

# GRADIENTWIND

ENGINEERS & SCIENTISTS

## PEDESTRIAN LEVEL WIND STUDY

150 Dun Skipper Drive  
Ottawa, Ontario

Report: 24-238-PLW



December 16, 2024

### PREPARED FOR

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## EXECUTIVE SUMMARY

This report describes a pedestrian level wind (PLW) study undertaken to satisfy Zoning By-Law Amendment (ZBLA) and Site Plan Control application submission requirements for the proposed residential development located at 150 Dun Skipper Drive 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-7, 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, transit stops, the proposed surface parking lot, drive aisle, walkways, gardens, and in the vicinity of building access points, are considered acceptable.
- 2) 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, (for example, 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 Cedar Creek Meadows Inc. to undertake a pedestrian level wind (PLW) study to satisfy Zoning By-Law Amendment (ZBLA) and Site Plan Control application submission requirements for the proposed residential development located at 150 Dun Skipper Drive in Ottawa, Ontario (hereinafter referred to as “subject site” or “proposed development”). Our mandate within the current 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 PMA Architectes in December 2024, 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 150 Dun Skipper Drive in Ottawa, situated to the northeast at the intersection of Dun Skipper Drive and Cedar Creek Drive on a parcel of land bordered by Dun Skipper Drive to the south, Cedar Creek Drive to the west, low-rise residential dwellings to the northwest, green space to the north, and a vacant lot to the east. The proposed development comprises two “L”-shaped 6-storey residential buildings topped with a mechanical penthouse (MPH). Building 1 with its short axis-oriented parallel with Dun Skipper Drive and Building 2 with its long axis-oriented parallel with Cedar Creek Drive, are situated to the south and north of the subject site, respectively.

The ground floors of Buildings 1 and 2 include main entrances to the east and west and residential units throughout the level. Gardens are proposed to the northeast and southeast of Buildings 1 and 2, respectively. Surface parking is situated central to the subject site and parking ramps are located to the north of Building 1 and at the southeast corner of the short axis of Building 2; access to these areas is provided by a drive aisle from Cedar Creek Drive. Buildings 1 and 2 are reserved for residential occupancy from Levels 2-6.

The near-field surroundings (defined as an area within 200 metres (m) of the subject site) comprise green spaces and vacant lots from the north clockwise to the east, a vacant lot and the Hindu Temple of Ottawa-Carleton to the east, low-rise commercial buildings with surface parking lots to the northeast and south, and low-rise residential dwellings from the south clockwise to the northwest. 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 a mix of suburban massing and green spaces from the west-southwest clockwise to the north-northeast, a quarry and low-rise commercial and industrial buildings from the east clockwise to the south-southeast, and a mix of mostly green spaces and dense forest in the remaining directions.

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 developments 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 subject 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.

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<sup>1</sup> City of Ottawa Terms of References: Wind Analysis  
[https://documents.ottawa.ca/sites/documents/files/wind\\_analysis\\_tor\\_en.pdf](https://documents.ottawa.ca/sites/documents/files/wind_analysis_tor_en.pdf)

## 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 subject 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.

## 4.2 Wind Speed Measurements

The PLW analysis was performed by simulating wind flows and gathering velocity data over a CFD model of the site for 16 wind directions. The CFD simulation model was centered on the proposed development, complete with surrounding massing within a radius of 510 m. The process was performed for two context massing scenarios, as noted in Section 2.

Mean and peak wind speed data obtained over the subject 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 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.

