PEDESTRIAN WIND ENVIRONMENT STUDY

ABBEY AREA PHASE 3, LONDON

WF389-02F02(REV4)- WE REPORT

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Prepared for:

WATES CONSTRUCTION LIMITED

WATES HOUSE, STATION APPROACH, LEATHERHEAD, SURREY, KT22 7SW.

30 YEARS OF EXCELLENCE IN WIND ENGINEERING

DOCUMENT CONTROL

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EXECUTIVE SUMMARY

This report presents the results of a detailed investigation into the wind environment impact on Phase 3 of the proposed Abbey Area development in London. Testing was performed at Windtech's boundary layer wind tunnel facility. The wind tunnel has a 3.0m wide working section and a fetch length of 14m, and measurements were taken from 16 wind directions at 22.5-degree increments. Testing was carried out using a 1:300 detailed scale model of the development. The effects of nearby buildings and land topography have been accounted for using a proximity model which represents an area with a radius of 375m.

Peak gust and mean wind speeds were measured at selected critical outdoor trafficable locations within and around the subject development. Wind velocity coefficients representing the local wind speeds are derived from the wind tunnel and are combined with a statistical model of the regional wind climate (which accounts for the directional strength and frequency of occurrence of the prevailing regional winds) to provide the equivalent full-scale wind speeds at the site. The wind speed measurements are compared with criteria for year-round safety and seasonal comfort. The effect of vegetation was excluded in the testing. The existing site conditions were also tested, for comparison. Additional treatments have been recommended, In-principle, for any area exposed to strong winds.

In total, two configurations were tested in the wind tunnel, which are described as follows:

- Scenario 1 – Existing Site Condition - The existing site with the existing surrounding buildings (baseline condition), excluding the existing soft-landscaping.
- Scenario 2 – Proposed with Existing Surrounds - The proposed development with the existing surrounding buildings.

The wind microclimate results when compared with the pedestrian comfort criteria are summarised as follows:

SCENARIO 1: EXISTING SITE CONDITION

Safety assessment

- Wind conditions do not exceed the safety criterion. The wind conditions at the site and surrounds are safe for pedestrian activities, including cyclist use throughout the year.

Comfort assessment

- All the thoroughfares at the site and surrounds are suitable for intended pedestrian activities (i.e., strolling and/or walking).
- During the summer season, the wind conditions at the neighbouring garden to the west of the site (Points 52 and 53) exceed the comfort criterion for sitting during the summer season. However, the wind conditions within the site and remaining surrounds are generally suitable for intended pedestrian activities (i.e., standing and/or sitting) during the summer season.
- The neighbouring roads are suitable for cyclist use throughout the year.

SCENARIO 2: PROPOSED WITH EXISTING SURROUNDS

Safety assessment

- The results for the proposed development with the existing surrounds indicate that the wind conditions are rated as safe for pedestrians and cyclist use throughout the year.

- At elevated levels, wind conditions on all balconies are rated as safe for occupant use throughout the year.

Comfort assessment

- The proposed development provides shelter to the windiest areas in the surrounds to the north (Points 62 and 65) where the wind conditions are calmer and are suitable for strolling during the worst season (winter). Wind microclimate at all throughfares is suitable for intended pedestrian activities throughout the year.

- The wind microclimate outside an entrance of Block A (Point 40) exceeds the comfort criterion for entrance use by occupants/visitors during the worst season (winter). Mitigation measures are recommended for this entrance. The wind microclimate outside all remaining entrances (including those to Blocks B and C) is suitable for occupant/visitors use throughout the year.

- The summer seasonal results show that the wind conditions exceed comfort criterion at seating/play areas at Points 28, 31, 32, 35, 37 and 38 for intended pedestrian activities. Mitigation measures are recommended for those areas. The wind microclimate around the remaining seating/play areas within the site boundary is shown to be suitable for the intended pedestrian activities.

- The assessment indicates that the wind microclimate conditions at all balconies are suitable for occupant use during the summer season.

- The wind conditions in the surrounds are suitable for their intended uses, ranging from standing to strolling during the worst season (winter). It should be noted that the wind conditions at the neighbouring garden to the west of the site (Point 53) are improved and are suitable for sitting during the summer season by the presence of the proposed development. In the neighbouring garden, associated with Point 52, the wind conditions are unsuitable for the intended sitting use. This was the case in the existing site condition.

- The neighbouring roads are also suitable for cyclist use throughout the year.

CONTENTS

1 INTRODUCTION

The proposed development comprises, Demolition and redevelopment of Emminster and Hinstock blocks including Belsize Priory Health Centre, Abbey Community Centre, public house and commercial units to provide new residential accommodation (Use Class C3) and ground floor commercial space (Use Class E/Sui Generis) to be used as flexible commercial units, across three buildings ranging from 4 to 11 storeys, along with car and bicycle parking, landscaping and all necessary ancillary and enabling works.The site is bounded by Abbey Road to the north-east, Belsize Road to the south-east and low-rise residential Blocks to the west. At ground level, the areas within and around the proposed development are expected to be used mostly as thoroughfares. Public seating and play areas are also proposed between the Blocks.

A wind tunnel study has been undertaken to determine wind speeds at selected critical outdoor trafficable areas within and around the subject development. The test procedures followed for this wind tunnel study were based on the Wind Microclimate Guidelines for developments in the City of London and the guidelines set out in the Australasian Wind Engineering Society Quality Assurance Manual (AWES-QAM-1-2019), ASCE 7-16 (Chapter C31), and CTBUH (2013) which are widely adopted and used in the UK and throughout the Europe.

A scale model of the development was prepared, including the surrounding buildings and land topography. Testing was performed at Windtech's boundary layer wind tunnel facility. The wind tunnel has a 3.0m wide working section and a fetch length of 14m, and measurements were taken from 16 wind directions at 22.5 degree increments. The wind tunnel was configured to the appropriate boundary layer wind profile for each wind direction. Wind speeds were measured using pressure-based wind speed sensors, positioned to monitor wind conditions at critical outdoor trafficable areas of the development.

The effect of vegetation was excluded in the testing. The existing site conditions were also tested, for comparison. The wind speeds measured during testing were combined with a statistical model of the regional wind climate to provide the equivalent full-scale wind speeds at the site. The wind speed measurements are compared with criteria for pedestrian comfort and safety, based on criteria for year-round safety and seasonal comfort. In-principle treatments have been recommended for any area which was exposed to strong winds. These treatments could be in the form of retaining vegetation that is already proposed for the site, or including additional vegetation, screens, awnings, etc.

2 WIND TUNNEL MODEL

Wind tunnel testing was carried out using a 1:300 scale model of the development and surroundings. The study model incorporates all necessary architectural features on the façade of the development to ensure an accurate wind flow is achieved around the model and was constructed using a Computer Aided Manufacturing (CAM) process to ensure that a high level of detail and accuracy is achieved. The effect of nearby buildings and land topography has been accounted for through the use of a proximity model, which represents a radius of 375m from the development site. In total, two configurations were tested in the wind tunnel, which are described as follows:

- Scenario 1 – Existing Site Condition - The existing site with the existing surrounding buildings (baseline condition), excluding the existing soft-landscaping.
- Scenario 2 – Proposed with Existing Surrounds - The proposed development with the existing surrounding buildings.

Photographs of the wind tunnel model are presented in Figures 1. Plans of the proximity model are provided in Figures 2.

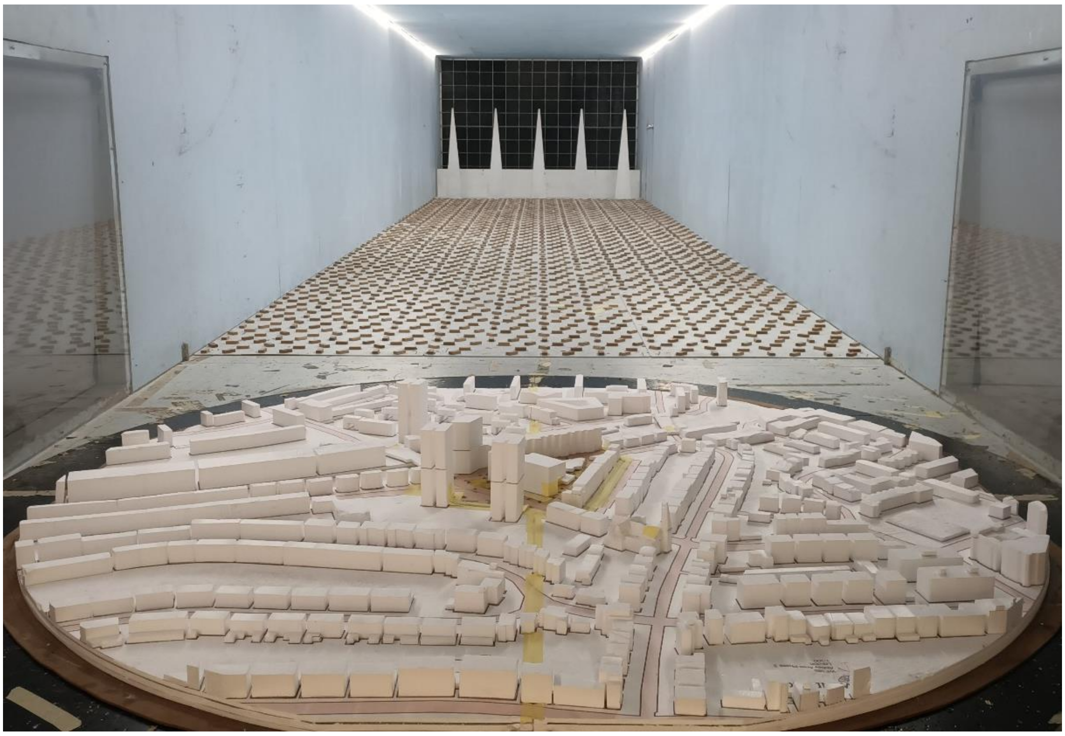


Figure 1a: Photograph of the Wind Tunnel Model: Existing with Existing Surrounds (view from the north)

Figure 1b: Photograph of the Wind Tunnel Model: Existing with Existing Surrounds (view from the south)

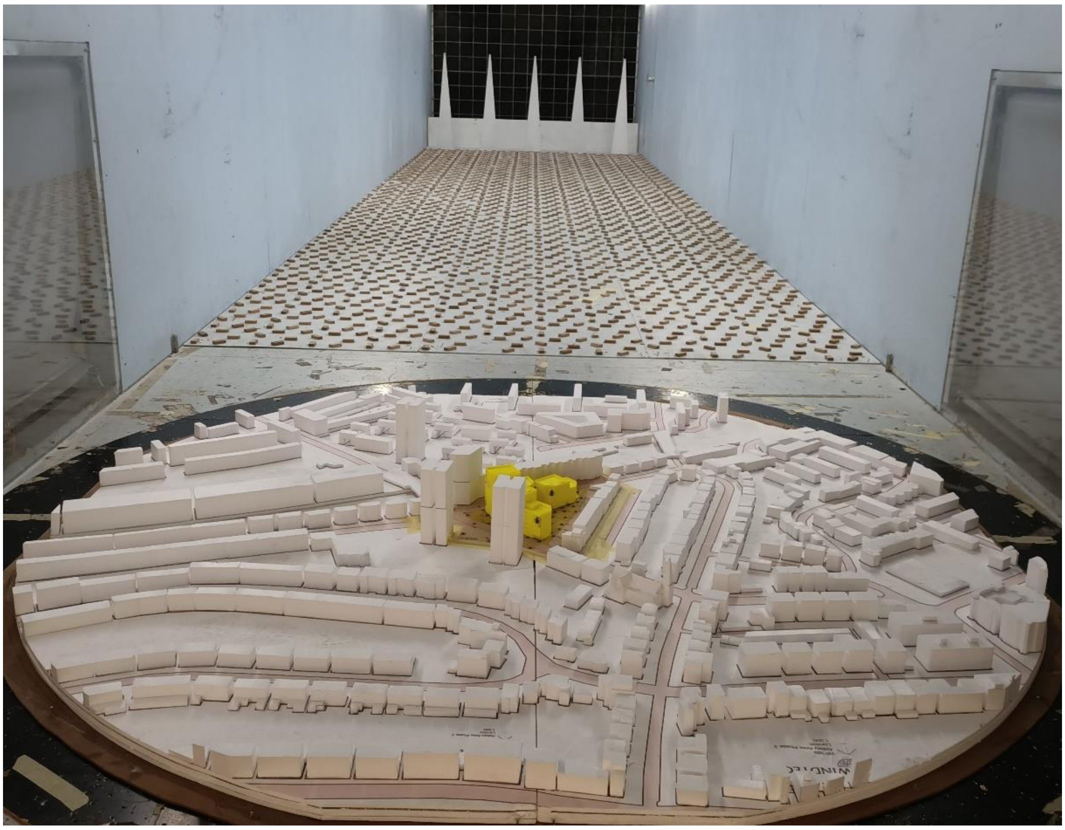


Figure 1c: Photograph of the Wind Tunnel Model: Proposed with Existing Surrounds (view from the north)

Figure 1d: Photograph of the Wind Tunnel Model: Proposed with Existing Surrounds (view from the south)

Figure 2a: Proximity Model Plan - Existing Site

Figure 2b: Proximity Model Plan - Proposed Development with Existing Surrounds

3 BOUNDARY LAYER WIND PROFILES AT THE SITE

The roughness of the surface of the earth has the effect of slowing down the wind near the ground. This effect is observed up to the boundary layer height, which can range between 500m to 3km above the earth's surface depending on the roughness of the surface (ie: oceans, open farmland, etc). Within this range the prevailing wind forms a boundary layer wind profile. Various wind codes and standards and other publications classify various types of boundary layer wind flows depending on the surface roughness z_0. Descriptions of typical boundary layer wind profiles, based on D.M. Deaves and R.I. Harris (1978), are summarised as follows:

- Flat terrain (0.002m < z_0 < 0.003m). Examples include inland water bodies such as lakes, dams, rivers, etc, and the open ocean.
- Semi-open terrain (0.006m < z_0 < 0.01m). Examples include flat deserts and plains.
- Open terrain (0.02m < z_0 < 0.03m). Examples include grassy fields, semi-flat plains, and open farmland (without buildings or trees).
- Semi-suburban/semi-forest terrain (0.06m < z_0 < 0.1m). Examples include farmland with scattered trees and buildings and very low-density suburban areas.
- Suburban/forest terrain (0.2m < z_0 < 0.3m). Examples include suburban areas of towns and areas with dense vegetation such as forests, bushland, etc.
- Semi-urban terrain (0.6m < z_0 < 1.0m). Examples include centres of small cities, industrial parks, etc.
- Urban terrain (2.0m < z_0 < 3.0m). Examples include centres of large cities with many high-rise towers, and also areas with many closely-spaced mid-rise buildings.

The boundary layer wind profile does not change instantly due to changes in the terrain roughness. It can take many kilometres (at least 100km) of a constant surface roughness for the boundary layer wind profile to achieve a state of equilibrium. Hence an analysis of the effect of changes in the upwind terrain roughness is necessary to determine an accurate boundary layer wind profile at the development site location.

The method from EN1991-1-4:2005 to account for changes in the upwind terrain roughness is overly simplistic. Hence an assessment of the upwind terrain roughness has been undertaken based on the far more detailed (and accurate) method given in ESDU-82026:2002. Aerial images showing the surrounding terrain are presented in Figures 3 for ranges of 5km and 50km from the edge of the proximity model used for the wind tunnel study. The resulting roughness factors and turbulence intensities at the site location are presented in Table 1, referenced to the study reference height of 30m above ground (which is approximately half the average height of the subject development, since typically we are most interested in the wind effects at the ground plane). Details of the boundary layer wind profiles at the site are combined with the regional wind model (see Section 4) to determine the site wind speeds.

Table 1: Approaching Boundary Layer Wind Profile Analysis Summary (at the study reference height)

Wind Sector (degrees)	Terrain and Height Multiplier			Turbulence Intensity	Equivalent Terrain Category (EN1991-1-4:2005 naming convention)
	$k_{tr,T=1hr}$ (hourly)	$k_{tr,T=10min}$ (10min)	$k_{tr,T=3s}$ (3sec)	I_v	
0	0.60	0.64	1.01	0.225	III
30	0.60	0.64	1.01	0.225	III
60	0.58	0.62	0.99	0.239	III
90	0.56	0.60	0.97	0.252	III
120	0.59	0.63	1.00	0.230	III
150	0.58	0.62	0.99	0.239	III
180	0.60	0.64	1.01	0.227	III
210	0.52	0.56	0.95	0.273	III
240	0.60	0.64	1.01	0.227	III
270	0.59	0.62	1.00	0.233	III
300	0.60	0.64	1.01	0.226	III
330	0.61	0.64	1.01	0.223	III

NOTE: These terrain and height multipliers are to be applied to a basic regional wind speed averaged over 3-seconds. Divide these values by 1.10 for a basic wind speed averaged over 0.2-seconds, 0.69 for a basic wind speed averaged over 10-minutes, or 0.66 for a basic wind speed averaged over 1-hour.

For each of the 16 wind directions tested in this study, the approaching boundary layer wind profiles modelled in the wind tunnel closely matched the profiles listed in Table 1. Plots of the boundary layer wind profiles used for the wind tunnel testing are presented in Appendix D of this report.

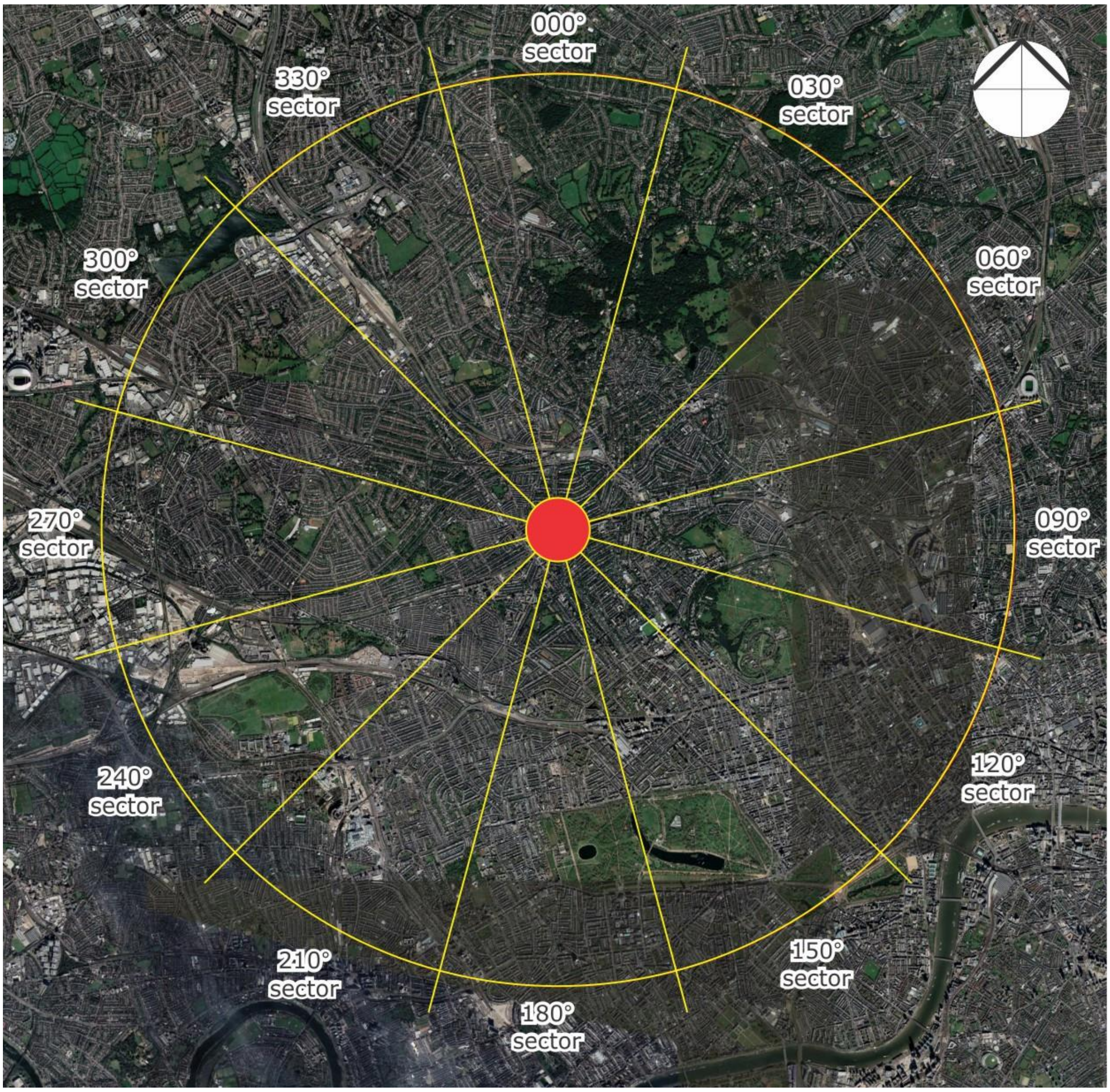


Figure 3a: Aerial Image of the Surrounding Terrain (radius of 5km from the edge of the proximity model)

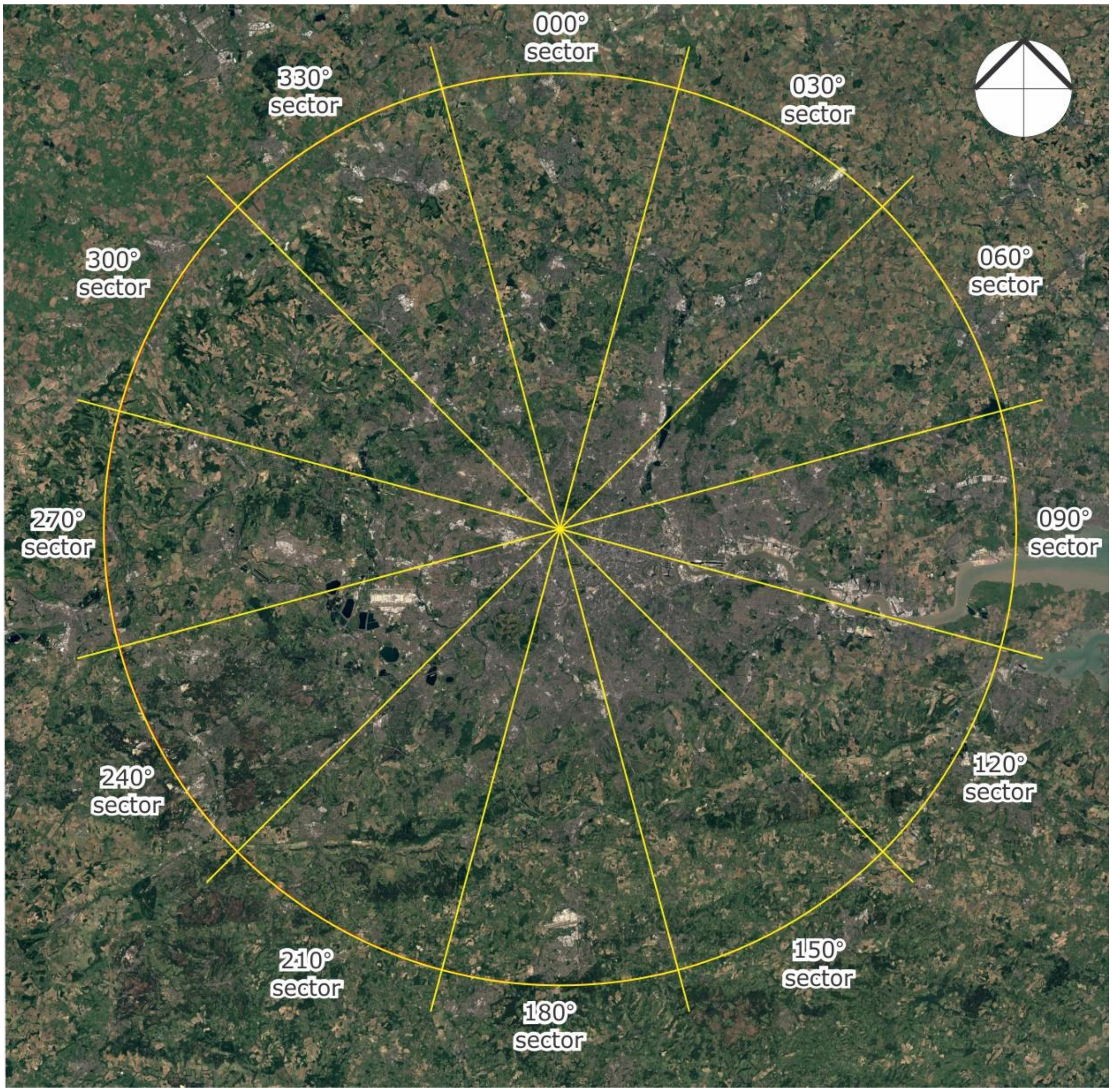


Figure 3b: Aerial Image of the Surrounding Terrain (radius of 50km)

4 REGIONAL WIND MODEL

The regional wind model used in this study was determined from an analysis of measured directional mean wind speeds obtained at the meteorological recording stations located at Heathrow, Gatwick and Stansted airports. A combined total of 136 years of wind climate data has been collected from these stations, and the data from each station has been corrected so that it represents winds over standard open terrain at a height of 10m above ground. From this analysis, directional probabilities of exceedance and directional wind speeds for the region are determined. The directional wind speeds are summarised in Table 2. The directional wind speeds and corresponding directional frequencies of occurrence are presented in Figures 4. Note that the regional wind climate has been examined for the year-round data, as well as for the summer and winter seasons.

The analysis indicates that the strongest winds of the region are mainly governed by the south-westerly winds, which are also the most frequently occurring winds for the region.

The recurrence interval examined in this study are for an exceedance of 5% (per 90 degree sector) of the pedestrian comfort and safety criteria using Gust-Equivalent Mean (GEM) wind speeds. Note that the 5% probability wind speeds presented in Table 2 are only used for the directional plots presented in Figures 4 and are not used for the integration of the probabilities.

Table 2: Regional 5% Exceedance Directional Wind Speeds
(hourly means, at 10m height in standard open terrain) (m/s)

Wind Direction	All Year	Summer	Winter
N	5.9	5.6	5.5
NNE	6.2	5.6	5.6
NE	6.5	5.8	6.4
ENE	6.1	5.6	6.4
E	5.5	5.3	5.7
ESE	4.8	4.7	4.9
SE	4.6	4.1	4.8
SSE	5.1	4.0	5.9
S	6.9	5.7	8.0
SSW	8.3	7.5	9.3
SW	8.9	8.1	9.8
WSW	8.2	7.2	9.2
W	7.6	6.9	8.7
WNW	6.5	6.2	7.1
NW	6.0	5.8	6.3
NNW	5.8	5.4	5.7

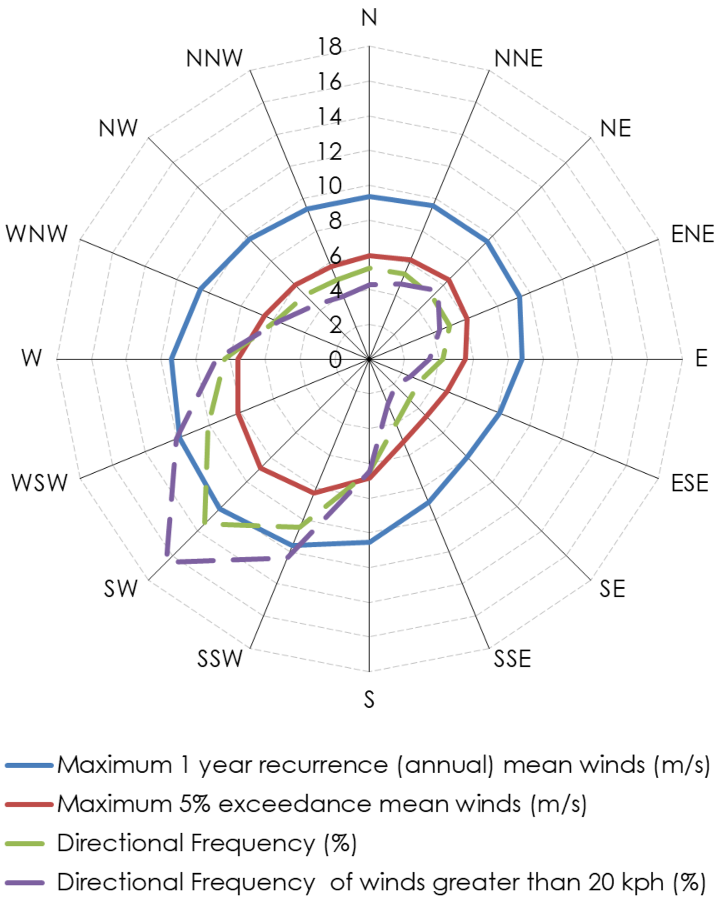


Figure 4a: Directional Annual and 5% Exceedance Hourly Mean Wind Speeds (referenced to 10m height in standard open terrain), and Frequencies of Occurrence, for London (all-year)

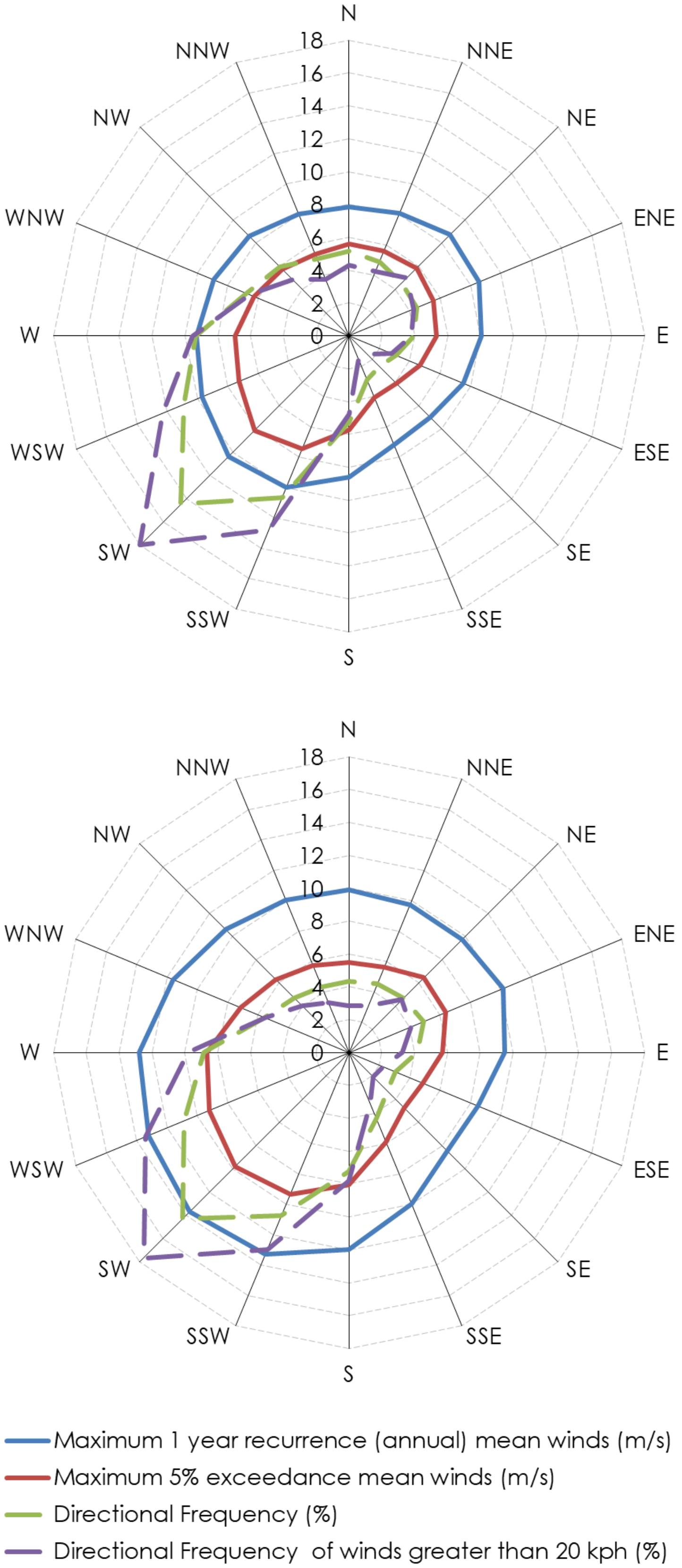


Figure 4b: Directional Annual and 5% Exceedance Hourly Mean Wind Speeds (referenced to 10m height in standard open terrain), and Frequencies of Occurrence, for London (summer top, winter bottom)

5 PEDESTRIAN WIND COMFORT AND SAFETY

The acceptability of wind conditions for an area is determined by comparing the measured wind speeds against an appropriate criteria. This section outlines how the measured wind speeds were obtained, the criteria considered for the development, as well as the critical trafficable areas that were assessed and their corresponding criteria designation.

5.1 Measured Wind Speeds

Wind speeds were measured using pressure-based wind speed sensors, positioned to monitor wind conditions at critical outdoor trafficable areas of the development. The reference mean free-stream wind speed measured in the wind tunnel, which is at a full-scale height of 200m and measured 3m upstream of the study model.

Measurements were acquired for 16 wind directions at 22.5 degree increments using a sample rate of 1,024Hz. The full methodology of determining the wind speed measurements at the site using pressure-based wind speed sensors is provided in Appendix B. Based on the results of the analysis of the boundary layer wind profiles at the site (see Section 3), and incorporating the regional wind model (see Section 4), the data sampling length of the wind tunnel test for each wind direction corresponds to a full-scale sample length ranging between 30 minutes and 1 hour. Research by A.W. Rofail and K.C.S. Kwok (1991) has shown that, in addition to the mean and standard deviation of the wind being stable for sample lengths of 15 minutes or more (full-scale), the peak value determined using the upcrossing method is stable for sample lengths of 30 minutes or more.

5.2 Wind Speed Criteria Used for This Study

For this study the measured wind conditions of the selected critical outdoor trafficable areas are compared against the Lawson Criteria for pedestrian safety and comfort (this is described in detail in Section A.6 of Appendix A). The criteria is applied to Gust Equivalent Mean (GEM) winds. In accordance with ASCE (2003), the GEM wind speed is defined as follows:

$$GEM = max\left(\bar{V}, \frac{\hat{V}}{1.85}\right) \tag{5.1}$$

where:

$\bar{V}$ is the mean wind speed.

$\hat{V}$ is the 3-second gust wind speed.

For pedestrian safety, the safety limit criterion of 15m/s applies to the year-round GEM winds with a probability of exceedance of less than 0.023%. For pedestrian comfort, the comfort criteria are used in conjunction with the seasonal GEM wind speeds with a probability of exceedance of less than 5%.

The criteria for pedestrian comfort and safety which are applied to this study are summarised in Tables 3 and 4, respectively.

Table 3: Pedestrian Comfort Criteria (T.V. Lawson, 2001)

Classification	Activities	5% exceedance Mean Wind Speed (m/s)
Uncomfortable	Winds of this magnitude are considered a nuisance for most activities, and wind mitigation is typically recommended.	>10
Walking	Relatively high speeds that can be tolerated if one's objective is to walk, run or cycle without lingering.	8-10
Strolling	Moderate breezes that would be appropriate for strolling along a city/town street, plaza or park.	6-8
Standing	Gentle breezes acceptable for main building entrances, pick-up/drop-off points and bus stops	4-6
Sitting	Light breezes desired for outdoor restaurants and seating areas where one can read a paper or comfortably sit for long periods	0-4

Table 4: Pedestrian Safety Criteria (T.V. Lawson, 2001)

Classification	Activities	Threshold Mean Wind Speed (m/s)
Unsafe for general Public & cyclists	Less able members of the public and cyclists find condition challenging	>15

5.3 Layout of Study Points

For this study, 90 study point locations were selected for analysis in the wind tunnel. This includes the following:

- Up to 66 study points on the ground level, along the pedestrian footpaths, trafficable areas, entrances, seating areas and roads.
- 24 study points on the critical balconies of development.

The locations of the various study points tested for this study, as well as the target wind speed criteria for the various outdoor trafficable areas of the development, are presented in Figures 5 in the form of marked-up plans. It should be noted that only the most critical outdoor locations of the development have been selected for analysis.

