

**PEDESTRIAN LEVEL  
WIND STUDY**

100 Gloucester Street  
Ottawa, Ontario

Report: 22-295-PLW



October 4, 2022

PREPARED FOR  
Claridge Homes  
210 Gladstone Avenue  
Ottawa, ON, K2P 0Y6

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## EXECUTIVE SUMMARY

This report describes a pedestrian level wind (PLW) study undertaken to satisfy simultaneous Zoning By-law Amendment and Site Plan Control application requirements for the proposed mixed-use residential development located at 100 Gloucester Street in Ottawa, Ontario (hereinafter referred to as “subject site” or “proposed development”). Our mandate within this study is to investigate pedestrian wind conditions within and surrounding the subject site, and to identify areas where wind conditions may interfere with certain pedestrian activities so that mitigation measures may be considered, where required.

The study involves simulation of wind speeds for selected wind directions in a three-dimensional (3D) computer model using the computational fluid dynamics (CFD) technique, combined with meteorological data integration, to assess pedestrian wind comfort and safety within and surrounding the subject site according to City of Ottawa wind comfort and safety criteria. The results and recommendations derived from these considerations are detailed in the main body of the report (Section 5), illustrated in Figures 3A-8, and summarized as follows:

- 1) All grade-level areas within and surrounding the subject site are predicted to experience conditions that are considered acceptable for the intended pedestrian uses throughout the year. Specifically, conditions over surrounding sidewalks, walkways, the laneway and drop-off area, the existing pool area, the outdoor amenity, and in the vicinity of building access points are predicted to be suitable for sitting throughout the year, which are considered acceptable.
- 2) Conditions over the potential amenity terrace serving the proposed development at Level 8 are predicted to be suitable for sitting throughout the year, which are considered acceptable.
- 3) Conditions over the amenity terrace serving the proposed development at the MPH level are predicted to be suitable for sitting during the typical use period, which are considered acceptable.
- 4) The foregoing statements and conclusions apply to common weather systems, during which no dangerous wind conditions, as defined in Section 4.4, are expected anywhere over the subject site. During extreme weather events, (e.g., thunderstorms, tornadoes, and downbursts), pedestrian safety is the main concern. However, these events are generally short-lived and infrequent and there is often sufficient warning for pedestrians to take appropriate cover.



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## **1. INTRODUCTION**

Gradient Wind Engineering Inc. (Gradient Wind) was retained by Claridge Homes to undertake a pedestrian level wind (PLW) study to satisfy simultaneous Zoning By-law Amendment and Site Plan Control application requirements for the proposed mixed-use residential development located at 100 Gloucester Street in Ottawa, Ontario (hereinafter referred to as “subject site” or “proposed development”). Our mandate within this study is to investigate pedestrian wind conditions within and surrounding the subject site, and to identify areas where wind conditions may interfere with certain pedestrian activities so that mitigation measures may be considered, where required.

Our work is based on industry standard computer simulations using the computational fluid dynamics (CFD) technique and data analysis procedures, City of Ottawa wind comfort and safety criteria, architectural drawings prepared by EVOQ Architecture, in September 2022, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent satellite imagery.

## **2. TERMS OF REFERENCE**

The subject site is located at 100 Gloucester Street in Ottawa; situated on the north side of a city block bordered by Gloucester Street to the northwest, Metcalfe Street to the northeast, Nepean Street to the southeast, and O’Connor Street to the southwest. Throughout this report, Gloucester Street is referred to as project north. An existing pool area is situated at the southwest corner of the subject site.

The proposed development comprises a near rectangular 27-storey building, topped with a mechanical penthouse (MPH). Above two below-grade parking levels, the ground floor of the proposed development is divided into two masses by a central north-south laneway. The eastern massing includes residential main entrances and lobby at the northwest corner, residential units from the northeast corner clockwise to the south, indoor amenity at the southwest corner, and central elevator core and staircase. A drop off area is situated along the north elevation, walkways are along the east and south elevations, and outdoor amenity is along the south elevation of the eastern massing. The western massing includes commercial space to the north, a residential main entrance to the east, a staircase at the southeast corner, waste room to the south, and a vault area at the southwest corner. Levels 2-27 are reserved for residential use.



Floorplate setbacks are situated near the northwest corner at Level 6 and to the east at Level 7. Private terraces are situated near the southwest corner at Levels 3-5 and along the south elevation at Levels 6-8. A potential amenity terrace is situated to the west at Level 8. The MPH level includes indoor mechanical space to the west. This level is also served by an amenity terrace from the north clockwise to the east, and outdoor mechanical space occupies the southeast corner.

The near-field surroundings, defined as an area within 200-metres (m) of the subject site, include a mix of mid- and high-rise buildings in all compass directions, with isolated low-rise buildings to the northeast and from the southeast clockwise to the west-southwest. Notably, two 27-storey mixed-use residential buildings are under construction at 70 Gloucester Street and 89-91 Nepean Street, to the immediate east and southeast, respectively, of the subject site. In addition, a 30-storey mixed-use residential building is proposed (awaiting Site Plan Control approval) at 180 Metcalfe Street, approximately 97 m to the east-southeast, a nine-storey residential building is proposed (awaiting Site Plan Control approval) at 230-233 Lisgar Street, approximately 150 m to the southeast, a 27-storey mixed-use residential building is proposed (awaiting Zoning By-law Amendment approval) at 257 Lisgar Street and 108 Nepean Street, approximately 80 m to the south, and an eight-storey apartment building is proposed (awaiting Zoning By-law Amendment and Site Plan Control approval) at 331 Cooper Street, approximately 190 m to the south of the subject site.

The far-field surroundings, defined as an area beyond the near-field but within a 2-kilometre (km) radius of the subject site, are characterized by low-rise massing with isolated mid- and high-rise buildings in all compass directions, with the cluster of high-rise buildings of the Downtown Ottawa core from the west clockwise to the east. The Rideau River is situated approximately 1.9 km to the southwest and the Rideau Canal flows from the south-southeast to the north where it meets the Ottawa River, which flows from the west to the north, approximately 790 m to the northwest of the subject site.

Site plans for the proposed and existing massing scenarios are illustrated in Figures 1A and 1B, while Figures 2A-2H illustrate the computational models used to conduct the study. The existing massing scenario includes the existing massing and any changes which have been approved by the City of Ottawa.

### **3. OBJECTIVES**

The principal objectives of this study are to (i) determine pedestrian level wind conditions at key areas within and surrounding the development site; (ii) identify areas where wind conditions may interfere with the intended uses of outdoor spaces; and (iii) recommend suitable mitigation measures, where required.

### **4. METHODOLOGY**

The approach followed to quantify pedestrian wind conditions over the site is based on CFD simulations of wind speeds across the study site within a virtual environment, meteorological analysis of the Ottawa area wind climate, and synthesis of computational data with City of Ottawa wind comfort and safety criteria<sup>1</sup>. The following sections describe the analysis procedures, including a discussion of the noted pedestrian wind criteria.

#### **4.1 Computer-Based Context Modelling**

A computer based PLW study was performed to determine the influence of the wind environment on pedestrian comfort over the proposed development site. Pedestrian comfort predictions, based on the mechanical effects of wind, were determined by combining measured wind speed data from CFD simulations with statistical weather data obtained from Ottawa Macdonald-Cartier International Airport. The general concept and approach to CFD modelling is to represent building and topographic details in the immediate vicinity of the study site on the surrounding model, and to create suitable atmospheric wind profiles at the model boundary. The wind profiles are designed to have similar mean and turbulent wind properties consistent with actual site exposures.

An industry standard practice is to omit trees, vegetation, and other existing and planned landscape elements from the model due to the difficulty of providing accurate seasonal representation of vegetation. The omission of trees and other landscaping elements produces slightly stronger wind speeds.

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<sup>1</sup> City of Ottawa Terms of References: Wind Analysis  
[https://documents.ottawa.ca/sites/default/files/torwindanalysis\\_en.pdf](https://documents.ottawa.ca/sites/default/files/torwindanalysis_en.pdf)

## 4.2 Wind Speed Measurements

The PLW analysis was performed by simulating wind flows and gathering velocity data over a CFD model of the subject site for 12 wind directions. The CFD simulation model was centered on the proposed development, complete with surrounding massing within a radius of 480 m. The process was repeated for two context massing scenarios, as noted in Section 2.

Mean and peak wind speed data obtained over the study site for each wind direction were interpolated to 36 wind directions at 10° intervals, representing the full compass azimuth. Measured wind speeds approximately 1.5 m above local grade, the potential common amenity terrace serving the proposed development at Level 8, and common amenity terrace serving the proposed development at the MPH level were referenced to the wind speed at gradient height to generate mean and peak velocity ratios, which were used to calculate full-scale values. Gradient height represents the theoretical depth of the boundary layer of the earth's atmosphere, above which the mean wind speed remains constant. Further details of the wind flow simulation technique are presented in Appendix A.

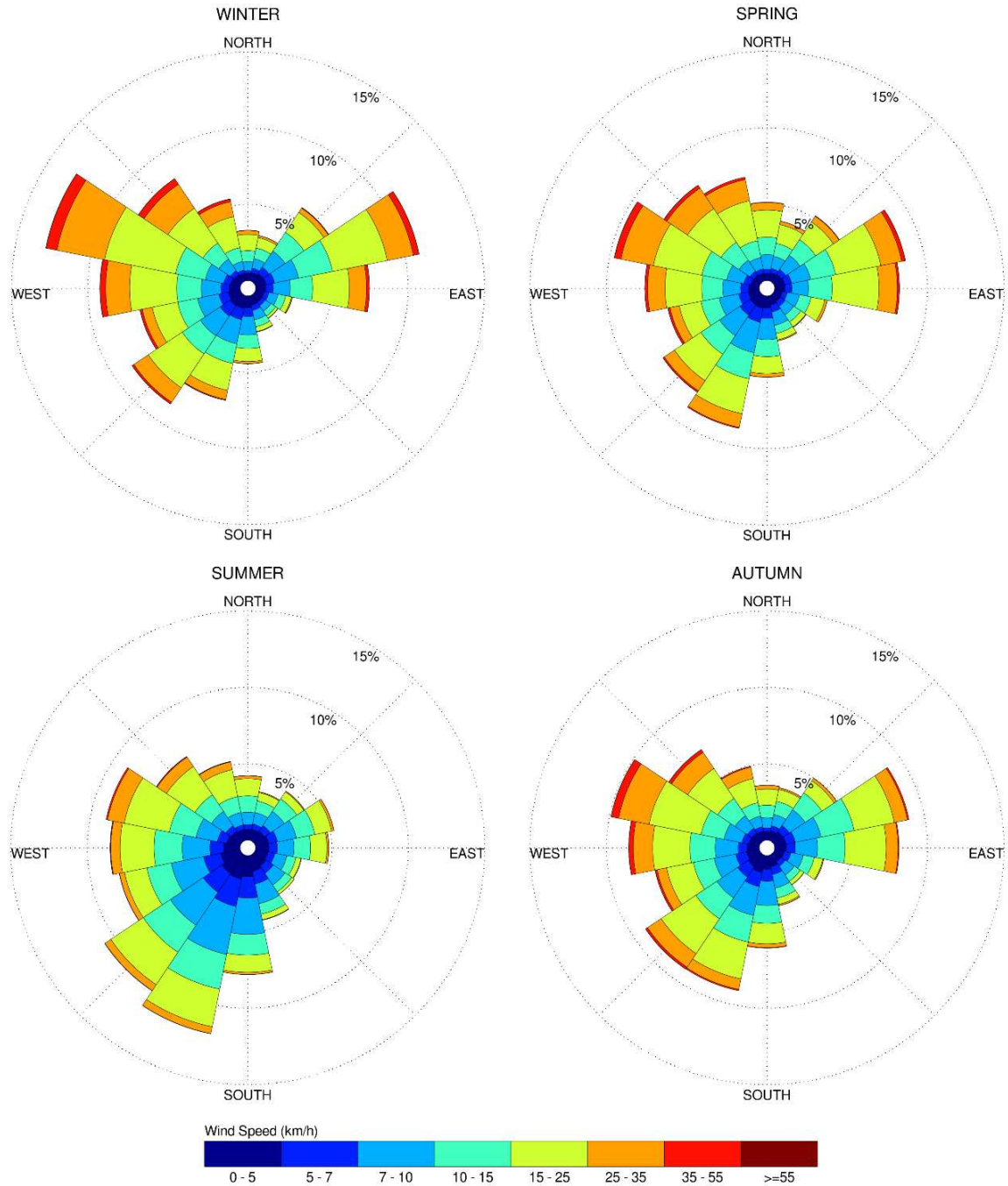
## 4.3 Historical Wind Speed and Direction Data