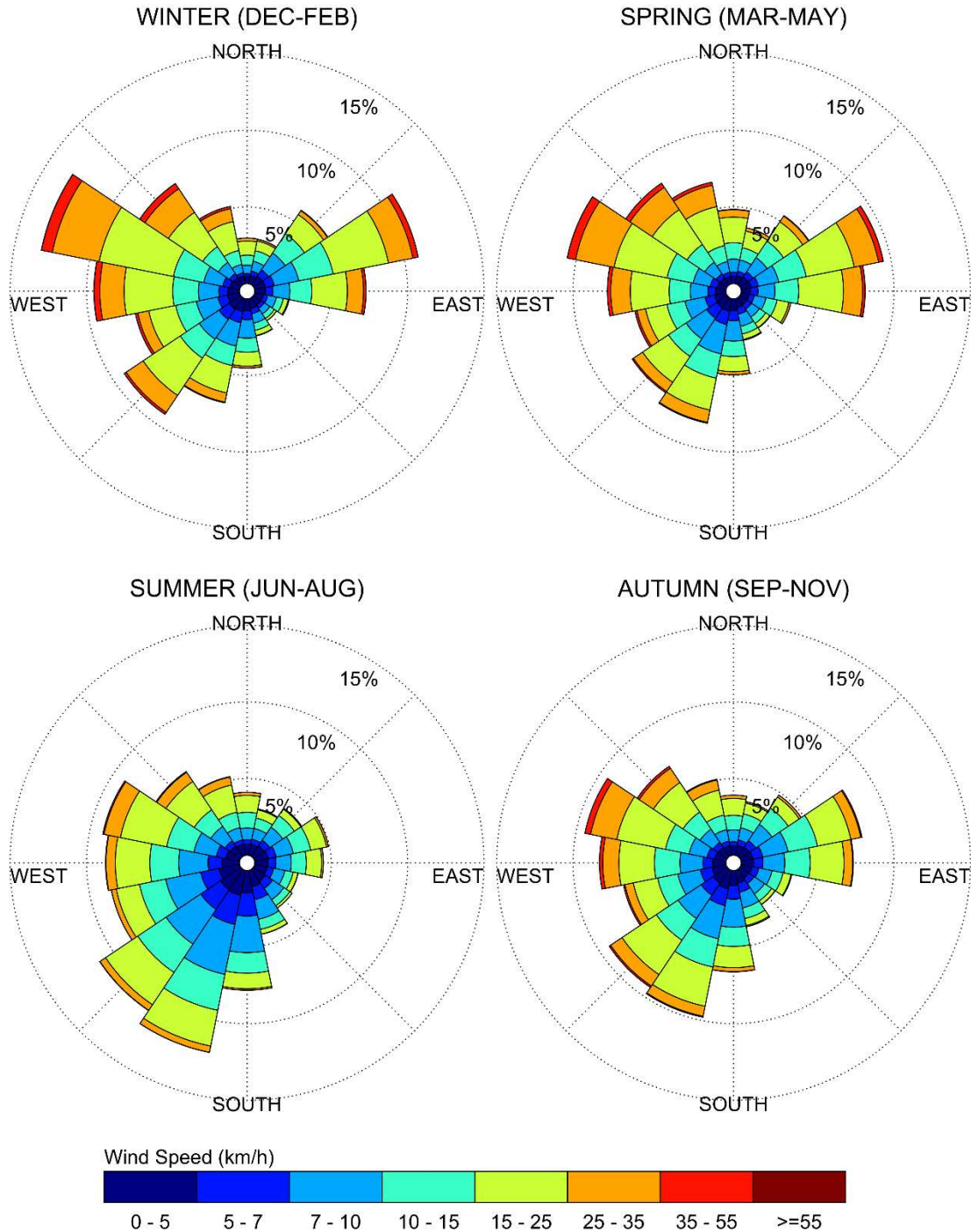
### 4.3 Historical Wind Speed and Direction Data

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 during the appropriate hours of pedestrian usage (that is, between 06:00 and 23:00) and divided into four distinct seasons, as stipulated in the wind criteria. Specifically, the spring season is defined as March through May, the summer season is defined as June through August, the autumn season is defined as September through November, and the winter season is defined as December through February, inclusive.