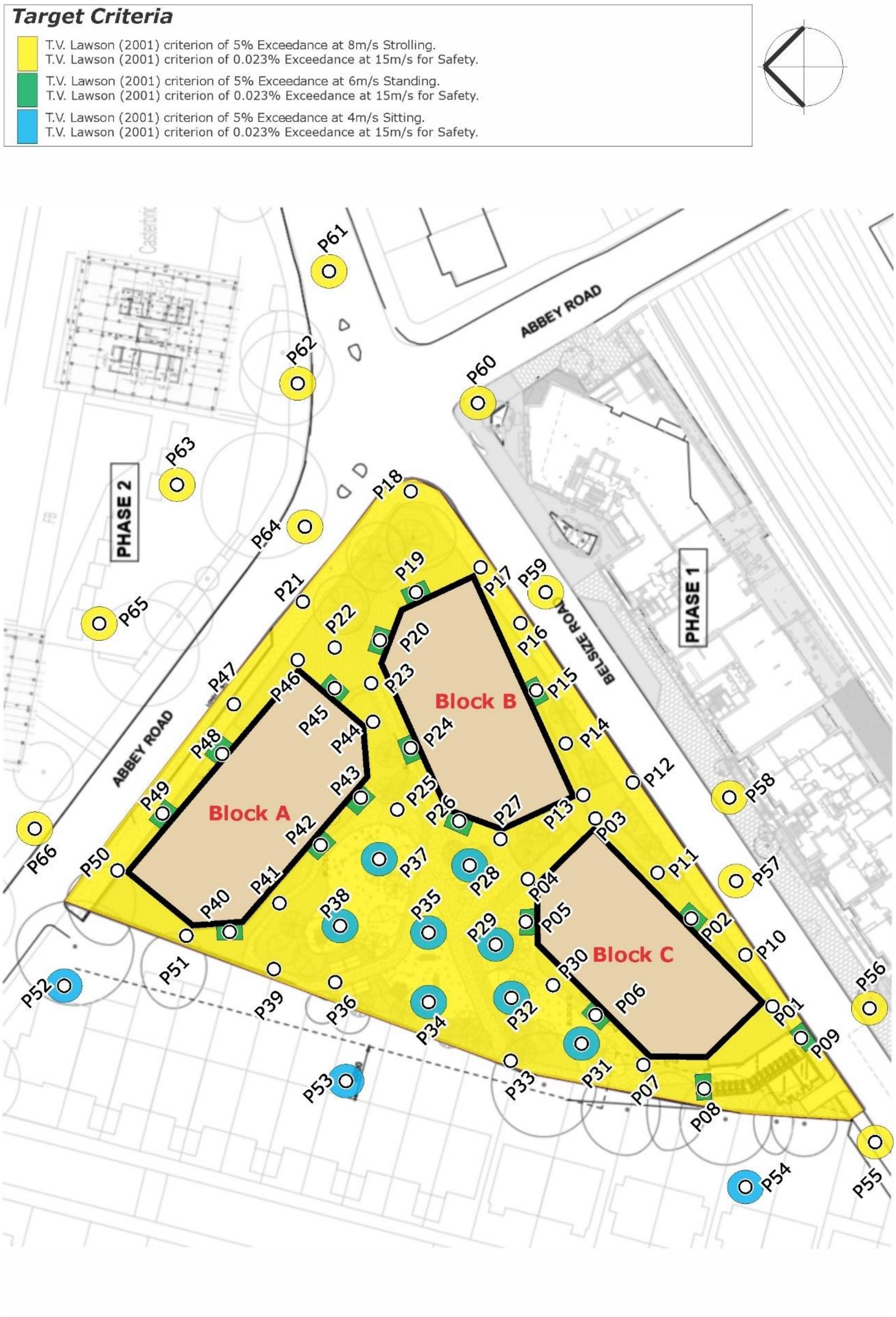


Figure 5a: Study Point Locations and Target Wind Speed Criteria – Ground Level Plan

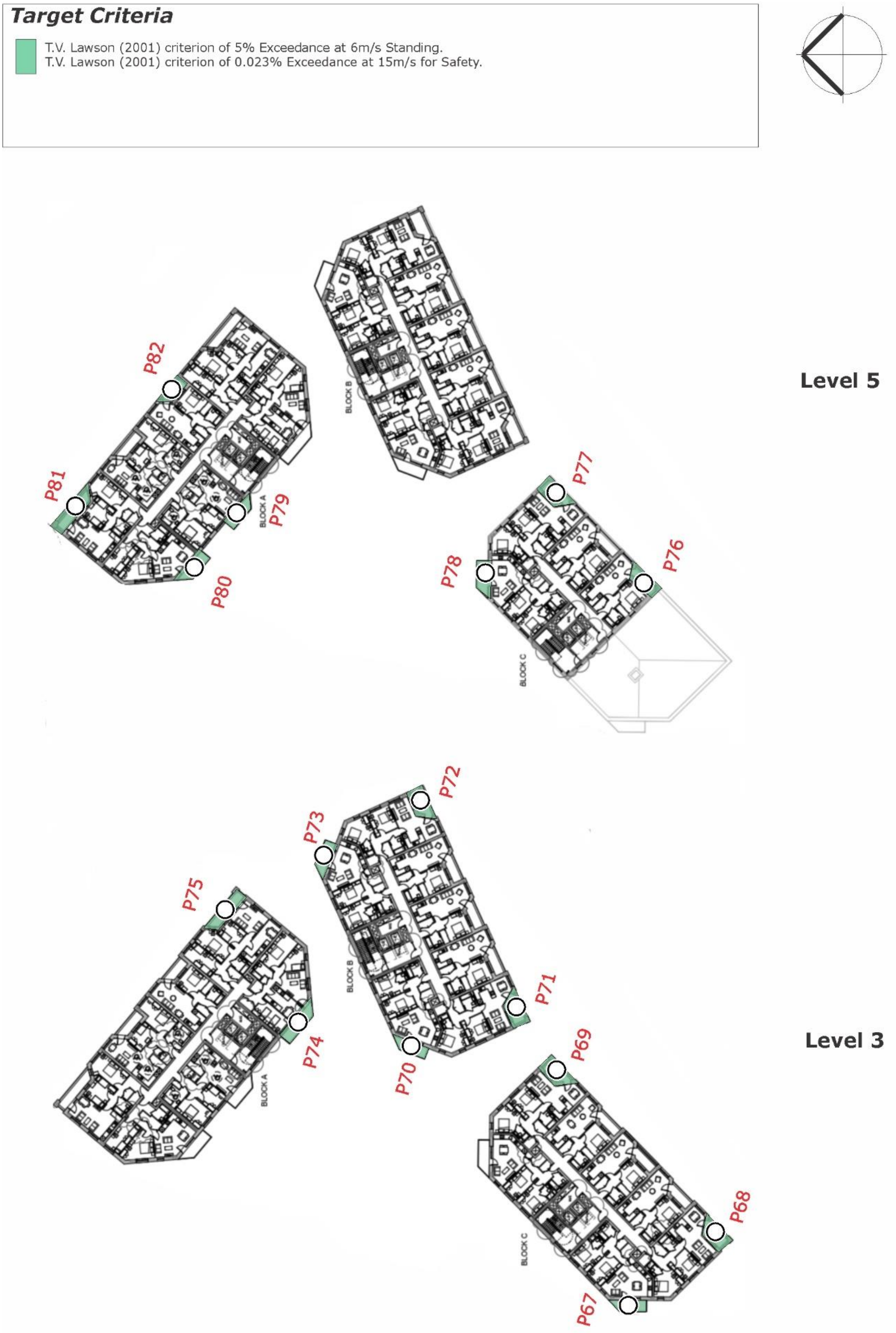


Figure 5b: Study Point Locations and Target Wind Speed Criteria – Balcony Level Plans, Levels 3 to 5.

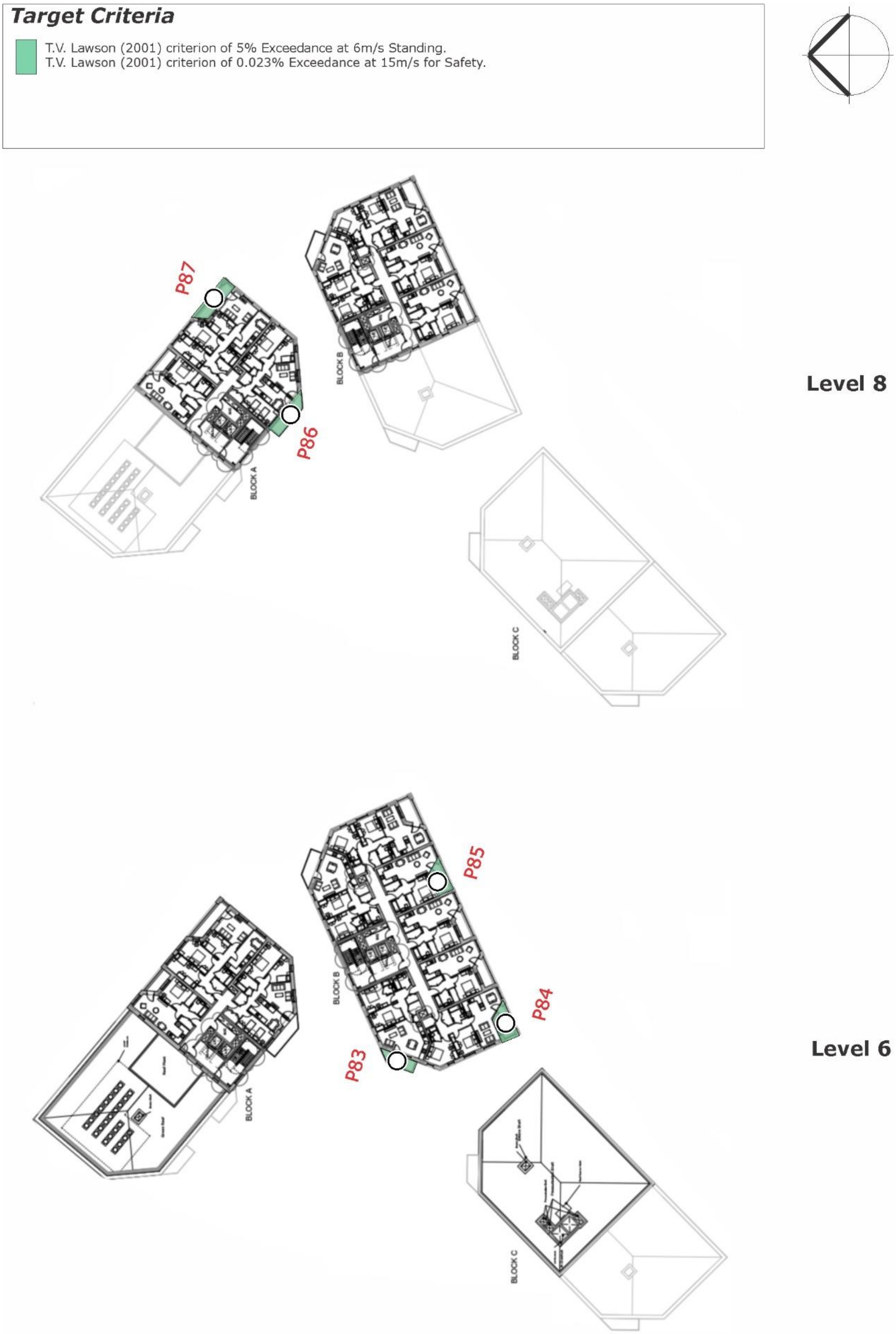


Figure 5c: Study Point Locations and Target Wind Speed Criteria – Balcony Level Plan, Levels 6 to 8.

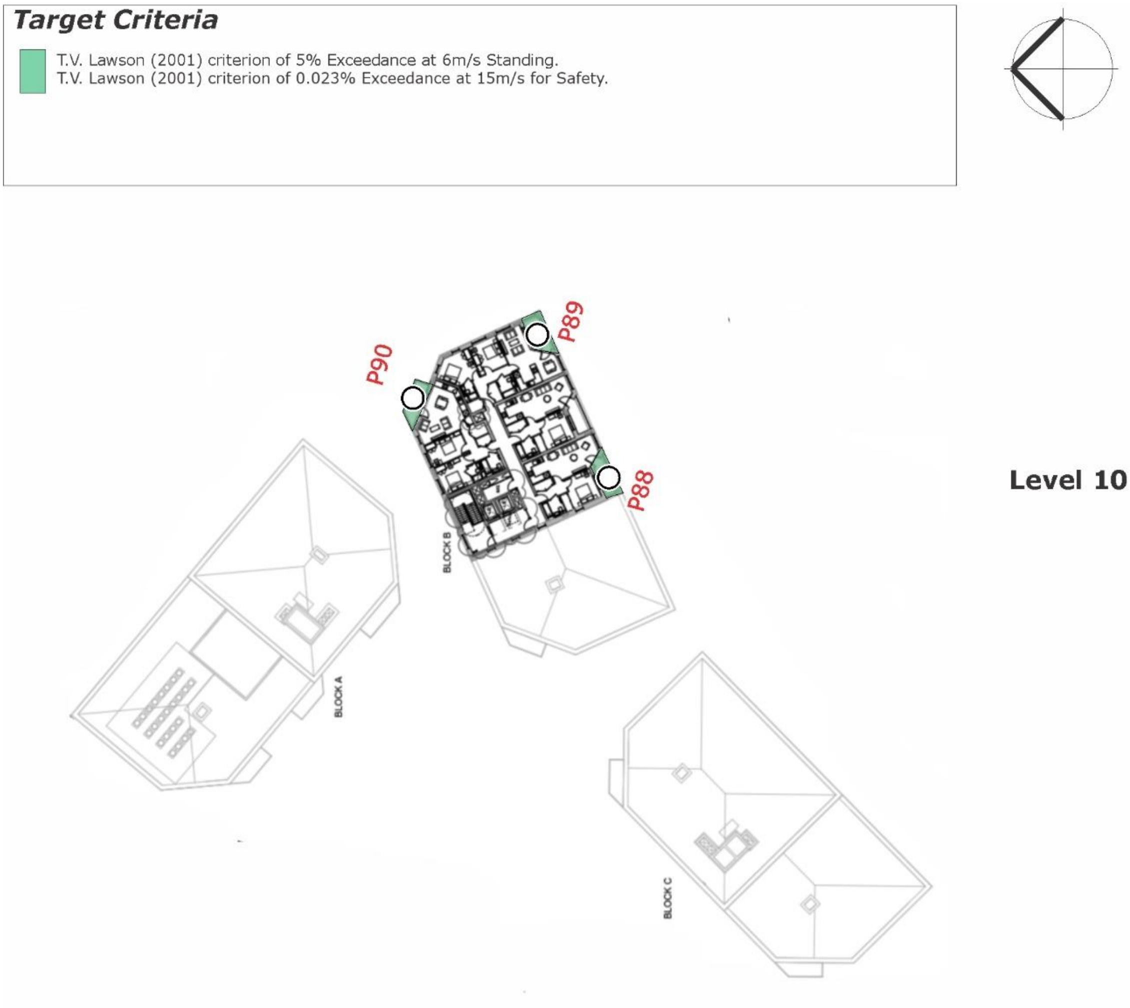


Figure 5d: Study Point Locations and Target Wind Speed Criteria – Balcony Plans, Level 10.

6 RESULTS AND DISCUSSION

As detailed in Section 2 of this report, the following two scenarios were tested in the wind tunnel:

- Scenario 1 – Existing Site Condition - The existing site with the existing surrounding buildings (baseline condition).
- Scenario 2 – Proposed with Existing Surrounds - The proposed development with the existing surrounding buildings.

The results of the wind tunnel study are presented in the form of velocity coefficient directional plots in Appendix C for all study points locations, and also shown on marked-up plans in Figures 6-7. The determination of whether or not the relevant criteria for pedestrian comfort or safety is satisfied is presented in Table 5 for each study point location.

6.1 Scenario 1: Existing Site Scenario

The results of the wind tunnel study for the existing site conditions indicate that wind conditions do not exceed the safety criterion at the ground level. Hence, the wind conditions at ground level are safe for pedestrian activities, including cyclist use throughout the year.

The windiest areas occur in the surrounds to the north of the site (Points 62 and 65) where the wind microclimate conditions are suitable for walking during the worst season (winter). All the remaining areas at the site and surrounds are suitable for strolling to sitting during the worst season. Hence, all the thoroughfares at the site and surrounds are suitable for intended pedestrian activities (i.e., strolling and/or walking).

During the summer season, apart from Points 62, 63 and 65, the wind conditions within the site and surrounds are suitable for standing and/or sitting. These conditions are expected to be suitable for intended pedestrian activities during the summer season. Albeit, thewind conditions at the neighbouring garden to the west of the site (Points 52 and 53) exceed the comfort criterion for sitting during the summer season.

The neighbouring roads are suitable for cyclist use throughout the year.

6.2 Scenario 2: Proposed Scenario with Existing Surrounds

The results for the proposed development with the existing surrounds indicate that the wind conditions at ground level do not exceed the safety criterion within the site and surrounds. The wind conditions at all the areas of the site and surroundings are rated as safe for pedestrians and cyclist use throughout the year.

At elevated levels, the wind conditions are also rated as safe for occupant use throughout the year.

6.2.1 Thoroughfares

In the presence of the proposed development at the site, winds funnelling between the proposed Blocks are likely to occur within the site. Despite this flow phenomenon, all throughfares are suitable for intended pedestrian activities throughout the year. The proposed development provides shelter to the windiest areas occurred for the existing scenario (Points 62 and 65) where the wind conditions are calmer and are suitable for strolling during the worst season (winter).

6.2.2 Entrances

The wind microclimate outside the entrances of Block A (Point 40) exceeds the comfort criterion for entrance use by occupants/visitors during the worst season (winter). Mitigation measures are recommended for this entrance. The wind microclimate outside remaining entrances (including those to Blocks B and C) is suitable for occupant/visitors use throughout the year.

6.2.3 Seating/Play Area

The summer seasonal results show that the wind conditions exceed comfort criterion at seating/play areas at Points 28, 31, 32, 35, 37 and 38 for intended pedestrian activities. Mitigation measures are recommended. The wind microclimate at the remaining seating/play areas is suitable for the intended pedestrian activities.

6.2.4 Balconies

With regards to pedestrian comfort, the pedestrian activity of 'standing' is considered as an appropriate target activity on the private balconies of the proposed development during the summer season. The assessment indicates that the wind microclimate conditions at all balconies are suitable for occupant use during the summer season.

As a general note, the use of loose glass-tops and light-weight sheets or covers (including loose BBQ lids) is not appropriate on outdoor terraces, balconies, and podiums. Furthermore, lightweight furniture is not recommended unless it is securely attached to the balcony or terrace floor slab.

6.2.5 Surrounds & Roads

The wind conditions in the surrounds are suitable for their intended uses, ranging from standing to strolling during the worst season (winter). It should be noted that the wind conditions at the neighbouring garden to the west of the site (Point 53) are improved and are suitable for sitting during the summer season by the presence of the proposed development. The neighbouring roads are also suitable for cyclist use throughout the year.

6.3 Proposed Mitigation Measures

Additional wind mitigation measures are proposed in Figures 8. With the inclusion of these treatments to the final design, it is expected that wind conditions for all outdoor trafficable areas within and around the development will be safe and comfortable throughout the year for the intended pedestrian uses.

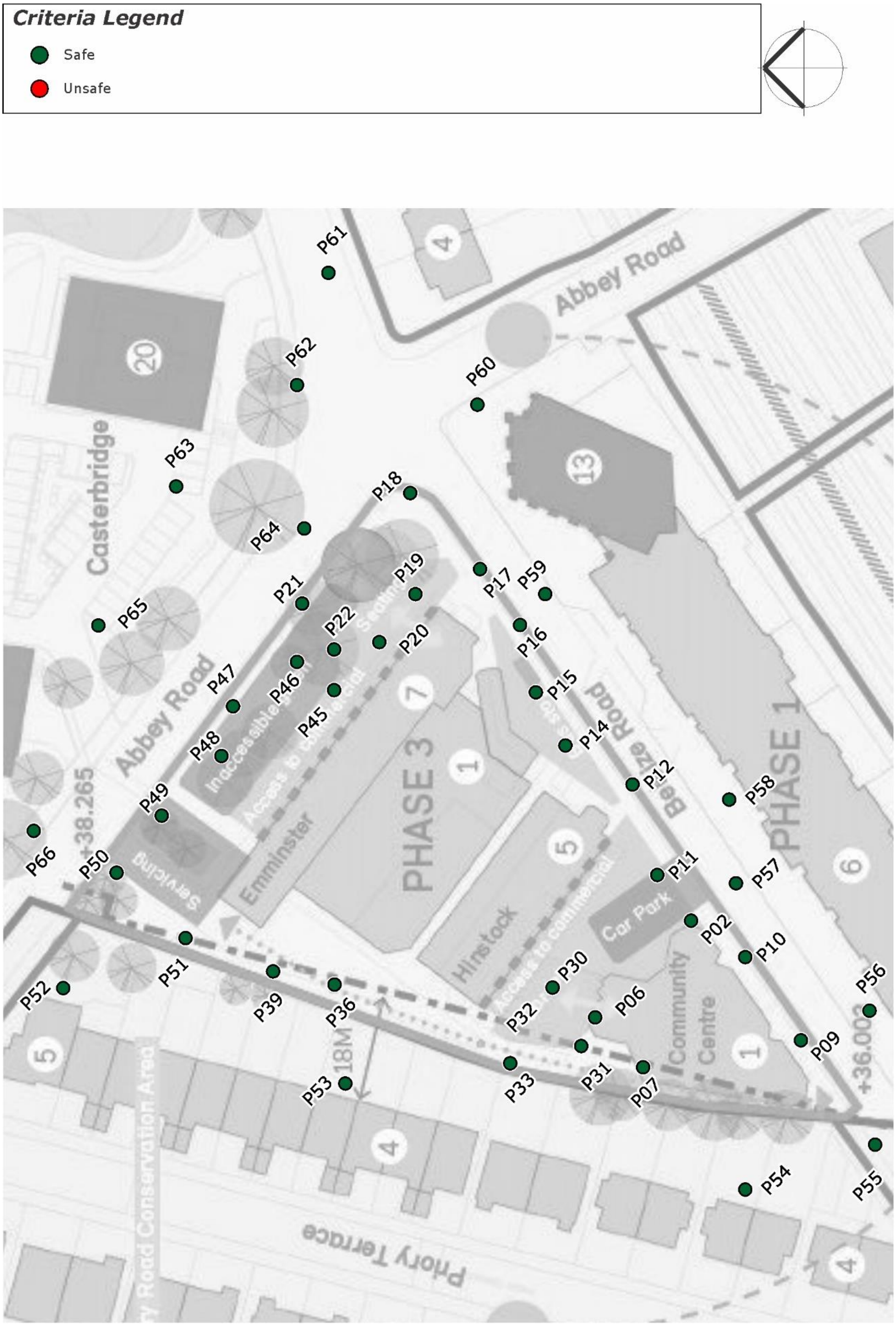


Figure 6a: Wind Tunnel Results – Existing Site Condition: Ground Level Plan, assessed against the safety criterion, (results shown without vegetation)

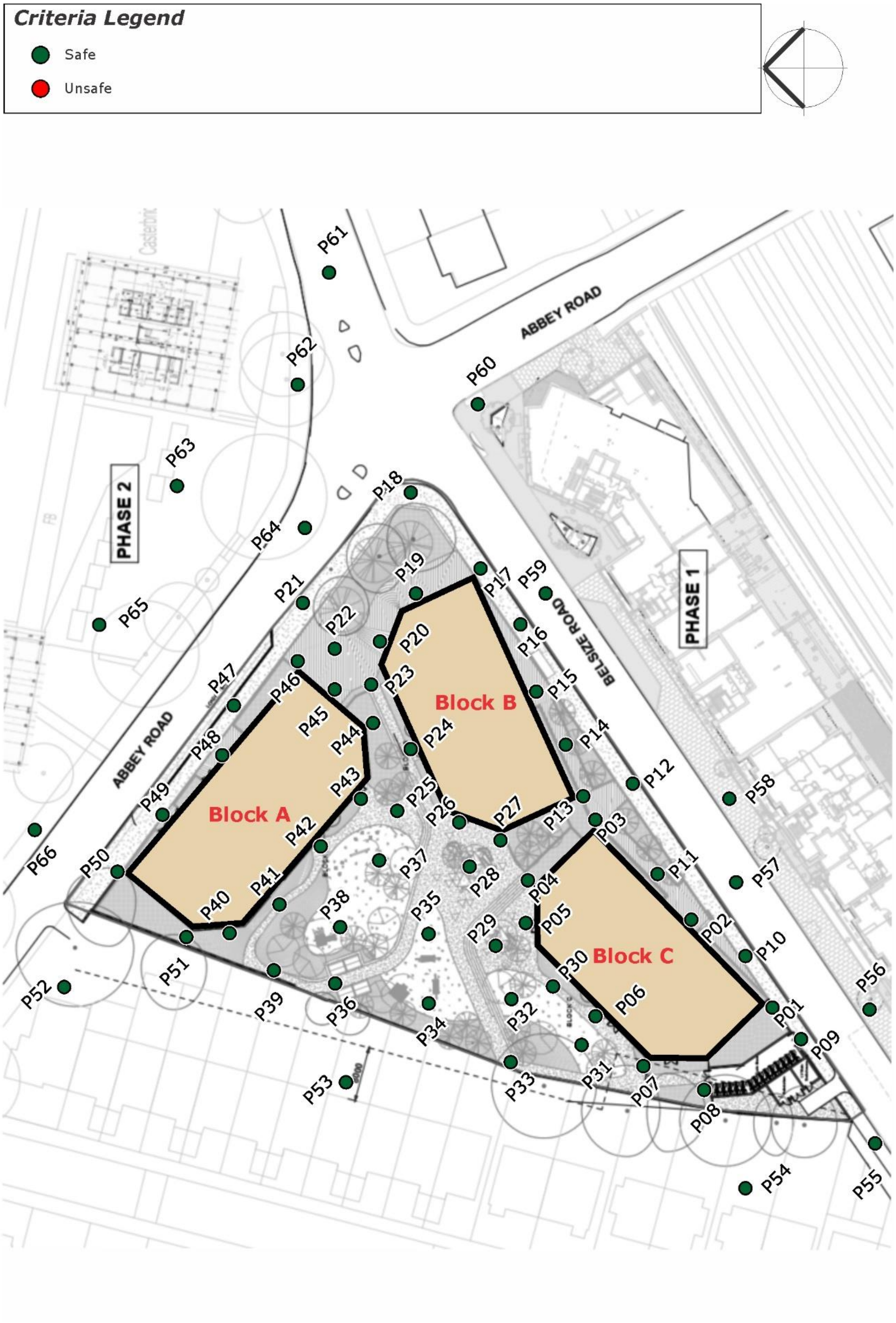


Figure 6b: Wind Tunnel Results – Proposed with Existing Surrounds: Ground Level Plan, assessed against the safety criterion, (results shown without vegetation)

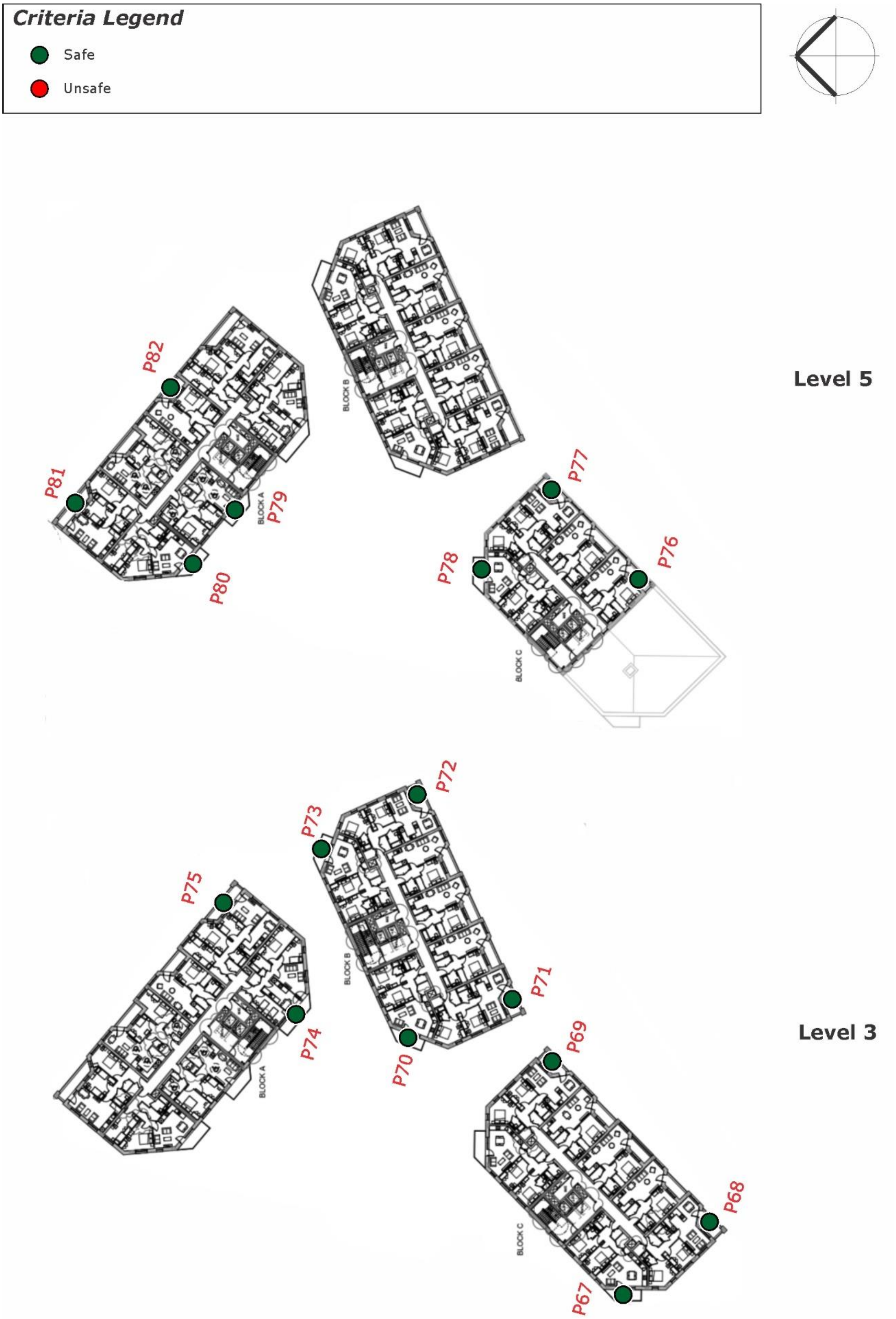


Figure 6c: Wind Tunnel Results – Proposed with Existing Surrounds: Balconies, Levels 3 to 5, assessed against the safety criterion.

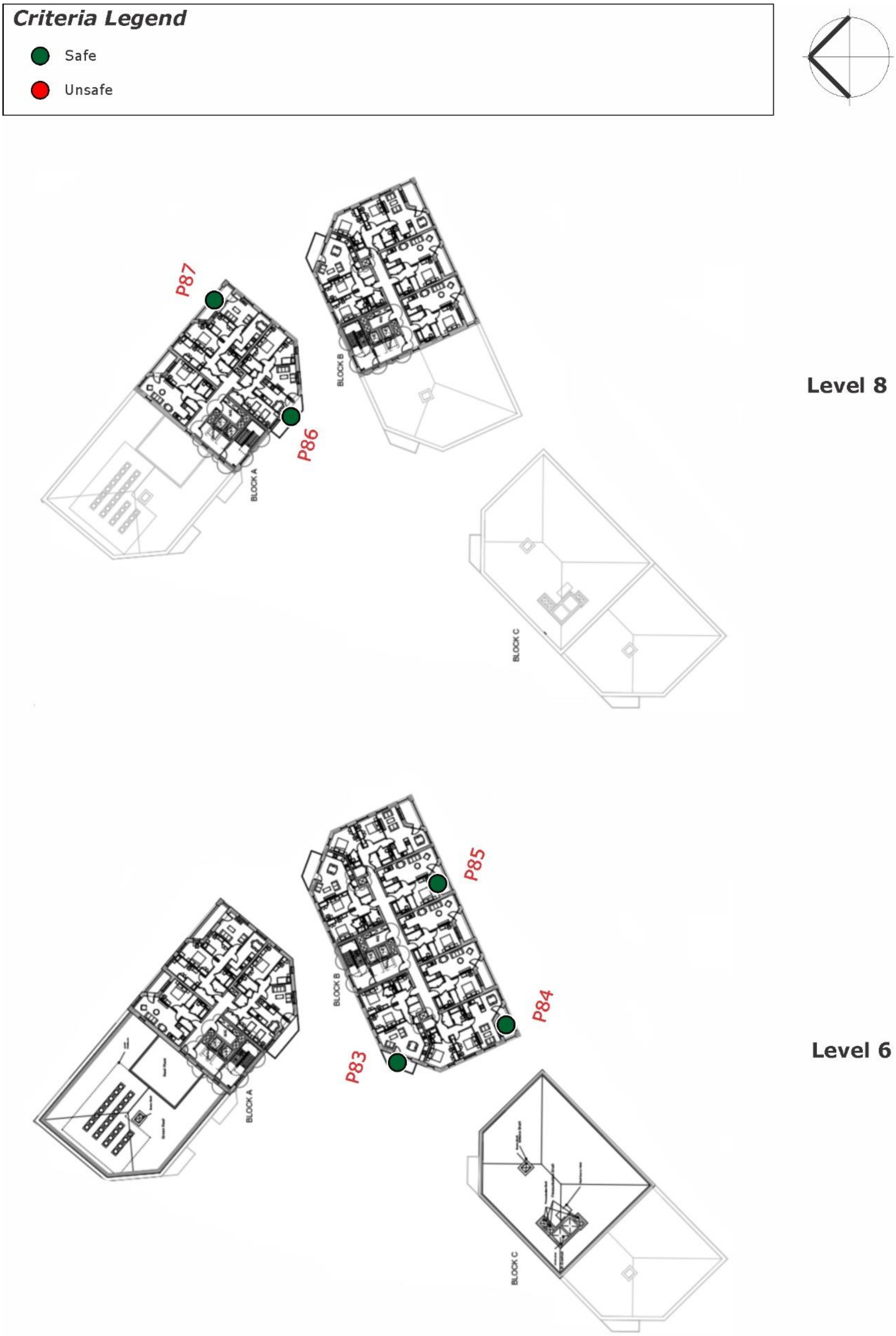


Figure 6d: Wind Tunnel Results – Proposed with Existing Surrounds: Balconies, Levels 3 to 5, assessed against the safety criterion.

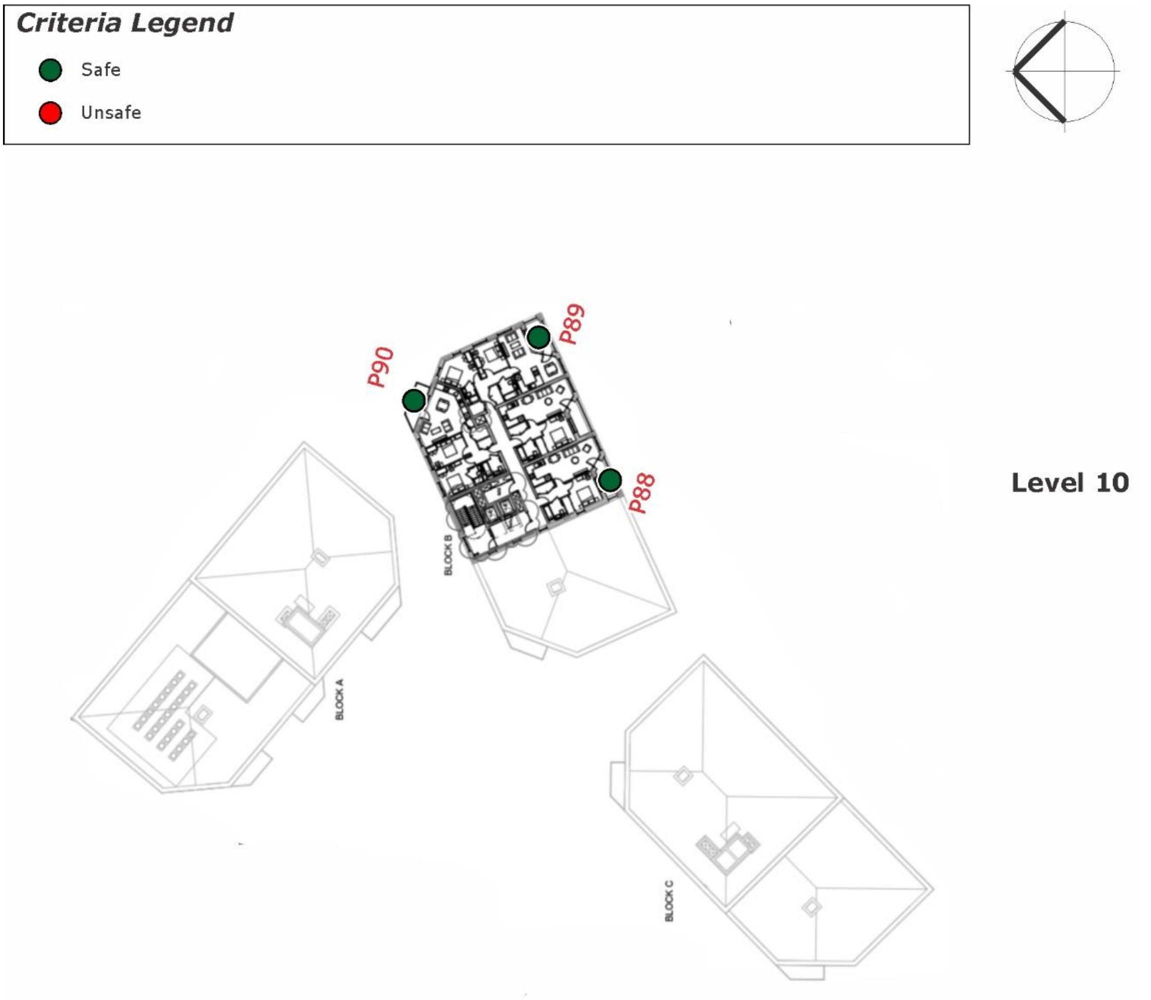


Figure 6e: Wind Tunnel Results – Proposed with Existing Surrounds: Balconies, Level 10, assessed against the safety criterion.