A statistical model for winds in Ottawa was developed from approximately 40 years of hourly meteorological wind data recorded at Ottawa Macdonald-Cartier International Airport and obtained from Environment and Climate Change Canada. Wind speed and direction data were analyzed for each month of the year to determine the statistically prominent wind directions and corresponding speeds, and to characterize similarities between monthly weather patterns.

The statistical model of the Ottawa area wind climate, which indicates the directional character of local winds on a seasonal basis, is illustrated on the following page. The plots illustrate seasonal distribution of measured wind speeds and directions in kilometers per hour (km/h). Probabilities of occurrence of different wind speeds are represented as stacked polar bars in sixteen azimuth divisions. The radial direction represents the percentage of time for various wind speed ranges per wind direction during the measurement period. The preferred wind speeds and directions can be identified by the longer length of the bars. For Ottawa, the most common winds occur for westerly wind directions, followed by those from the east, while the most common wind speeds are below 36 km/h. The directional preference and relative magnitude of wind speed changes somewhat from season to season.



## SEASONAL DISTRIBUTION OF WIND OTTAWA MACDONALD-CARTIER INTERNATIONAL AIRPORT



### Notes:

1. Radial distances indicate percentage of time of wind events.
2. Wind speeds are mean hourly in km/h, measured at 10 m above the ground.



#### 4.4 Pedestrian Comfort and Safety Criteria – City of Ottawa

Pedestrian comfort and safety criteria are based on the mechanical effects of wind without consideration of other meteorological conditions (that is, temperature, relative humidity). The comfort criteria assume that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Five pedestrian comfort classes are based on 20% non-exceedance mean wind speed ranges, which include (1) Sitting; (2) Standing; (3) Strolling; (4) Walking; and (5) Uncomfortable. More specifically, the comfort classes and associated mean wind speed ranges are summarized as follows:

- 1) **Sitting:** Mean wind speeds no greater than 10 km/h occurring at least 80% of the time. The equivalent gust wind speed is approximately 16 km/h.
- 2) **Standing:** Mean wind speeds no greater than 14 km/h occurring at least 80% of the time. The equivalent gust wind speed is approximately 22 km/h.
- 3) **Strolling:** Mean wind speeds no greater than 17 km/h occurring at least 80% of the time. The equivalent gust wind speed is approximately 27 km/h.
- 4) **Walking:** Mean wind speeds no greater than 20 km/h occurring at least 80% of the time. The equivalent gust wind speed is approximately 32 km/h.
- 5) **Uncomfortable:** Uncomfortable conditions are characterized by predicted values that fall below the 80% target for walking. Brisk walking and exercise, such as jogging, would be acceptable for moderate excesses of this criterion.

The pedestrian safety wind speed criterion is based on the approximate threshold that would cause a vulnerable member of the population to fall. A 0.1% exceedance gust wind speed of 90 km/h is classified as dangerous. The gust speeds, and equivalent mean speeds, are selected based on 'The Beaufort Scale', presented on the following page, which describes the effects of forces produced by varying wind speed levels on objects. Gust speeds are included because pedestrians tend to be more sensitive to wind gusts than to steady winds for lower wind speed ranges. For strong winds approaching dangerous levels, this effect is less important because the mean wind can also create problems for pedestrians.

**THE BEAUFORT SCALE**

Number	Description	Gust Wind Speed (km/h)	Description
2	Light Breeze	9-17	Wind felt on faces
3	Gentle Breeze	18-29	Leaves and small twigs in constant motion; wind extends light flags
4	Moderate Breeze	30-42	Wind raises dust and loose paper; small branches are moved
5	Fresh Breeze	43-57	Small trees in leaf begin to sway
6	Strong Breeze	58-74	Large branches in motion; Whistling heard in electrical wires; umbrellas used with difficulty
7	Moderate Gale	75-92	Whole trees in motion; inconvenient walking against wind
8	Gale	93-111	Breaks twigs off trees; generally impedes progress

Experience and research on people’s perception of mechanical wind effects has shown that if the wind speed levels are exceeded for more than 20% of the time, the activity level would be judged to be uncomfortable by most people. For instance, if a mean wind speed of 10 km/h (equivalent gust wind speed of approximately 16 km/h) were exceeded for more than 20% of the time most pedestrians would judge that location to be too windy for sitting. Similarly, if mean wind speed of 20 km/h (equivalent gust wind speed of approximately 32 km/h) at a location were exceeded for more than 20% of the time, walking or less vigorous activities would be considered uncomfortable. As these criteria are based on subjective reactions of a population to wind forces, their application is partly based on experience and judgment.

Once the pedestrian wind speed predictions have been established throughout the site, the assessment of pedestrian comfort involves determining the suitability of the predicted wind conditions for discrete regions within and surrounding the subject site. This step involves comparing the predicted comfort classes to the desired comfort classes, which are dictated by the location type for each region (that is, a sidewalk, building entrance, amenity space, or other). An overview of common pedestrian location types and their typical windiest desired comfort classes are summarized on the following page. Depending on the programming of a space, the desired comfort class may differ from this table.



**DESIRED PEDESTRIAN COMFORT CLASSES FOR VARIOUS LOCATION TYPES**

Location Types	Desired Comfort Classes
Primary Building Entrance	Standing
Secondary Building Access Point	Walking
Public Sidewalk / Bicycle Path	Walking
Outdoor Amenity Space	Sitting (Typical Use Period)
Café / Patio / Bench / Garden	Sitting (Typical Use Period)
Transit Stop (Without Shelter)	Standing
Transit Stop (With Shelter)	Walking
Public Park / Plaza	Sitting (Typical Use Period)
Garage / Service Entrance	Walking
Parking Lot	Walking
Vehicular Drop-Off Zone	Walking

## 5. RESULTS AND DISCUSSION

The following discussion of the predicted pedestrian wind conditions for the subject site is accompanied by Figures 3A-6B, illustrating wind conditions at grade level for the proposed and existing massing scenarios, and by Figures 7A-7D, illustrating wind conditions over the potential common amenity terrace serving the proposed development at Level 8 and the common amenity terrace serving the proposed development at the MPH level. Conditions are presented as continuous contours of wind comfort throughout the subject site and correspond to the comfort classes noted in Section 4.4. Wind conditions suitable for sitting are represented by the colour blue, standing by green, strolling by yellow, and walking by orange; uncomfortable conditions are represented by the colour magenta.

Conditions within the noted common amenity terrace serving the proposed development are also reported for the typical use period, which is defined as May to October, inclusive. Figure 8 illustrates wind comfort conditions consistent with the comfort classes in Section 4.4.

Wind conditions throughout the subject site are considered acceptable for the intended pedestrian uses. The details of these conditions are summarized in the following pages.

## 5.1 Wind Comfort Conditions – Ground Floor

Following the introduction of the proposed development, all grade-level areas within and surrounding the subject site are predicted to experience conditions that are considered acceptable for the intended pedestrian uses throughout the year. Specifically, conditions over the adjacent sidewalk areas along Gloucester Street, Nepean Street, and O'Connor Street are predicted to be suitable for sitting throughout the year. Owing to the protection of the building façades, the existing pool area at the southwest corner of the subject site, the drop-off area to the north, the central north-south laneway intersecting the proposed development, along the walkways to the east and south, the outdoor amenity to the south, and in the vicinity of all building access points are predicted to be suitable for sitting throughout the year. The noted conditions are unchanged from existing conditions. For both proposed and existing massing scenarios, grade-level wind conditions surrounding the subject site are considered acceptable.

## 5.2 Wind Comfort Conditions – Common Amenity Terraces

**Potential Level 8 Common Amenity Terrace:** Wind conditions within the potential common amenity terrace serving the proposed development at Level 8 are predicted to be suitable for sitting throughout the year. The noted conditions are considered acceptable.

**MPH Level Common Amenity Terrace:** Wind conditions within the common amenity terrace serving the proposed development at the MPH level are predicted to be suitable for sitting during the typical use period, as illustrated in Figure 8. The noted conditions are considered acceptable according to the City of Ottawa wind comfort criteria.

## 5.3 Wind Safety

Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no pedestrian areas within or surrounding the subject site are expected to experience conditions that could be considered dangerous, as defined in Section 4.4.

## 5.4 Applicability of Results

Pedestrian wind comfort and safety have been quantified for the specific configuration of existing and foreseeable construction around the subject site. Future changes (that is, construction or demolition) of these surroundings may cause changes to the wind effects in two ways, namely: (i) changes beyond the immediate vicinity of the subject site would alter the wind profile approaching the subject site; and (ii) development in proximity to the subject site would cause changes to local flow patterns.

Regarding primary and secondary building access points, wind conditions predicted in this study are only applicable to pedestrian comfort and safety. As such, the results should not be construed to indicate wind loading on doors and associated hardware.