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 prominent 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 prominence 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 Wind Comfort and Safety Criteria – City of Ottawa

Pedestrian wind comfort and safety criteria are based on the mechanical effects of wind without consideration of other meteorological conditions (that is, temperature and relative humidity). The comfort criteria assume that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Five pedestrian comfort classes based on 20% non-exceedance mean wind speed ranges are used to assess pedestrian comfort: (1) Sitting; (2) Standing; (3) Strolling; (4) Walking; and (5) Uncomfortable. The gust speeds, and equivalent mean speeds, are selected based on the Beaufort scale, which describes the effects of forces produced by varying wind speed levels on objects. 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. Specifically, the comfort classes, associated wind speed ranges, and limiting criteria are summarized as follows:

##### PEDESTRIAN WIND COMFORT CLASS DEFINITIONS

| Wind Comfort Class | Mean Speed (km/h) | Description  |
|--------------------|-------------------|--|
| SITTING            | $\leq 10$         | 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.  |
| STANDING           | $\leq 14$         | 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.  |
| STROLLING          | $\leq 17$         | 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.  |
| WALKING            | $\leq 20$         | 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.  |
| UNCOMFORTABLE      | $> 20$            | 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. |



Regarding wind safety, 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. From calculations of stability, it can be shown that gust wind speeds of 90 km/h would be the approximate threshold wind speed that would cause an average elderly person in good health to fall. Notably, 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.

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 subject 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 target 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 target comfort classes are summarized on the following page. Depending on the programming of a space, the desired comfort class may differ from this table.

### TARGET PEDESTRIAN WIND COMFORT CLASSES FOR VARIOUS LOCATION TYPES

| Location Types                  | Target Comfort Classes |
|---------------------------------|------------------------|
| Primary Building Entrance       | Standing               |
| Secondary Building Access Point | Walking                |
| Public Sidewalk / Bicycle Path  | Walking                |
| Outdoor Amenity Space           | Sitting / Standing     |
| Café / Patio / Bench / Garden   | Sitting / Standing     |
| Transit Stop (Without Shelter)  | Standing               |
| Transit Stop (With Shelter)     | Walking                |
| Public Park / Plaza             | Sitting / Standing     |
| 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, which illustrate wind conditions at grade level for the proposed and existing massing scenarios. Conditions are presented as continuous contours of wind comfort throughout the subject site and correspond to the comfort classes presented in Section 4.4.

Wind comfort conditions are also reported for the typical use period, which is defined as May to October, inclusive. Figure 7 illustrates wind comfort conditions at grade level during this period, consistent with the comfort classes illustrated in Section 4.4.

Conditions at all areas studied are considered acceptable for the intended pedestrian uses. The details of these conditions are summarized in the following pages for each area of interest.



## 5.1 Wind Comfort Conditions

**Sidewalks and Transit Stops along Dun Skipper Drive:** Following the introduction of the proposed development, wind comfort conditions over the nearby public sidewalks along Dun Skipper Drive are predicted to be suitable for standing, or better, during the summer and autumn, becoming suitable for mostly standing during the winter, and suitable for a mix of standing and strolling during the spring. Conditions in the vicinity of the transit stops along Dun Skipper Drive are predicted to be suitable for sitting during the summer, becoming suitable for standing during the remaining seasons. The noted conditions are considered acceptable.

Under the existing massing prior to the introduction of the proposed development, conditions over the sidewalks along Dun Skipper Drive are predicted to be suitable for a mix of sitting and standing during the summer, becoming suitable for standing during the autumn, and suitable for a mix of standing and strolling during the spring and winter. Under the existing massing, conditions in the vicinity of the nearby transit stops along Dun Skipper Drive are predicted to be suitable for sitting during the summer, becoming suitable for standing throughout the remainder of the year. Notably, the introduction of the proposed development is predicted to improve wind conditions over most areas along Dun Skipper Drive as compared to existing conditions and wind conditions with the proposed development are considered acceptable for public sidewalks and transit stops.

**Sidewalks along Cedar Creek Drive:** Following the introduction of the proposed development, conditions over the nearby public sidewalks along Cedar Creek Drive are predicted to be suitable for mostly sitting during the summer, becoming suitable for a mix of mostly sitting and standing during the remaining seasons. The noted conditions are considered acceptable.

