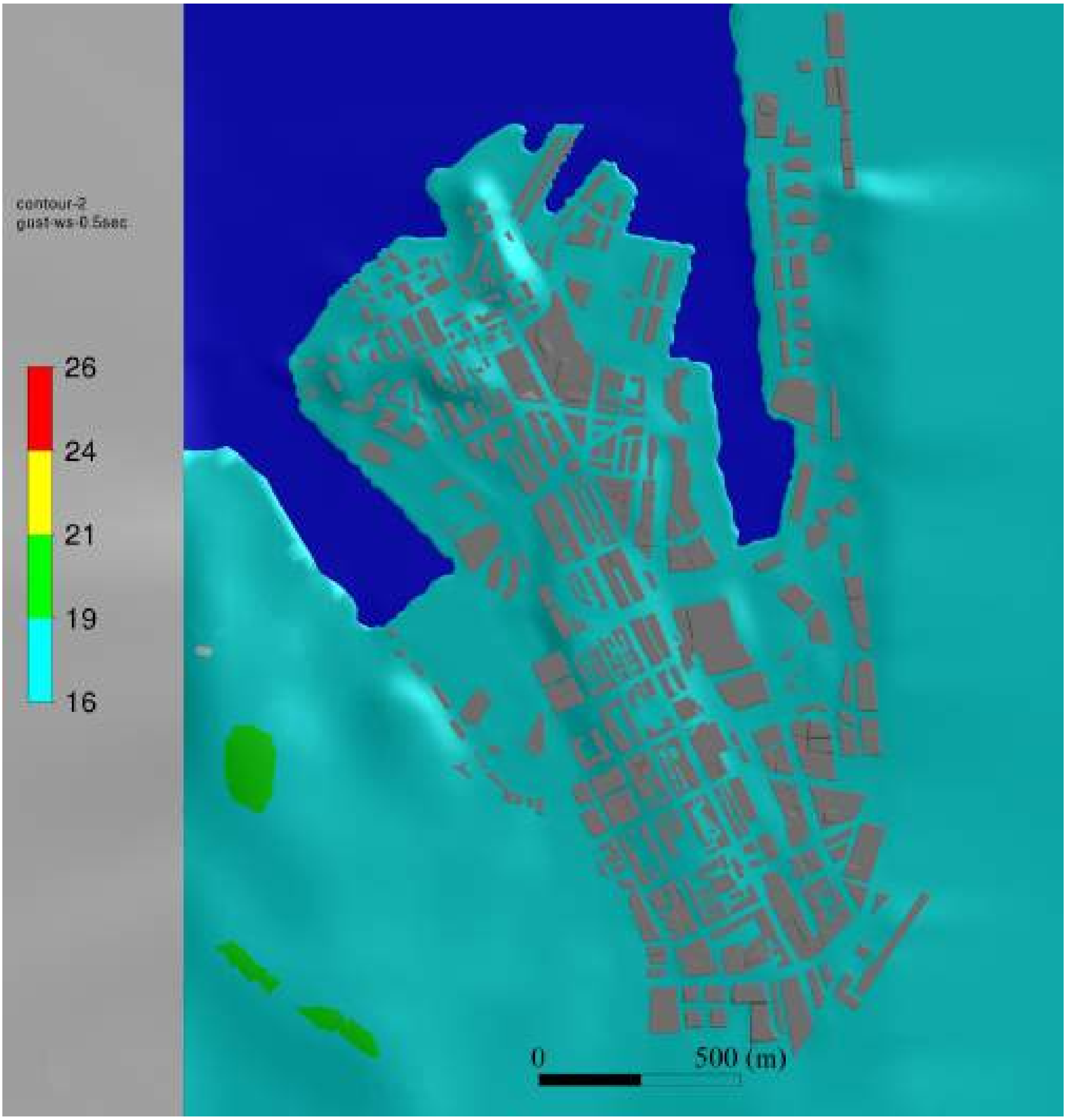


Figure 34 *Pedestrian safety assessment – 9.3 m/s @ 225°. Contours of local 0.5 s gust wind speed @ 1.5 m*