## 6. CONCLUSIONS AND RECOMMENDATIONS

A complete summary of the predicted wind conditions is provided in Section 5 and illustrated in Figures 3A-8. Based on computer simulations using the CFD technique, meteorological data analysis of the Ottawa wind climate, City of Ottawa wind comfort and safety criteria, and experience with numerous similar developments, the study concludes the following:

- 1) All grade-level areas within and surrounding the subject site are predicted to experience conditions that are considered acceptable for the intended pedestrian uses throughout the year. Specifically, conditions over surrounding sidewalks, walkways, the laneway and drop-off area, the existing pool area, the outdoor amenity, and in the vicinity of building access points are predicted to be suitable for sitting throughout the year, which are considered acceptable.
- 2) Conditions over the potential amenity terrace serving the proposed development at Level 8 are predicted to be suitable for sitting throughout the year, which are considered acceptable.
- 3) Conditions over the amenity terrace serving the proposed development at the MPH level are predicted to be suitable for sitting during the typical use period, which are considered acceptable.

- 4) The foregoing statements and conclusions apply to common weather systems, during which no dangerous wind conditions, as defined in Section 4.4, are expected anywhere over the subject site. During extreme weather events, (e.g., thunderstorms, tornadoes, and downbursts), pedestrian safety is the main concern. However, these events are generally short-lived and infrequent and there is often sufficient warning for pedestrians to take appropriate cover.

Sincerely,

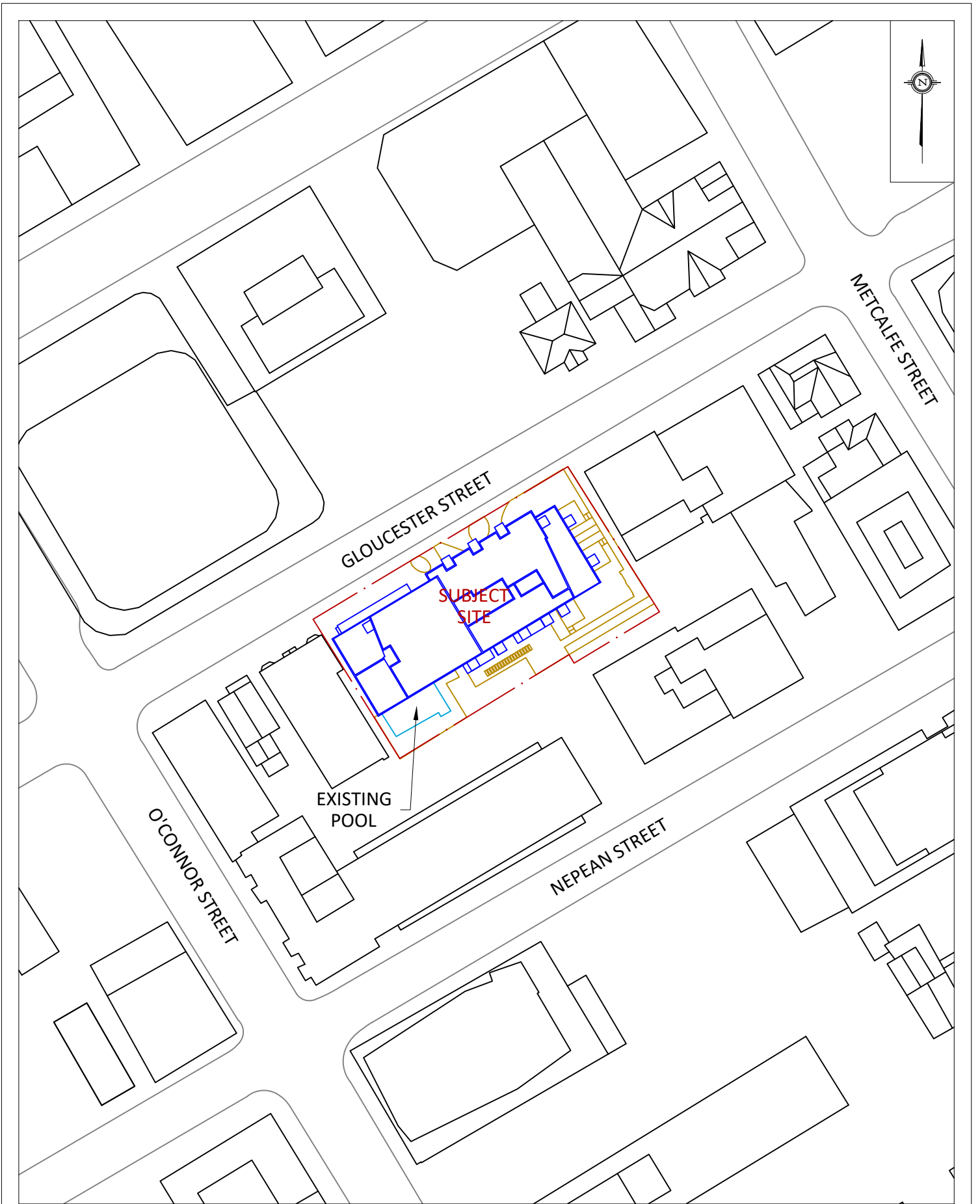
***Gradient Wind Engineering Inc.***



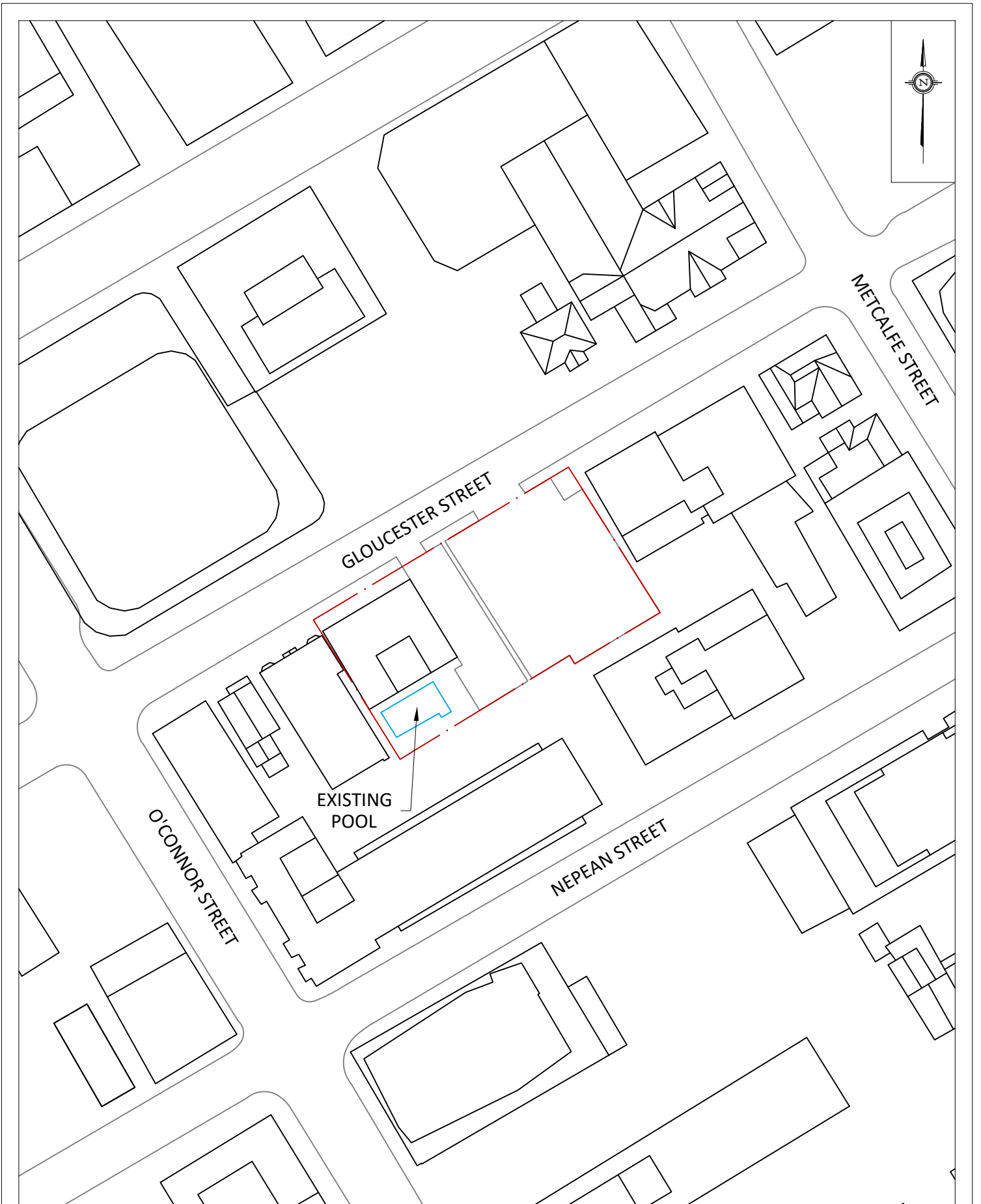
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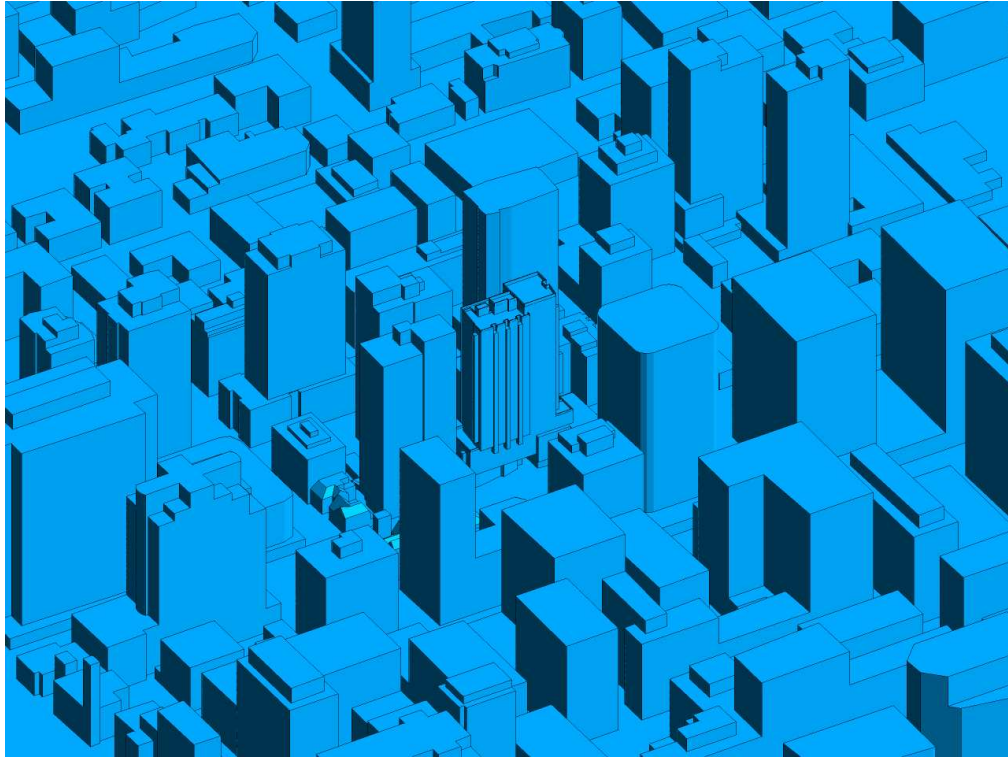