Under the existing massing, conditions along Cedar Creek Drive are predicted to be suitable for mostly sitting during the summer, becoming suitable for a mix of sitting and standing during the autumn, and suitable for mostly standing during the spring and winter. The introduction of the proposed development is predicted to improve comfort levels along Cedar Creek Drive, and conditions with the proposed development are considered acceptable for public sidewalks.



**Drive Aisle, Surface Parking, and Walkways within the Subject Site:** Wind conditions over the central drive aisle and surface parking serving the proposed development are predicted to be suitable for standing, or better, throughout the year, with a region suitable for strolling between Buildings 1 and 2 during the spring and winter. Conditions over the walkways along the east, south, and west elevations of the buildings are predicted to be suitable for mostly sitting during the summer, becoming suitable for a mix of sitting and standing during the remaining seasons. The noted conditions are considered acceptable.

**Gardens within the Subject Site:** During the typical use period, conditions over the gardens situated to the northeast of Building 1 and to the southeast of Building 2 are predicted to be suitable for sitting. The noted conditions are considered acceptable.

**Building Access Points:** Owing to the protection of the building's façades, conditions in the vicinity of the primary and secondary access points serving the proposed development are predicted to be suitable for sitting throughout the year, which is considered acceptable.

## 5.2 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.

## 5.3 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.



## 6. CONCLUSIONS AND RECOMMENDATIONS

A complete summary of the predicted wind conditions is provided in Section 5 and illustrated in Figures 3A-7. 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, transit stops, the proposed surface parking lot, drive aisle, walkways, gardens, and in the vicinity of building access points, are considered acceptable.
- 2) 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, (for example, 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.***