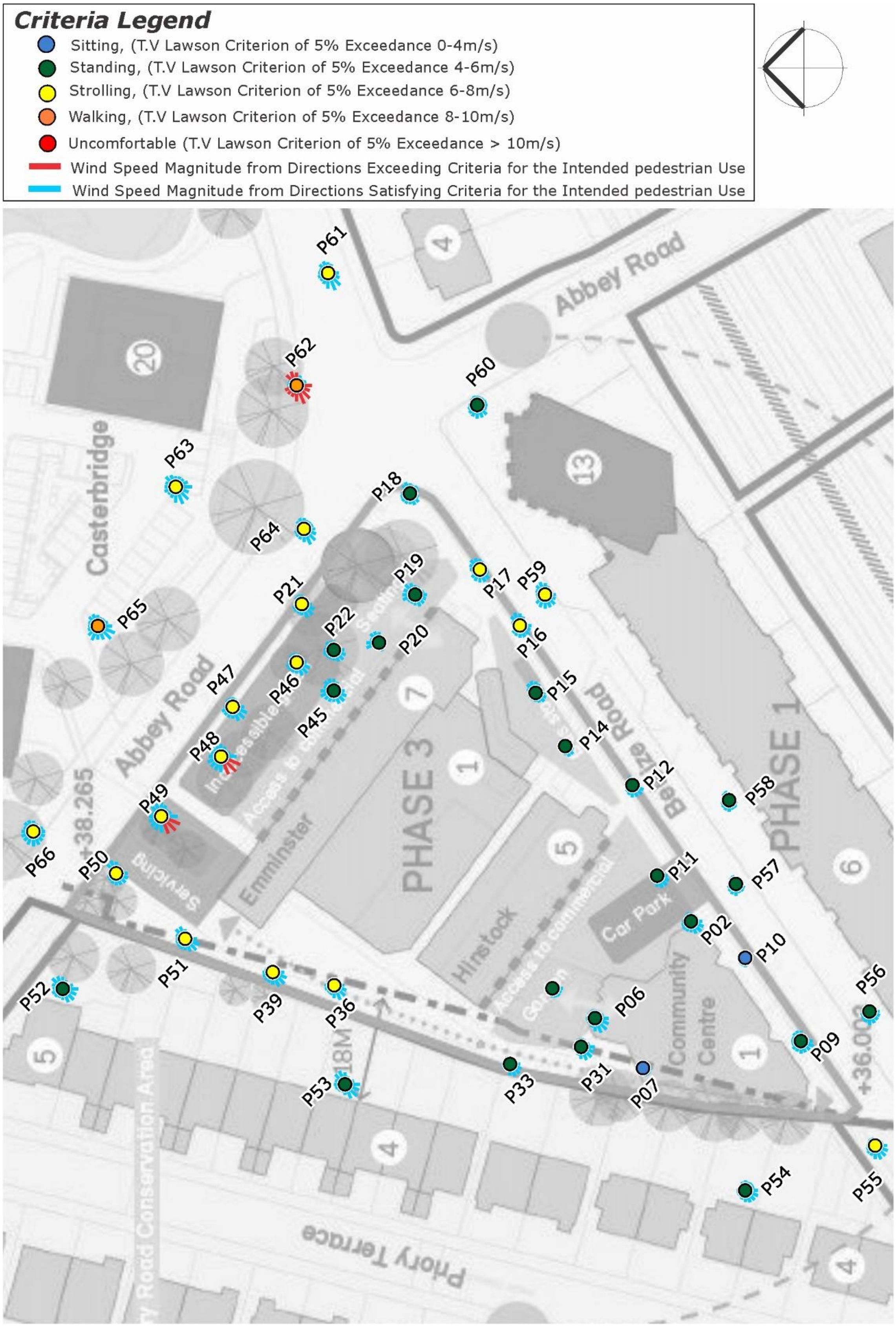


Figure 7a: Wind Tunnel Results – Existing Site Conditions: Ground Level Plan, Winter Season (Worst Season, results shown without vegetation)

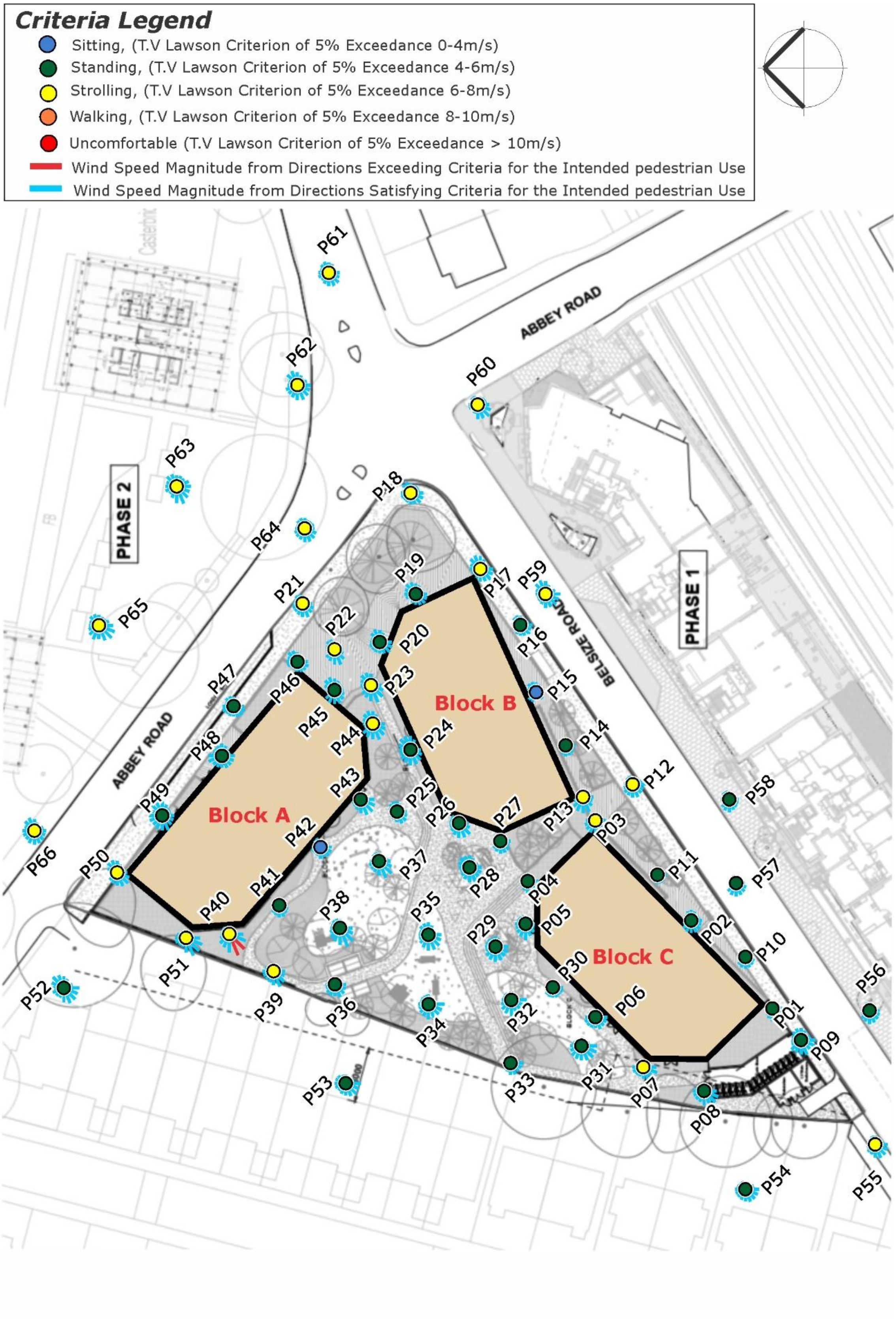


Figure 7b: Wind Tunnel Results – Proposed with Existing Surrounds: Ground Level Plan, Winter Season (Worst Season, results shown without vegetation)

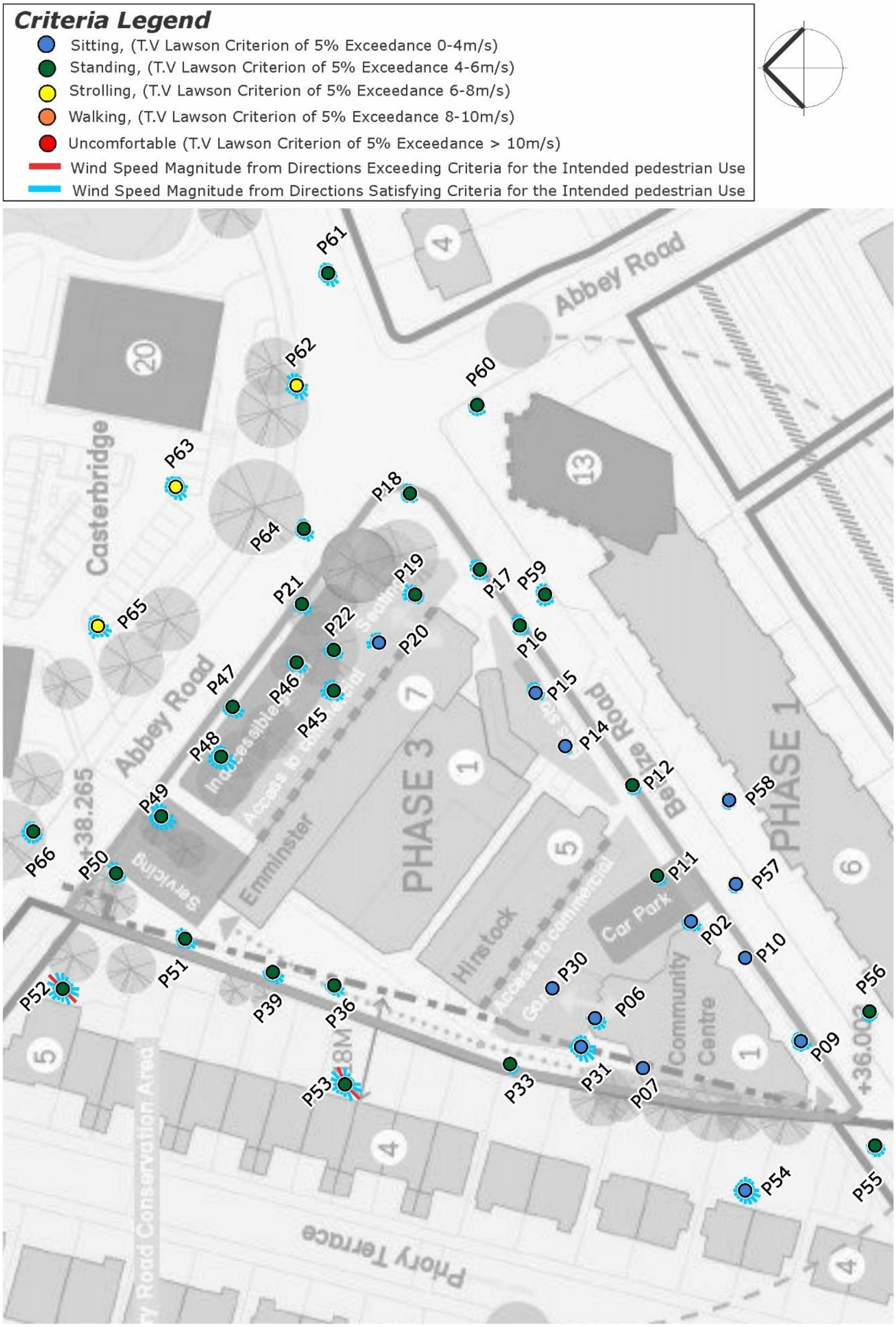


Figure 7c: Wind Tunnel Results – Existing Site Conditions: Ground Level Plan, Summer Season (Best Season) (results shown without vegetation)

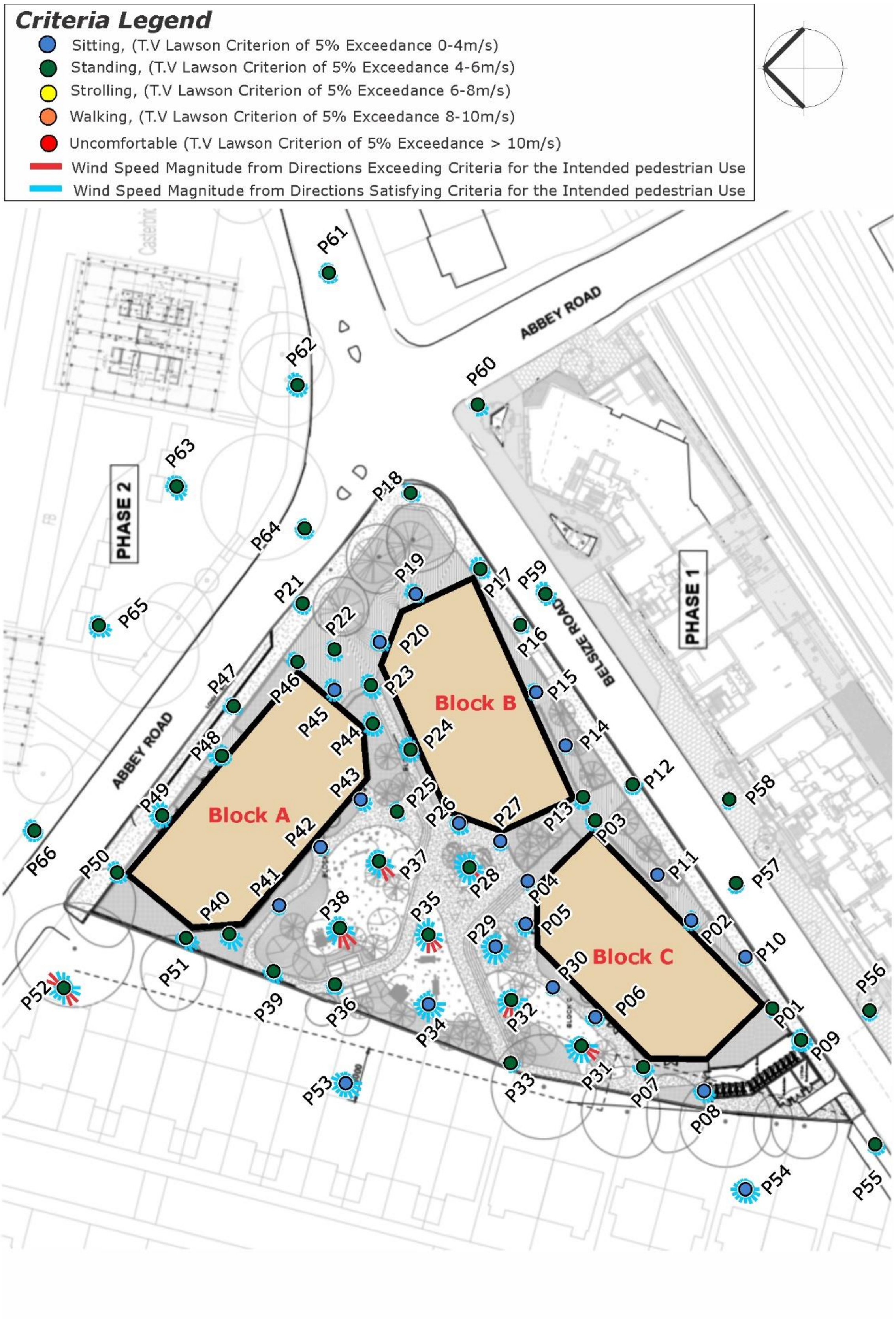


Figure 7d: Wind Tunnel Results – Proposed with Existing Surrounds: Ground Level Plan, Summer Season (Best Season, results shown without vegetation)

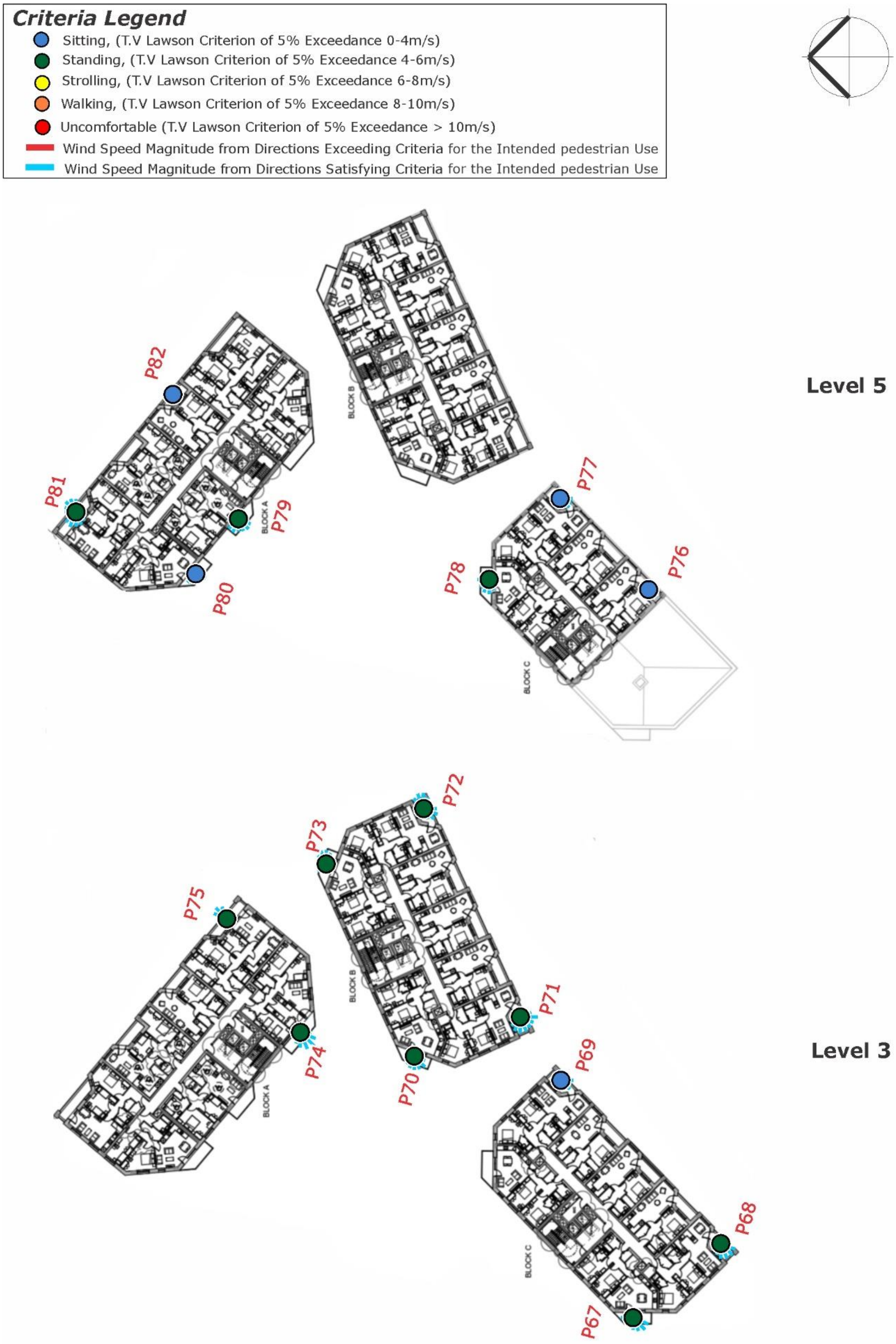


Figure 7e: Wind Tunnel Results – Proposed with Existing Surrounds: Balconies Levels 3 to 5, Summer Season (Best Season)

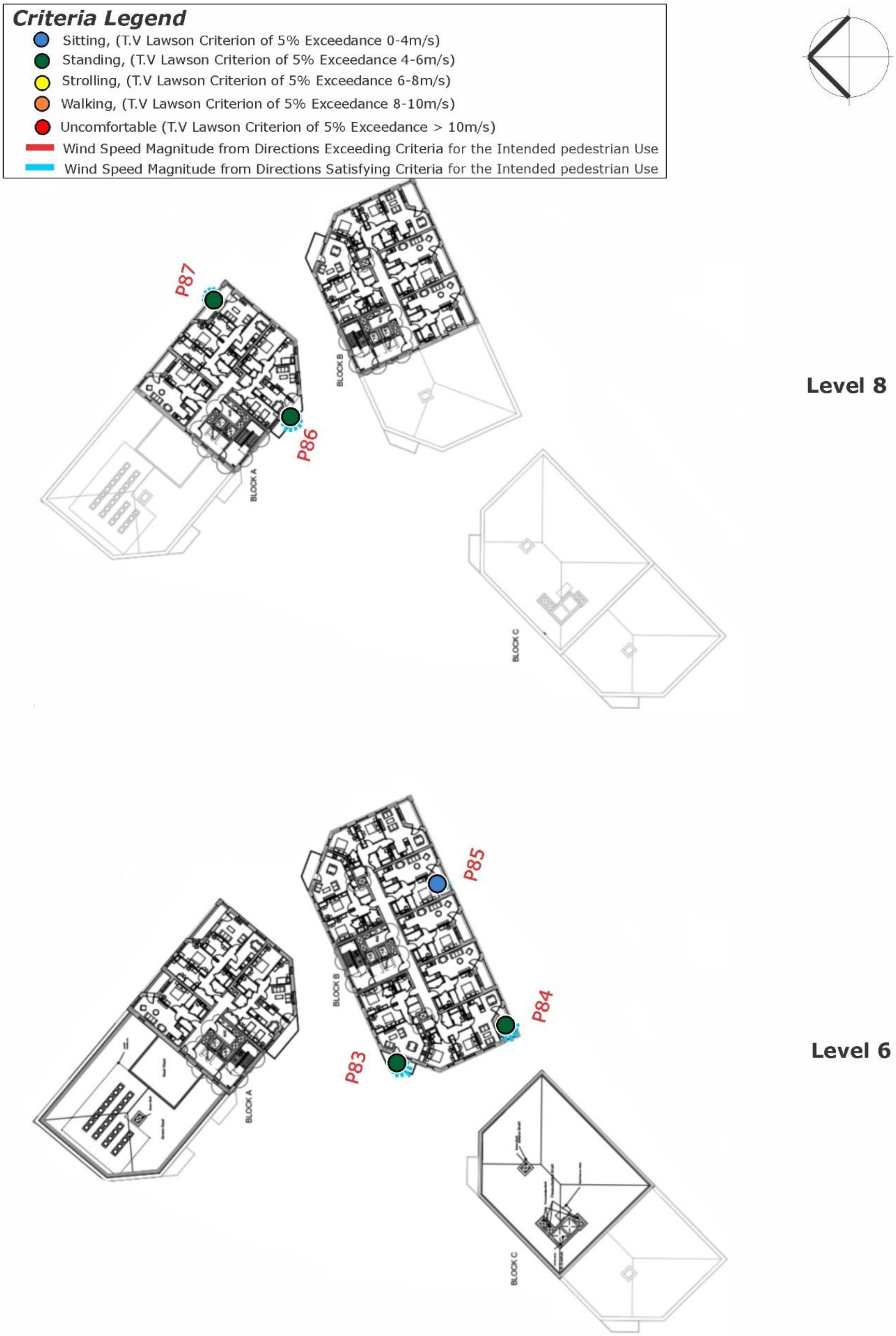


Figure 7f: Wind Tunnel Results – Proposed with Existing Surrounds: Balconies Levels 6 to 8, Summer Season (Best Season)

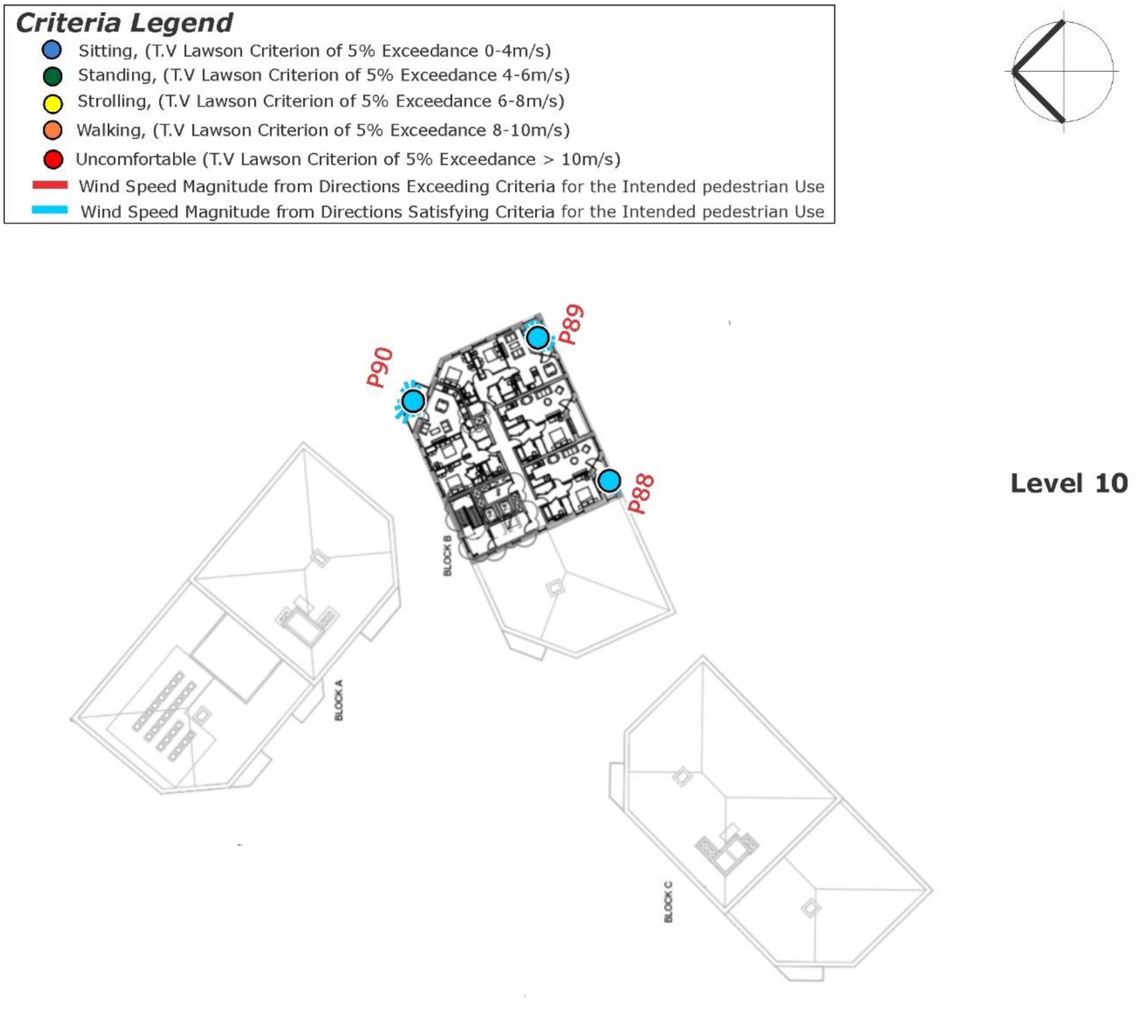


Figure 7g: Wind Tunnel Results – Proposed with Existing Surrounds: Balconies Level 10, Summer Season (Best Season)

Table 5: Wind Tunnel Results Summary

Study Point	Summer Comfort Assessment (up to 5% exceedance permitted)			Winter Comfort Assessment (up to 5% exceedance permitted)			All-Year Safety Assessment (up to 0.023% exceedance permitted)		Final Grade	Treatment
	Criterion (m/s)	Exceedance Result	Grade	Criterion (m/s)	Exceedance Result	Grade	Exceedance Result	Grade		
P01 (Scenario 2)	8	0.01%	Pass	8	0.33%	Pass	0.000%	Pass	Pass	
P02 (Scenario 1)	6	0.04%	Pass	6	0.61%	Pass	0.000%	Pass	Pass	
P02 (Scenario 2)	6	0.04%	Pass	6	0.46%	Pass	0.000%	Pass	Pass	
P03 (Scenario 2)	8	0.09%	Pass	8	0.89%	Pass	0.001%	Pass	Pass	
P04 (Scenario 2)	8	0.00%	Pass	8	0.16%	Pass	0.000%	Pass	Pass	
P05 (Scenario 2)	6	0.14%	Pass	6	1.36%	Pass	0.000%	Pass	Pass	
P06 (Scenario 1)	6	0.11%	Pass	6	1.62%	Pass	0.000%	Pass	Pass	
P06 (Scenario 2)	6	0.04%	Pass	6	0.48%	Pass	0.000%	Pass	Pass	
P07 (Scenario 1)	8	0.00%	Pass	8	0.00%	Pass	0.000%	Pass	Pass	
P07 (Scenario 2)	8	0.08%	Pass	8	1.10%	Pass	0.000%	Pass	Pass	
P08 (Scenario 2)	6	0.18%	Pass	6	2.18%	Pass	0.000%	Pass	Pass	
P09 (Scenario 1)	6	0.06%	Pass	6	0.65%	Pass	0.000%	Pass	Pass	
P09 (Scenario 2)	6	0.34%	Pass	6	3.01%	Pass	0.000%	Pass	Pass	
P10 (Scenario 1)	8	0.00%	Pass	8	0.01%	Pass	0.000%	Pass	Pass	
P10 (Scenario 2)	8	0.01%	Pass	8	0.14%	Pass	0.000%	Pass	Pass	
P11 (Scenario 1)	8	0.01%	Pass	8	0.29%	Pass	0.000%	Pass	Pass	
P11 (Scenario 2)	8	0.00%	Pass	8	0.01%	Pass	0.000%	Pass	Pass	
P12 (Scenario 1)	8	0.01%	Pass	8	0.23%	Pass	0.000%	Pass	Pass	
P12 (Scenario 2)	8	0.05%	Pass	8	0.77%	Pass	0.000%	Pass	Pass	
P13 (Scenario 2)	8	0.28%	Pass	8	2.20%	Pass	0.004%	Pass	Pass	
P14 (Scenario 1)	8	0.00%	Pass	8	0.03%	Pass	0.000%	Pass	Pass	
P14 (Scenario 2)	8	0.00%	Pass	8	0.05%	Pass	0.000%	Pass	Pass	
P15 (Scenario 1)	6	0.09%	Pass	6	0.53%	Pass	0.000%	Pass	Pass	
P15 (Scenario 2)	6	0.03%	Pass	6	0.18%	Pass	0.000%	Pass	Pass	
P16 (Scenario 1)	8	0.17%	Pass	8	0.88%	Pass	0.000%	Pass	Pass	
P16 (Scenario 2)	8	0.01%	Pass	8	0.23%	Pass	0.000%	Pass	Pass	
P17 (Scenario 1)	8	0.14%	Pass	8	0.88%	Pass	0.001%	Pass	Pass	
P17 (Scenario 2)	8	0.34%	Pass	8	1.64%	Pass	0.001%	Pass	Pass	
P18 (Scenario 1)	8	0.06%	Pass	8	0.47%	Pass	0.000%	Pass	Pass	
P18 (Scenario 2)	8	0.06%	Pass	8	0.61%	Pass	0.000%	Pass	Pass	
P19 (Scenario 1)	6	0.39%	Pass	6	1.45%	Pass	0.000%	Pass	Pass	
P19 (Scenario 2)	6	0.17%	Pass	6	0.82%	Pass	0.000%	Pass	Pass	

Study Point	Summer Comfort Assessment (up to 5% exceedance permitted)			Winter Comfort Assessment (up to 5% exceedance permitted)			All-Year Safety Assessment (up to 0.023% exceedance permitted)		Final Grade	Treatment
	Criterion (m/s)	Exceedance Result	Grade	Criterion (m/s)	Exceedance Result	Grade	Exceedance Result	Grade		
P20 (Scenario 1)	6	0.23%	Pass	6	0.89%	Pass	0.000%	Pass	Pass	
P20 (Scenario 2)	6	0.17%	Pass	6	1.09%	Pass	0.000%	Pass	Pass	
P21 (Scenario 1)	8	0.05%	Pass	8	0.81%	Pass	0.000%	Pass	Pass	
P21 (Scenario 2)	8	0.06%	Pass	8	0.80%	Pass	0.000%	Pass	Pass	
P22 (Scenario 1)	8	0.04%	Pass	8	0.46%	Pass	0.000%	Pass	Pass	
P22 (Scenario 2)	8	0.12%	Pass	8	1.29%	Pass	0.001%	Pass	Pass	
P23 (Scenario 2)	8	0.49%	Pass	8	3.41%	Pass	0.005%	Pass	Pass	
P24 (Scenario 2)	6	0.66%	Pass	6	3.11%	Pass	0.000%	Pass	Pass	
P25 (Scenario 2)	8	0.03%	Pass	8	0.26%	Pass	0.000%	Pass	Pass	
P26 (Scenario 2)	6	0.10%	Pass	6	1.31%	Pass	0.000%	Pass	Pass	
P27 (Scenario 2)	8	0.01%	Pass	8	0.23%	Pass	0.000%	Pass	Pass	
P28 (Scenario 2)	4	6.38%	Fail	6	2.03%		0.000%	Pass	Fail	Soft landscaping
P29 (Scenario 2)	4	4.52%	Pass	6	1.70%		0.000%	Pass	Pass	
P30 (Scenario 1)	8	0.00%	Pass	8	0.02%	Pass	0.000%	Pass	Pass	
P30 (Scenario 2)	8	0.00%	Pass	8	0.08%	Pass	0.000%	Pass	Pass	
P31 (Scenario 1)	4	1.97%	Pass	6	0.81%		0.000%	Pass	Pass	
P31 (Scenario 2)	4	7.33%	Fail	6	3.48%		0.000%	Pass	Fail	Soft landscaping
P32 (Scenario 2)	4	6.29%	Fail	6	3.02%		0.000%	Pass	Fail	Soft landscaping
P33 (Scenario 1)	8	0.01%	Pass	8	0.27%	Pass	0.000%	Pass	Pass	
P33 (Scenario 2)	8	0.01%	Pass	8	0.27%	Pass	0.000%	Pass	Pass	
P34 (Scenario 2)	4	5.27%	Pass	6	2.48%		0.000%	Pass	Pass	
P35 (Scenario 2)	4	6.68%	Fail	6	2.38%		0.000%	Pass	Fail	Soft landscaping
P36 (Scenario 1)	8	0.06%	Pass	8	0.92%	Pass	0.001%	Pass	Pass	
P36 (Scenario 2)	8	0.04%	Pass	8	0.52%	Pass	0.000%	Pass	Pass	
P37 (Scenario 2)	4	6.48%	Fail	6	2.77%		0.000%	Pass	Fail	Soft landscaping
P38 (Scenario 2)	4	11.98%	Fail	6	5.43%		0.000%	Pass	Fail	Soft landscaping
P39 (Scenario 1)	8	0.13%	Pass	8	1.64%	Pass	0.001%	Pass	Pass	
P39 (Scenario 2)	8	0.14%	Pass	8	1.48%	Pass	0.002%	Pass	Pass	
P40 (Scenario 2)	6	1.98%	Pass	6	11.01%	Fail	0.002%	Pass	Fail	Recess
P41 (Scenario 2)	8	0.01%	Pass	8	0.15%	Pass	0.000%	Pass	Pass	
P42 (Scenario 2)	6	0.01%	Pass	6	0.16%	Pass	0.000%	Pass	Pass	
P43 (Scenario 2)	6	0.16%	Pass	6	2.06%	Pass	0.000%	Pass	Pass	

Study Point	Summer Comfort Assessment (up to 5% exceedance permitted)			Winter Comfort Assessment (up to 5% exceedance permitted)			All-Year Safety Assessment (up to 0.023% exceedance permitted)		Final Grade	Treatment
	Criterion (m/s)	Exceedance Result	Grade	Criterion (m/s)	Exceedance Result	Grade	Exceedance Result	Grade		
P44 (Scenario 2)	8	0.48%	Pass	8	3.23%	Pass	0.004%	Pass	Pass	
P45 (Scenario 1)	6	0.44%	Pass	6	2.09%	Pass	0.000%	Pass	Pass	
P45 (Scenario 2)	6	0.27%	Pass	6	1.55%	Pass	0.000%	Pass	Pass	
P46 (Scenario 1)	8	0.07%	Pass	8	0.96%	Pass	0.000%	Pass	Pass	
P46 (Scenario 2)	8	0.09%	Pass	8	0.48%	Pass	0.000%	Pass	Pass	
P47 (Scenario 1)	8	0.14%	Pass	8	1.71%	Pass	0.001%	Pass	Pass	
P47 (Scenario 2)	8	0.06%	Pass	8	0.51%	Pass	0.000%	Pass	Pass	
P48 (Scenario 1)	6	1.96%	Pass	6	11.95%	Fail	0.001%	Pass	Fail	Existing condition
P48 (Scenario 2)	6	0.43%	Pass	6	1.83%	Pass	0.000%	Pass	Pass	
P49 (Scenario 1)	6	2.20%	Pass	6	12.28%	Fail	0.001%	Pass	Fail	Existing condition
P49 (Scenario 2)	6	1.54%	Pass	6	5.16%	Fail	0.000%	Pass	Fail	Soft landscaping
P50 (Scenario 1)	8	0.15%	Pass	8	0.81%	Pass	0.000%	Pass	Pass	
P50 (Scenario 2)	8	0.21%	Pass	8	1.43%	Pass	0.001%	Pass	Pass	
P51 (Scenario 1)	8	0.20%	Pass	8	1.68%	Pass	0.001%	Pass	Pass	
P51 (Scenario 2)	8	0.57%	Pass	8	5.22%	Pass	0.008%	Pass	Pass	
P52 (Scenario 1)	4	7.38%	Fail	6	2.58%		0.000%	Pass	Fail	Existing condition
P52 (Scenario 2)	4	10.42%	Fail	6	3.79%		0.000%	Pass	Fail	Existing condition
P53 (Scenario 1)	4	7.65%	Fail	6	2.81%		0.000%	Pass	Fail	Existing condition
P53 (Scenario 2)	4	3.86%	Pass	6	1.58%		0.000%	Pass	Pass	
P54 (Scenario 1)	4	1.68%	Pass	6	0.54%		0.000%	Pass	Pass	
P54 (Scenario 2)	4	2.03%	Pass	6	0.74%		0.000%	Pass	Pass	
P55 (Scenario 1)	8	0.06%	Pass	8	0.90%	Pass	0.000%	Pass	Pass	
P55 (Scenario 2)	8	0.04%	Pass	8	0.78%	Pass	0.000%	Pass	Pass	
P56 (Scenario 1)	8	0.02%	Pass	8	0.38%	Pass	0.000%	Pass	Pass	
P56 (Scenario 2)	8	0.03%	Pass	8	0.45%	Pass	0.000%	Pass	Pass	
P57 (Scenario 1)	8	0.01%	Pass	8	0.15%	Pass	0.000%	Pass	Pass	
P57 (Scenario 2)	8	0.04%	Pass	8	0.49%	Pass	0.000%	Pass	Pass	
P58 (Scenario 1)	8	0.01%	Pass	8	0.13%	Pass	0.000%	Pass	Pass	
P58 (Scenario 2)	8	0.02%	Pass	8	0.29%	Pass	0.000%	Pass	Pass	
P59 (Scenario 1)	8	0.21%	Pass	8	1.40%	Pass	0.001%	Pass	Pass	
P59 (Scenario 2)	8	0.35%	Pass	8	2.20%	Pass	0.002%	Pass	Pass	
P60 (Scenario 1)	8	0.05%	Pass	8	0.68%	Pass	0.000%	Pass	Pass	