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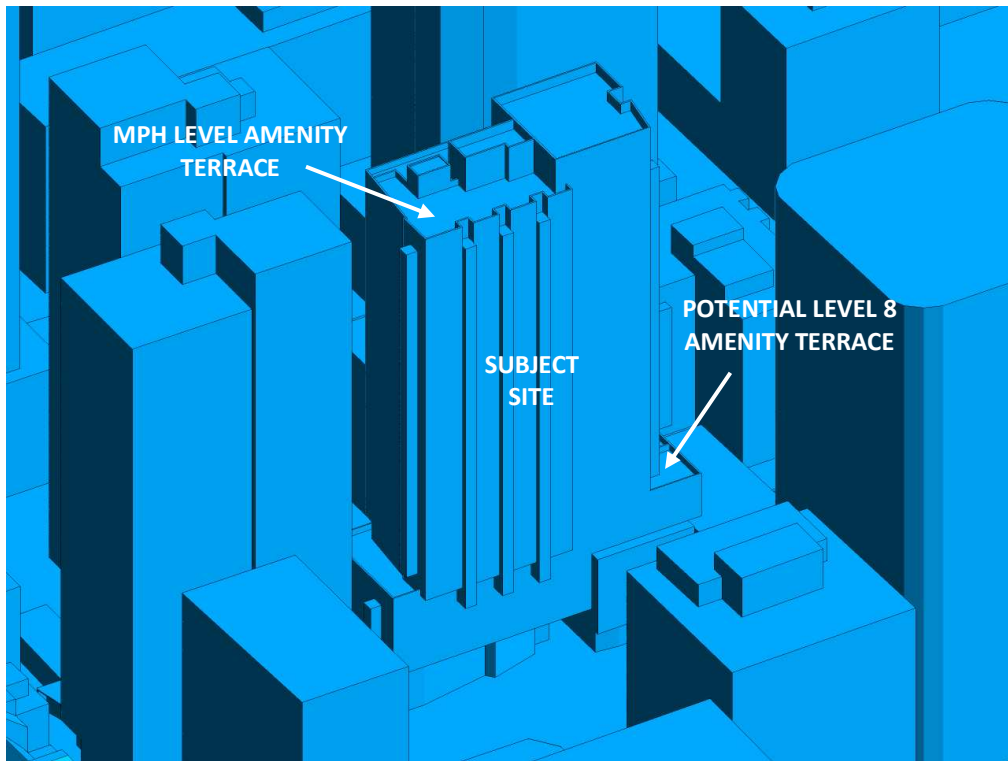