Omar Rioseco, B.Eng.  
Junior Wind Scientist

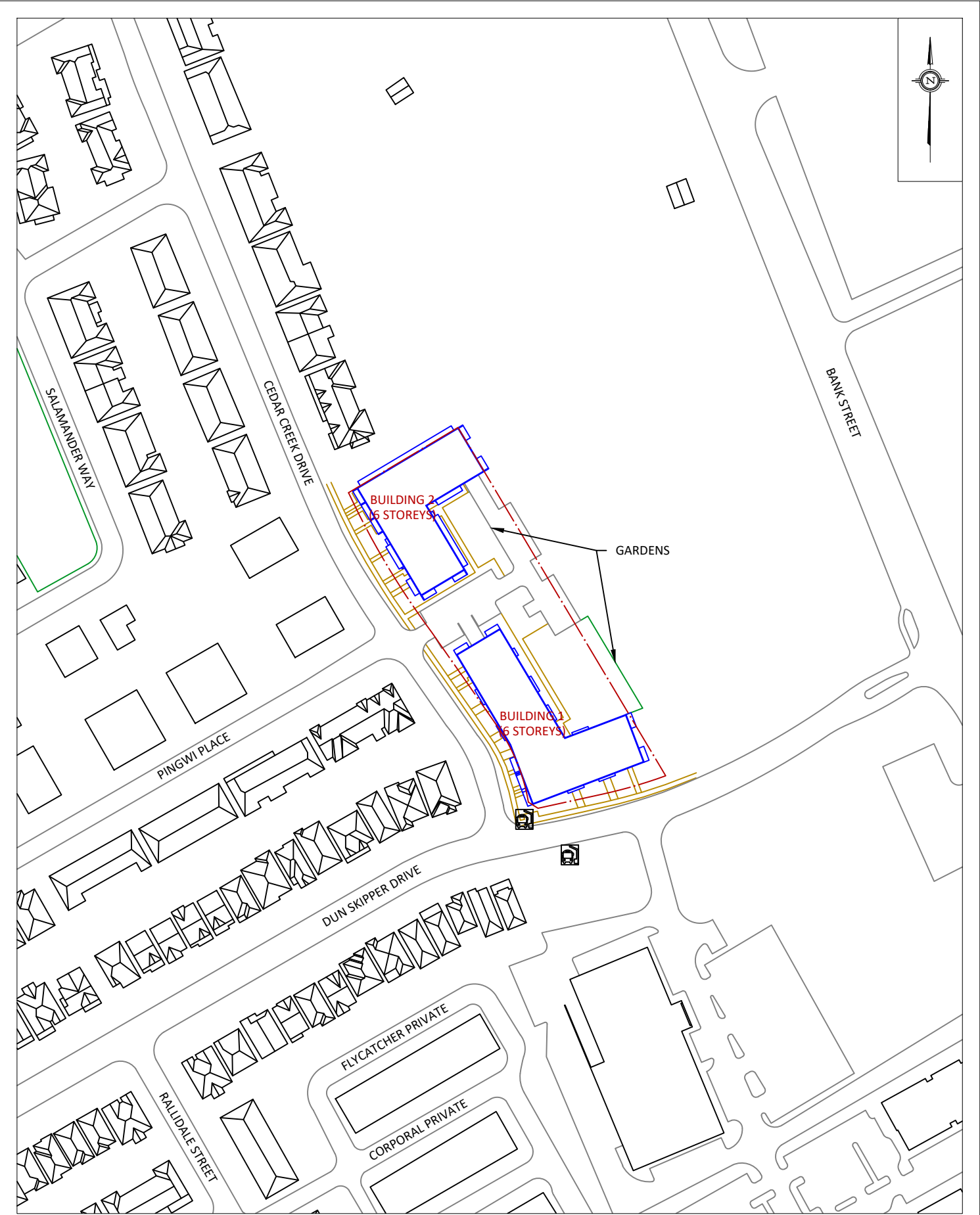


Sunny Kang, B.A.S.  