Study Point	Summer Comfort Assessment (up to 5% exceedance permitted)			Winter Comfort Assessment (up to 5% exceedance permitted)			All-Year Safety Assessment (up to 0.023% exceedance permitted)		Final Grade	Treatment
	Criterion (m/s)	Exceedance Result	Grade	Criterion (m/s)	Exceedance Result	Grade	Exceedance Result	Grade		
P60 (Scenario 2)	8	0.09%	Pass	8	1.38%	Pass	0.001%	Pass	Pass	
P61 (Scenario 1)	8	0.37%	Pass	8	3.06%	Pass	0.005%	Pass	Pass	
P61 (Scenario 2)	8	0.08%	Pass	8	0.86%	Pass	0.000%	Pass	Pass	
P62 (Scenario 1)	8	0.97%	Pass	8	5.92%	Fail	0.012%	Pass	Fail	Existing condition
P62 (Scenario 2)	8	0.52%	Pass	8	2.91%	Pass	0.003%	Pass	Pass	
P63 (Scenario 1)	8	0.66%	Pass	8	5.05%	Pass	0.007%	Pass	Pass	
P63 (Scenario 2)	8	0.57%	Pass	8	4.00%	Pass	0.007%	Pass	Pass	
P64 (Scenario 1)	8	0.16%	Pass	8	1.60%	Pass	0.001%	Pass	Pass	
P64 (Scenario 2)	8	0.08%	Pass	8	0.90%	Pass	0.000%	Pass	Pass	
P65 (Scenario 1)	8	0.65%	Pass	8	5.77%	Fail	0.006%	Pass	Fail	Existing condition
P65 (Scenario 2)	8	0.53%	Pass	8	4.83%	Pass	0.005%	Pass	Pass	
P66 (Scenario 1)	8	0.28%	Pass	8	1.99%	Pass	0.003%	Pass	Pass	
P66 (Scenario 2)	8	0.29%	Pass	8	1.67%	Pass	0.002%	Pass	Pass	
P67 (Scenario 2)	6	0.83%	Pass	6	7.50%		0.000%	Pass	Pass	
P68 (Scenario 2)	6	0.94%	Pass	6	7.84%		0.000%	Pass	Pass	
P69 (Scenario 2)	6	0.12%	Pass	6	1.58%		0.000%	Pass	Pass	
P70 (Scenario 2)	6	0.36%	Pass	6	3.46%		0.000%	Pass	Pass	
P71 (Scenario 2)	6	1.93%	Pass	6	10.60%		0.003%	Pass	Pass	
P72 (Scenario 2)	6	1.70%	Pass	6	7.48%		0.001%	Pass	Pass	
P73 (Scenario 2)	6	0.70%	Pass	6	2.13%		0.000%	Pass	Pass	
P74 (Scenario 2)	6	2.46%	Pass	6	12.29%		0.002%	Pass	Pass	
P75 (Scenario 2)	6	0.66%	Pass	6	1.80%		0.000%	Pass	Pass	
P76 (Scenario 2)	6	0.02%	Pass	6	0.30%		0.000%	Pass	Pass	
P77 (Scenario 2)	6	0.14%	Pass	6	1.81%		0.000%	Pass	Pass	
P78 (Scenario 2)	6	0.37%	Pass	6	2.80%		0.000%	Pass	Pass	
P79 (Scenario 2)	6	0.51%	Pass	6	3.97%		0.000%	Pass	Pass	
P80 (Scenario 2)	6	0.10%	Pass	6	0.86%		0.000%	Pass	Pass	
P81 (Scenario 2)	6	1.38%	Pass	6	5.87%		0.001%	Pass	Pass	
P82 (Scenario 2)	6	0.03%	Pass	6	0.20%		0.000%	Pass	Pass	
P83 (Scenario 2)	6	1.54%	Pass	6	10.39%		0.001%	Pass	Pass	
P84 (Scenario 2)	6	1.30%	Pass	6	9.19%		0.001%	Pass	Pass	
P85 (Scenario 2)	6	0.06%	Pass	6	1.04%		0.000%	Pass	Pass	
P86 (Scenario 2)	6	0.81%	Pass	6	5.91%		0.001%	Pass	Pass	

Study Point	Summer Comfort Assessment (up to 5% exceedance permitted)			Winter Comfort Assessment (up to 5% exceedance permitted)			All-Year Safety Assessment (up to 0.023% exceedance permitted)		Final Grade	Treatment
	Criterion (m/s)	Exceedance Result	Grade	Criterion (m/s)	Exceedance Result	Grade	Exceedance Result	Grade		
P87 (Scenario 2)	6	0.49%	Pass	6	1.63%		0.000%	Pass	Pass	
P88 (Scenario 2)	6	0.03%	Pass	6	0.47%		0.000%	Pass	Pass	
P89 (Scenario 2)	6	1.02%	Pass	6	6.10%		0.000%	Pass	Pass	
P90 (Scenario 2)	6	5.04%	Pass	6	9.42%		0.012%	Pass	Pass	

Note: The percent exceedances for the comfort results in Table 5 include a 0.5% added tolerance. However, the results within this report are based on the exceedances without the added tolerance.

Figure 8: Proposed Mitigation Measures – Ground Level Plan

7 REFERENCES

American Society of Civil Engineers (ASCE), 2003, "Outdoor Human Comfort and its Assessment – State of the Art".

American Society of Civil Engineers (ASCE), ASCE-7-16, 2016, "Minimum Design Loads for Buildings and Other Structures".

Australasian Wind Engineering Society, QAM-1, 2019, "Quality Assurance Manual: Wind Engineering Studies of Buildings", edited by Rofail A.W., et al.

Australasian Wind Engineering Society (AWES), 2014, "Guidelines for Pedestrian Wind Effects Criteria".

Council on Tall Buildings and Urban Habitat (CTBUH), 2013, "Wind tunnel testing of high-rise buildings", CTBUH Technical Guides.

Davenport, A.G., 1972, "An approach to human comfort criteria for environmental conditions". Colloquium on Building Climatology, Stockholm.

Deaves, D.M. and Harris, R.I., 1978, "A mathematical model of the structure of strong winds." Construction Industry and Research Association (U.K), Report 76.

Engineering Science Data Unit, 1982, London, ESDU82026, "Strong Winds in the Atmospheric Boundary Layer, Part 1: Hourly Mean Wind Speeds", with Amendments A to E (issued in 2002).

Lawson, T.V., (2001), "Building Aerodynamics". Imperial College Press.

Melbourne, W.H., 1978, "Criteria for Environmental Wind Conditions". Journal of Wind Engineering and Industrial Aerodynamics, vol. 3, pp241-249.

Rofail, A.W., and Kwok, K.C.S., 1991, "A Reliability Study of Wind Tunnel Results of Cladding Pressures". Proceedings of the 8th International Conference on Wind Engineering, Canada.

Rofail, A.W., 2007, "Comparison of Wind Environment Criteria against Field Observations". 12th International Conference of Wind Engineering, Cairns, Australia.

Standards Australia and Standards New Zealand, AS/NZS 1170.2, 2011, "SAA Wind Loading Standard, Part 2: Wind Actions".

APPENDIX A PUBLISHED ENVIRONMENTAL CRITERIA

A.1 Wind Effects on People

The acceptability of wind in an area is dependent upon the use of the area. For example, people walking or window-shopping will tolerate higher wind speeds than those seated at an outdoor restaurant. Quantifying wind comfort has been the subject of much research and many researchers, such as A.G. Davenport, T.V. Lawson, W.H. Melbourne, and A.D. Penwarden, have published criteria for pedestrian comfort for pedestrians in outdoor spaces for various types of activities. This section discusses and compares the various published criteria.

A.2 A.D. Penwarden (1973) Criteria for Mean Wind Speeds

A.D. Penwarden (1973) developed a modified version of the Beaufort scale which describes the effects of various wind intensities on people. Table A.1 presents the modified Beaufort scale. Note that the effects listed in this table refers to wind conditions occurring frequently over the averaging time (a probability of occurrence exceeding 5%). Higher ranges of wind speeds can be tolerated for rarer events.

Table A.1: Summary of Wind Effects on People (A.D. Penwarden, 1973)

Type of Winds	Beaufort Number	Hourly Mean Wind Speed (m/s)	Effects
Calm	0	0 - 0.3	
Calm, light air	1	0.3 - 1.6	No noticeable wind
Light breeze	2	1.6 - 3.4	Wind felt on face
Gentle breeze	3	3.4 - 5.5	Hair is disturbed, clothing flaps, newspapers difficult to read
Moderate breeze	4	5.5 – 8.0	Raises dust, dry soil and loose paper, hair disarranged
Fresh breeze	5	8.0 – 10.8	Force of wind felt on body, danger of stumbling
Strong breeze	6	10.8 – 13.9	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, wind noise on ears unpleasant
Near gale	7	13.9 – 17.2	Inconvenience felt when walking
Gale	8	17.2 - 20.8	Generally impedes progress, difficulty balancing in gusts
Strong gale	9	20.8 – 24.5	People blown over

A.3 A.G. Davenport (1972) Criteria for Mean Wind Speeds

A.G. Davenport (1972) also determined a set of criteria in terms of the Beaufort scale and for various return periods. Table A.2 presents a summary of the criteria based on a probability of exceedance of 5%.

Table A.2: Criteria by A.G. Davenport (1972)

Classification	Activities	5% exceedance Mean Wind Speed (m/s)
Walking Fast	Acceptable for walking, main public accessways.	7.5 - 10.0
Strolling, Skating	Slow walking, etc.	5.5 - 7.5
Short Exposure Activities	Generally acceptable for walking & short duration stationary activities such as window-shopping, standing or sitting in plazas.	3.5 - 5.5
Long Exposure Activities	Generally acceptable for long duration stationary activities such as in outdoor restaurants & theatres and in parks.	0 - 3.5

A.4 T.V. Lawson (1975) Criteria for Mean Wind Speeds

In 1973, T.V. Lawson, while referring to the Beaufort wind speeds of A.D. Penwarden (1973) (as listed in Table A.1), quoted that a Beaufort 4 wind speed would be acceptable if it is not exceeded for more than 4% of the time, and that a Beaufort 6 wind speed would be unacceptable if it is exceeded more than 2% of the time. Later, in 1975, T.V. Lawson presented a set of criteria very similar to those presented in A.G. Davenport (1972) (as listed in Table A.2). These criteria are presented in Table A.3 and Table A.4 for safety and comfort respectively.

Table A.3: Safety Criteria by T.V. Lawson (1975)

Classification	Activities	Annual Mean Wind Speed (m/s)
Safety (all weather areas)	Accessible by the general public.	0 – 15
Safety (fair weather areas)	Private areas, balconies/terraces, etc.	0 – 20

Table A.4: Comfort Criteria by T.V. Lawson (1975)

Classification	Activities	5% exceedance Mean Wind Speed (m/s)
Business Walking	Objective Walking from A to B.	8 - 10
Pedestrian Walking	Slow walking, etc.	6 - 8
Short Exposure Activities	Pedestrian standing or sitting for short times.	4 – 6
Long Exposure Activities	Pedestrian sitting for a long duration.	0 - 4

A.5 W.H. Melbourne (1978) Criteria for Gust Wind Speeds

W.H. Melbourne (1978) introduced a set of criteria for the assessment of environmental wind conditions that were developed for a temperature range of 10°C to 30°C and for people suitably dressed for outdoor conditions. These criteria are presented in Table A.5, and are based on maximum gust wind speeds with a probability of exceedance of once per year.

Table A.5: Criteria by W.H. Melbourne (1978)

Classification	Activities	Annual Gust Wind Speed (m/s)
Limit for Safety	Completely unacceptable: people likely to get blown over.	23
Marginal	Unacceptable as main public accessways.	16 - 23
Comfortable Walking	Acceptable for walking, main public accessways	13 - 16
Short Exposure Activities	Generally acceptable for walking & short duration stationary activities such as window-shopping, standing or sitting in plazas.	10 - 13
Long Exposure Activities	Generally acceptable for long duration stationary activities such as in outdoor restaurants & theatres and in parks.	0 - 10

A.6 Lawson Criteria (2001) for Mean Wind Speeds

In 2001 the T.V. Lawson criteria described in Section A.4 was revised by T.V. Lawson. This is often referred to as the Lawson Criteria. Details of the comfort criteria are presented in the table below and are based on the exceedance of the threshold wind speeds, occurring less than 5% of the time. This criterion defines a reasonable allowance for extreme and relatively infrequent winds that are tolerable within each category.

Table A.6: Pedestrian Comfort Criteria (T.V. Lawson, 2001)

Classification	Activities	5% exceedance Mean Wind Speed (m/s)
Uncomfortable	Winds of this magnitude are considered a nuisance for most activities, and wind mitigation is typically recommended.	>10
Walking	Relatively high speeds that can be tolerated if one's objective is to walk, run or cycle without lingering.	8-10
Strolling	Moderate breezes that would be appropriate for strolling along a city/town street, plaza or park.	6-8
Standing	Gentle breezes acceptable for main building entrances, pick-up/drop-off points and bus stops	4-6
Sitting	Light breezes desired for outdoor restaurants and seating areas where one can read a paper or comfortably sit for long periods	0-4

Details of the safety criteria are presented in the table below, and are based on exceedance of 0.023% of the threshold wind speeds, occurring annually.

Table A.7: Pedestrian Safety Criteria (T.V. Lawson, 2001)

Classification	Activities	Threshold Mean Wind Speed (m/s)
Unsafe for general Public & cyclists	Less able members of the public and cyclists find condition challenging	>15

A.7 Comparison of the Published Wind Speed Criteria

W.H. Melbourne (1978) presented a comparison of the criteria of various researchers on a probabilistic basis. Figure A.1 presents the results of this comparison, and indicates that the criteria of W.H. Melbourne (1978) are comparatively quite conservative. This conclusion was also observed by A.W. Rofail (2007) when undertaking on-site remedial studies. The results of A.W. Rofail (2007) concluded that the criteria by W.H. Melbourne (1978) generally overstates the wind effects in a typical urban setting due to the assumption of a fixed 15% turbulence intensity for all areas. It was observed in A.W. Rofail (2007) that the 15% turbulence intensity assumption is not real and that the turbulence intensities at 1.5m above ground is at least 20% and in a suburban or urban setting is generally in the range of 30% to 60%.

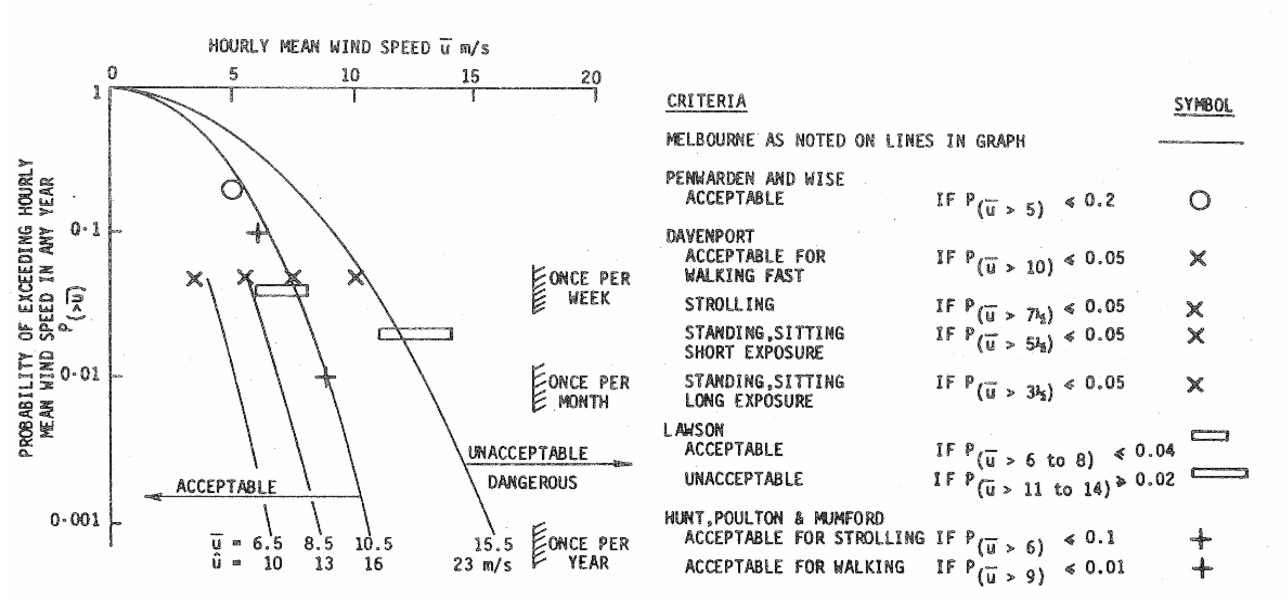


Figure A.1: Comparison of Various Mean and Gust Wind Environment Criteria, assuming 15% turbulence and a Gust Factor of 1.5 (W.H. Melbourne, 1978)

A.8 References relating to Pedestrian Comfort Criteria

Davenport, A.G., 1972, “An approach to human comfort criteria for environmental conditions”. Colloquium on Building Climatology, Stockholm.

Davenport, A.G., 1977, “The prediction of risk under wind loading”, 2nd International Conference on Structural Safety and Reliability, Munich, Germany, pp511-538.

Lawson, T.V., 1973, “The wind environment of buildings: a logical approach to the establishment of criteria”. Bristol University, Department of Aeronautical Engineering.

Lawson, T.V., 1975, “The determination of the wind environment of a building complex before construction”. Bristol University, Department of Aeronautical Engineering.

Lawson, T.V., (2001), "Building Aerodynamics". Imperial College Press.

Melbourne, W.H., 1978, “Criteria for Environmental Wind Conditions”. Journal of Wind Engineering and Industrial Aerodynamics, vol. 3, pp241-249.

Penwarden, A.D. (1973). “Acceptable Wind Speeds in Towns”, Building Science, vol. 8: pp259–267.

Penwarden, A.D., Wise A.F.E., 1975, “Wind Environment Around Buildings”. Building Research Establishment Report, London.

Rofail, A.W., 2007, “Comparison of Wind Environment Criteria against Field Observations”. 12th International Conference of Wind Engineering, Cairns, Australia.

APPENDIX B DATA ACQUISITION

The wind tunnel testing procedures utilised for this study were based on the guidelines set out in the Australasian Wind Engineering Society Quality Assurance Manual (AWES-QAM-1-2019), ASCE 7-16 (Chapter C31), and CTBUH (2013). The wind speed measurements for the wind tunnel study were determined as coefficients using data acquired by either Dantec hot-wire probe anemometers or pressure-based wind speed sensors and converted to full-scale wind speeds using details of the regional wind climate obtained from an analysis of directional wind speed recordings from the local meteorological recording station(s).

B.1 Measurement of the Velocity Coefficients

The study model and proximity model were setup within the wind tunnel which was configured to the appropriate boundary layer profile, and the wind velocity measurements were monitored using either Dantec hot-wire probe anemometers or pressure-based wind speed sensors at selected critical outdoor locations. The wind velocity results presented in this study for each study point are representative of wind at a full-scale height of approximately 1.5m above ground/slab level. In the case of the Dantec hot-wire probe anemometers, the support of the probe is mounted such that the probe wire is vertical as much as possible to ensure that the measured wind speeds are independent of wind direction along the horizontal plane. In addition, care was taken in the alignment of the hot-wire probe wire and in avoiding wall-heating effects.

Wind speed measurements were made in the wind tunnel for 16 wind directions, at 22.5° increments. Data was acquired for each wind direction using a sample rate of 1024Hz. The sample length was determined to produce a full-scale sample time that is sufficient for this type of study. In the case of the pressure-based wind speed sensors, the phase lag between the various channels where data is acquired simultaneously is within 10% of a typical pressure cycle, and the signal is low-pass filtered at 500Hz and then digital filtering is applied over this range to provide an unbiased response from the pressure measurement system (A.W. Rofail, 2004).

The mean, gust and standard deviation velocity coefficients were determined from the data acquired in the wind tunnel. The gust velocity coefficients were also derived for each wind direction from by the following relation:

$$\hat{C}_V = \bar{C}_V + g \cdot \sigma_{C_V} \tag{B.1}$$

where:

$\hat{C}_V$ is the gust velocity coefficient.

$\bar{C}_V$ is the mean velocity coefficient.

g is the peak factor, taken as 3.0 for a 3-sec gust and 3.4 for a 0.5-sec gust.

σ_{C_V} is the standard deviation of the velocity coefficient measurement.

In the case of a Dantec hot-wire probe anemometer, the velocity coefficient is obtained as follows:

$$C_V = \frac{C_{V,study}}{C_{V,200m}} \qquad \text{B.2}$$

where:

$C_{V,study}$ is the velocity coefficient measurement obtained from the Dantec hot-wire probe anemometer at the study point location.

$C_{V,200m}$ is the velocity coefficient measurement obtained from the Dantec hot-wire probe anemometer at the free-stream reference location at 200m height upwind of the model in the wind tunnel.

However, in the case of the pressure-based wind speed sensors, these are determined from the measured differential mean, standard deviation and maximum pressure coefficients obtained from the wind speed sensor. For this analysis all calculations are performed on the square root of the differential pressure measurements. The velocity coefficient at the pressure-based wind speed sensor location is then calculated as follows:

$$C_V = \frac{\alpha + \beta\sqrt{\Delta p}}{V_{200m}} \qquad \text{B.3}$$

where:

C_V is the velocity coefficient measurement at the study point location.

α is a calibration coefficient for the pressure-based wind speed sensor.

β is a calibration coefficient for the pressure-based wind speed sensor.

Δp is the differential pressure obtained from the pressure-based wind speed sensor at the study point location.

V_{200m} is the wind speed at the free-stream reference location of 200m height (full-scale) in the wind tunnel, which is determined directly in the wind tunnel using a pitot static probe.

B.2 Calculation of the Full-Scale Results

The full-scale results determine if the wind conditions at a study location satisfy the designated criteria of that location. More specifically, the full-scale results need to determine the probability of exceedance of a given wind speed at a study location. To determine the probability of exceedance, the measured velocity coefficients were combined with a statistical model of the local wind climate that relates wind speed to a probability of exceedance. Details of the wind climate model are outlined in Section 4 of the main report.

The statistical model of the wind climate includes the impact of wind directionality as any local variations in wind speed or frequency with wind direction. This is important as the wind directions that produce the highest wind speed events for a region may not coincide with the most wind exposed direction at the site.

The methodology adopted for the derivation of the full-scale results for the maximum gust and the GEM wind speeds are outlined in the following sub-sections.

B.3 Maximum Gust Wind Speeds

The full-scale maximum gust wind speed at each study point location is derived from the velocity coefficient using the following relationship:

$$V_{study} = V_{ref,RH} \left(\frac{k_{200m,tr,T=1hr}}{k_{RH,tr,T=1hr}} \right) C_V \qquad \text{B.4}$$

where:

V_{study} is the full-scale wind speed at the study point location.

$V_{ref,RH}$ is the full-scale reference wind speed at the study reference height. This value is determined by combining the directional wind speed data for the region (detailed in Section 4) and the upwind terrain and height multipliers for the site (detailed in Section 3).

$k_{200m,tr,T=1hr}$ is the hourly mean terrain and height multiplier at the free-stream reference location of 200m height.

$k_{RH,tr,T=1hr}$ is the hourly mean terrain and height multiplier at the study reference height (Section 4).

C_V is the velocity coefficient, obtained from either Equation B.2 (in the case of Dantec hot-wire probe anemometers) or Equation B.3 (in the case of pressure-based wind speed sensors).

The value of $V_{ref,RH}$ varies with each prevailing wind direction. Wind directions where there is a high probability that a strong wind will occur have a higher directional wind speed than other directions. To determine the directional wind speeds, a probability level must be assigned for each wind direction. These probability levels are set following the approach used in AS/NZS1170.2:2011, which assumes that the major contributions to the combined probability of exceedance of a typical load effect comes from only two 45 degree sectors.

B.4 Maximum Gust-Equivalent Mean Wind Speeds

The contribution to the probability of exceedance of a specified wind speed (ie: the desired wind speed for pedestrian comfort, as per the criteria) was calculated for each wind direction. These contributions are then combined over all wind directions to calculate the total probability of exceedance of the specified wind speed. To calculate the probability of exceedance for a specified wind speed a statistical wind climate model was used to describe the relationship between directional wind speeds and the probability of exceedance. A detailed description of the methodology is given by T.V. Lawson (1980).

The criteria used in this study is referenced to a probability of exceedance of 5% of a specified wind speed.

B.5 References relating to Data Acquisition

American Society of Civil Engineers (ASCE), ASCE-7-16, 2016, “Minimum Design Loads for Buildings and Other Structures”.

Australasian Wind Engineering Society, QAM-1, 2019, “Quality Assurance Manual: Wind Engineering Studies of Buildings”, edited by Rofail A.W., et al.

Council on Tall Buildings and Urban Habitat (CTBUH), 2013, “Wind tunnel testing of high-rise buildings”, CTBUH Technical Guides.

Lawson, T.V., 1980, “Wind Effects on Buildings - Volume 1, Design Applications”. Applied Science Publishers Ltd, Ripple Road, Barking, Essex, England.

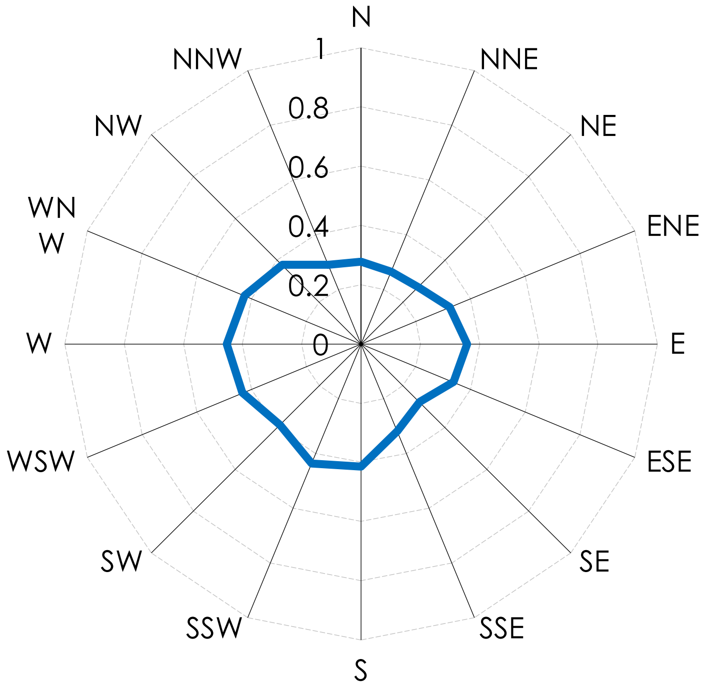
Lawson, T.V., (2001), "Building Aerodynamics". Imperial College Press.

Rofail A.W., Tonin, R., and Hanafi, D., 2004, “Sensitivity of frequency response to type of tubing”, Australasian Wind Engineering Workshop, Darwin.

Standards Australia and Standards New Zealand, AS/NZS 1170.2, 2011, “SAA Wind Loading Standard, Part 2: Wind Actions”.

APPENDIX C MEASURED VELOCITY COEFFICIENTS

Velocity Coefficient Results for P01



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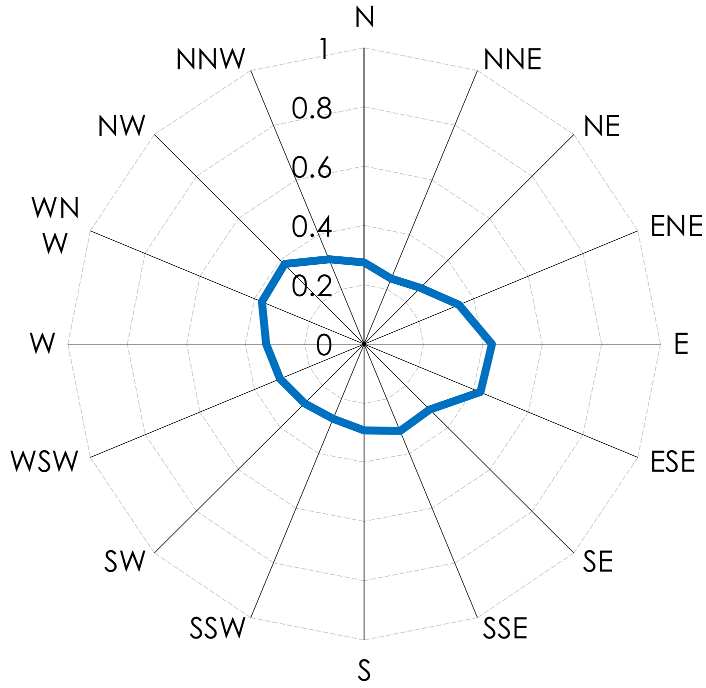
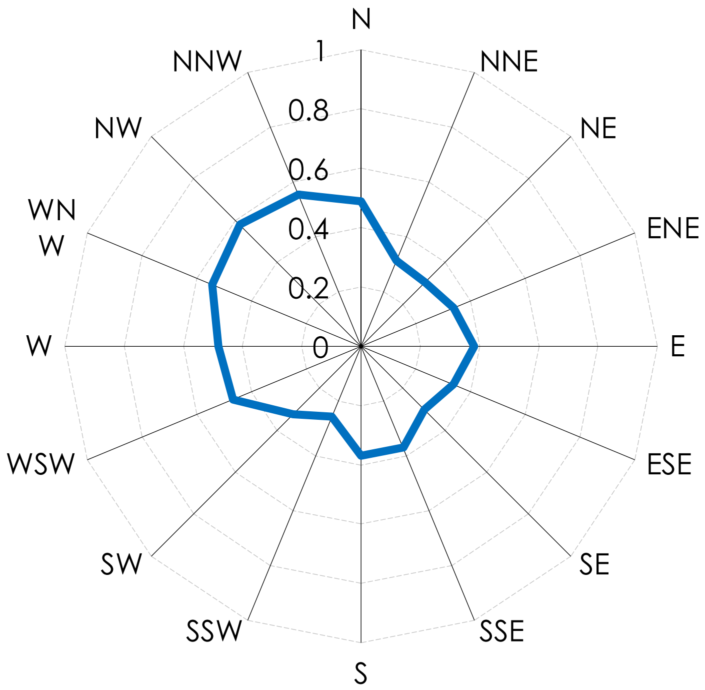
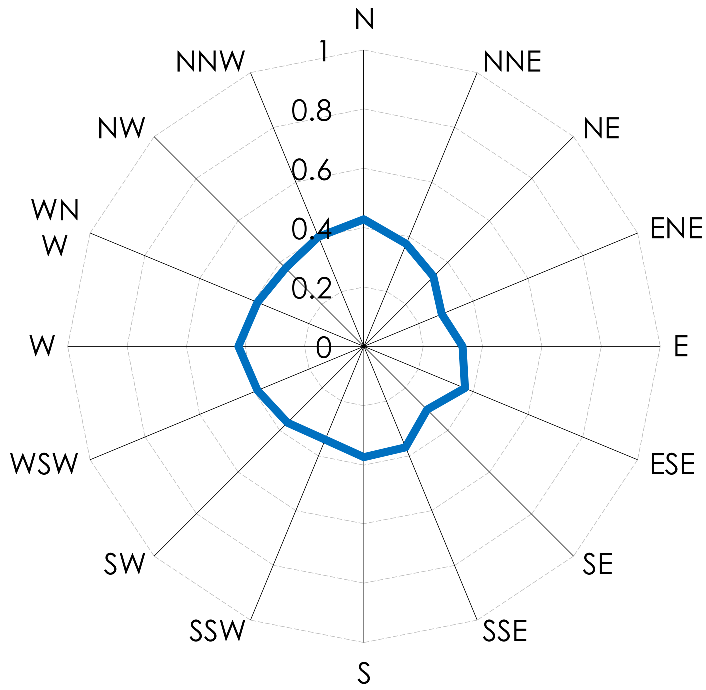


Velocity Coefficient Results for P03

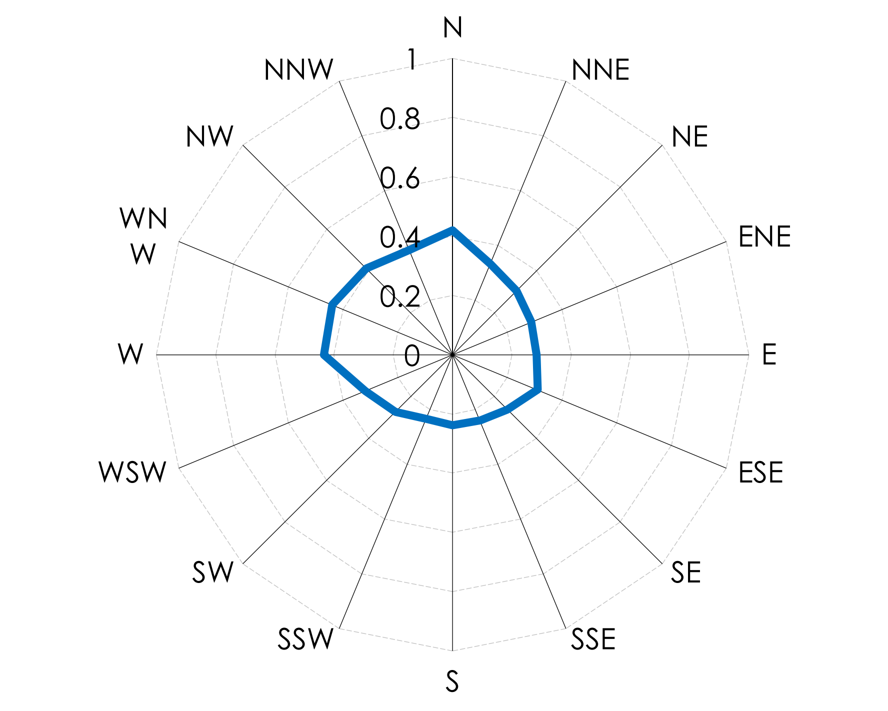
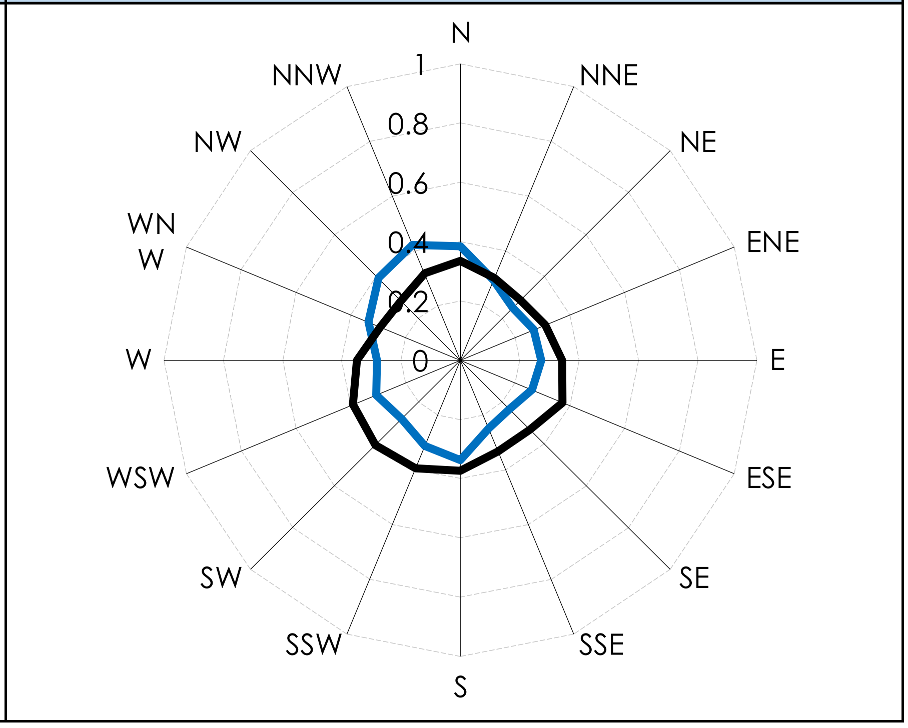