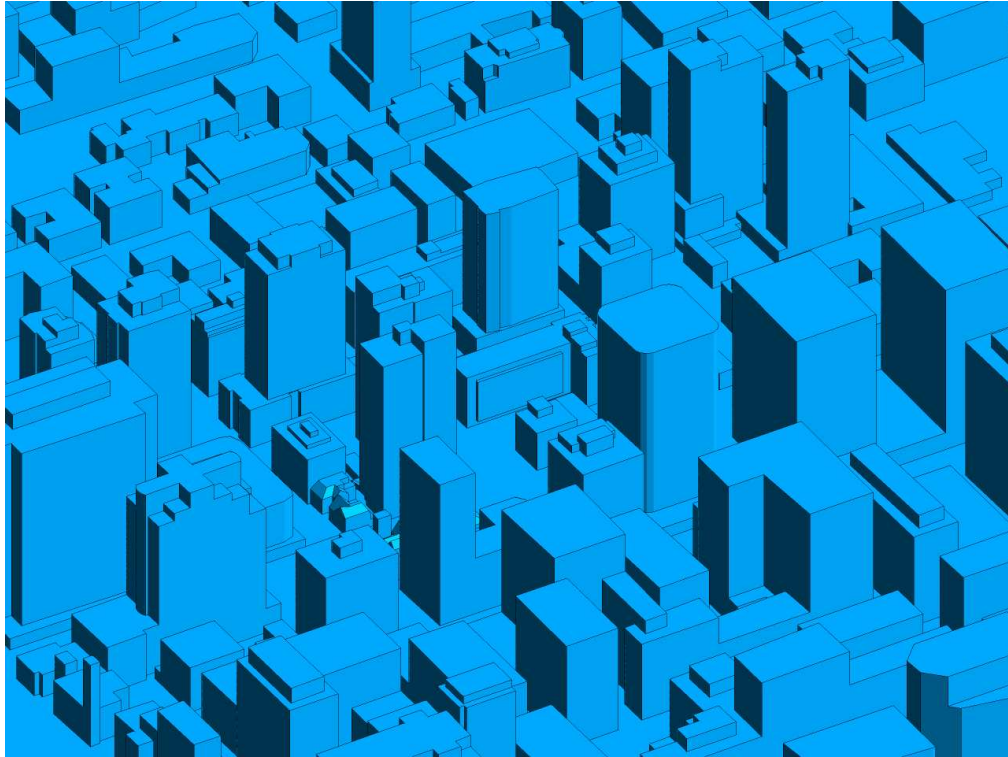


**FIGURE 2A: COMPUTATIONAL MODEL, PROPOSED MASSING, NORTH PERSPECTIVE**

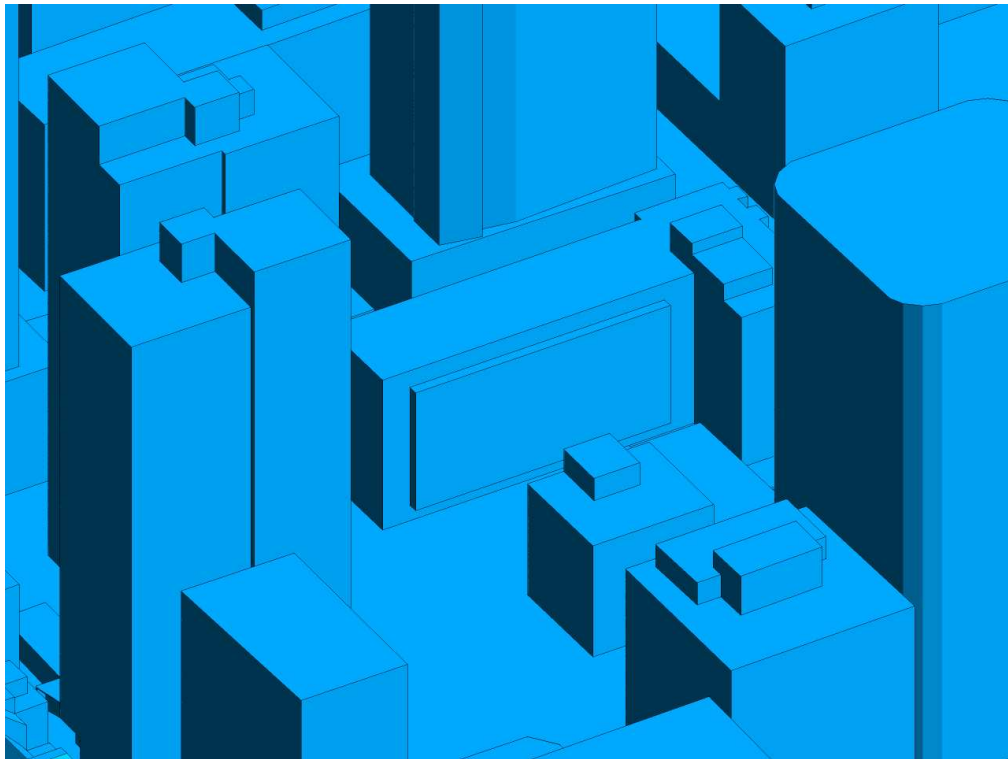


**FIGURE 2B: CLOSE UP OF FIGURE 2A**

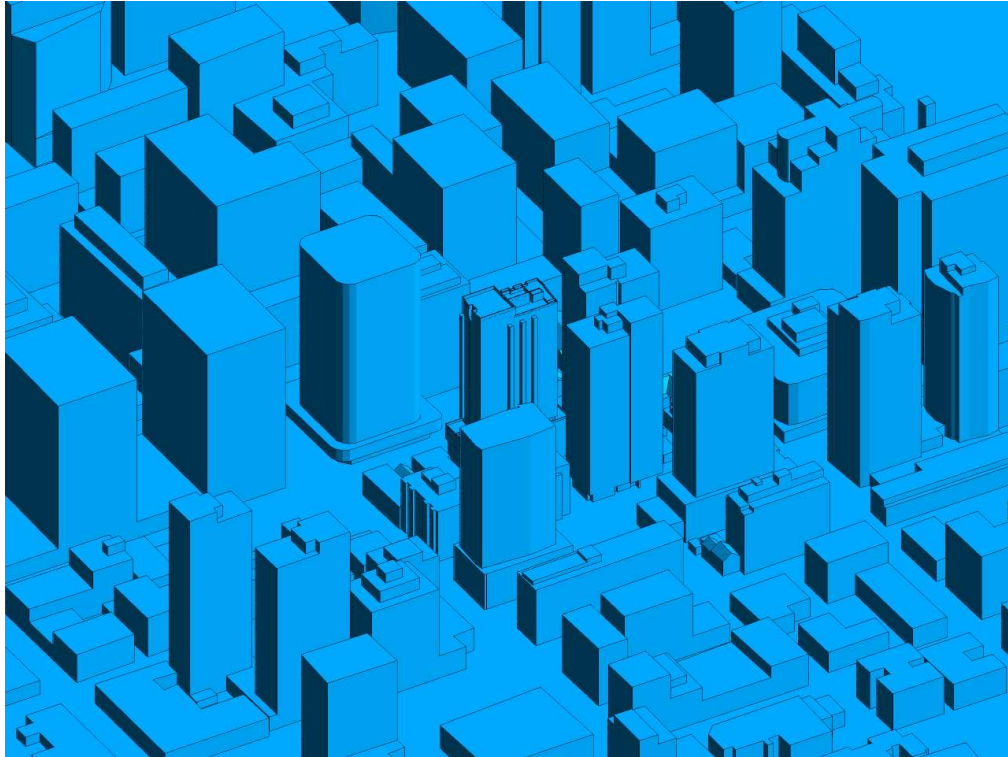




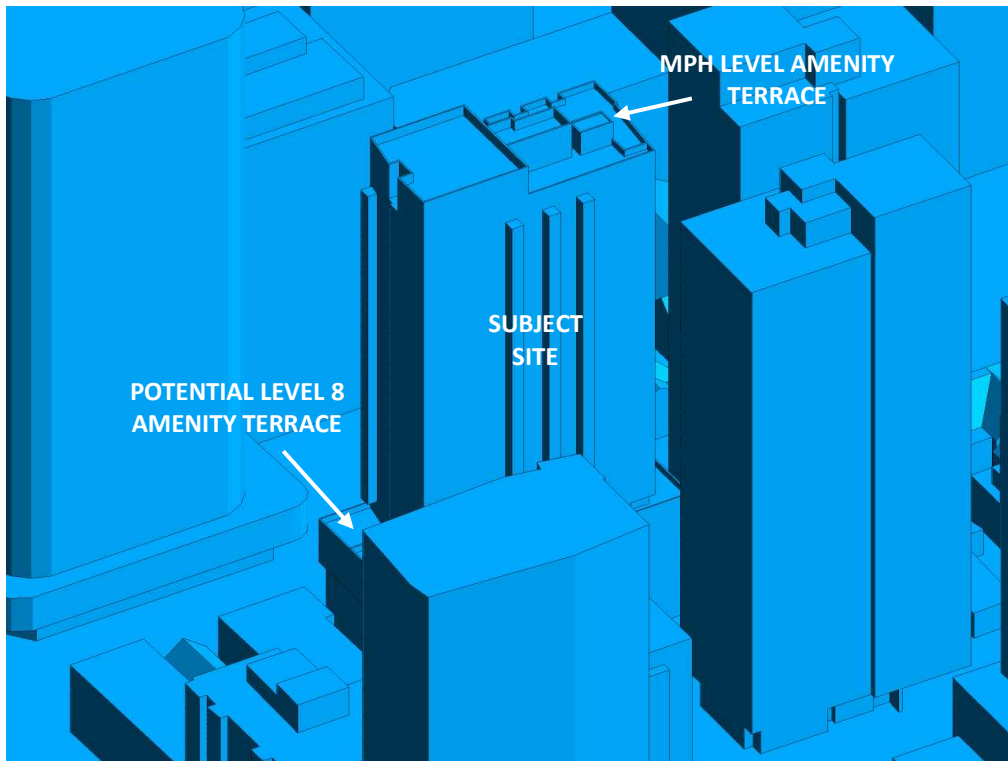
**FIGURE 2C: COMPUTATIONAL MODEL, EXISTING MASSING, NORTH PERSPECTIVE**



**FIGURE 2D: CLOSE UP OF FIGURE 2C**



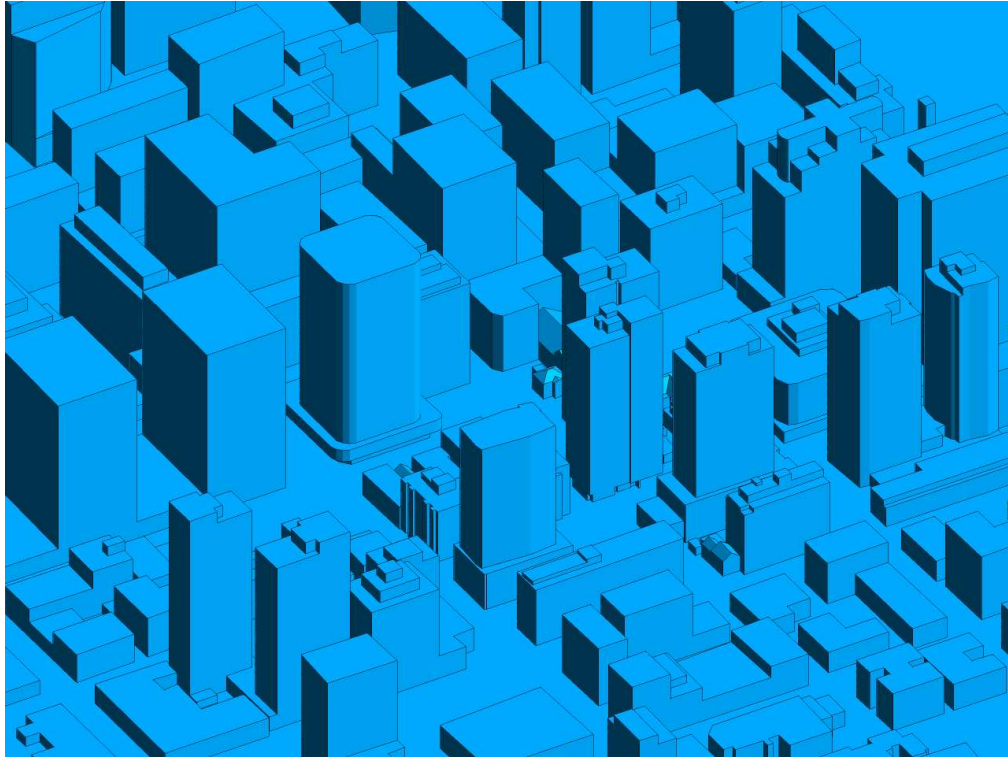
**FIGURE 2E: COMPUTATIONAL MODEL, PROPOSED MASSING, SOUTH PERSPECTIVE**



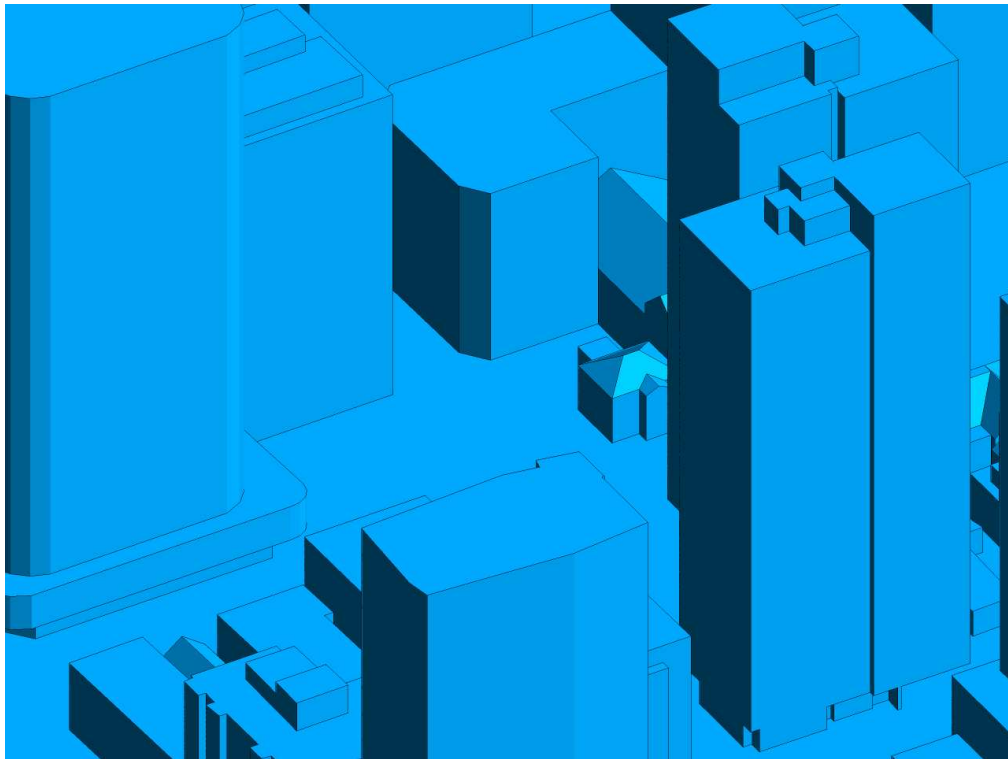