Project Coordinator



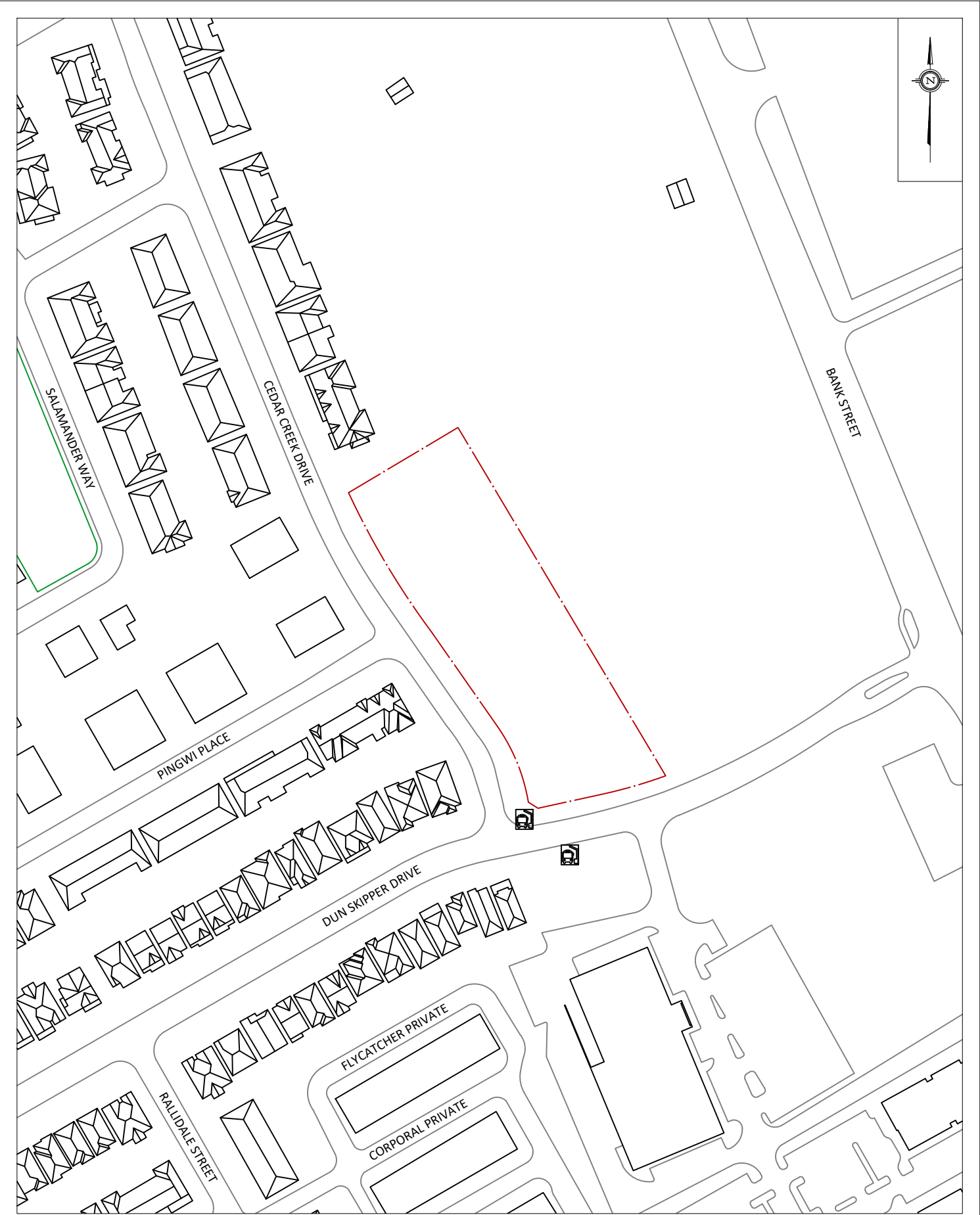
David Huitema, M.Eng., P.Eng.  
CFD Lead Engineer