Velocity Coefficient Results for P04



Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

Velocity Coefficient Results for P05	Velocity Coefficient Results for P06
	

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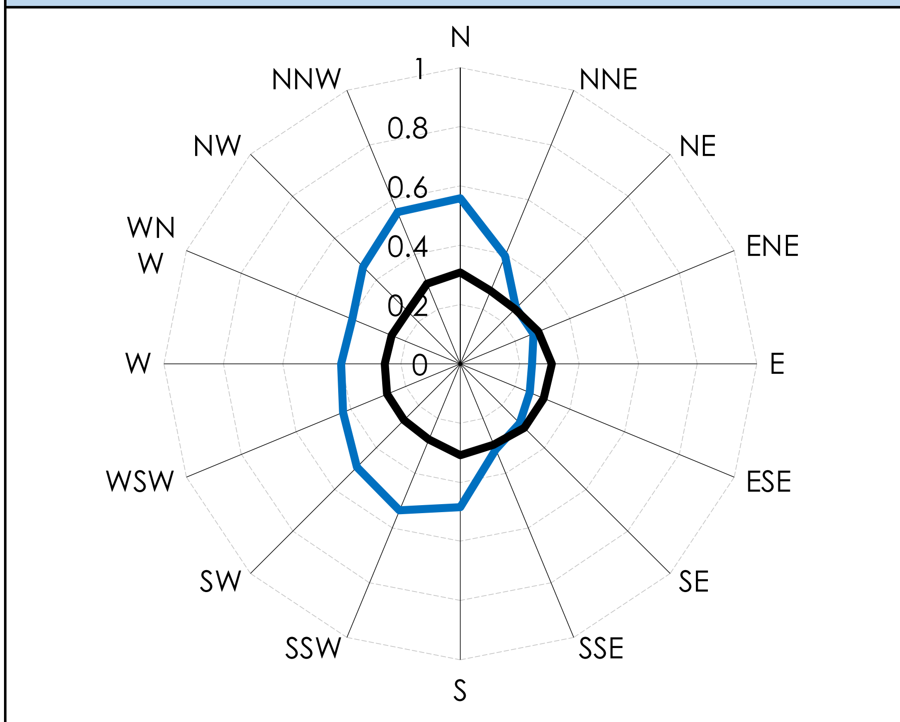	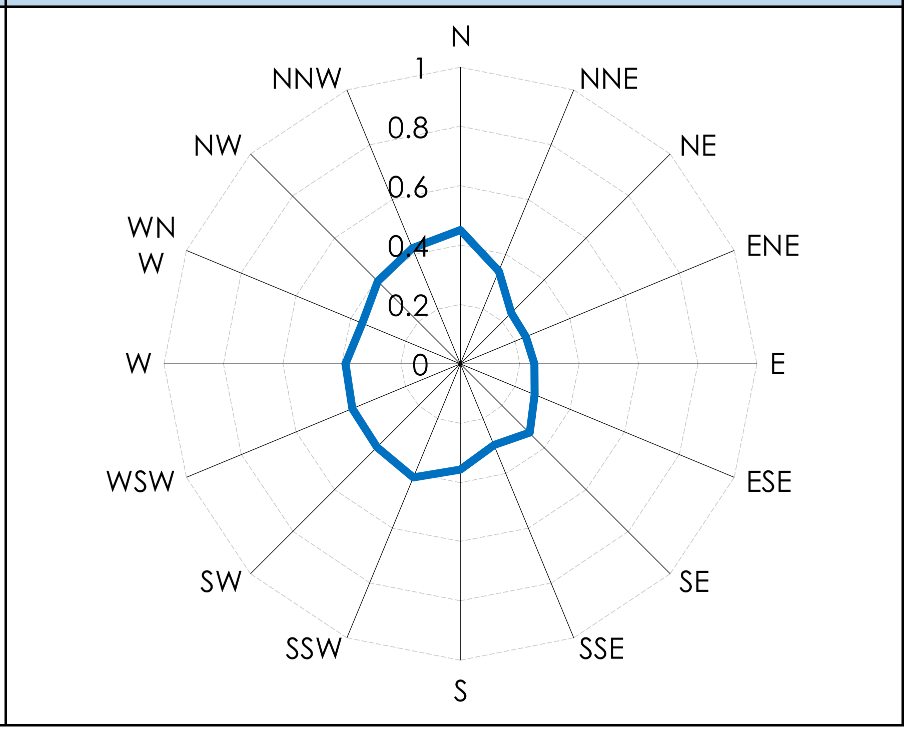

Legend
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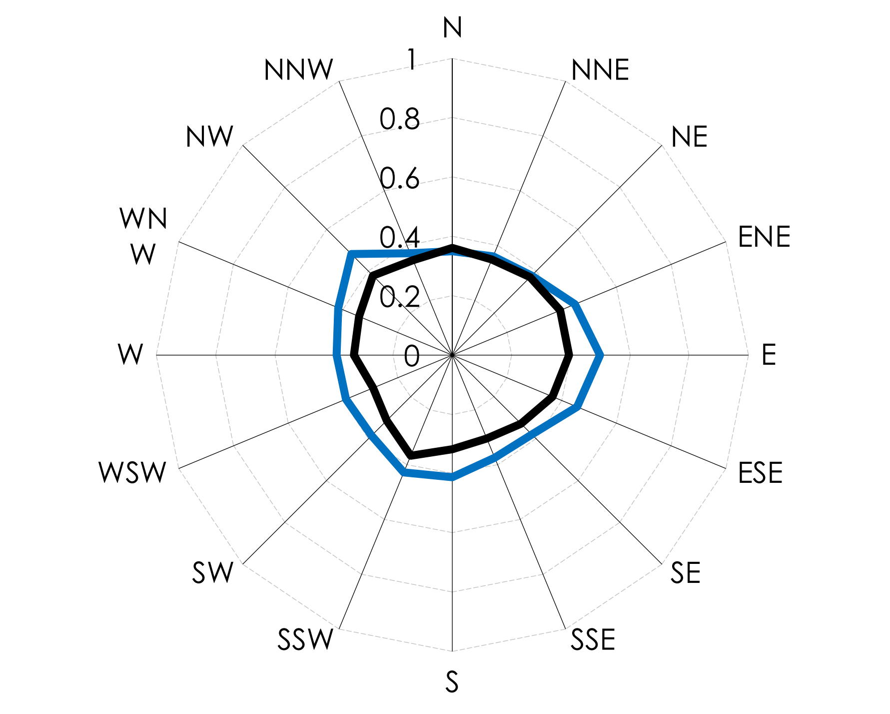
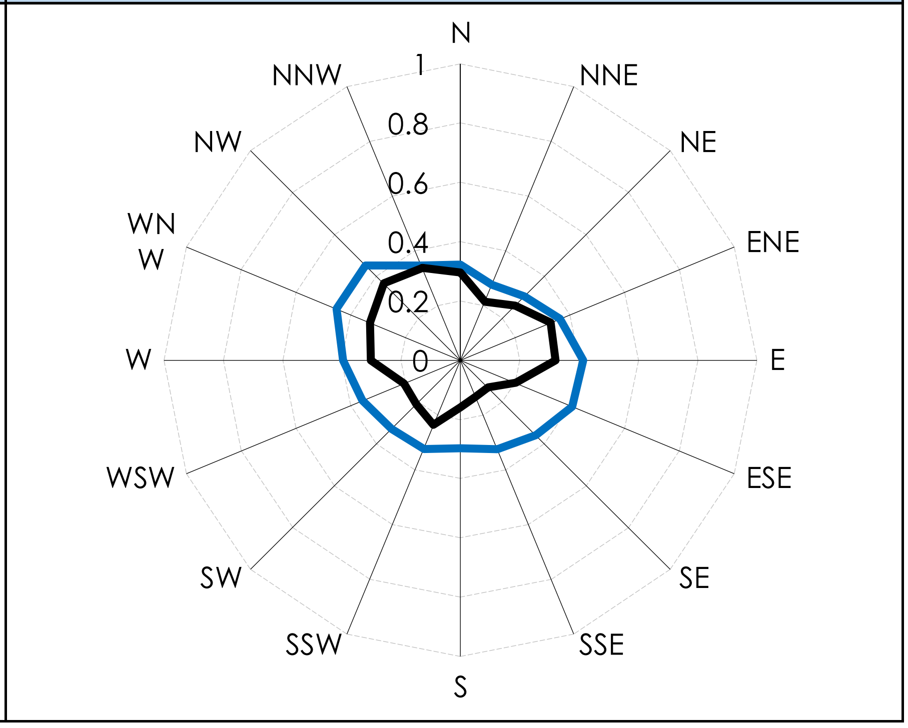
- Existing Site Condition

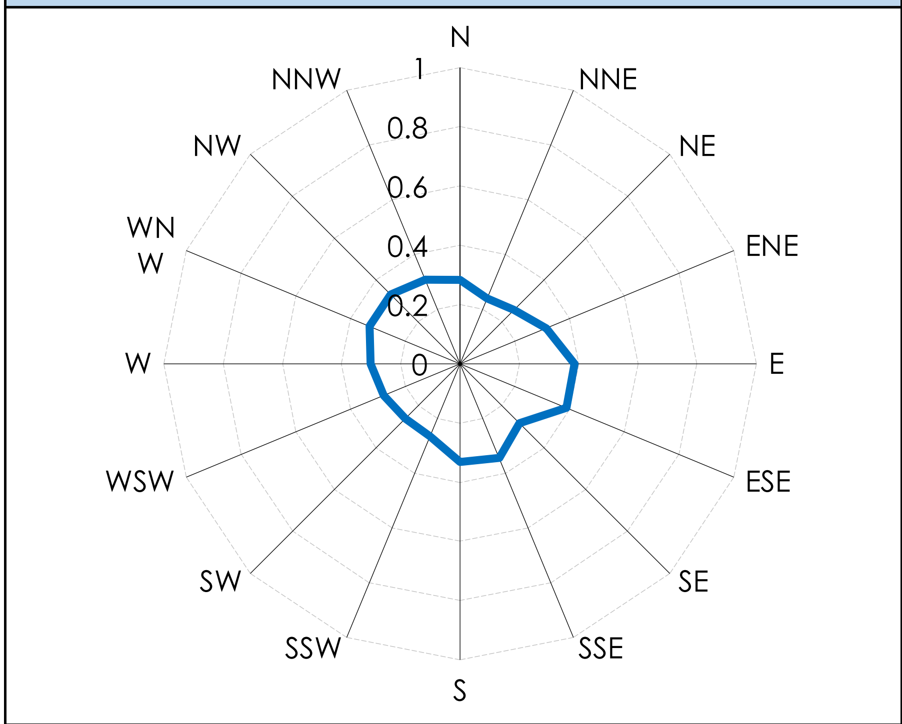
Velocity Coefficient Results for P09



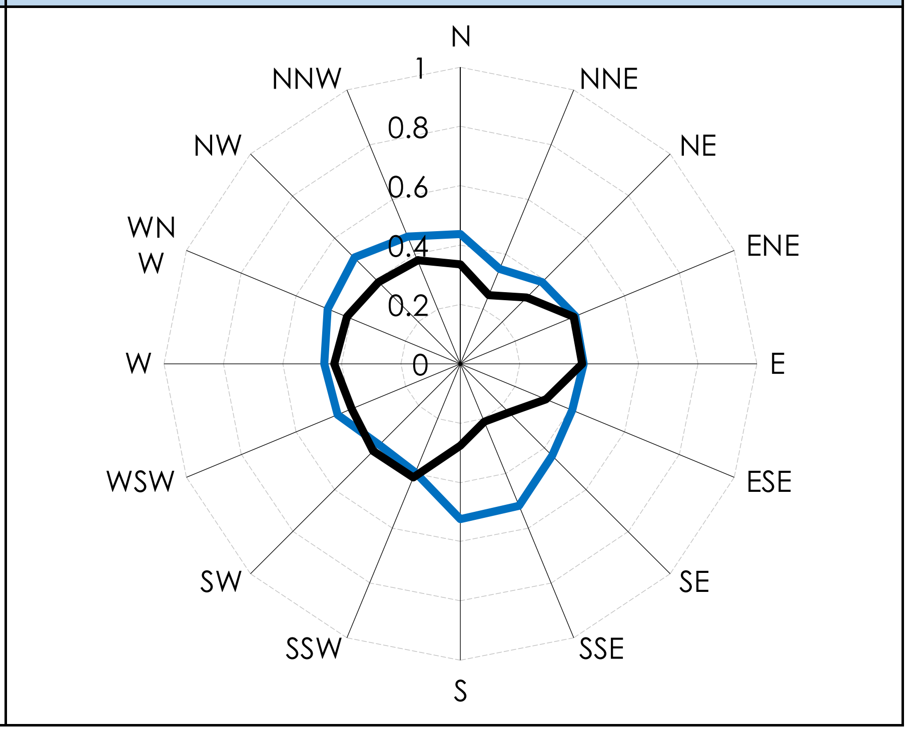
Velocity Coefficient Results for P10



Velocity Coefficient Results for P11

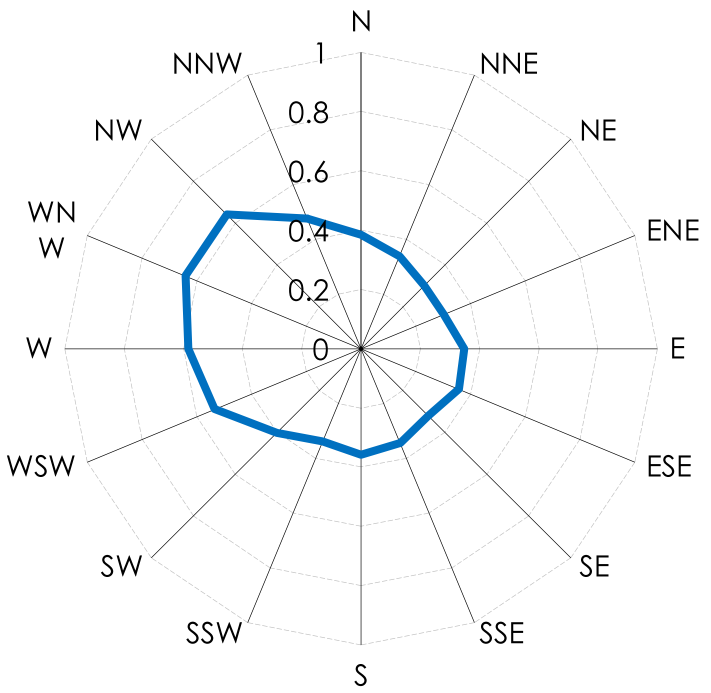


Velocity Coefficient Results for P12



Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

Velocity Coefficient Results for P13



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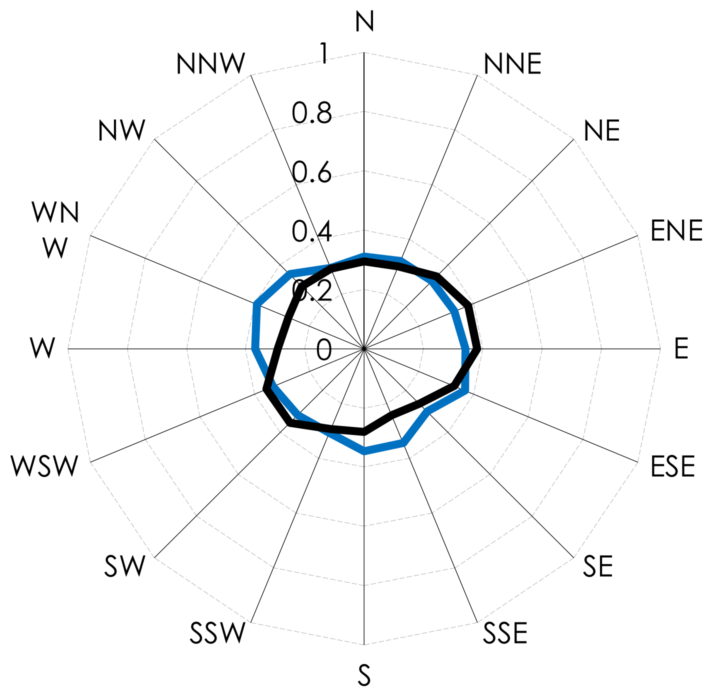
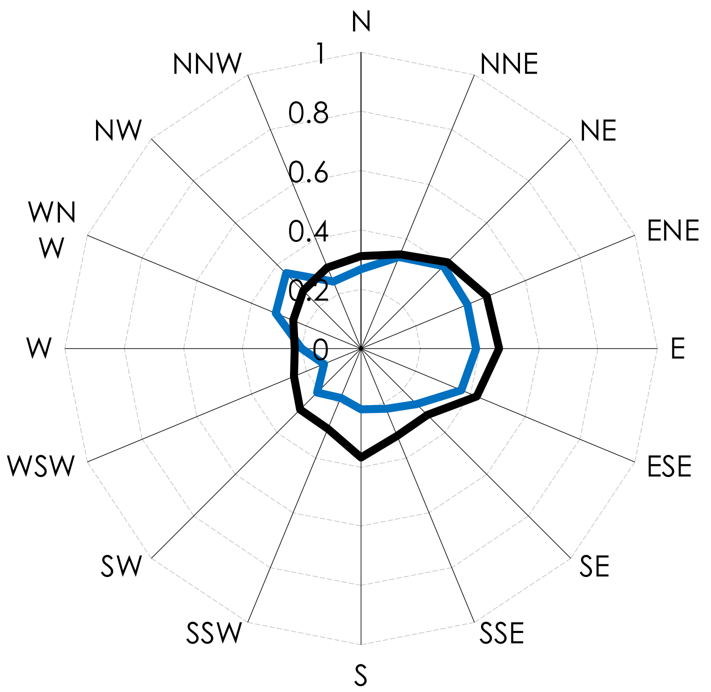
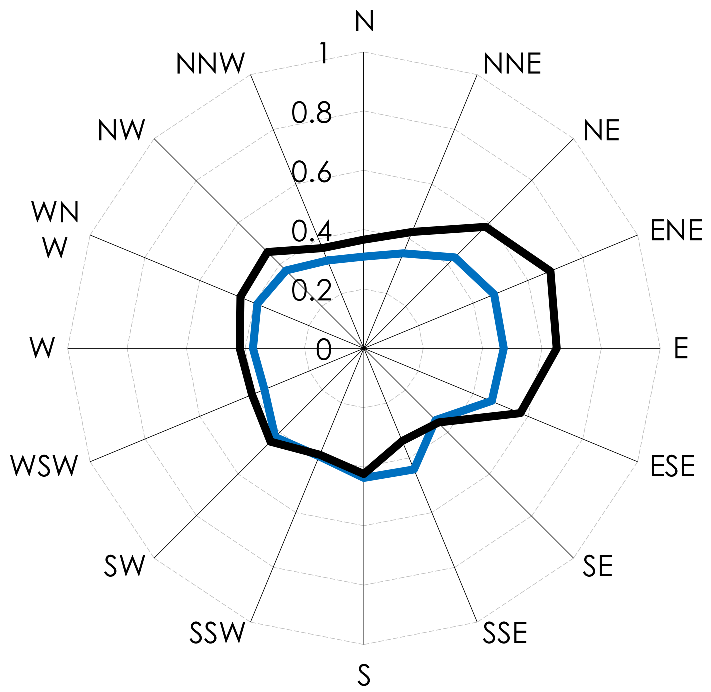


Velocity Coefficient Results for P15



Velocity Coefficient Results for P16



Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

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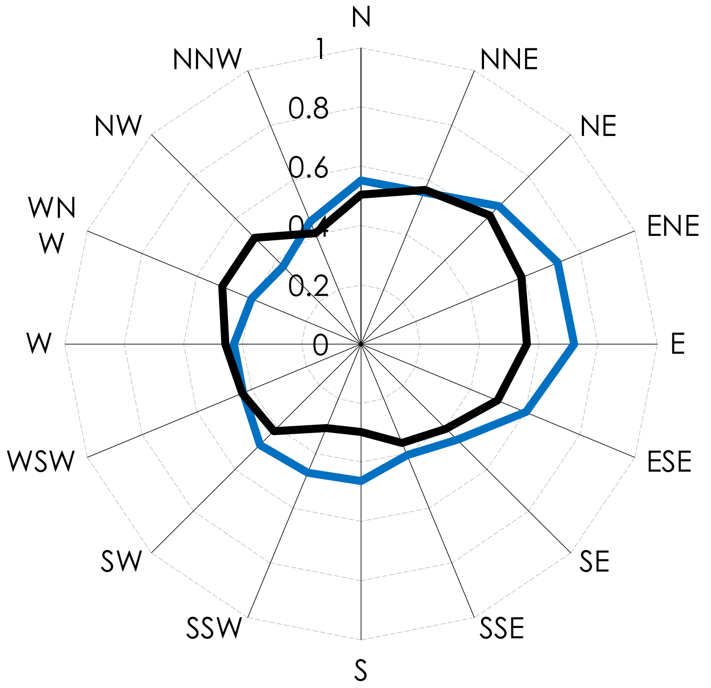	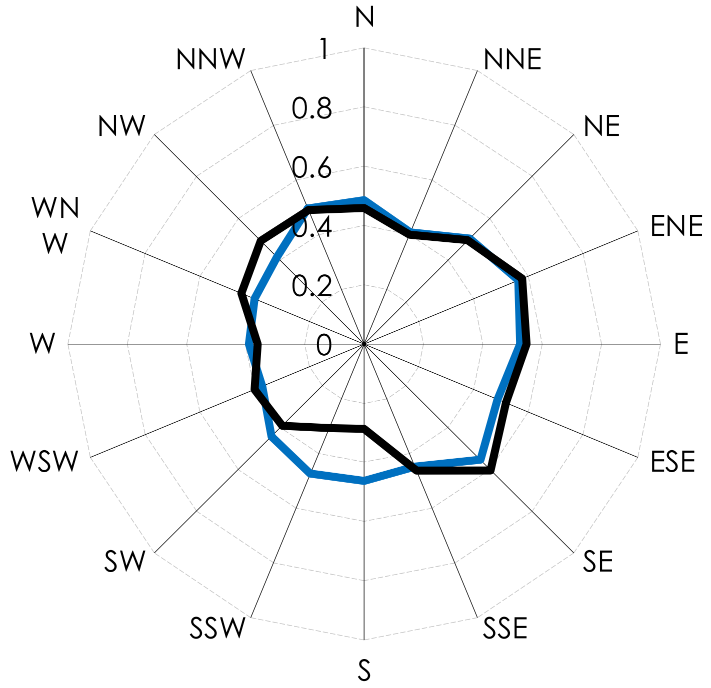

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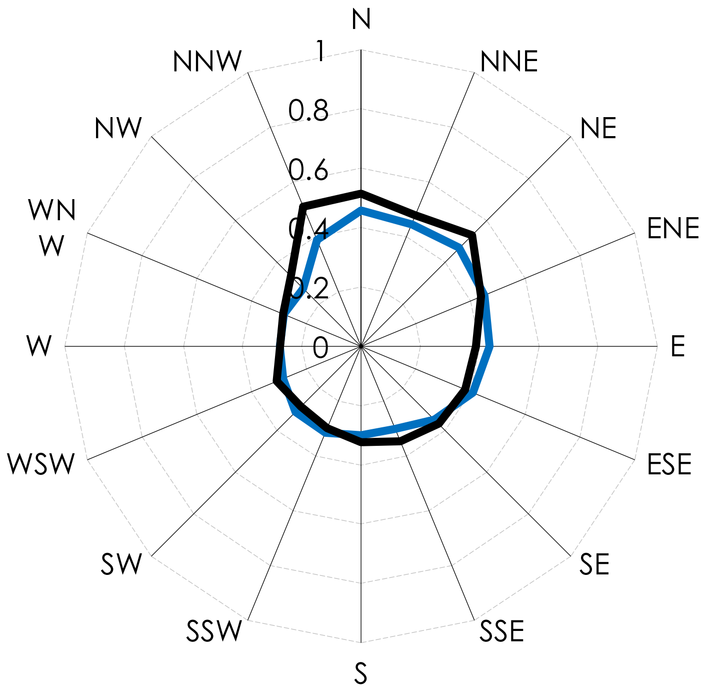	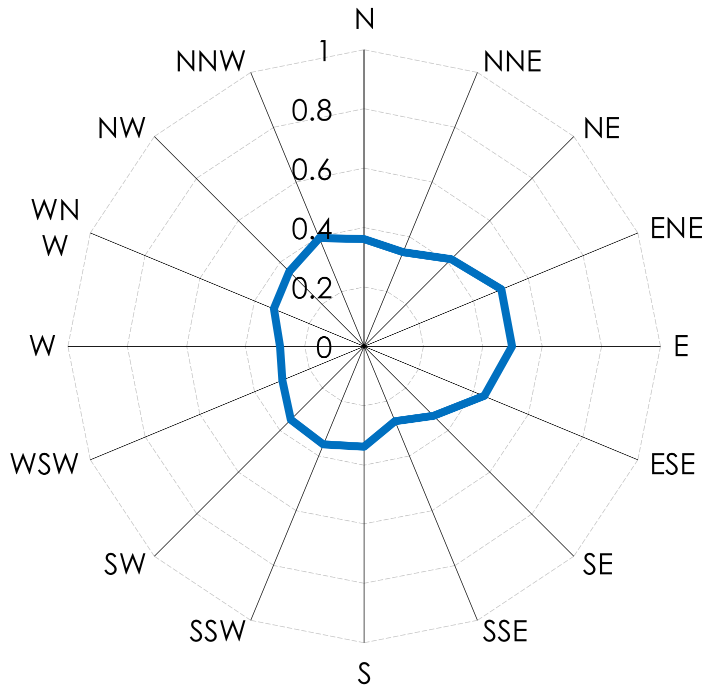

Legend
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- Existing Site Condition

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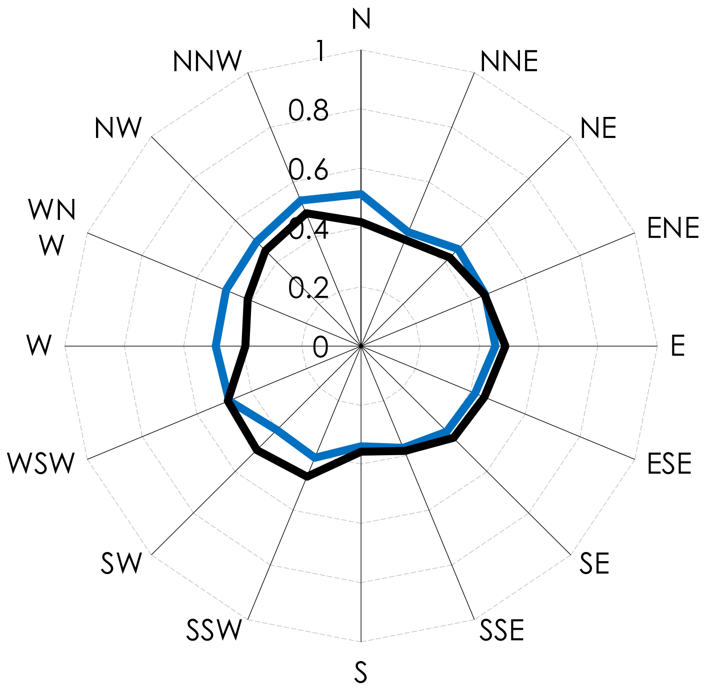
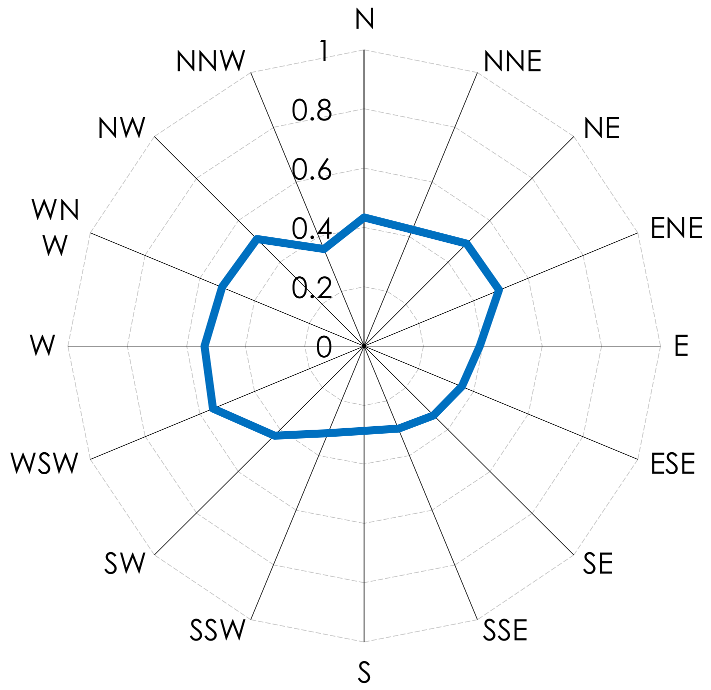
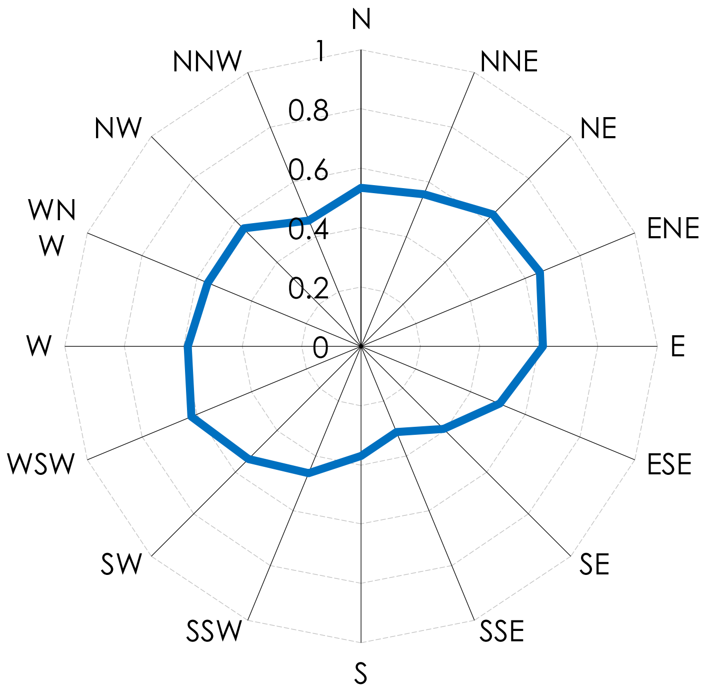
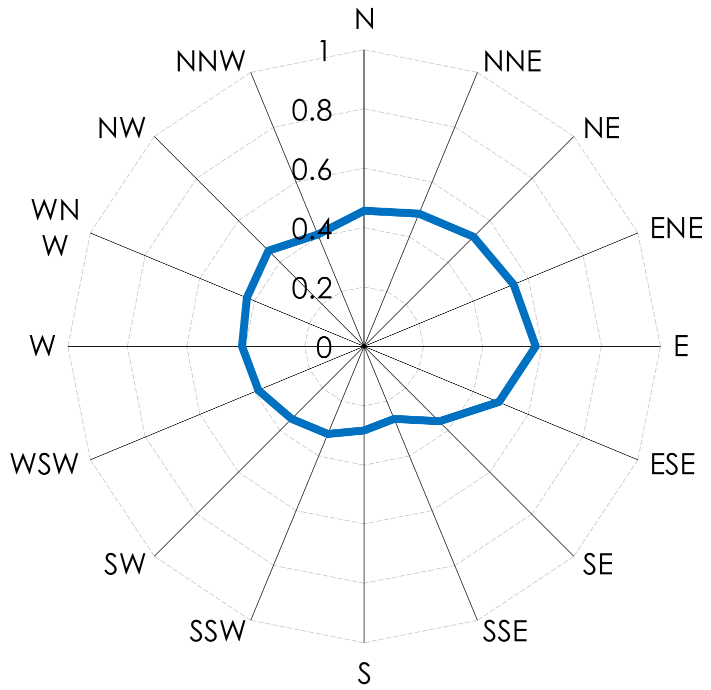




Velocity Coefficient Results for P23	Velocity Coefficient Results for P24





Legend
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- Existing Site Condition

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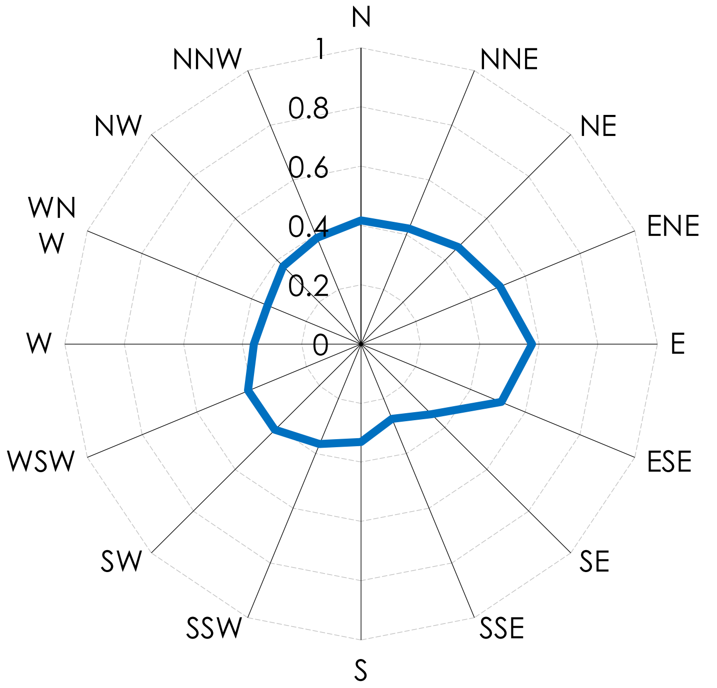	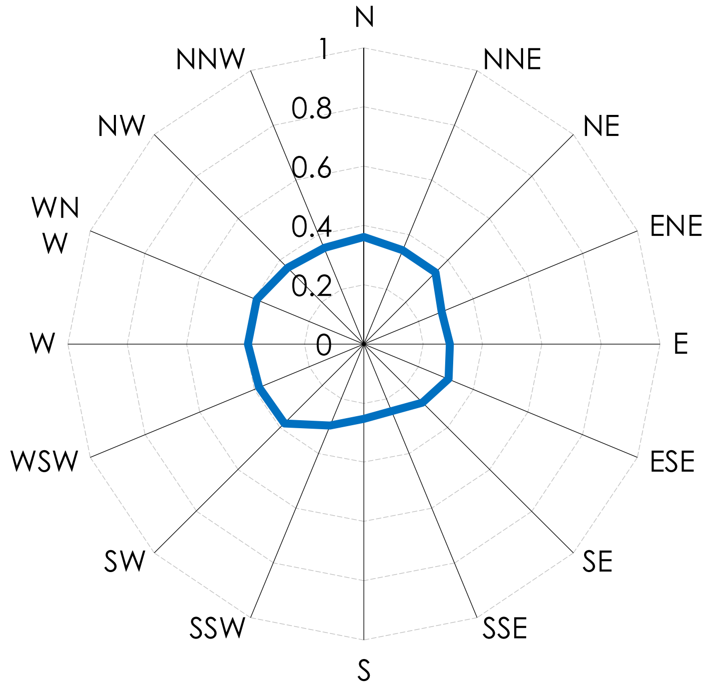