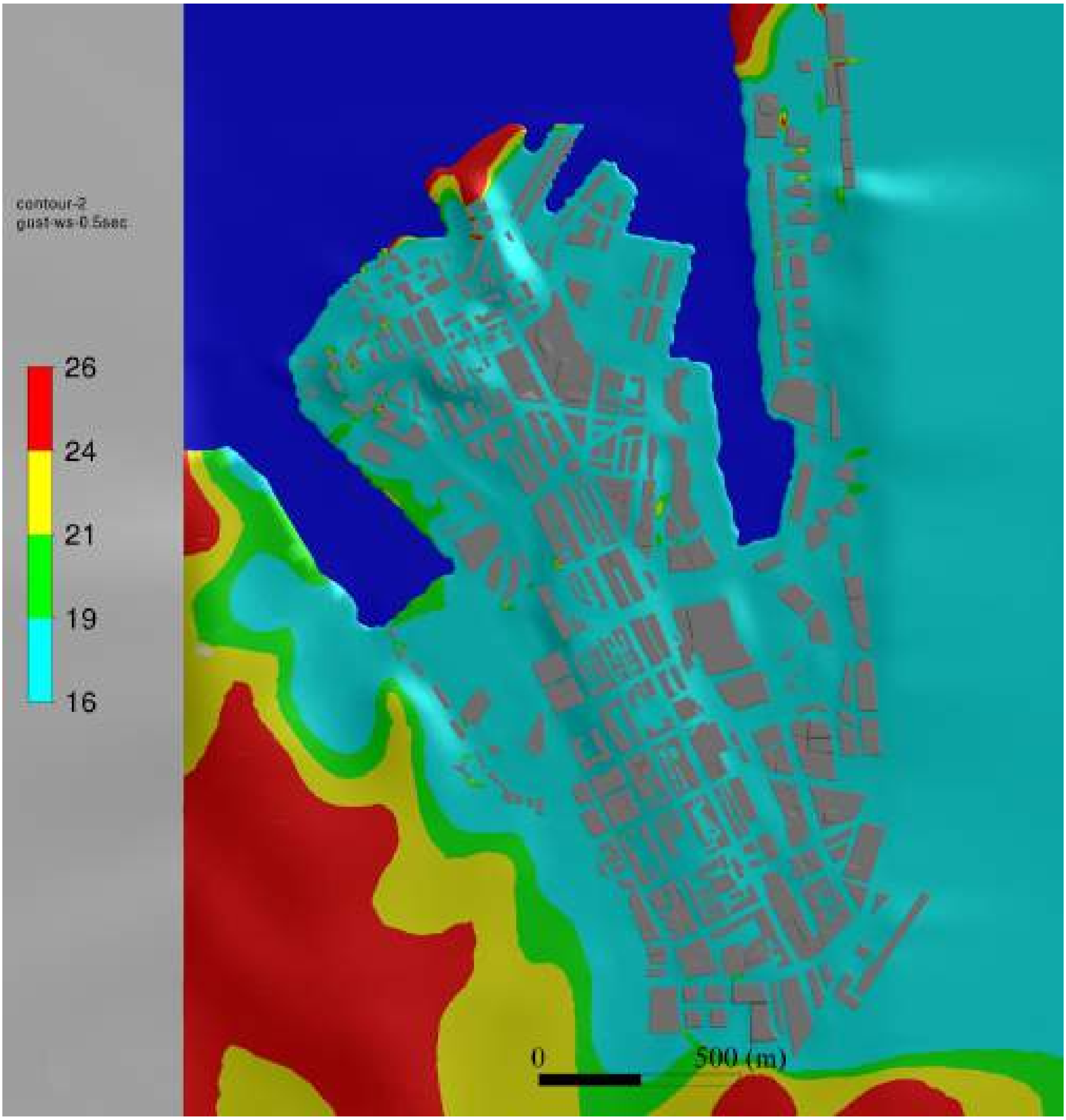


Figure 35 Pedestrian safety assessment – 13.6 m/s @ 270°. Contours of local 0.5 s gust wind speed @ 1.5 m