**FIGURE 2F: CLOSE UP OF FIGURE 2E**







**FIGURE 2G: COMPUTATIONAL MODEL, EXISTING MASSING, SOUTH PERSPECTIVE**



**FIGURE 2H: CLOSE UP OF FIGURE 2G**



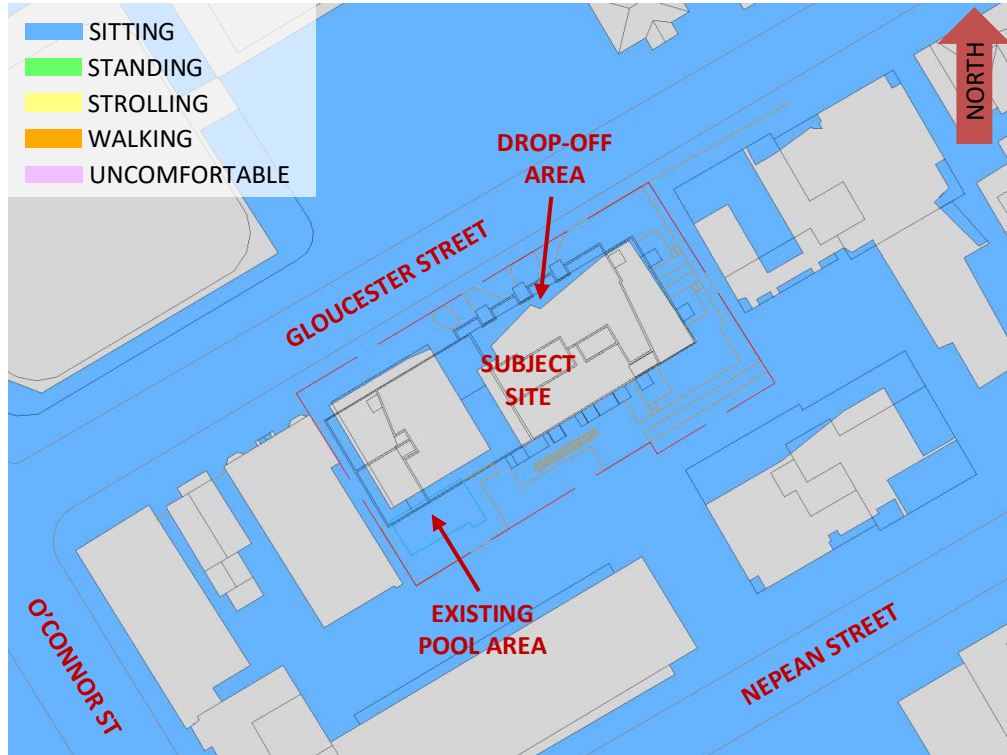


FIGURE 3A: SPRING – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING

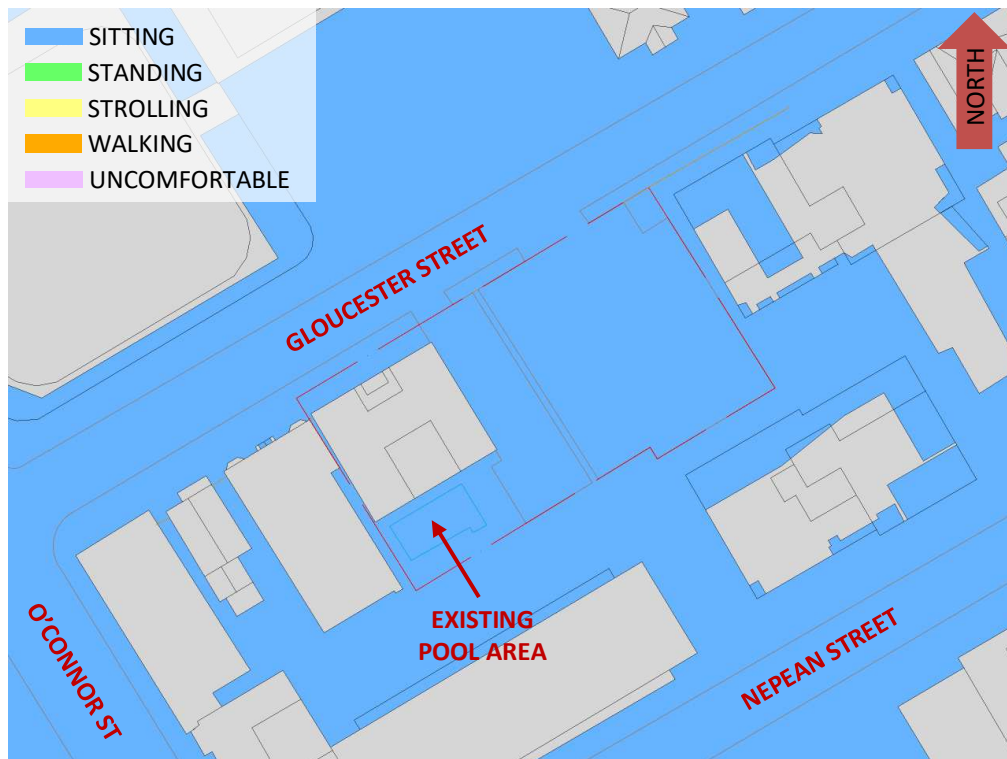


FIGURE 3B: SPRING – WIND COMFORT, GRADE LEVEL – EXISTING MASSING



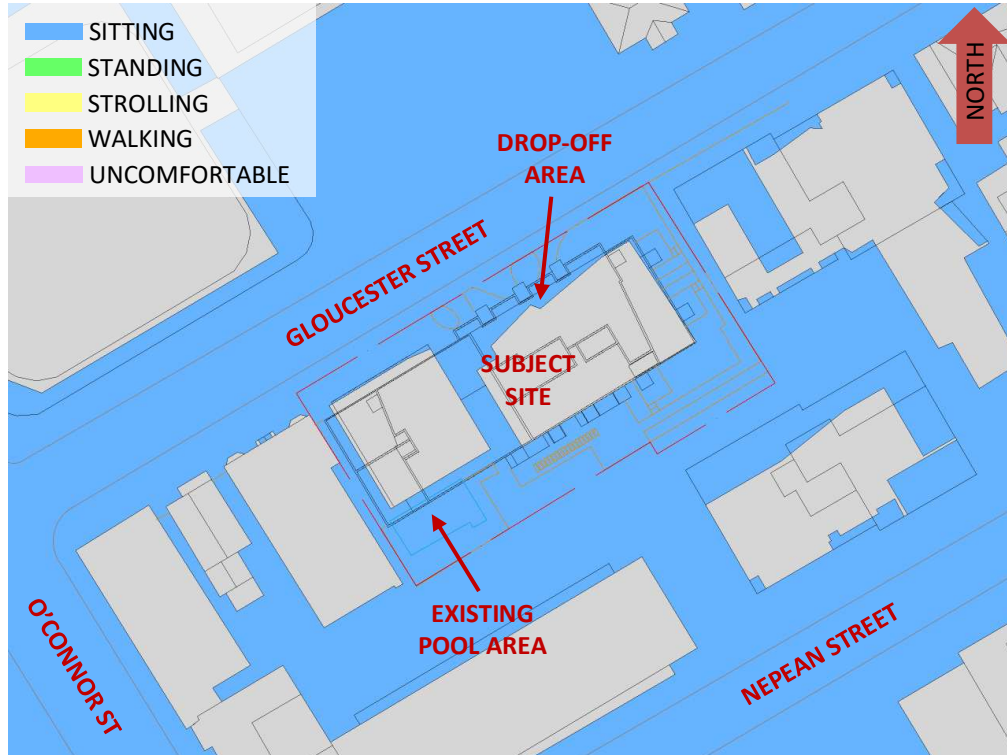


FIGURE 4A: SUMMER – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING

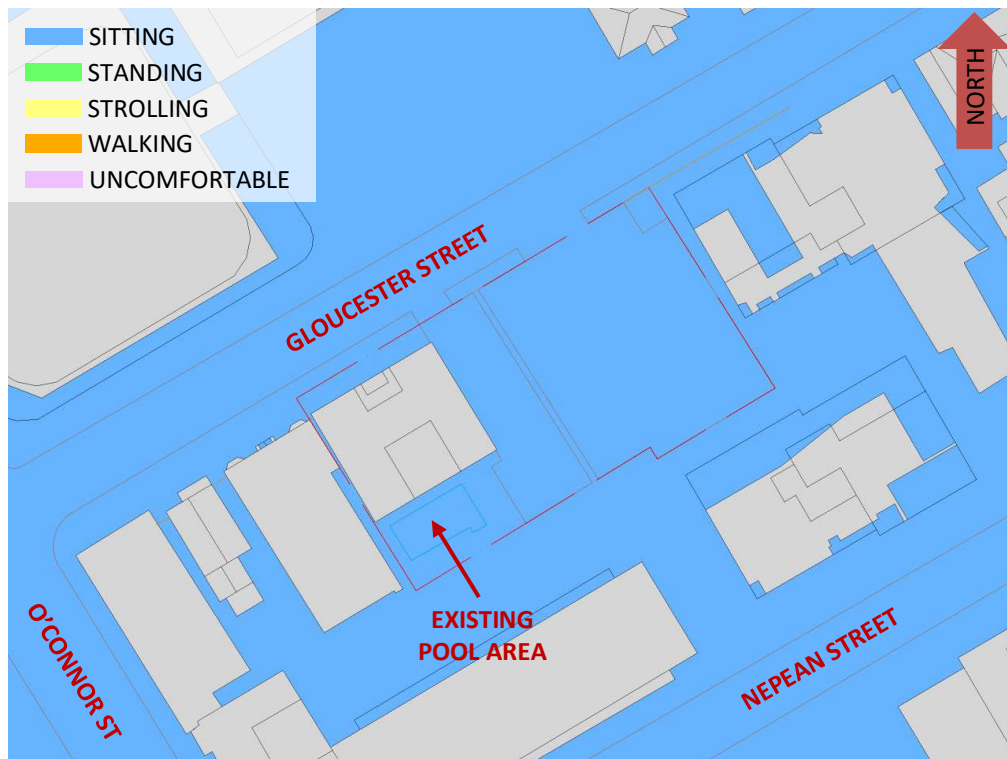