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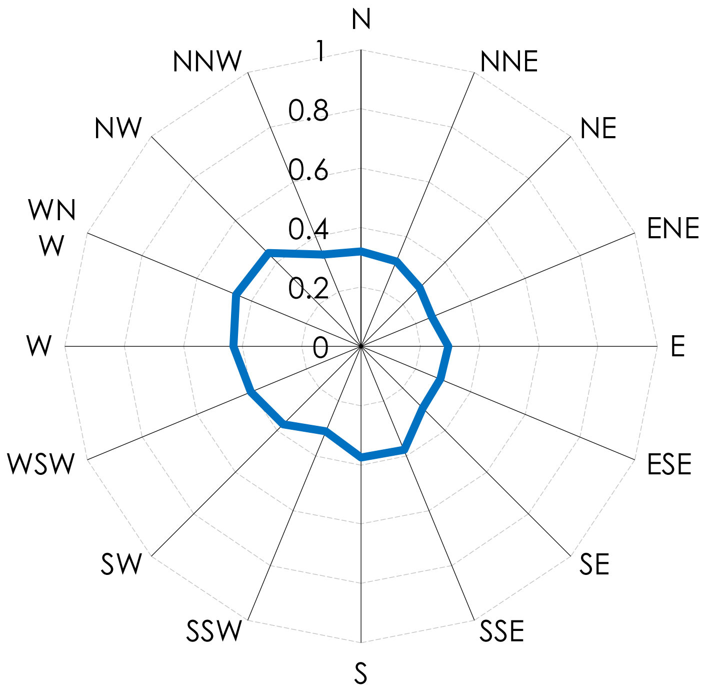
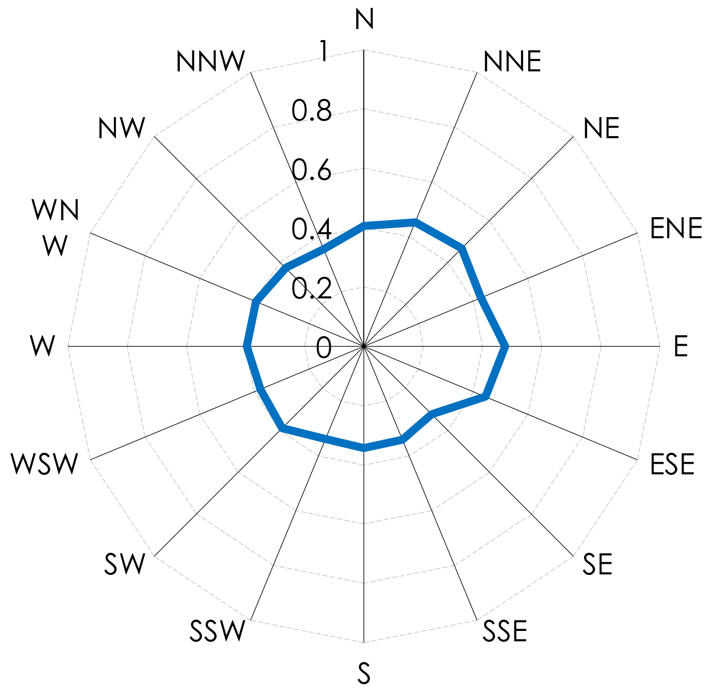
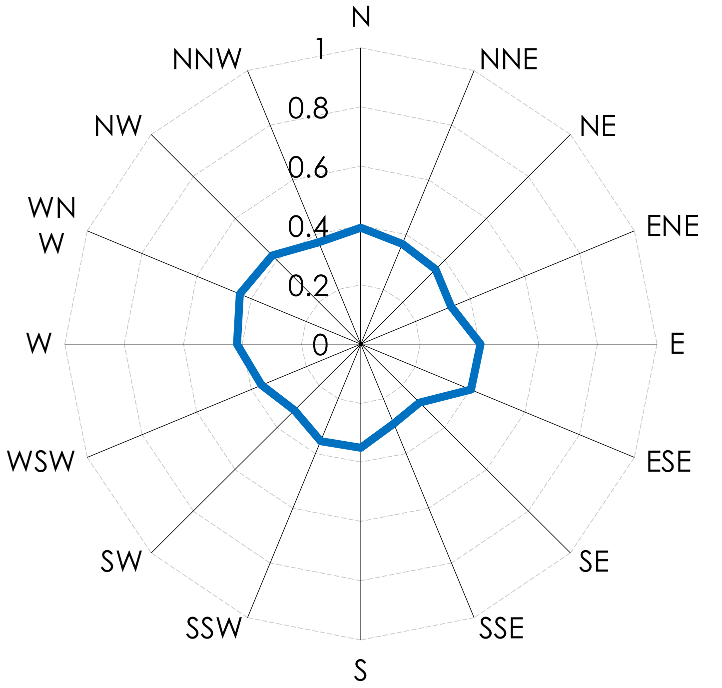
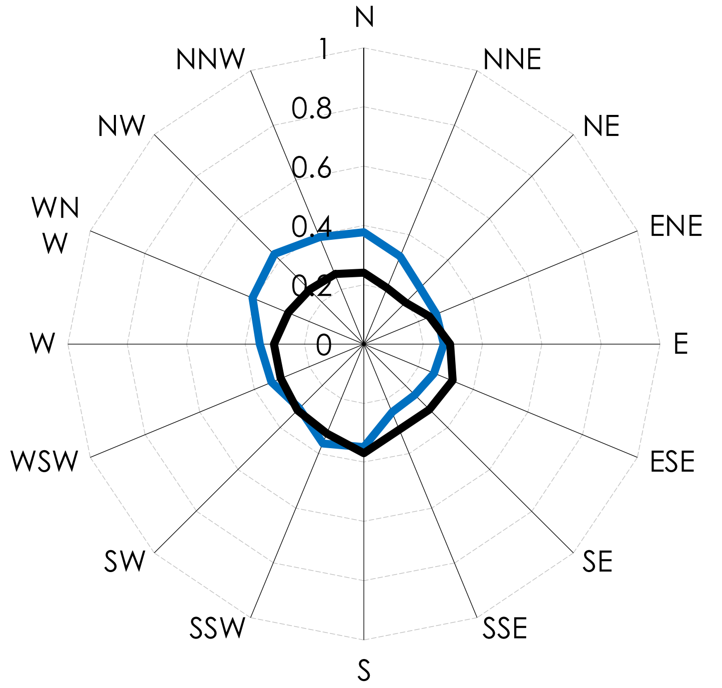
	

Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

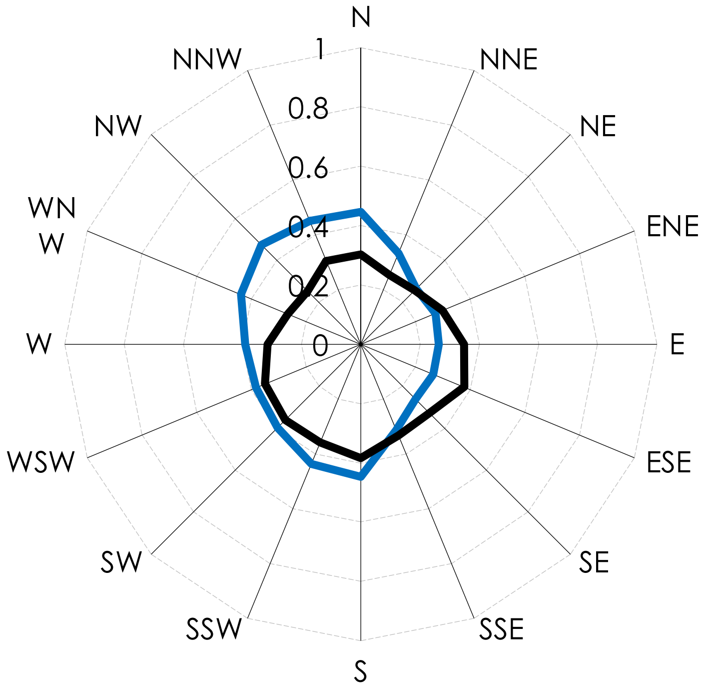
Velocity Coefficient Results for P29



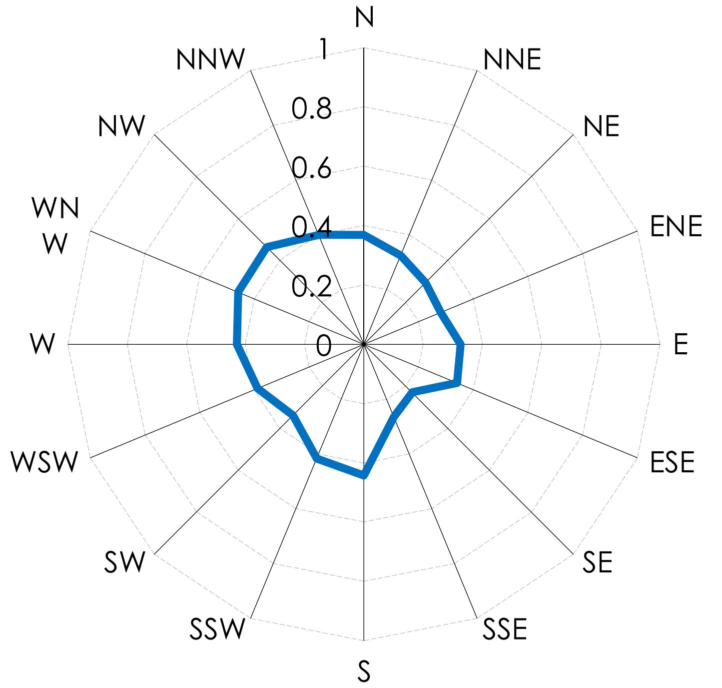
Velocity Coefficient Results for P30



Velocity Coefficient Results for P31



Velocity Coefficient Results for P32



Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

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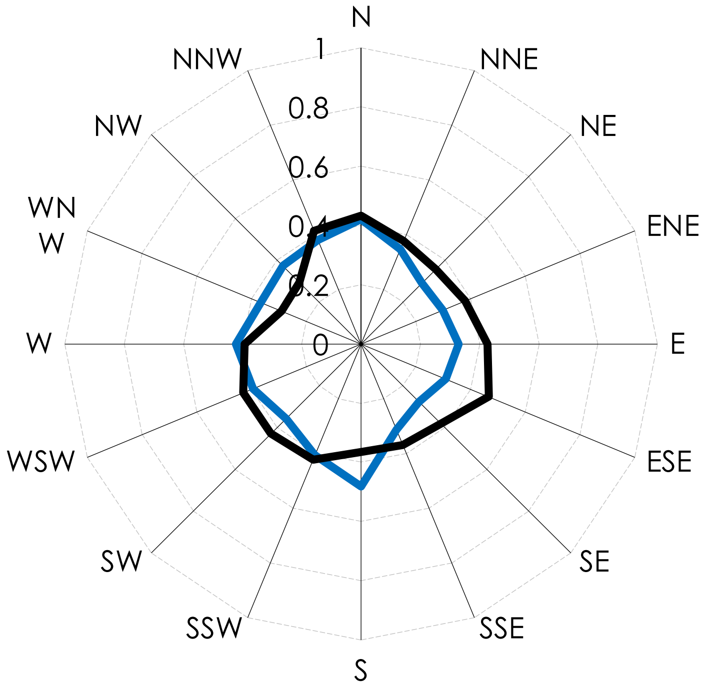	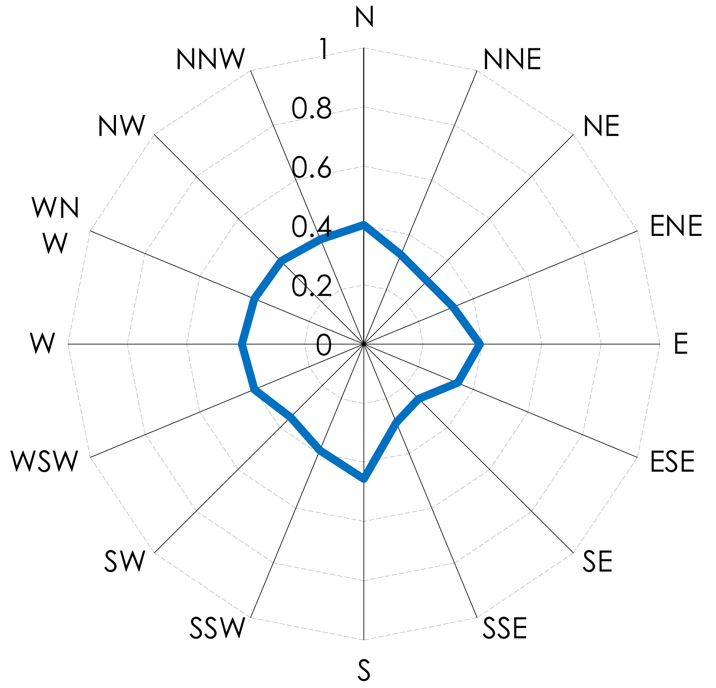

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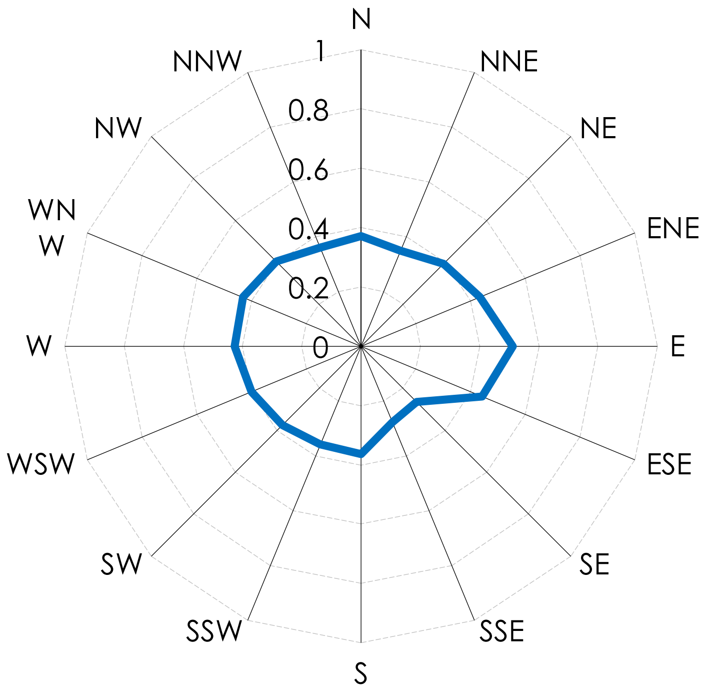
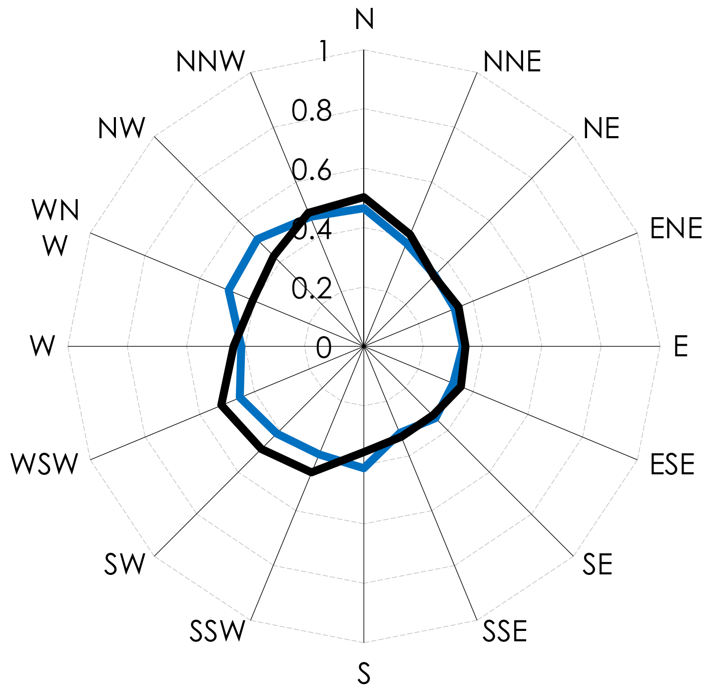
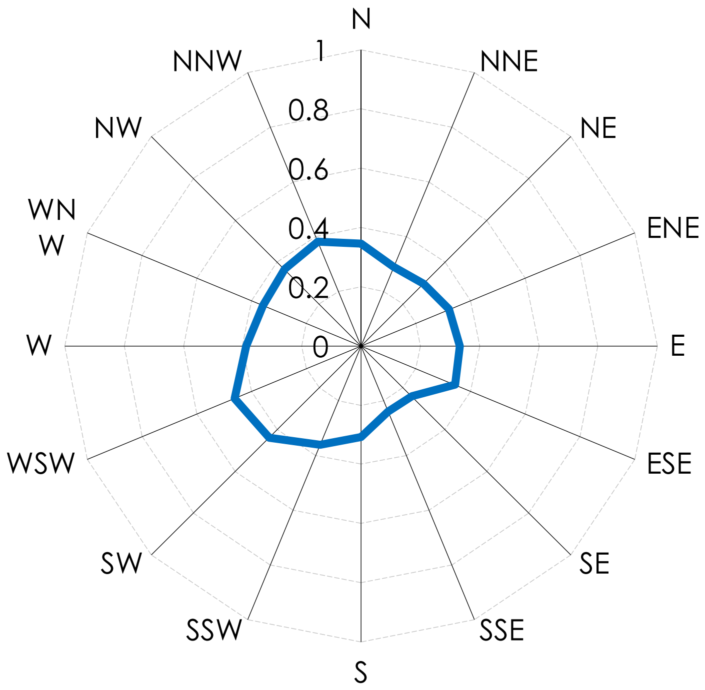
	

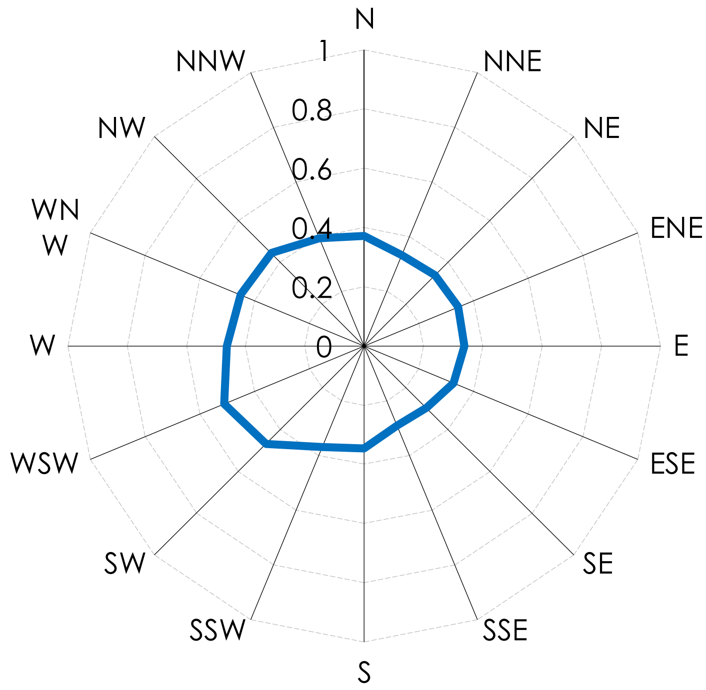
Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

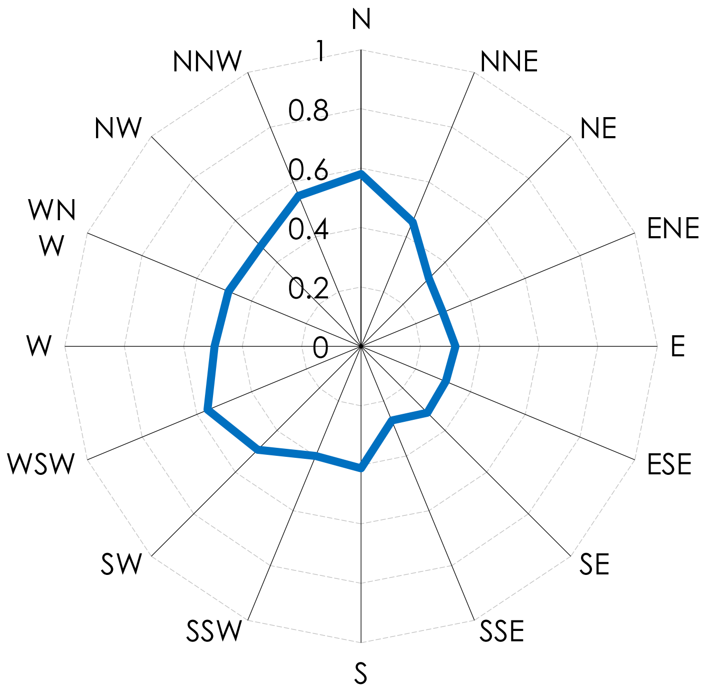
Velocity Coefficient Results for P37



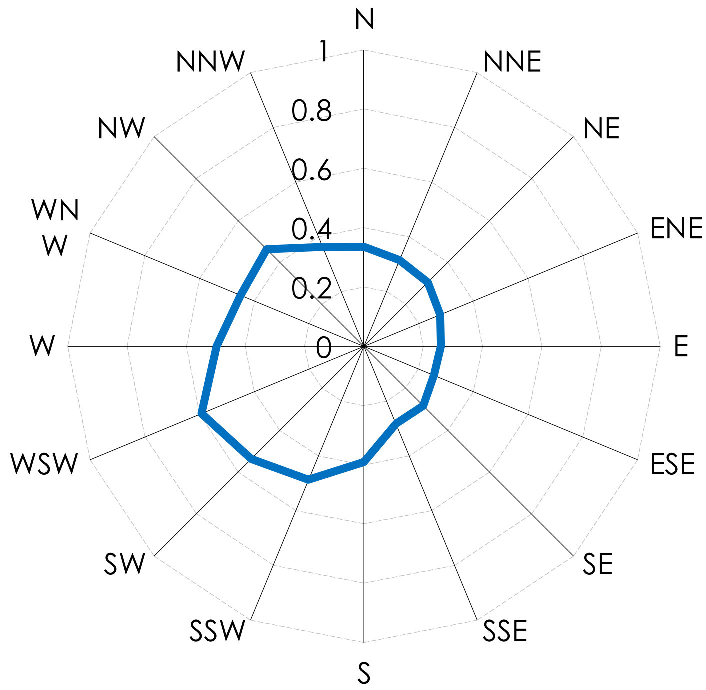
Velocity Coefficient Results for P38



Velocity Coefficient Results for P39



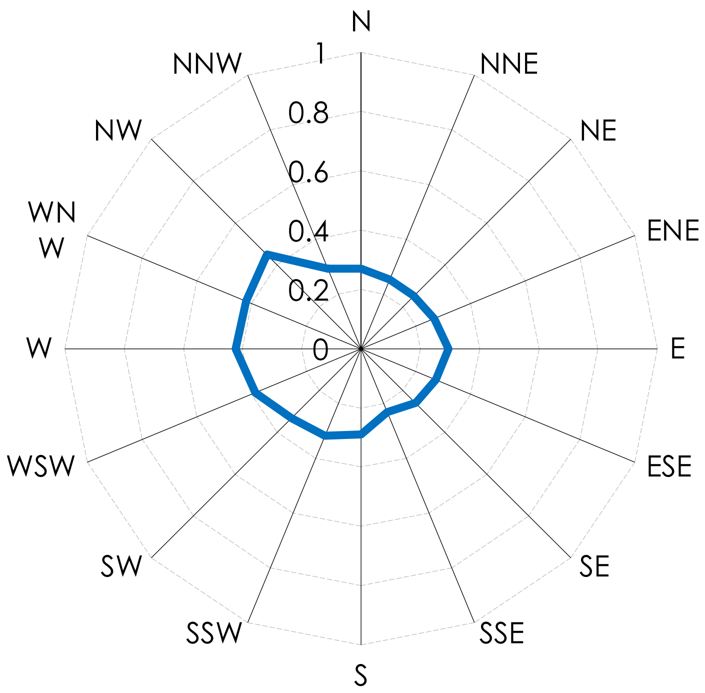
Velocity Coefficient Results for P40

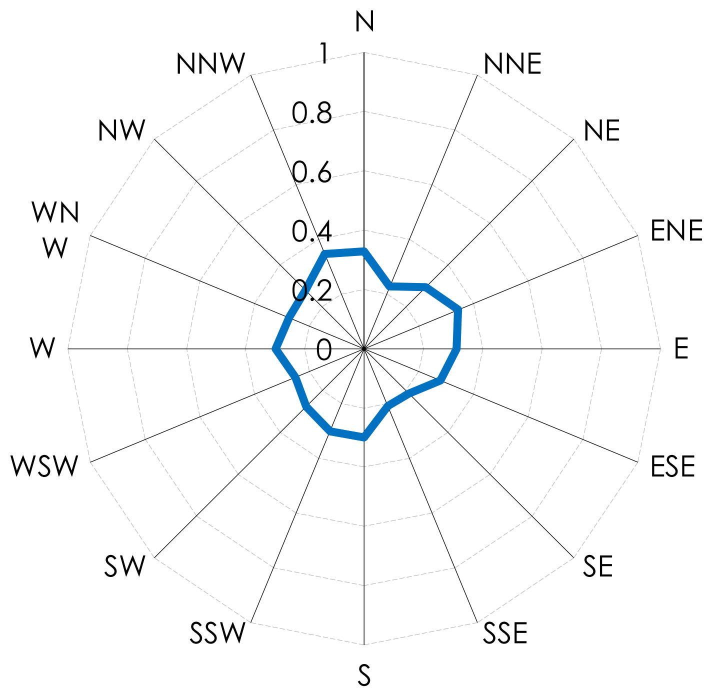


Legend

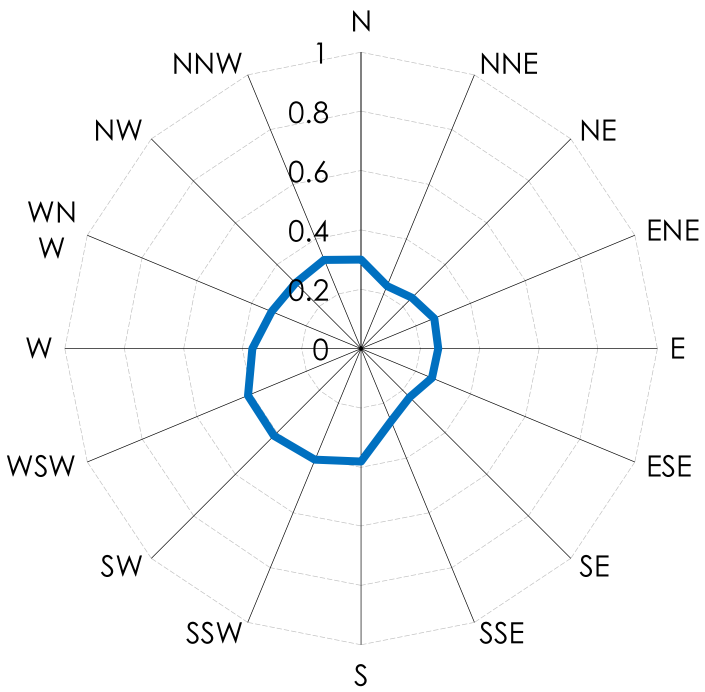
- Proposed Development with Existing Surrounds
- Existing Site Condition

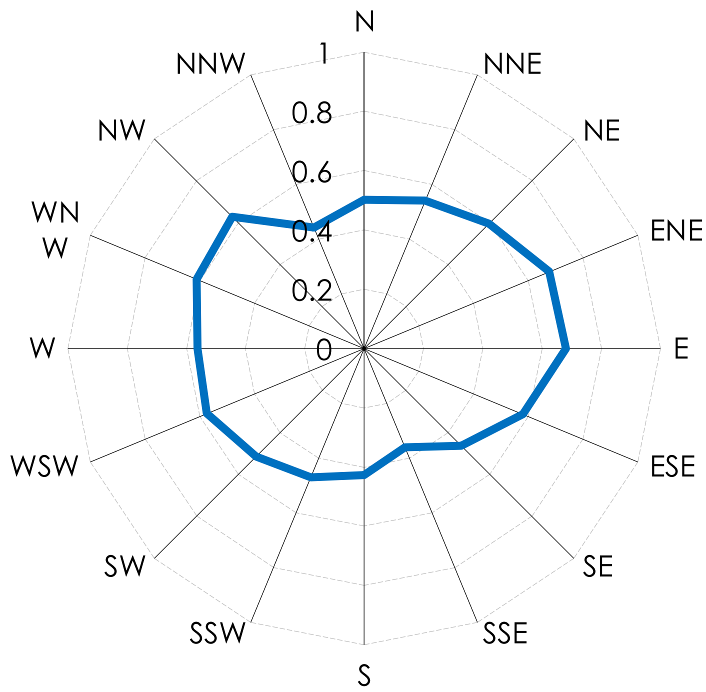
Velocity Coefficient Results for P41	Velocity Coefficient Results for P42





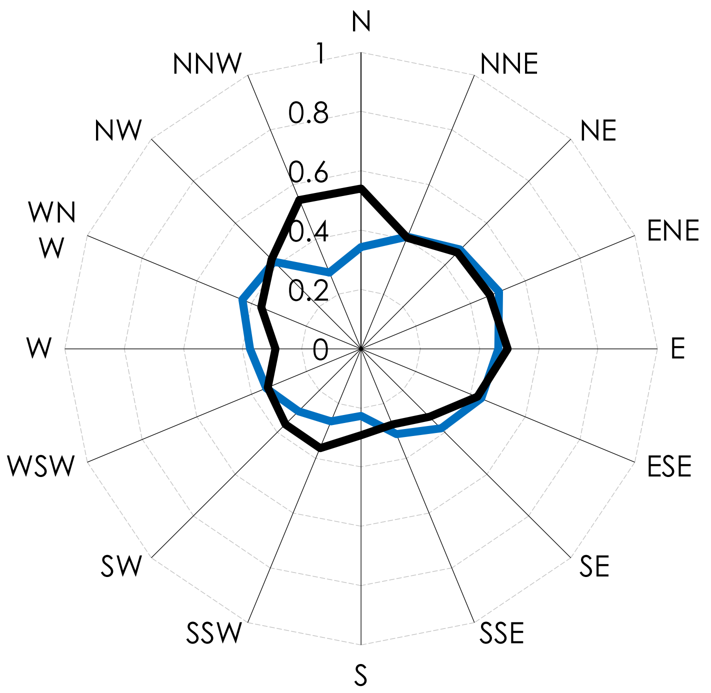
Velocity Coefficient Results for P43	Velocity Coefficient Results for P44



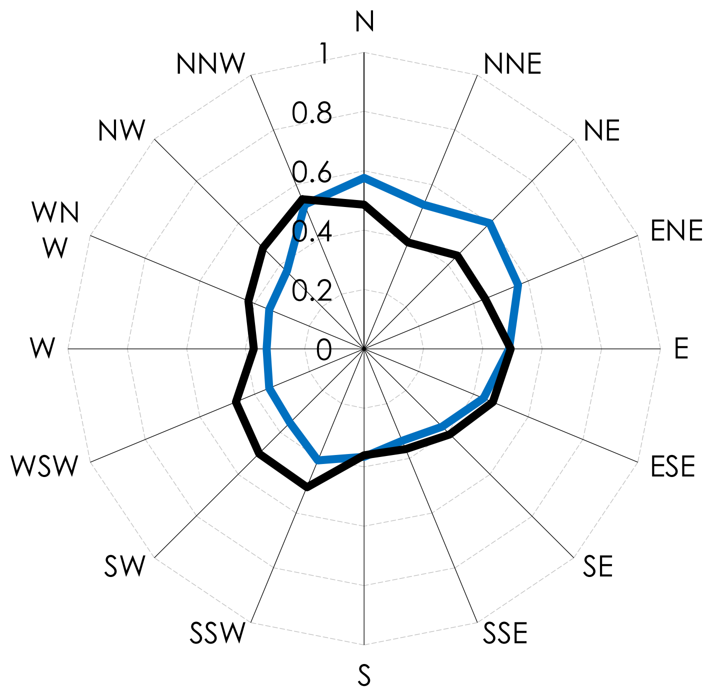


Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

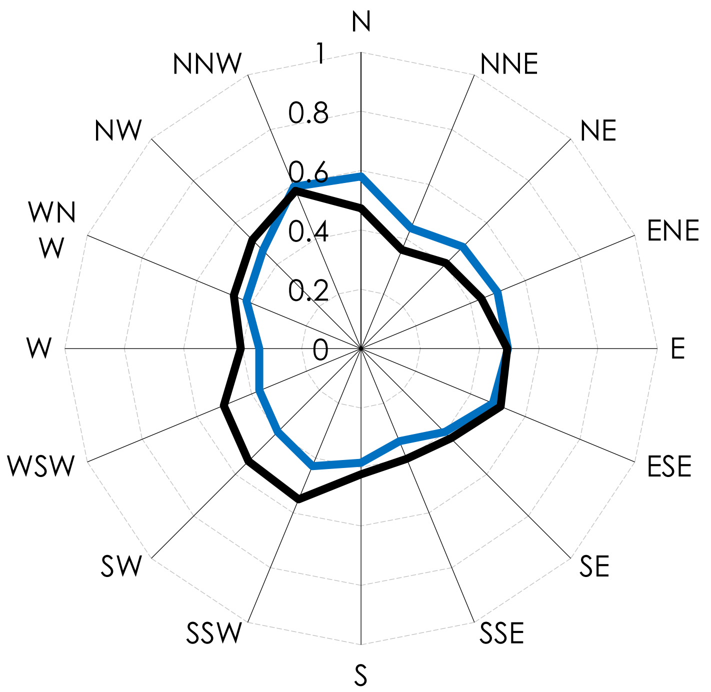
Velocity Coefficient Results for P45



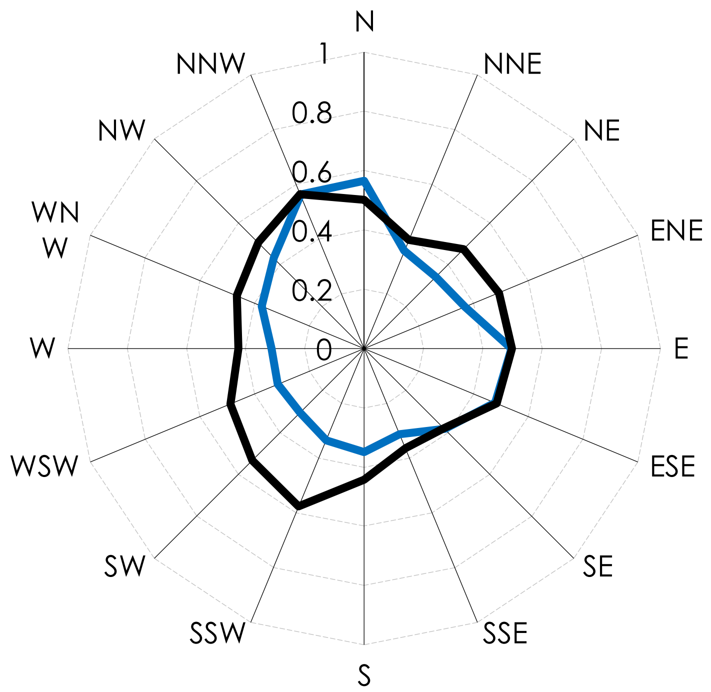
Velocity Coefficient Results for P46



Velocity Coefficient Results for P47



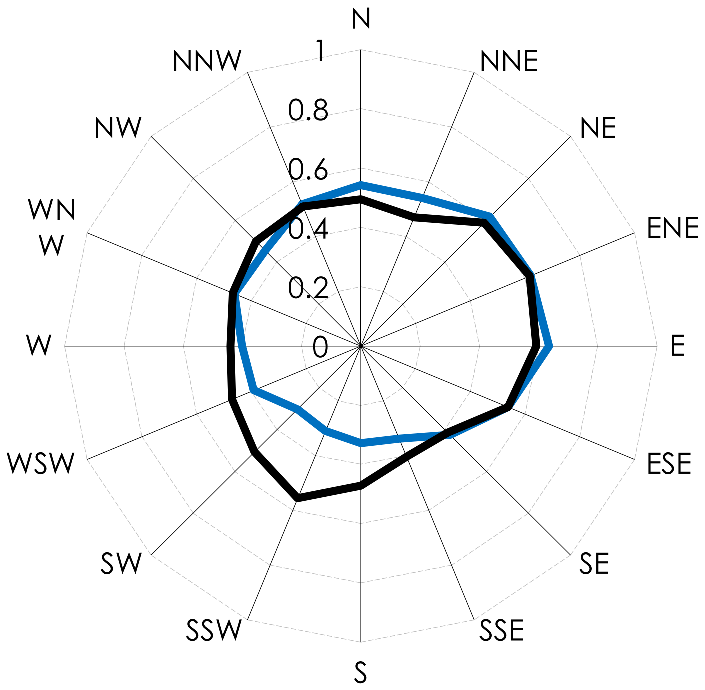
Velocity Coefficient Results for P48



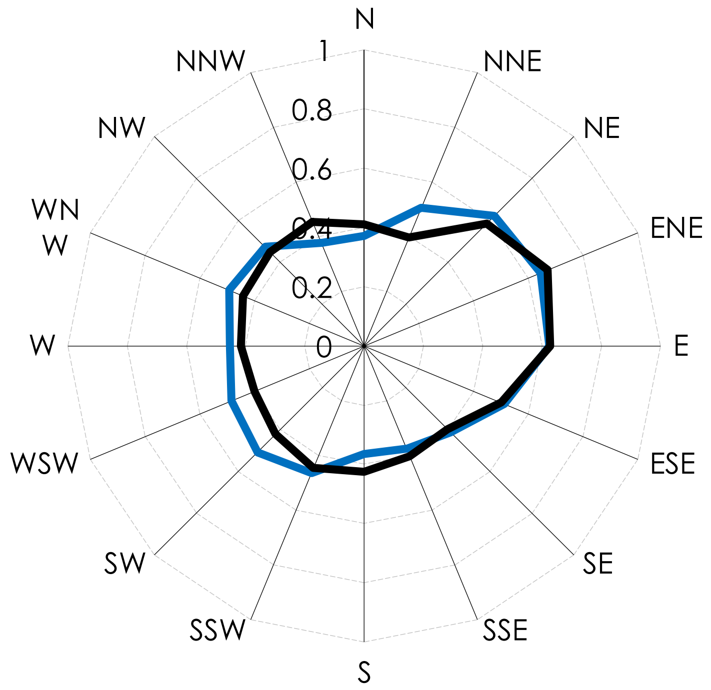
Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