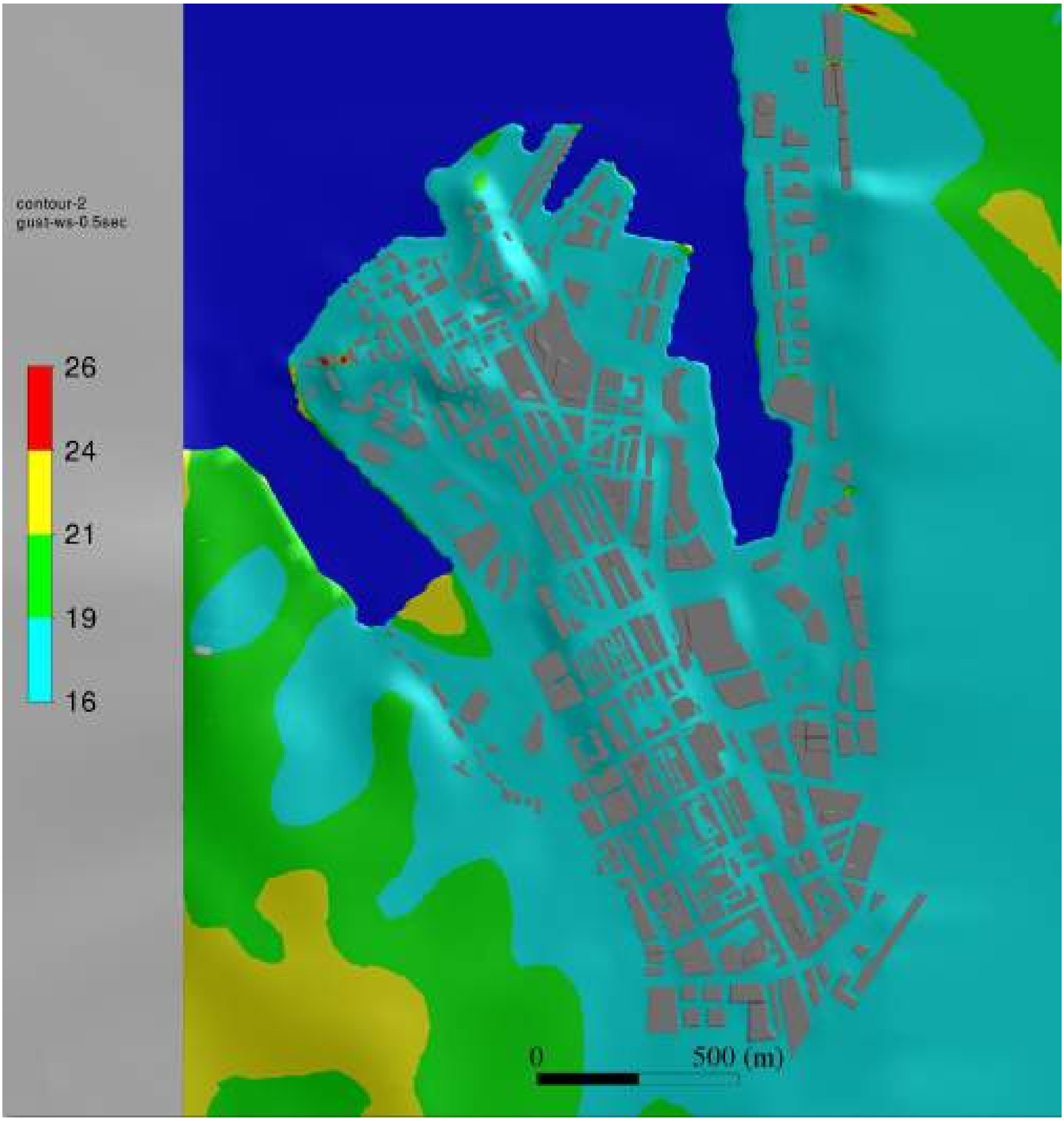
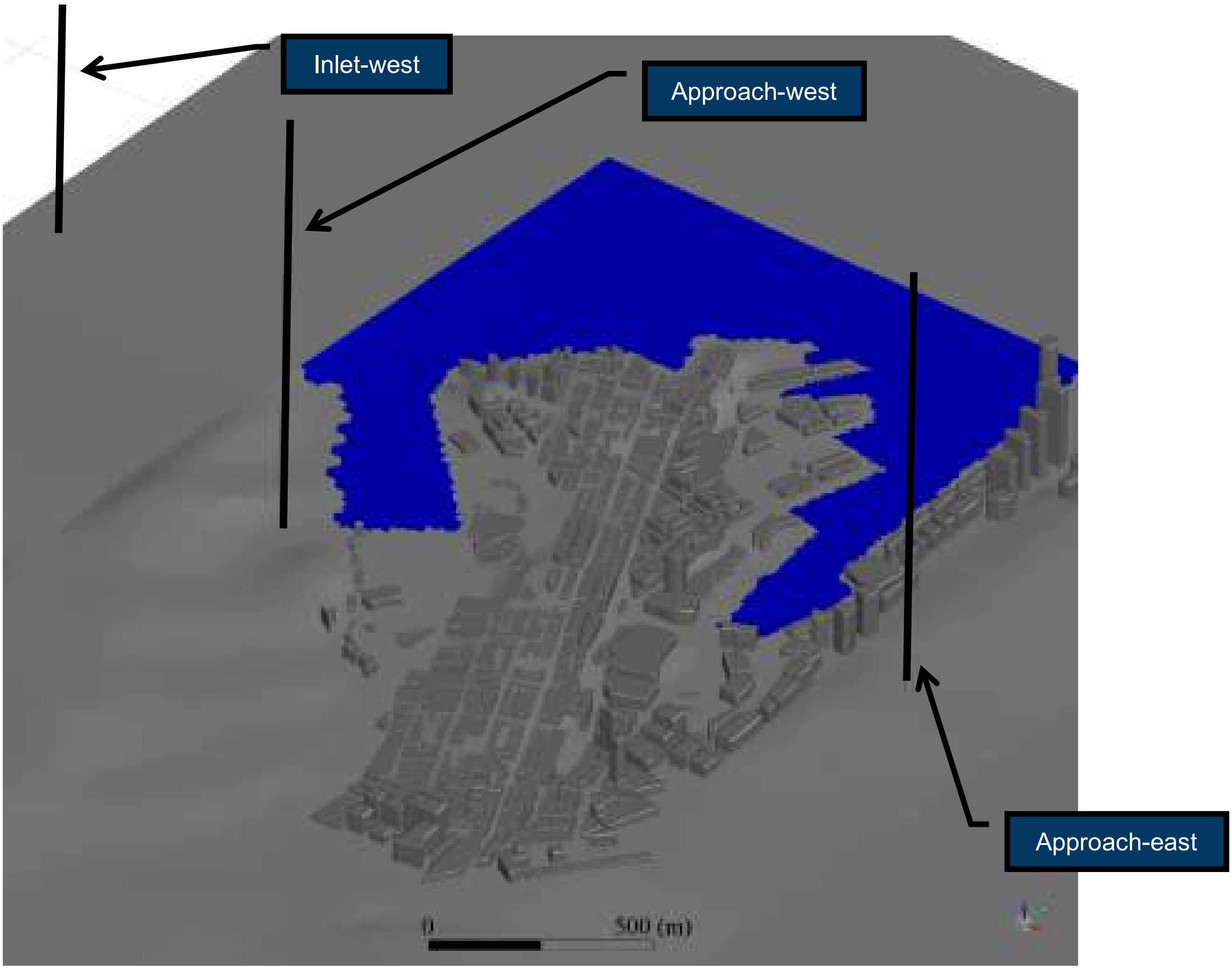