FIGURE 4B: SUMMER – WIND COMFORT, GRADE LEVEL – EXISTING MASSING





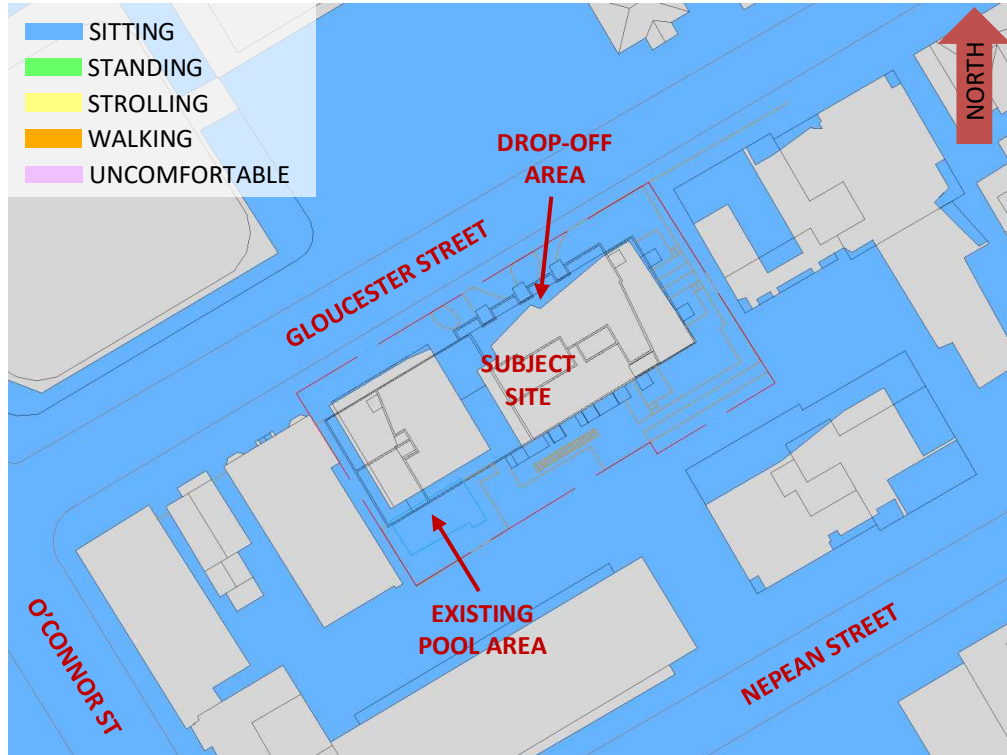


FIGURE 5A: AUTUMN – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING

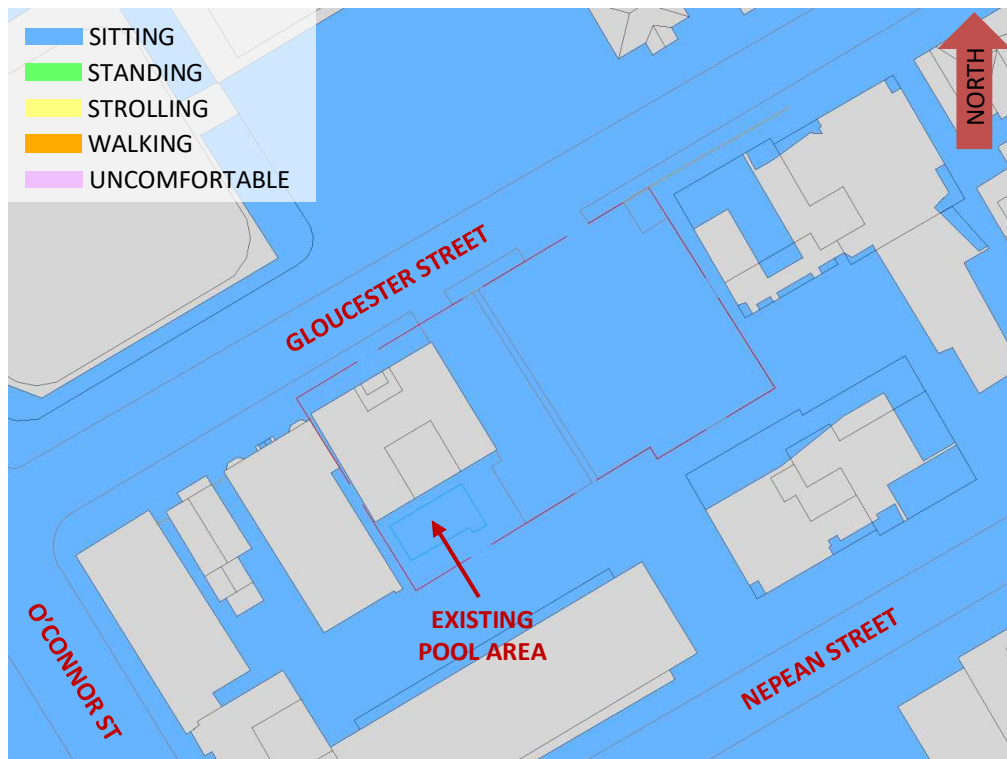


FIGURE 5B: AUTUMN – WIND COMFORT, GRADE LEVEL – EXISTING MASSING



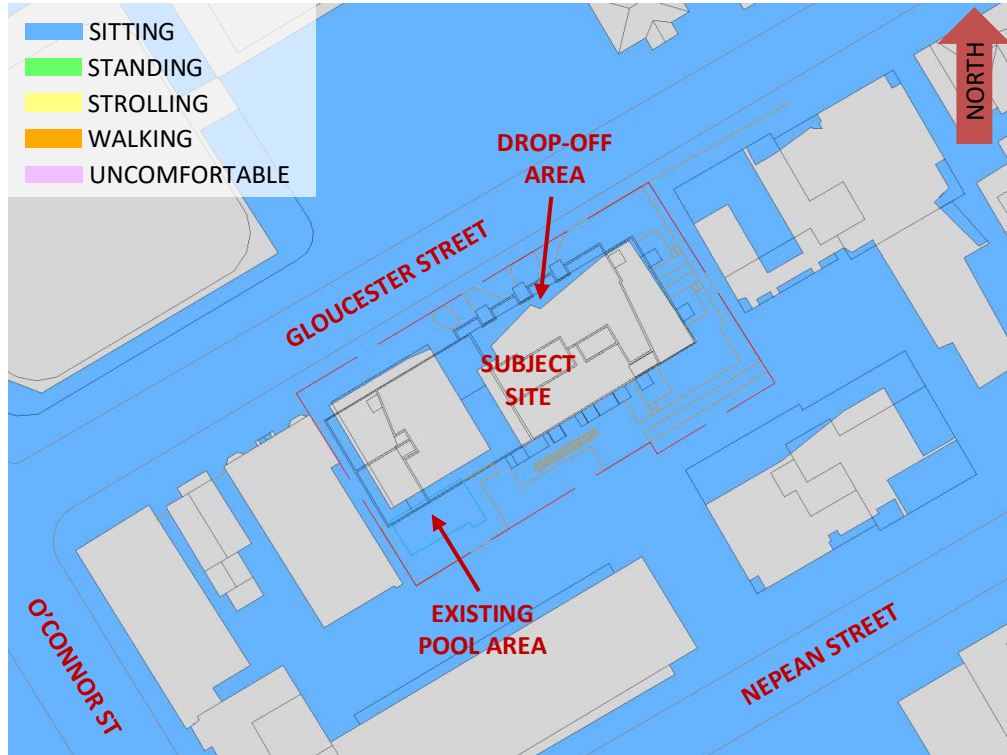


FIGURE 6A: WINTER – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING

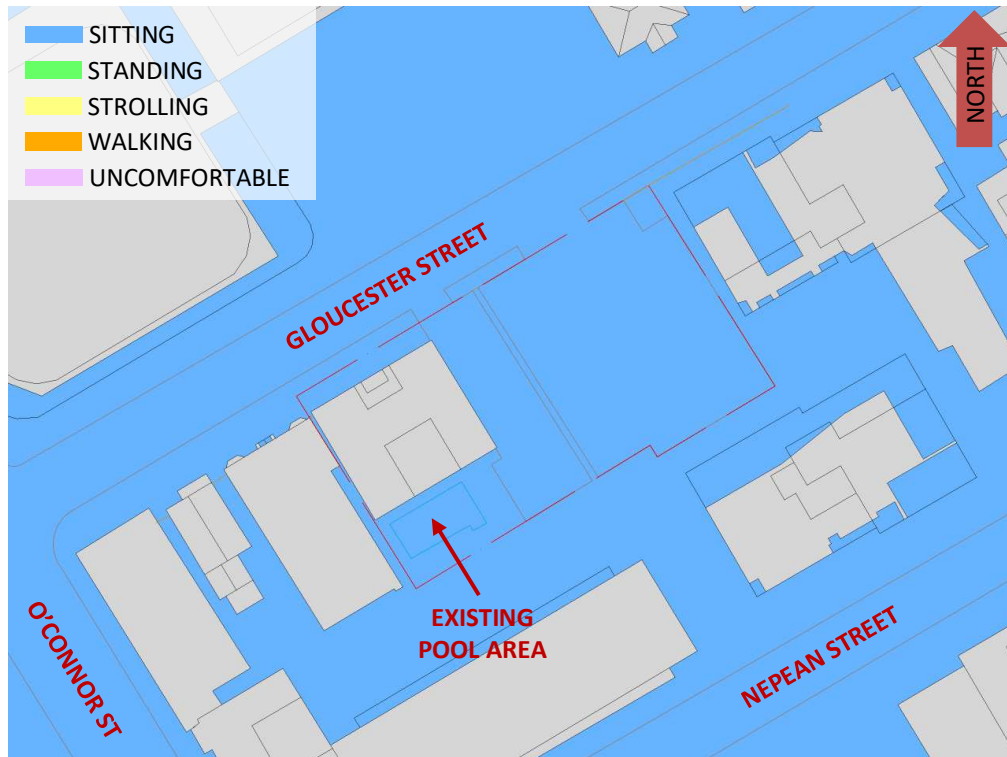
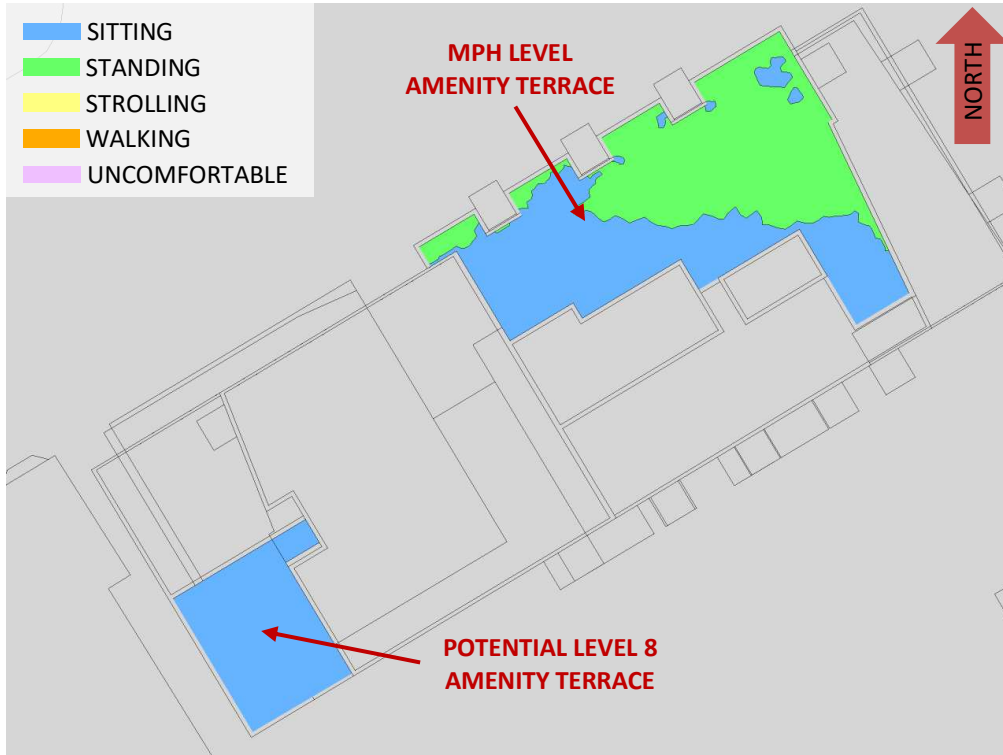
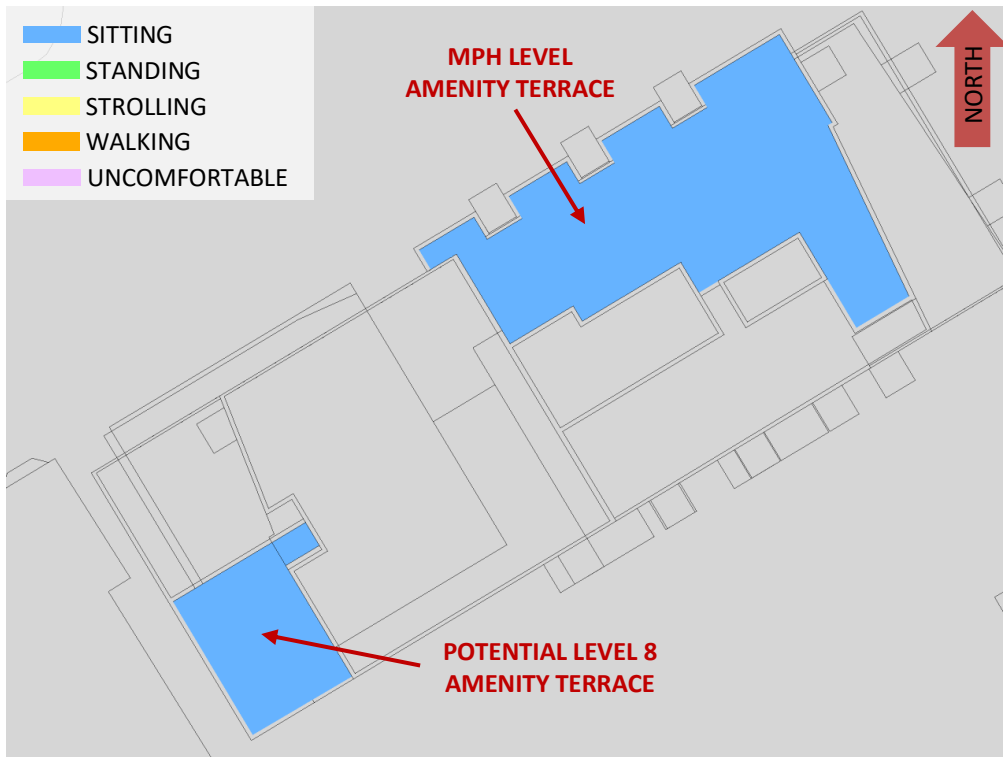