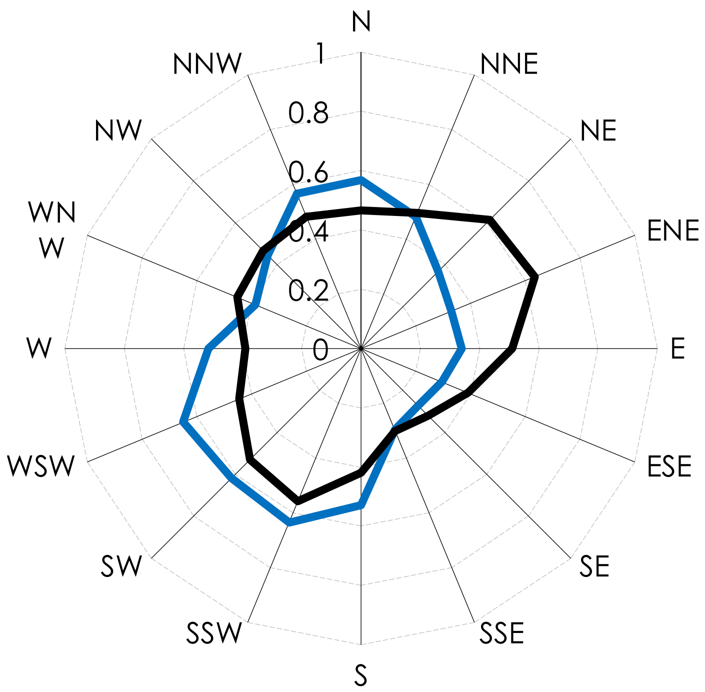
Velocity Coefficient Results for P49



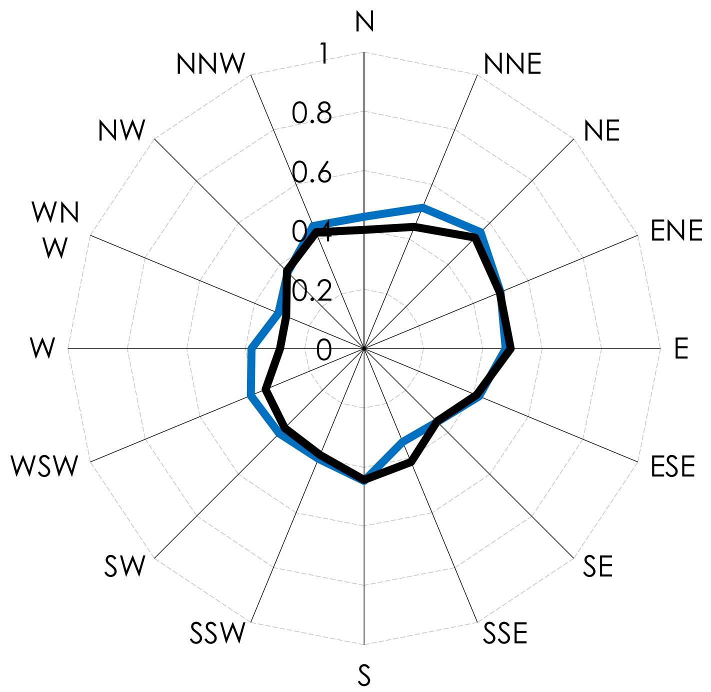
Velocity Coefficient Results for P50



Velocity Coefficient Results for P51



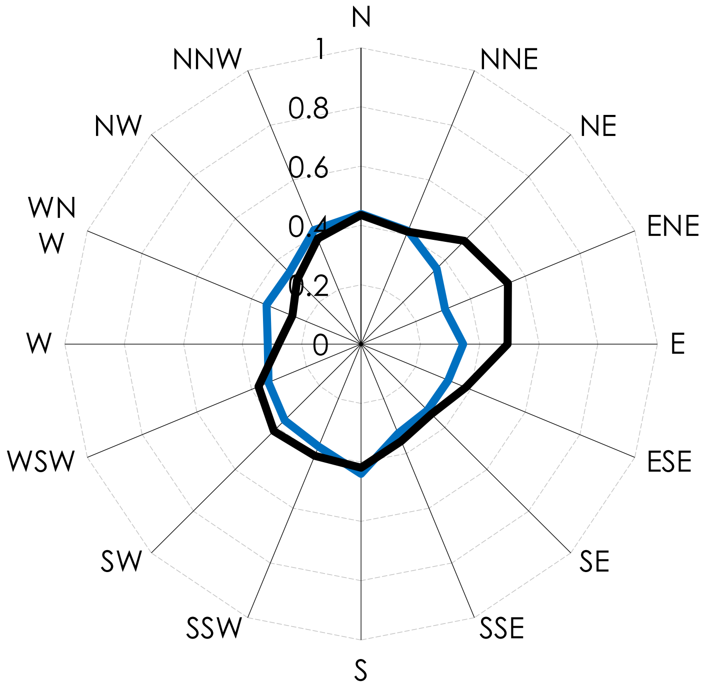
Velocity Coefficient Results for P52



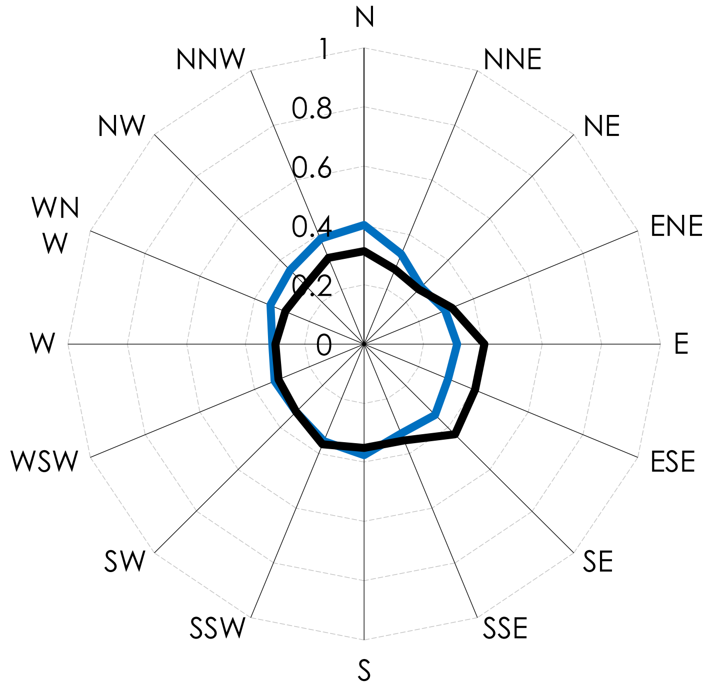
Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

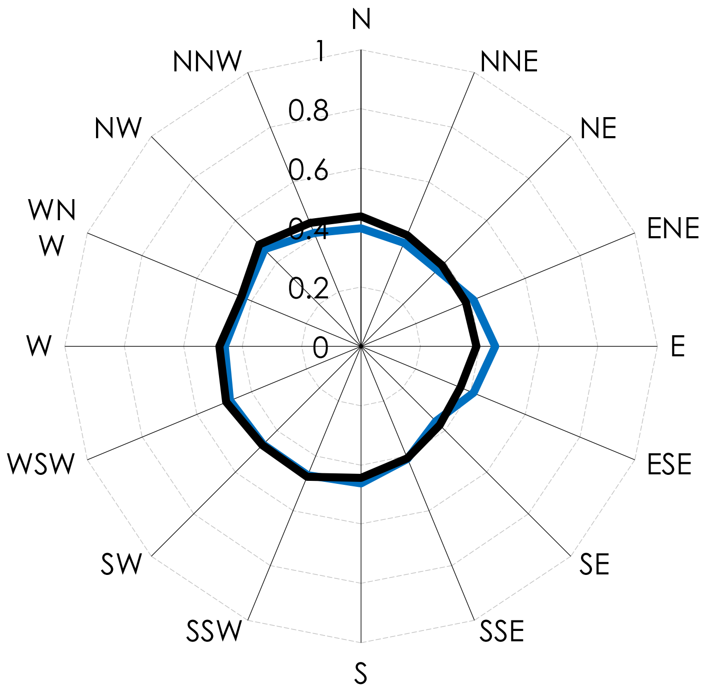
Velocity Coefficient Results for P53



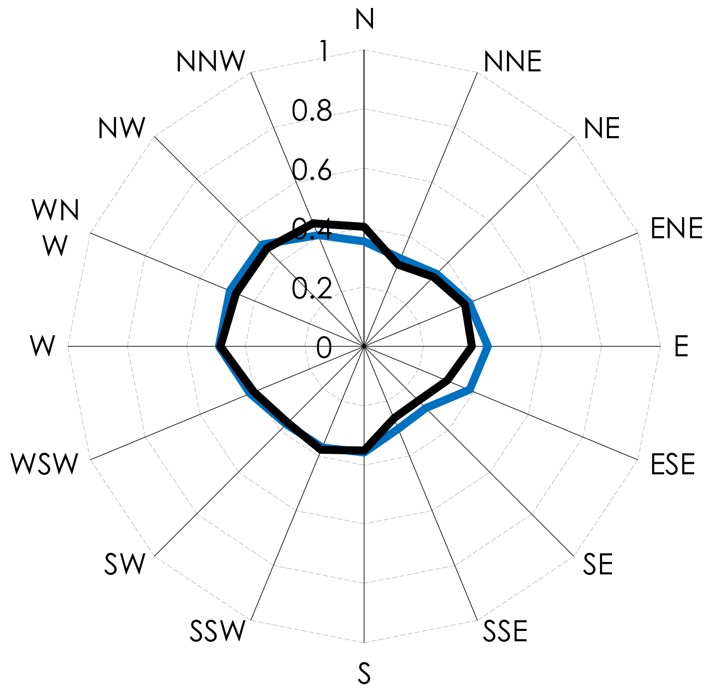
Velocity Coefficient Results for P54



Velocity Coefficient Results for P55



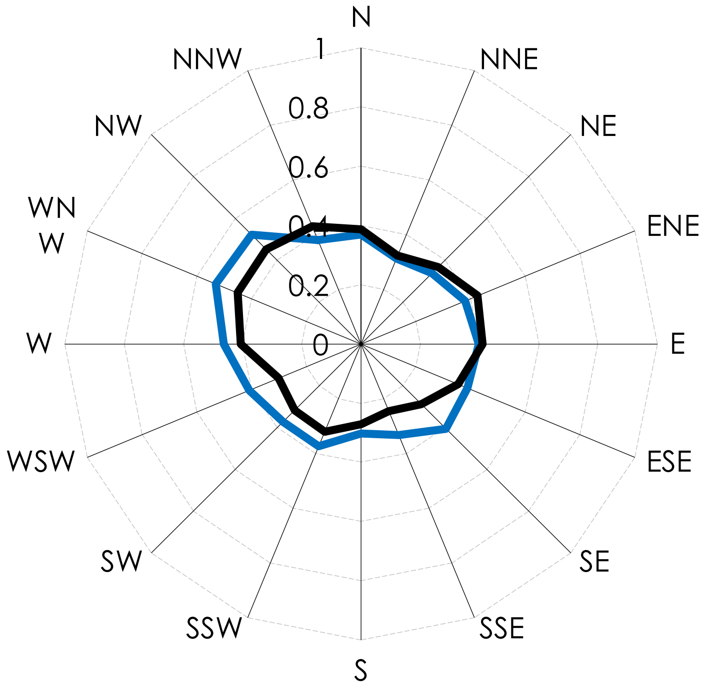
Velocity Coefficient Results for P56



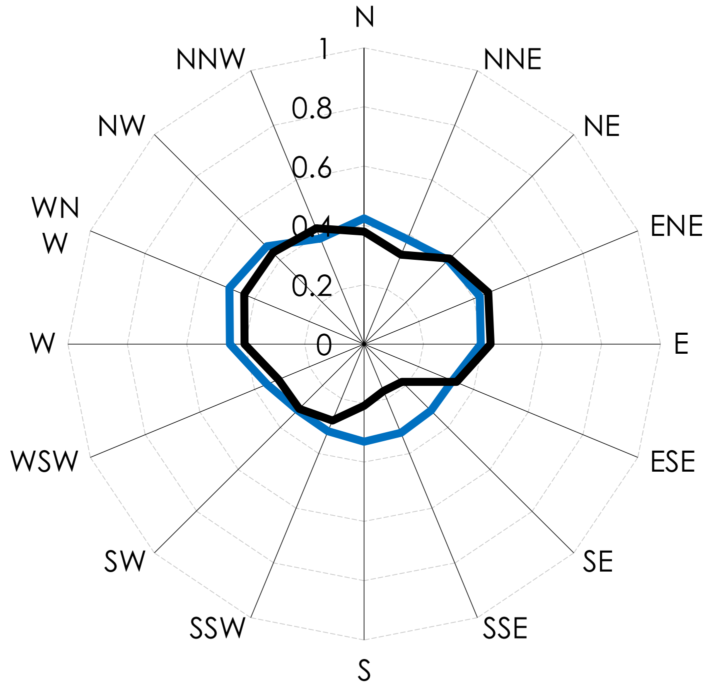
Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

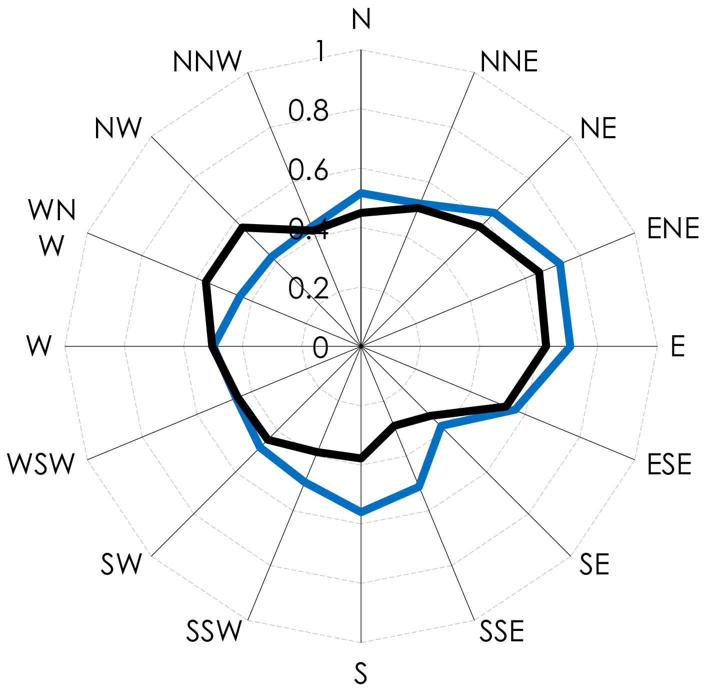
Velocity Coefficient Results for P57



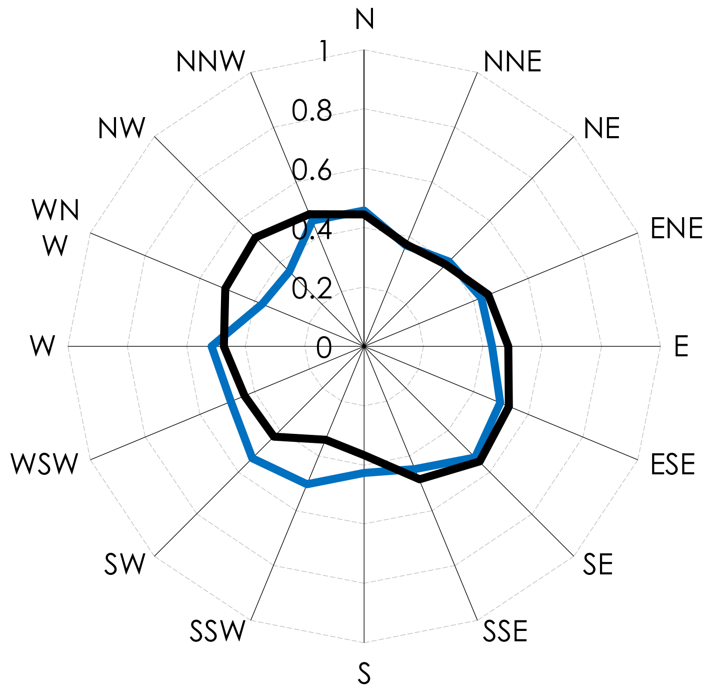
Velocity Coefficient Results for P58



Velocity Coefficient Results for P59



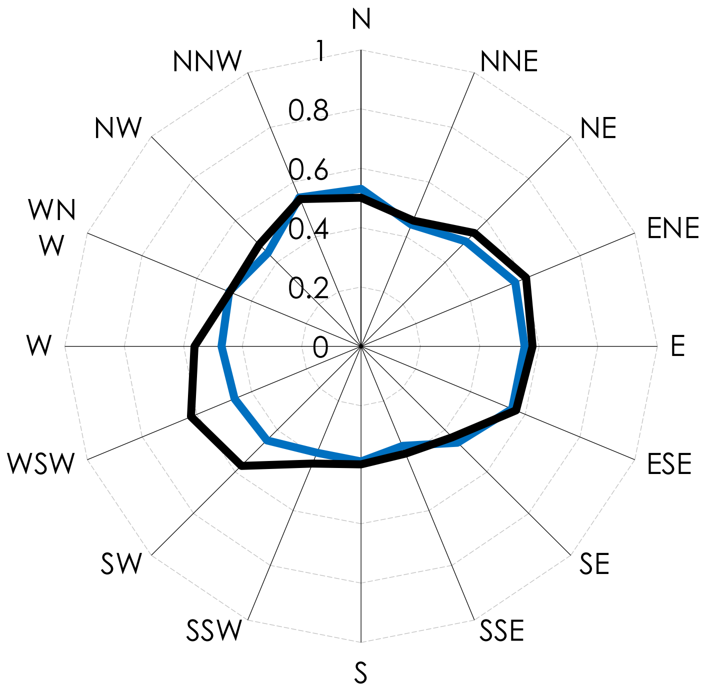
Velocity Coefficient Results for P60



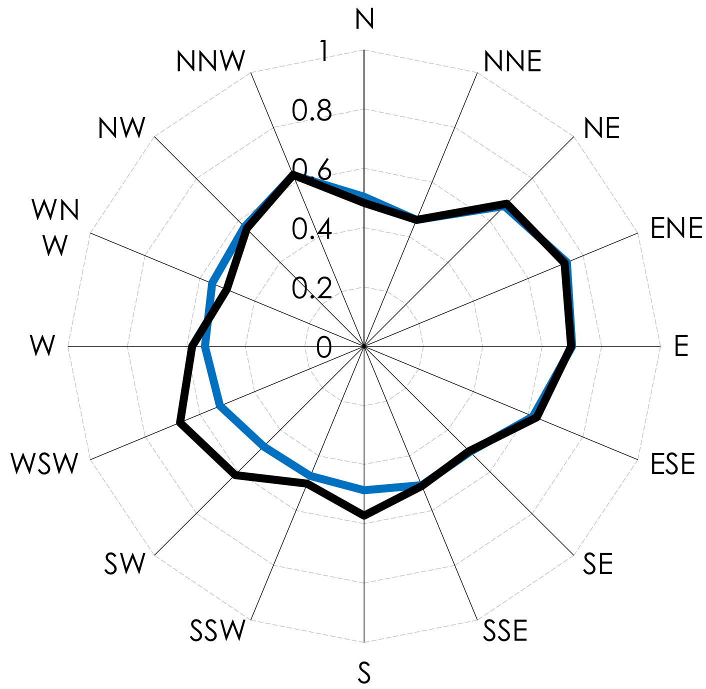
Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

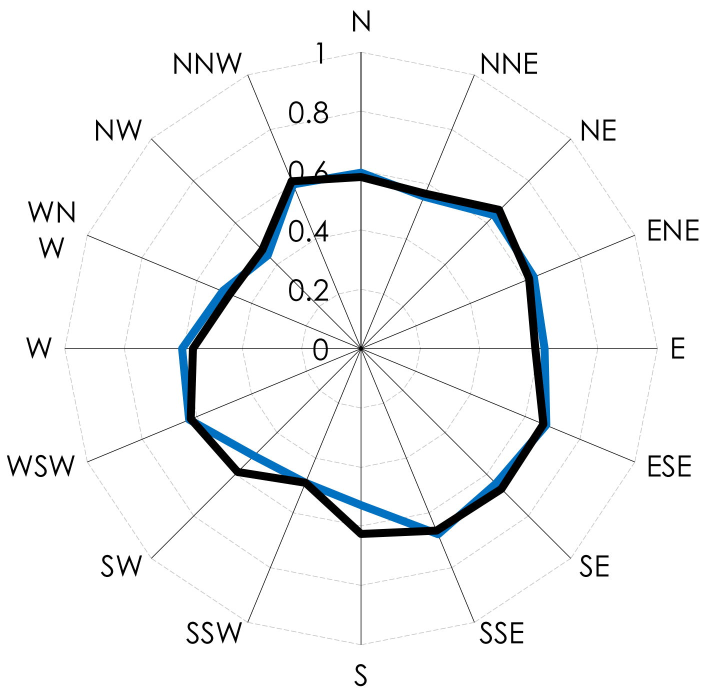
Velocity Coefficient Results for P61



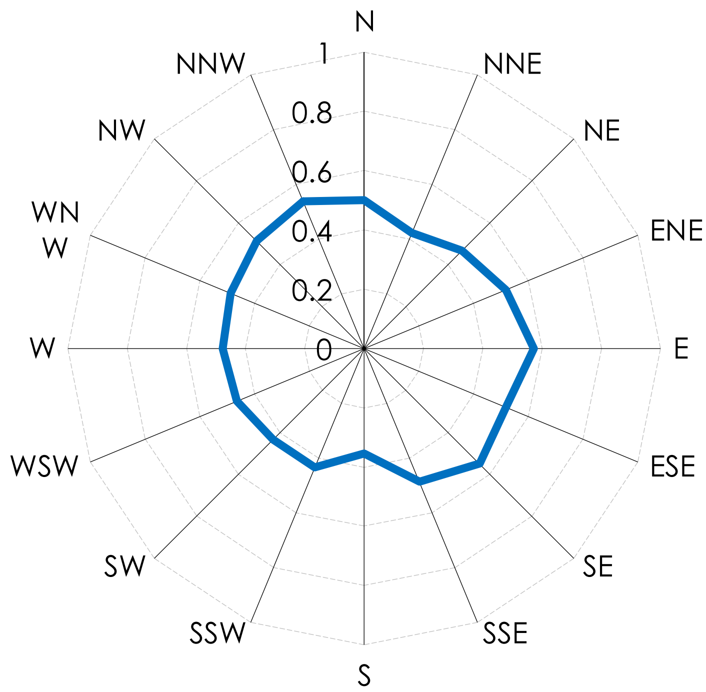
Velocity Coefficient Results for P62



Velocity Coefficient Results for P63

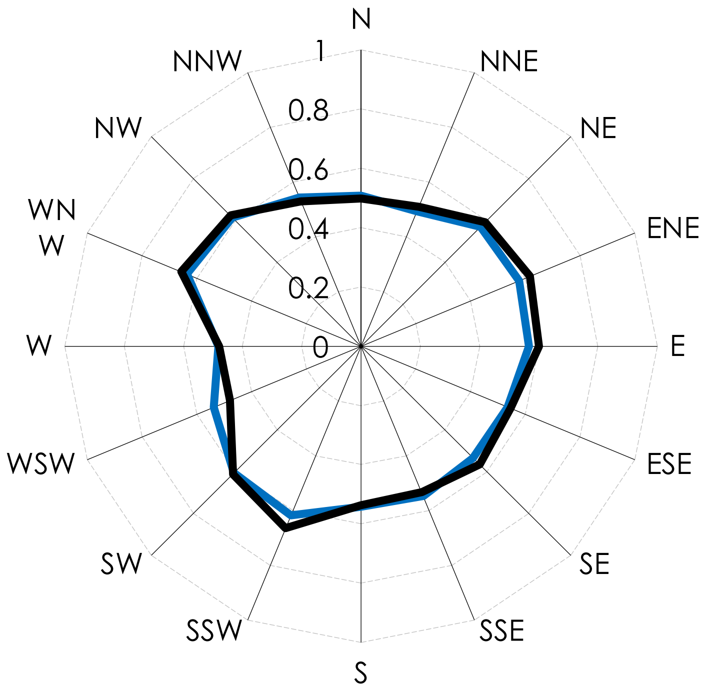
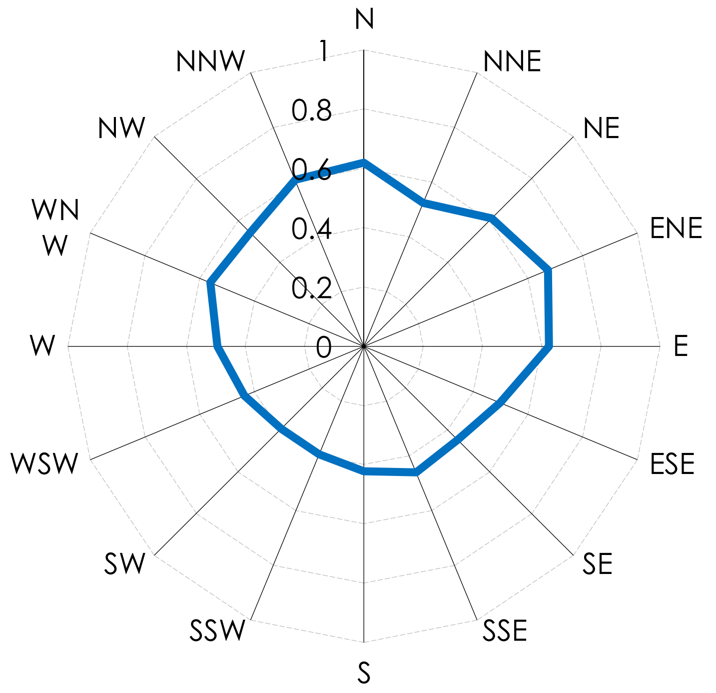


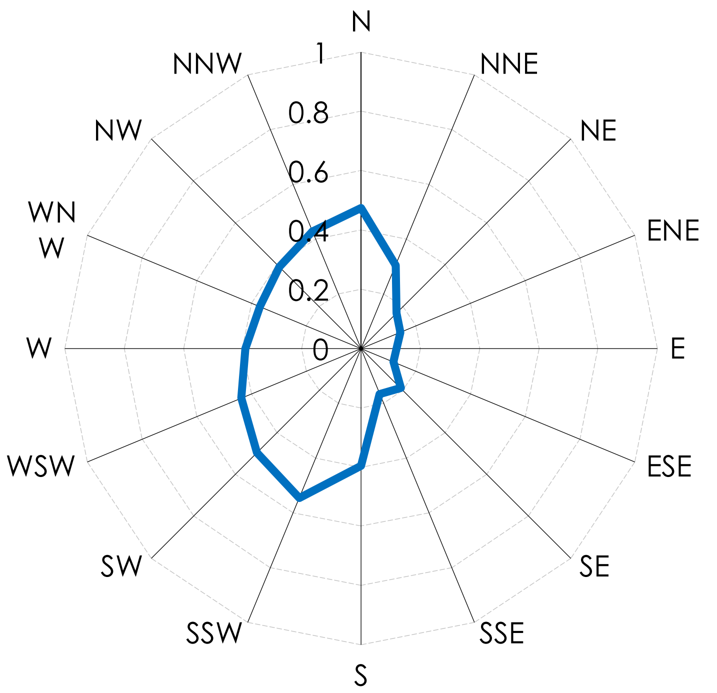
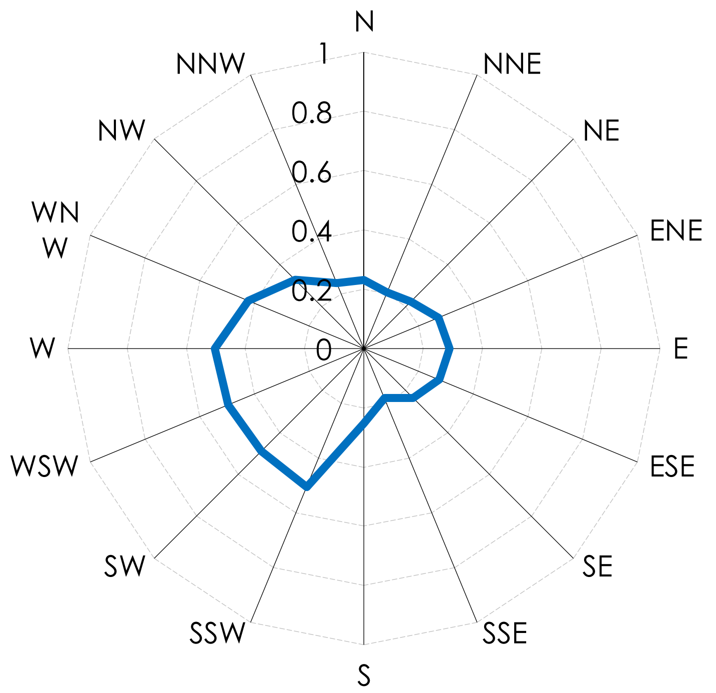
Velocity Coefficient Results for P64



Legend

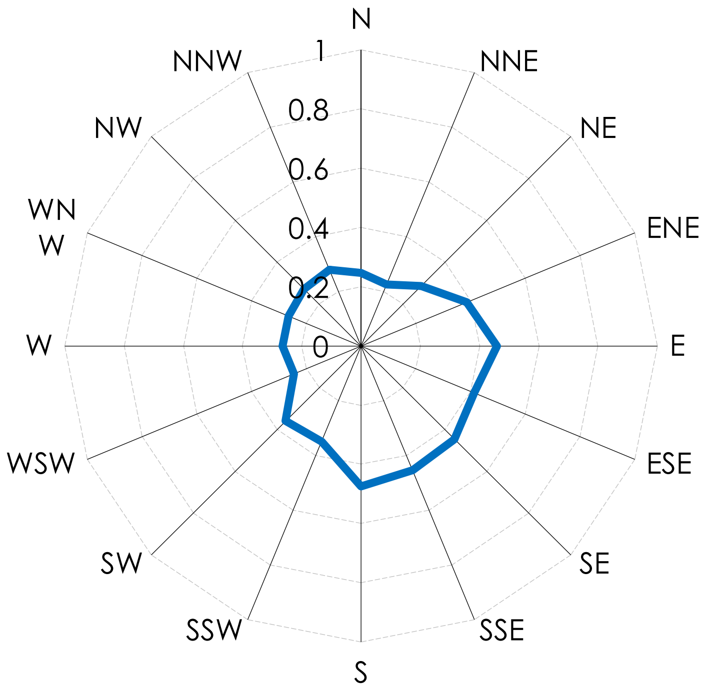
- Proposed Development with Existing Surrounds
- Existing Site Condition

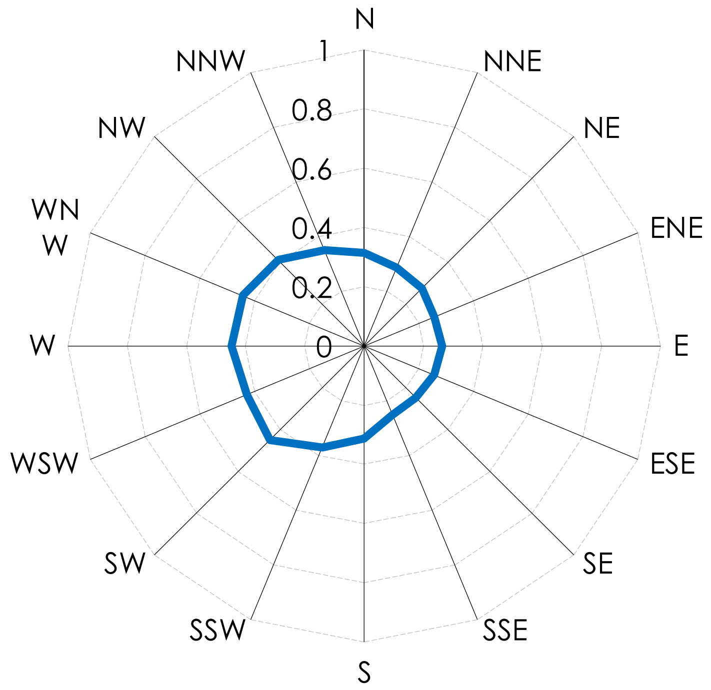
Velocity Coefficient Results for P65	Velocity Coefficient Results for P66
	

Velocity Coefficient Results for P67	Velocity Coefficient Results for P68
	

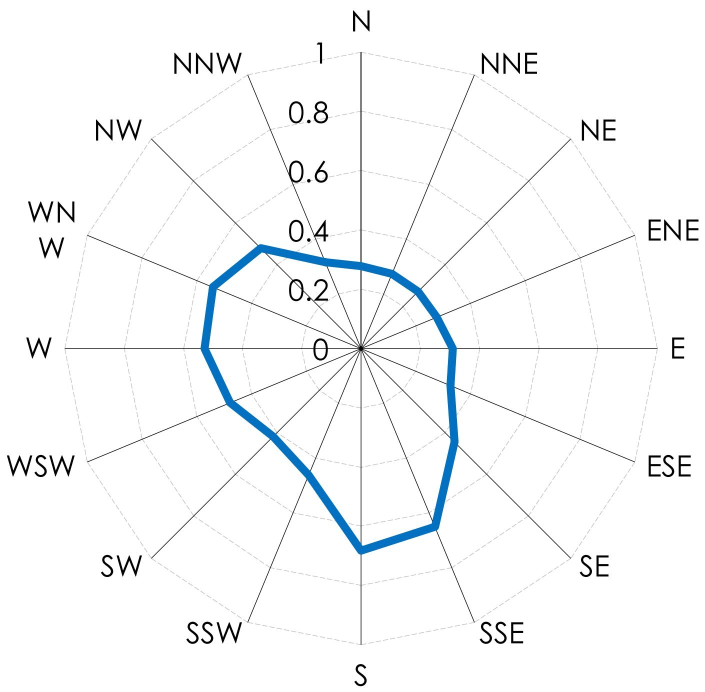
Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

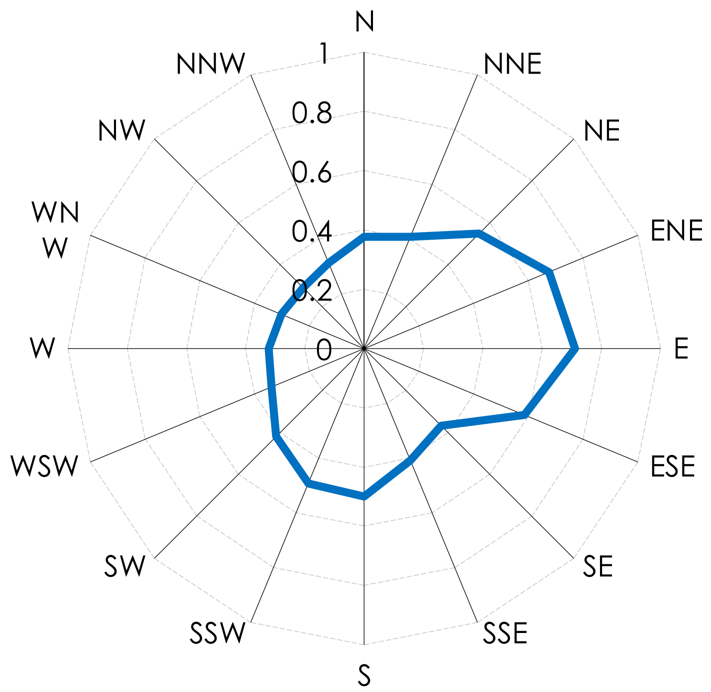
Velocity Coefficient Results for P69	Velocity Coefficient Results for P70





Velocity Coefficient Results for P71	Velocity Coefficient Results for P72

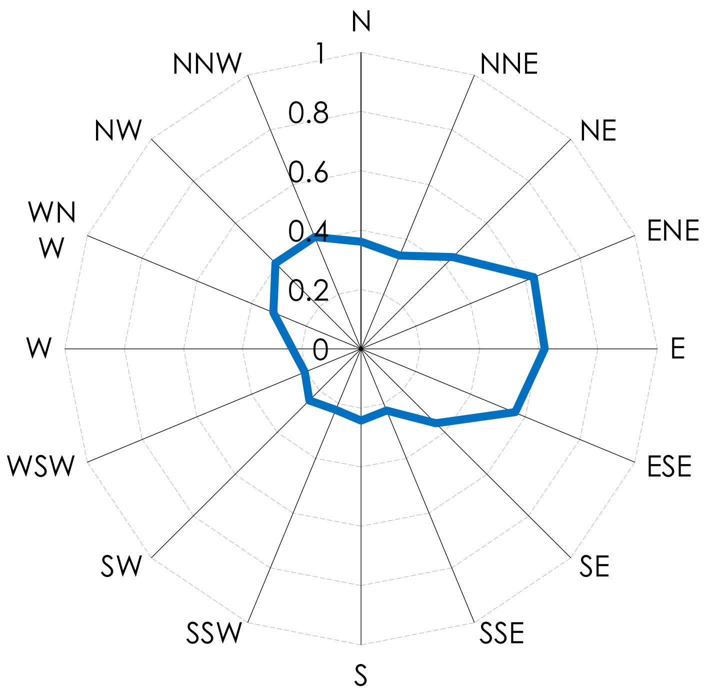




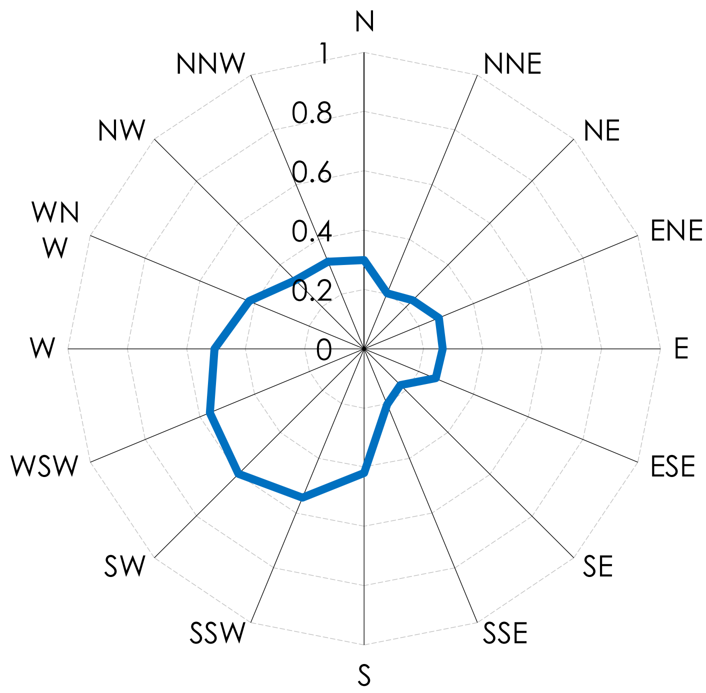
Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