Figure 36 Pedestrian safety assessment – 11.4 m/s @ 315°. Contours of local 0.5 s gust wind speed @ 1.5 m

Appendix F

Wind Velocity Profile Evolution



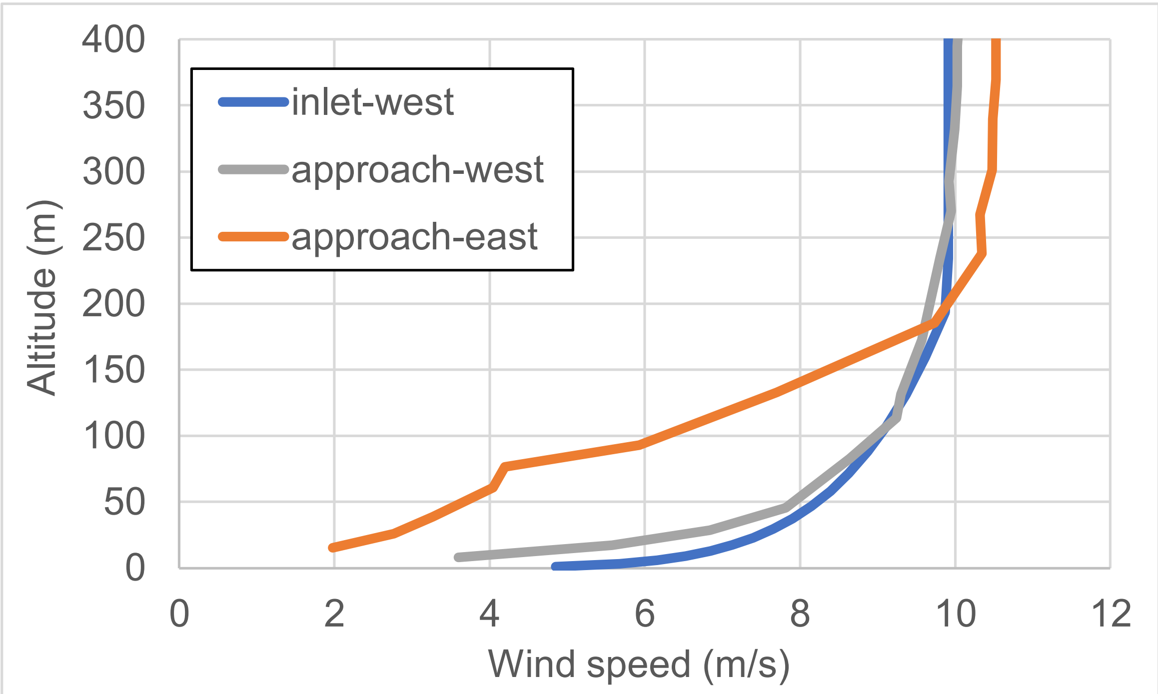


Figure 37 *Modelled velocity profile for case ID 027, 7.8 mm/s @ 270°*

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