FIGURE 6B: WINTER – WIND COMFORT, GRADE LEVEL – EXISTING MASSING



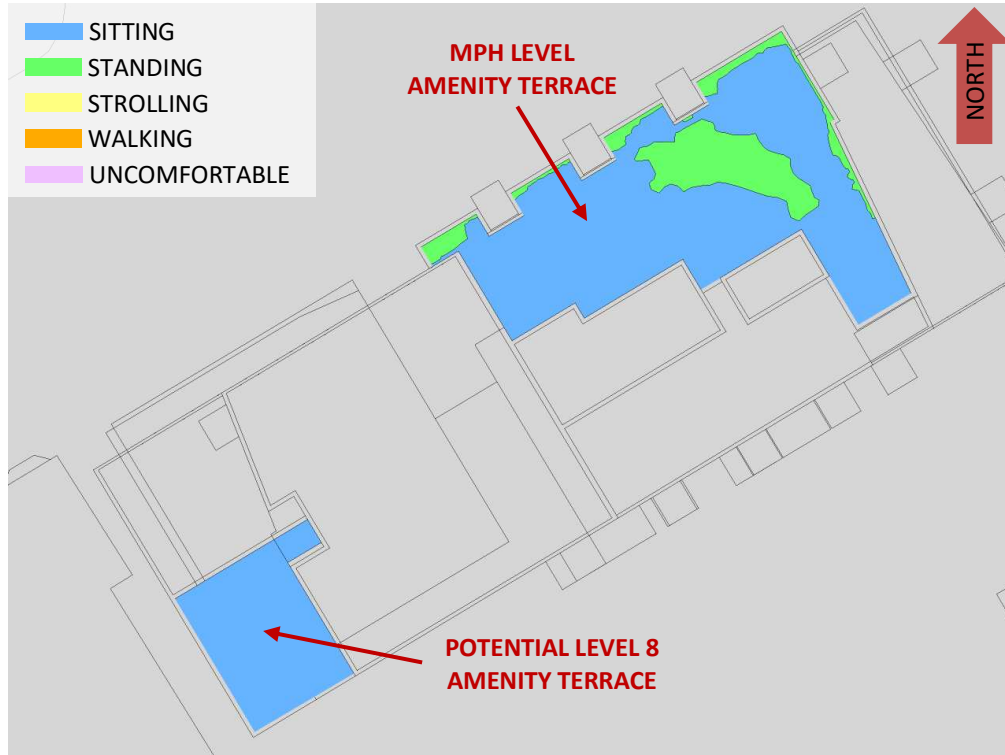


**FIGURE 7A: SPRING – WIND COMFORT, COMMON AMENITY TERRACES**

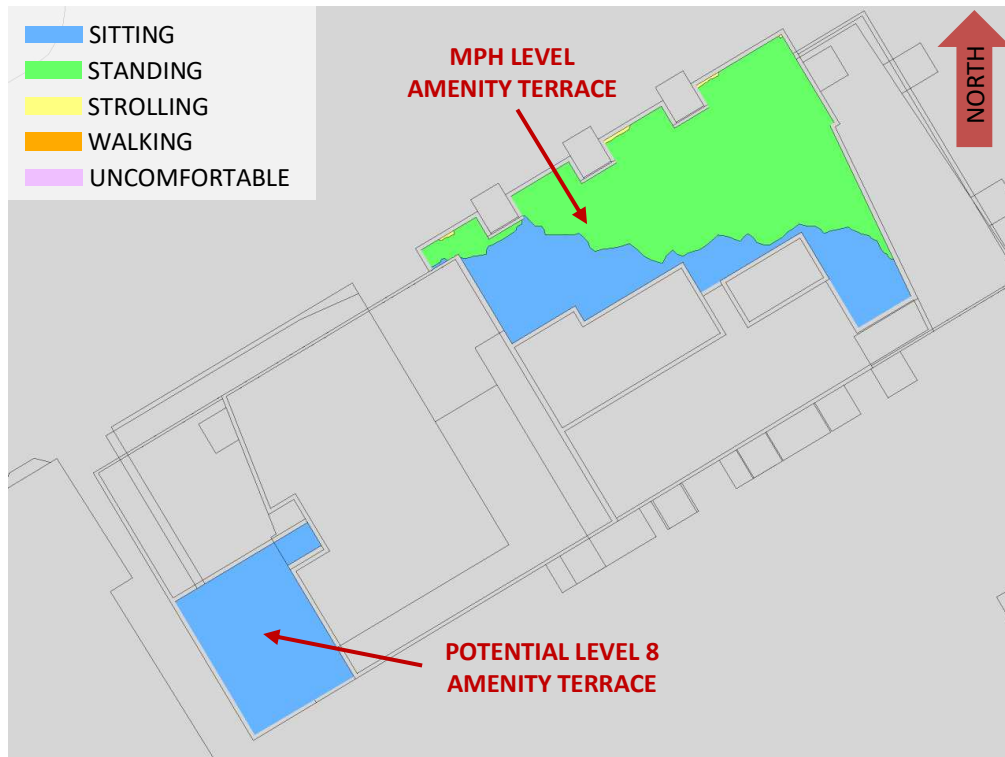


**FIGURE 7B: SUMMER – WIND COMFORT, COMMON AMENITY TERRACES**



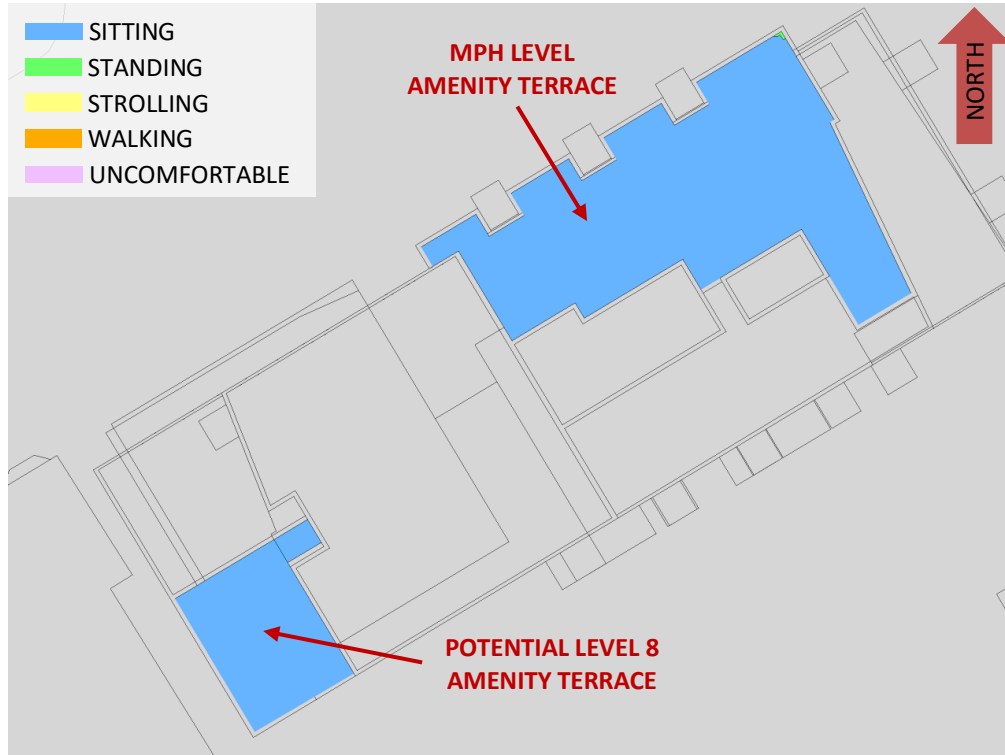


**FIGURE 7C: AUTUMN – WIND COMFORT, COMMON AMENITY TERRACES**



**FIGURE 7D: WINTER – WIND COMFORT, COMMON AMENITY TERRACES**





**FIGURE 8: TYPICAL USE PERIOD, COMMON AMENITY TERRACES**





# GRADIENTWIND

ENGINEERS & SCIENTISTS



## APPENDIX A

### SIMULATION OF THE ATMOSPHERIC BOUNDARY LAYER

## **SIMULATION OF THE ATMOSPHERIC BOUNDARY LAYER**

The atmospheric boundary layer (ABL) is defined by the velocity and turbulence profiles according to industry standard practices. The mean wind profile can be represented, to a good approximation, by a power law relation, Equation (1), giving height above ground versus wind speed (1), (2).

$$U = U_g \left( \frac{Z}{Z_g} \right)^\alpha \quad \text{Equation (1)}$$

where,  $U$  = mean wind speed,  $U_g$  = gradient wind speed,  $Z$  = height above ground,  $Z_g$  = depth of the boundary layer (gradient height), and  $\alpha$  is the power law exponent.

For the model,  $U_g$  is set to 6.5 metres per second (m/s), which approximately corresponds to the 60% mean wind speed for Ottawa based on historical climate data and statistical analyses. When the results are normalized by this velocity, they are relatively insensitive to the selection of gradient wind speed.

$Z_g$  is set to 540 m. The selection of gradient height is relatively unimportant, so long as it exceeds the building heights surrounding the subject site. The value has been selected to correspond to our physical wind tunnel reference value.

$\alpha$  is determined based on the upstream exposure of the far-field surroundings (that is, the area that it not captured within the simulation model).



Table 1 presents the values of  $\alpha$  used in this study, while Table 2 presents several reference values of  $\alpha$ . When the upstream exposure of the far-field surroundings is a mixture of multiple types of terrain, the  $\alpha$  values are a weighted average with terrain that is closer to the subject site given greater weight.

**TABLE 1: UPSTREAM EXPOSURE (ALPHA VALUE) VS TRUE WIND DIRECTION**

Wind Direction (Degrees True)	Alpha Value ( $\alpha$ )
0	0.26
49	0.27
74	0.26
103	0.26
167	0.25
197	0.25
217	0.25
237	0.28
262	0.30
282	0.28
301	0.25
324	0.24

**TABLE 2: DEFINITION OF UPSTREAM EXPOSURE (ALPHA VALUE)**

Upstream Exposure Type	Alpha Value ( $\alpha$ )
Open Water	0.14-0.15
Open Field	0.16-0.19
Light Suburban	0.21-0.24
Heavy Suburban	0.24-0.27
Light Urban	0.28-0.30
Heavy Urban	0.31-0.33

The turbulence model in the computational fluid dynamics (CFD) simulations is a two-equation shear-stress transport (SST) model, and thus the ABL turbulence profile requires that two parameters be defined at the inlet of the domain. The turbulence profile is defined following the recommendations of the Architectural Institute of Japan for flat terrain (3).

$$I(Z) = \begin{cases} 0.1 \left( \frac{Z}{Z_g} \right)^{-\alpha-0.05}, & Z > 10 \text{ m} \\ 0.1 \left( \frac{10}{Z_g} \right)^{-\alpha-0.05}, & Z \leq 10 \text{ m} \end{cases} \quad \text{Equation (2)}$$

$$L_t(Z) = \begin{cases} 100 \text{ m} \sqrt{\frac{Z}{30}}, & Z > 30 \text{ m} \\ 100 \text{ m}, & Z \leq 30 \text{ m} \end{cases} \quad \text{Equation (3)}$$

where,  $I$  = turbulence intensity,  $L_t$  = turbulence length scale,  $Z$  = height above ground, and  $\alpha$  is the power law exponent used for the velocity profile in Equation (1).

Boundary conditions on all other domain boundaries are defined as follows: the ground is a no-slip surface; the side walls of the domain have a symmetry boundary condition; the top of the domain has a specified shear, which maintains a constant wind speed at gradient height; and the outlet has a static pressure boundary condition.

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