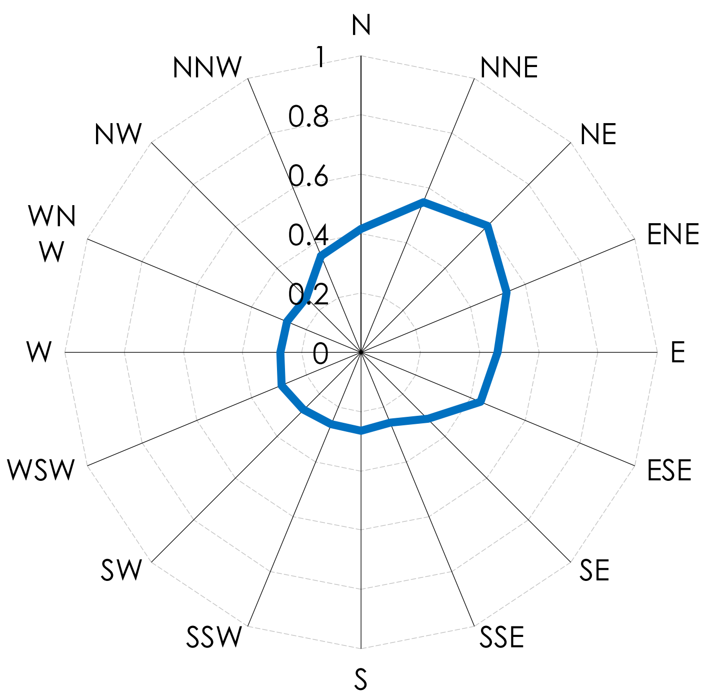
Velocity Coefficient Results for P73



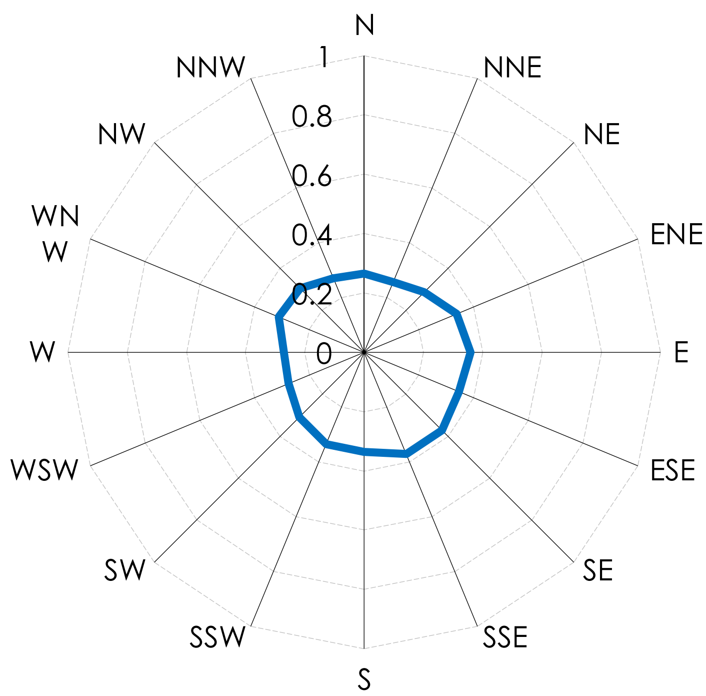
Velocity Coefficient Results for P74



Velocity Coefficient Results for P75

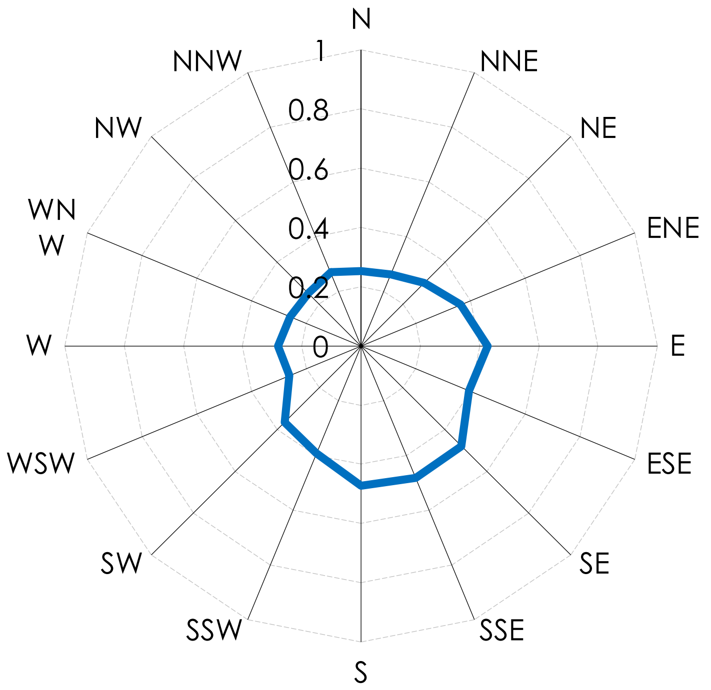


Velocity Coefficient Results for P76

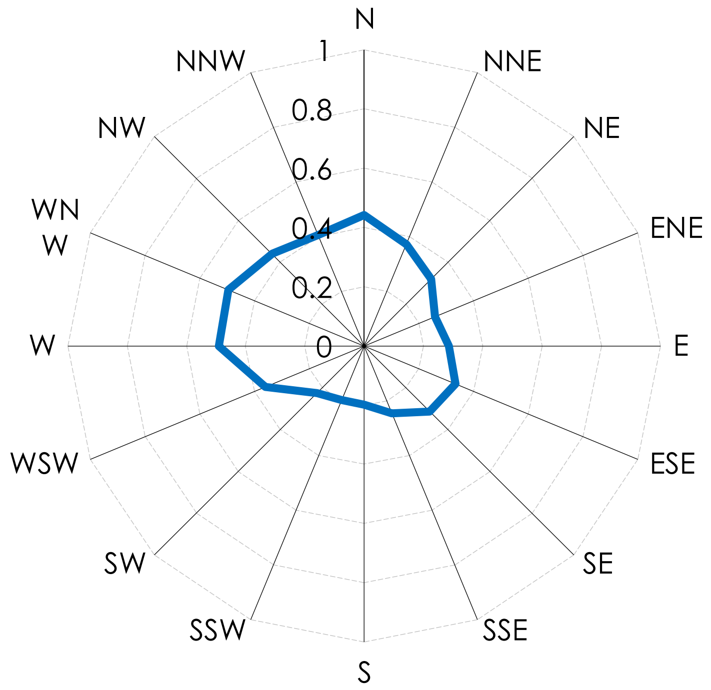


Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

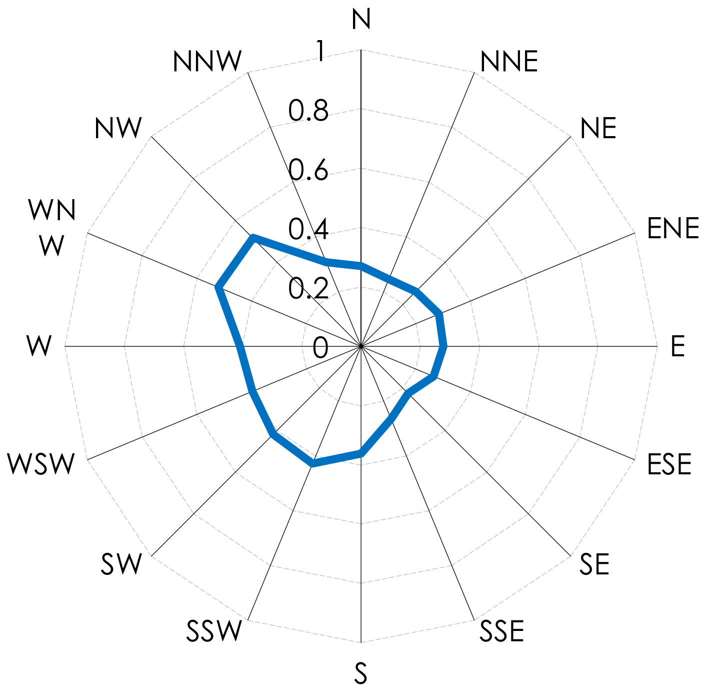
Velocity Coefficient Results for P77



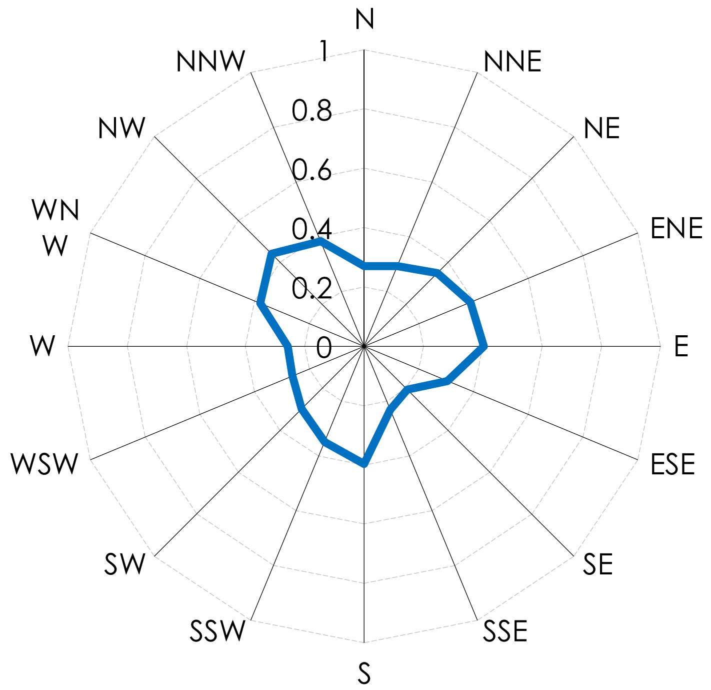
Velocity Coefficient Results for P78



Velocity Coefficient Results for P79

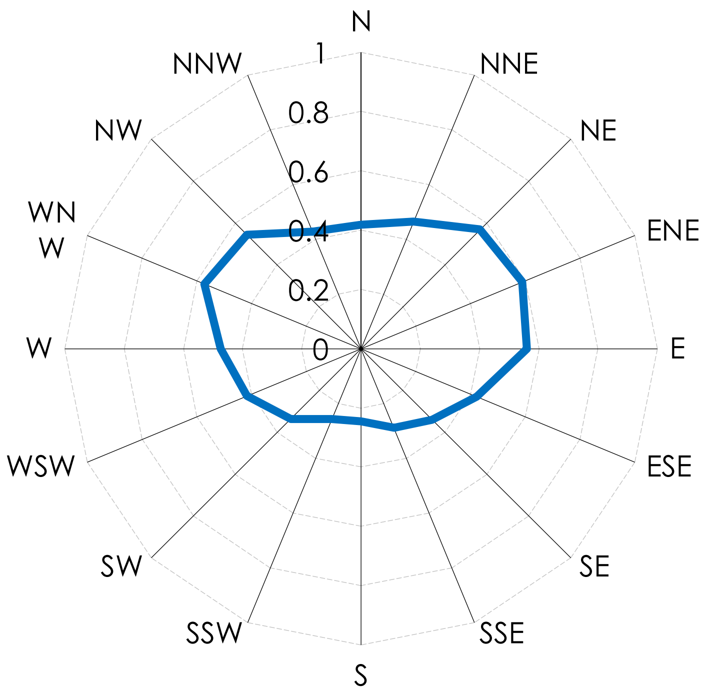


Velocity Coefficient Results for P80

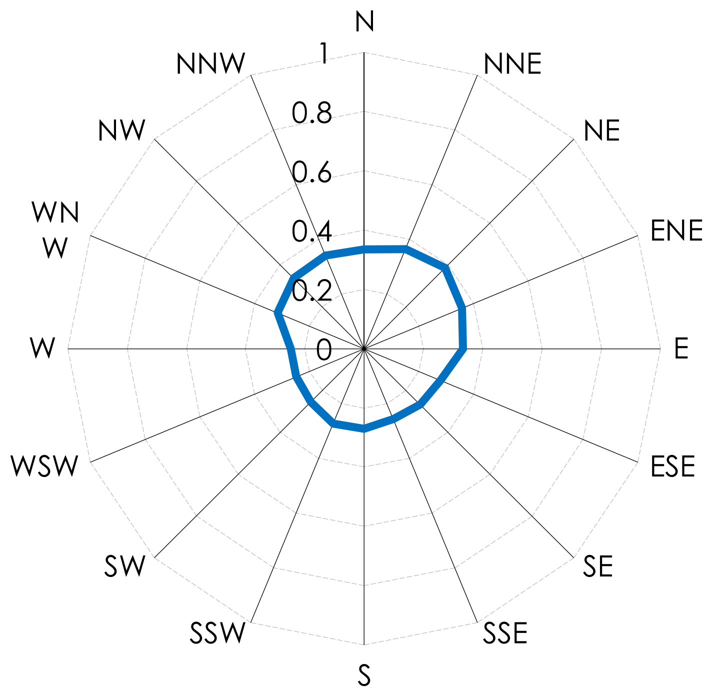


Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

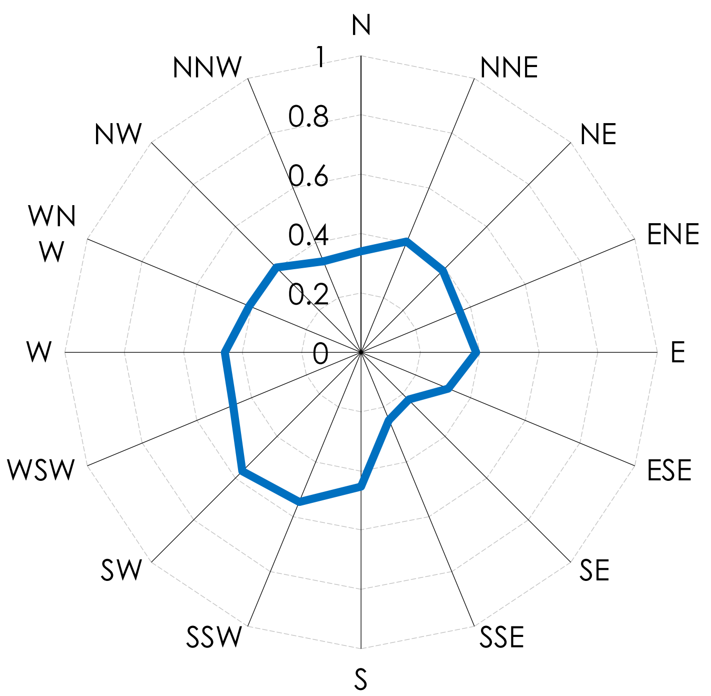
Velocity Coefficient Results for P81



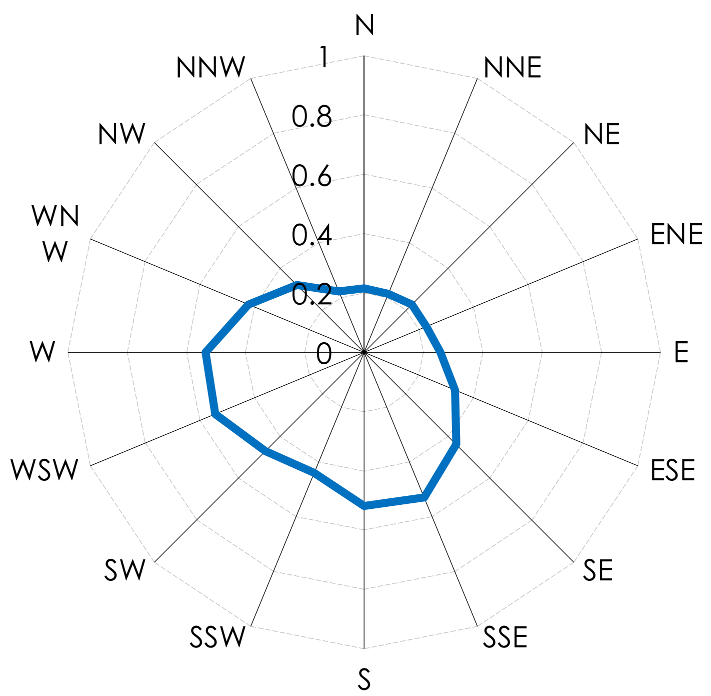
Velocity Coefficient Results for P82



Velocity Coefficient Results for P83



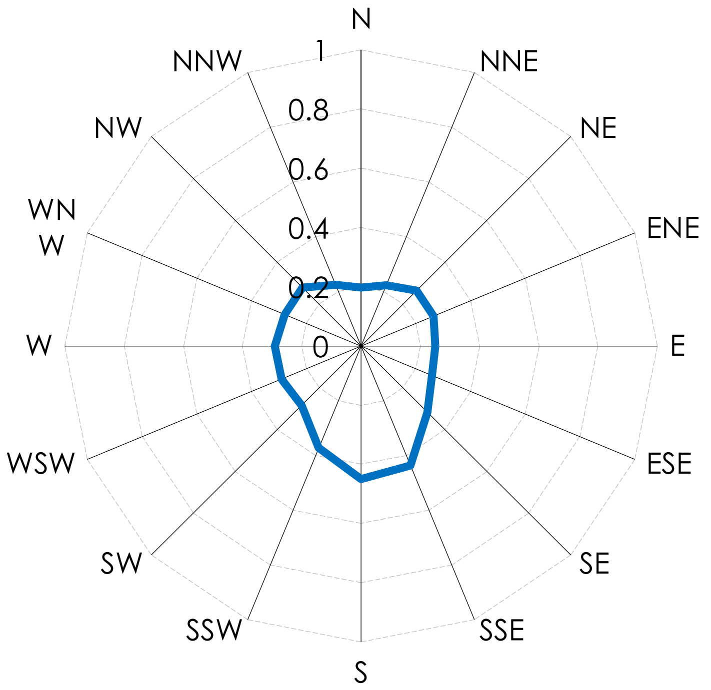
Velocity Coefficient Results for P84

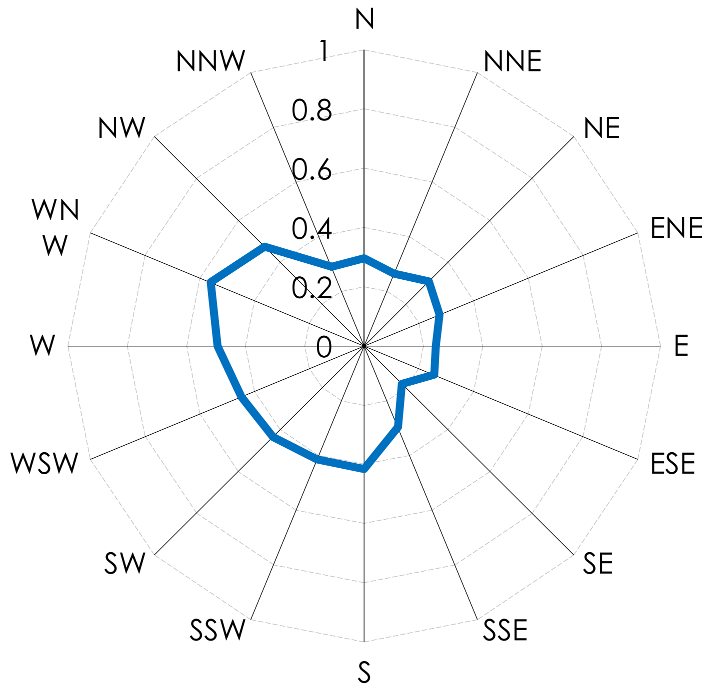


Legend

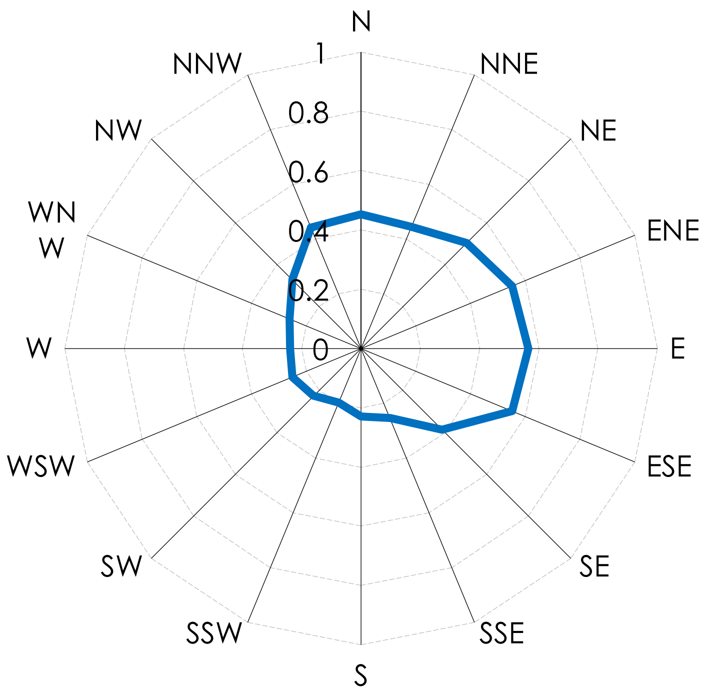
- Proposed Development with Existing Surrounds
- Existing Site Condition

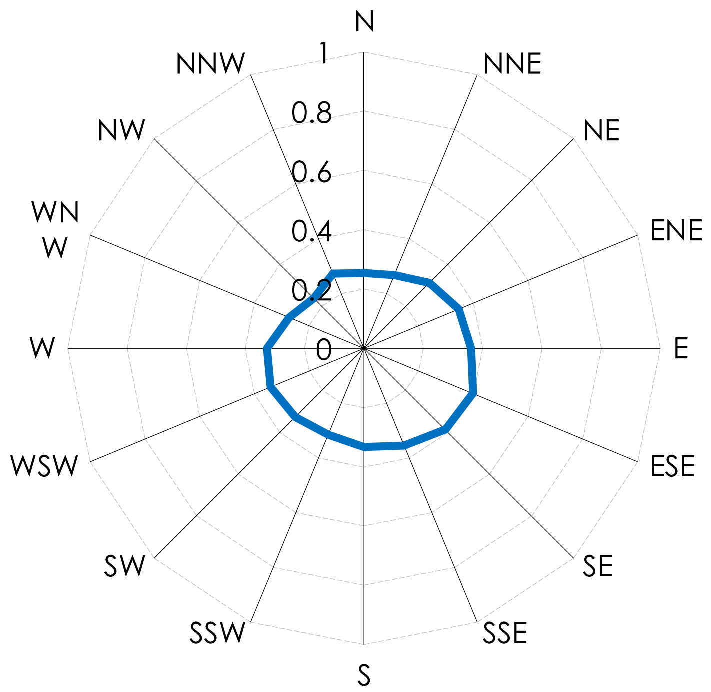
Velocity Coefficient Results for P85	Velocity Coefficient Results for P86





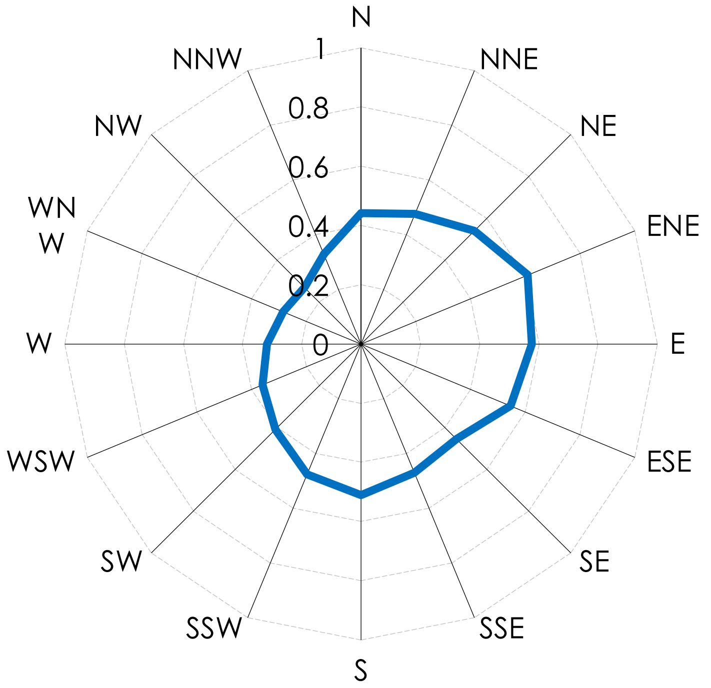
Velocity Coefficient Results for P87	Velocity Coefficient Results for P88



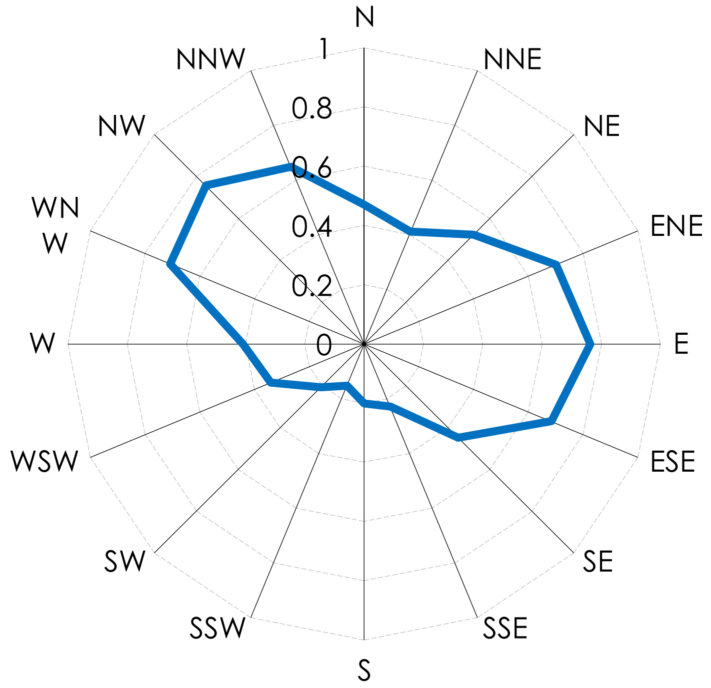


Legend
- Proposed Development with Existing Surrounds
- Existing Site Condition

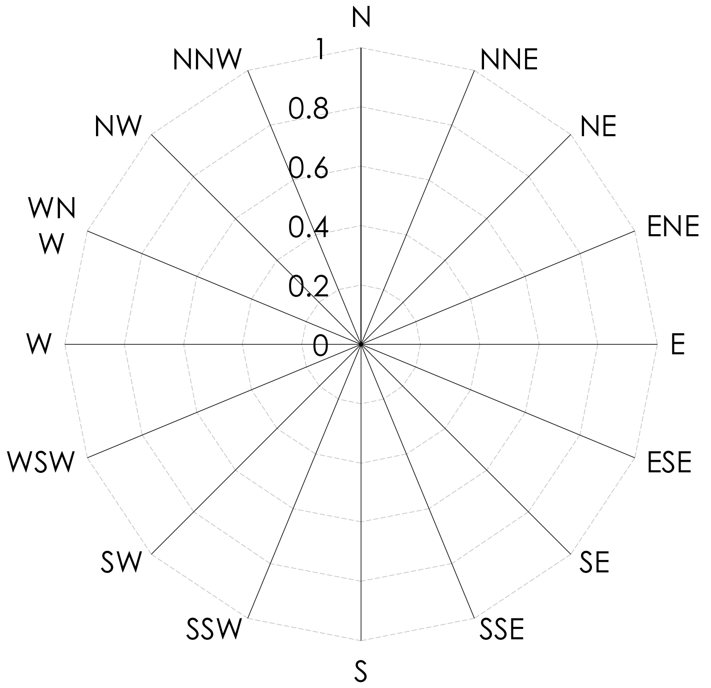
Velocity Coefficient Results for P89



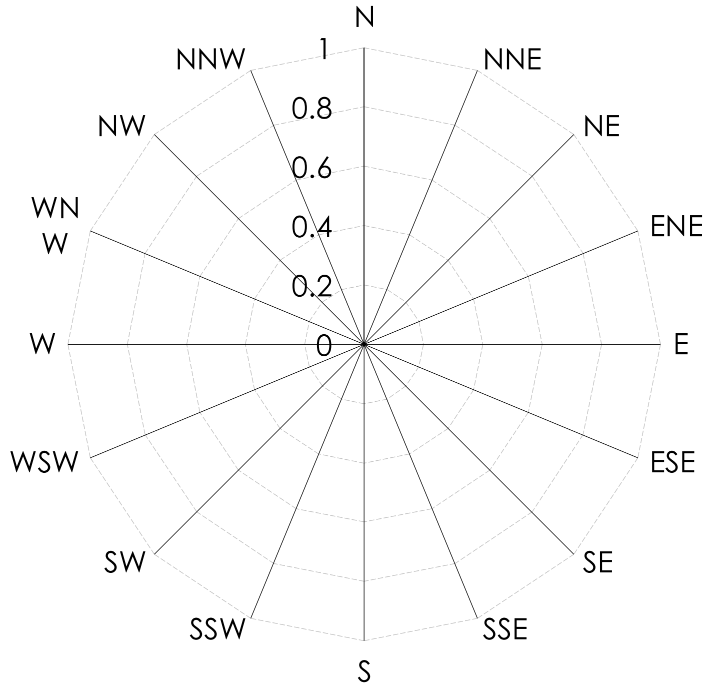
Velocity Coefficient Results for P90



Velocity Coefficient Results for 0



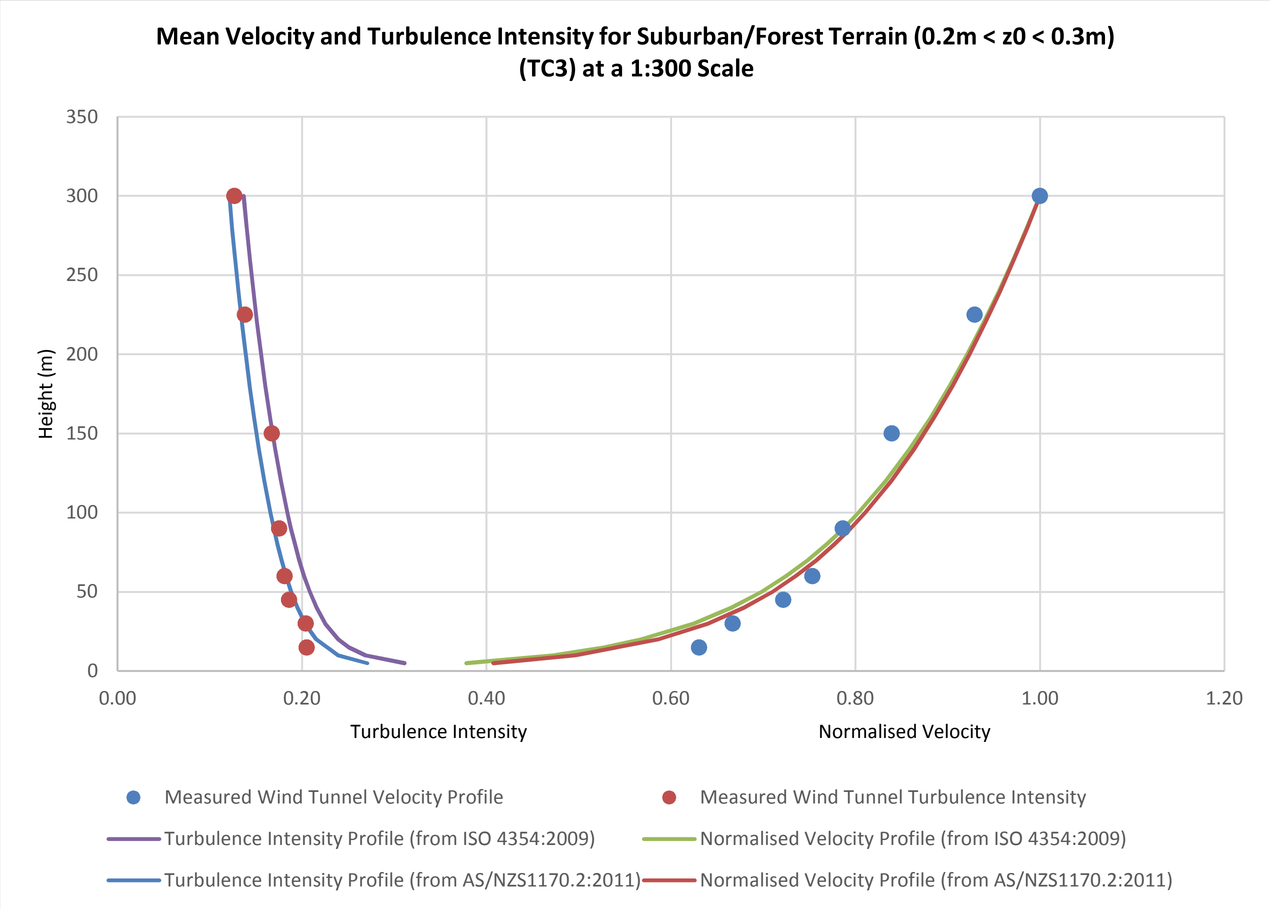
Velocity Coefficient Results for 0

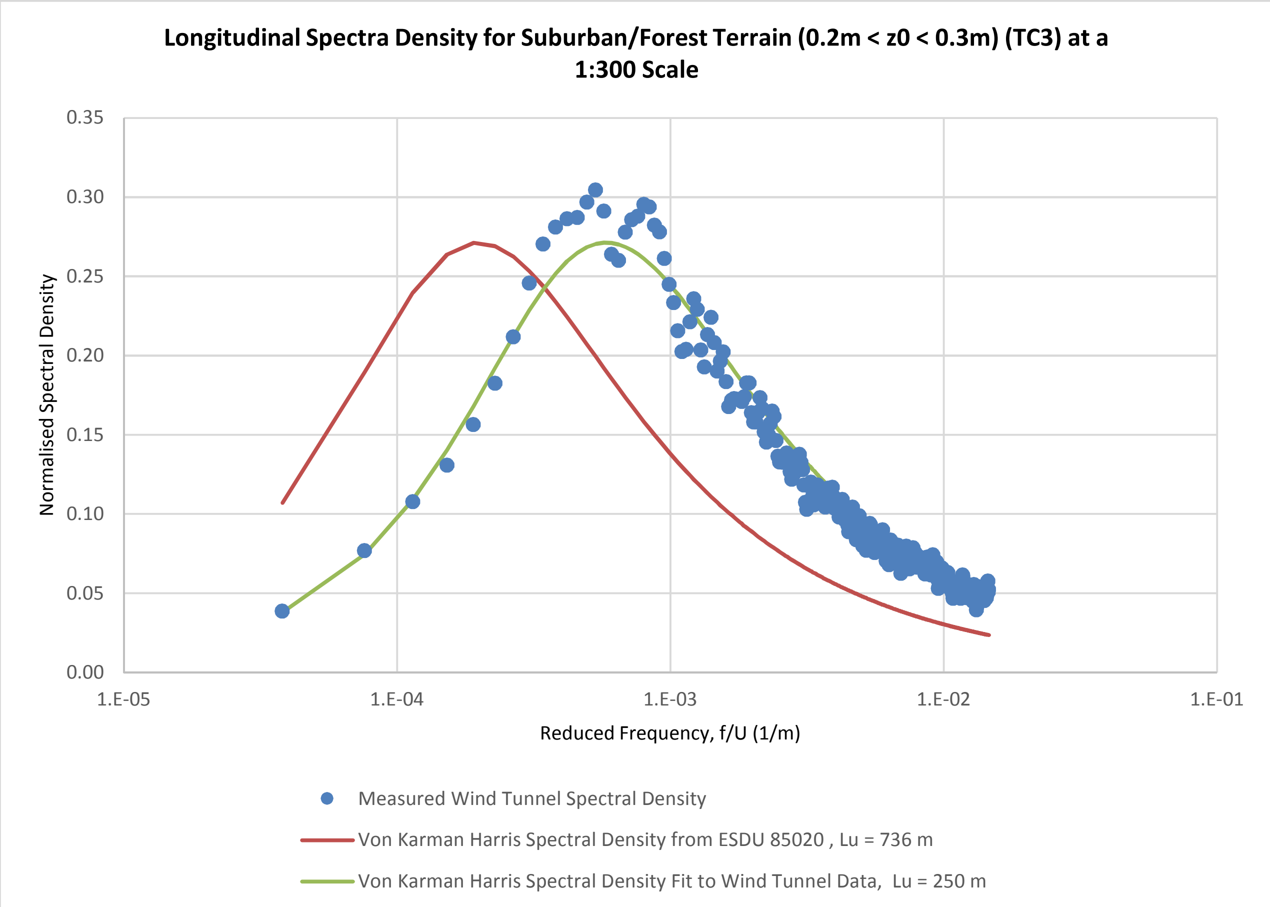


Legend

- Proposed Development with Existing Surrounds
- Existing Site Condition

APPENDIX D VELOCITY AND TURBULENCE INTENSITY PROFILES


Mean Velocity and Turbulence Intensity for Suburban/Forest Terrain (0.2m < z0 < 0.3m) (TC3) at a 1:300 Scale
Height (m)
350
300
250
200
150
100
50
0
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Turbulence Intensity
Normalised Velocity
Measured Wind Tunnel Velocity Profile
Measured Wind Tunnel Turbulence Intensity
Turbulence Intensity Profile (from ISO 4354:2009)
Normalised Velocity Profile (from ISO 4354:2009)
Turbulence Intensity Profile (from AS/NZS1170.2:2011)
Normalised Velocity Profile (from AS/NZS1170.2:2011)


Longitudinal Spectra Density for Suburban/Forest Terrain (0.2m < z0 < 0.3m) (TC3) at a 1:300 Scale
Normalised Spectral Density
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
Reduced Frequency, f/U (1/m)
Measured Wind Tunnel Spectral Density
Von Karman Harris Spectral Density from ESDU 85020 , Lu = 736 m
Von Karman Harris Spectral Density Fit to Wind Tunnel Data, Lu = 250 m