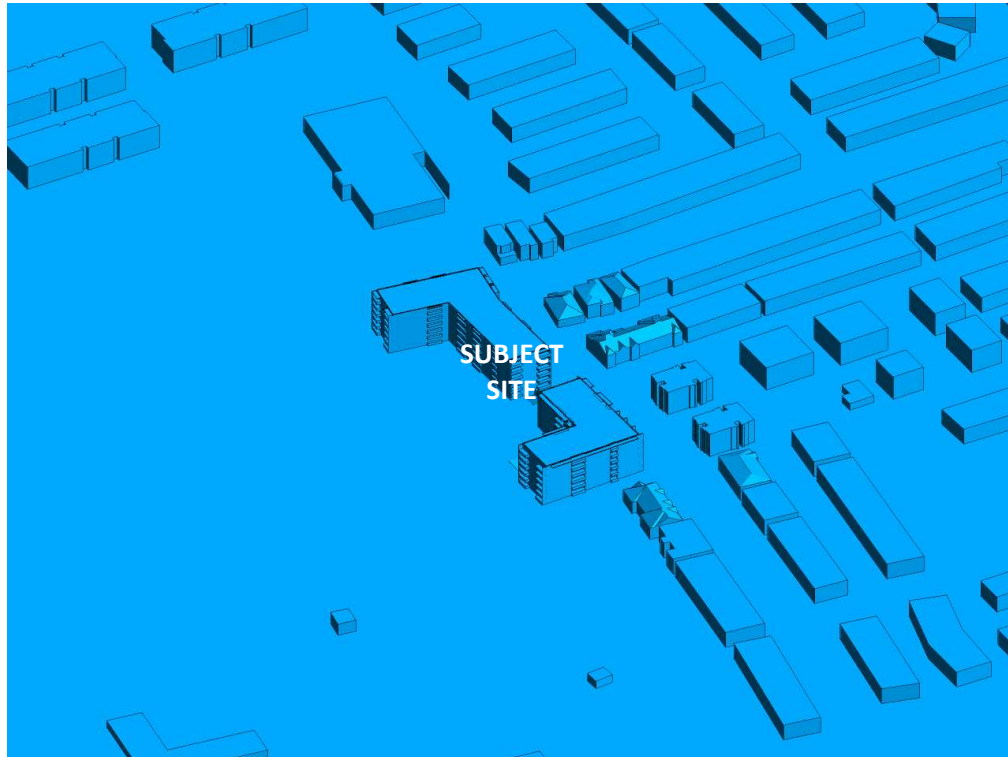


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| <b>GRADIENTWIND</b><br>ENGINEERS & SCIENTISTS<br>127 WALGREEN ROAD, OTTAWA, ON<br>613 836 0934 • GRADIENTWIND.COM | PROJECT<br>150 DUN SKIPPER DRIVE, OTTAWA<br>PEDESTRIAN LEVEL WIND STUDY |                              | DESCRIPTION<br><br>FIGURE 1A:<br>PROPOSED SITE PLAN AND SURROUNDING CONTEXT |
|   | SCALE<br>1:2000   | DRAWING NO.<br>24-238-PLW-1A |   |
|   | DATE<br>DECEMBER 16, 2024   | DRAWN BY<br>S.K.             |   |
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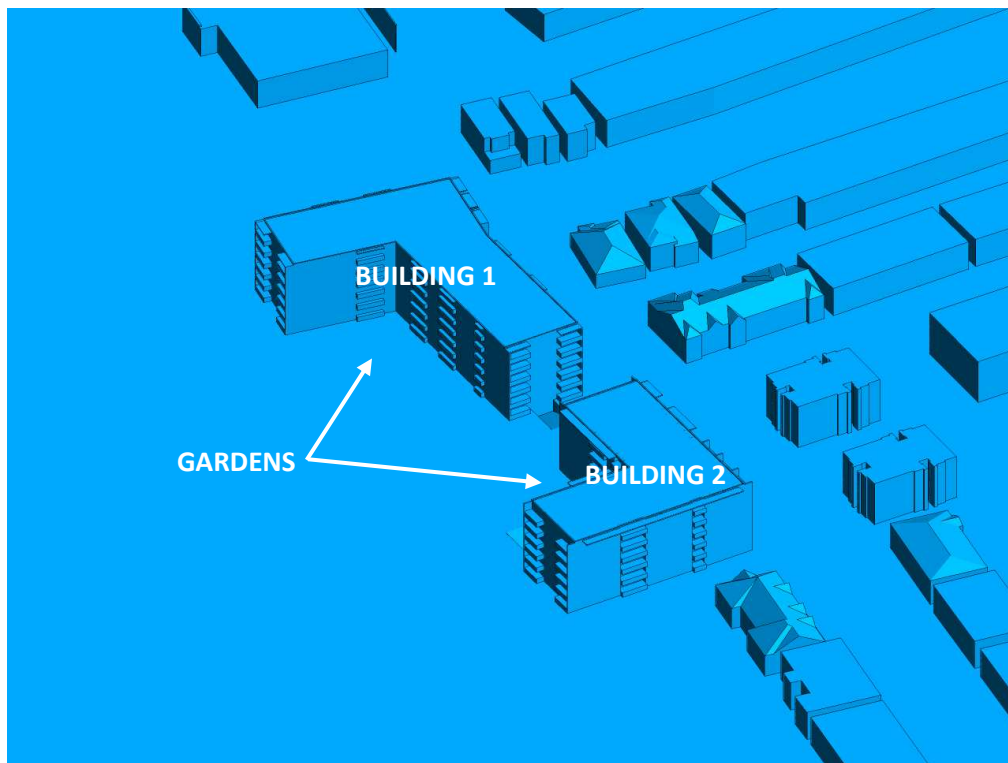




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| <b>GRADIENTWIND</b><br>ENGINEERS & SCIENTISTS<br>127 WALGREEN ROAD, OTTAWA, ON<br>613 836 0934 • GRADIENTWIND.COM | PROJECT<br>150 DUN SKIPPER DRIVE, OTTAWA<br>PEDESTRIAN LEVEL WIND STUDY |                              | DESCRIPTION<br><br>FIGURE 1B:<br>EXISTING SITE PLAN AND SURROUNDING CONTEXT |
|   | SCALE<br>1:2000   | DRAWING NO.<br>24-238-PLW-1B |   |
|   | DATE<br>DECEMBER 16, 2024   | DRAWN BY<br>S.K.             |   |
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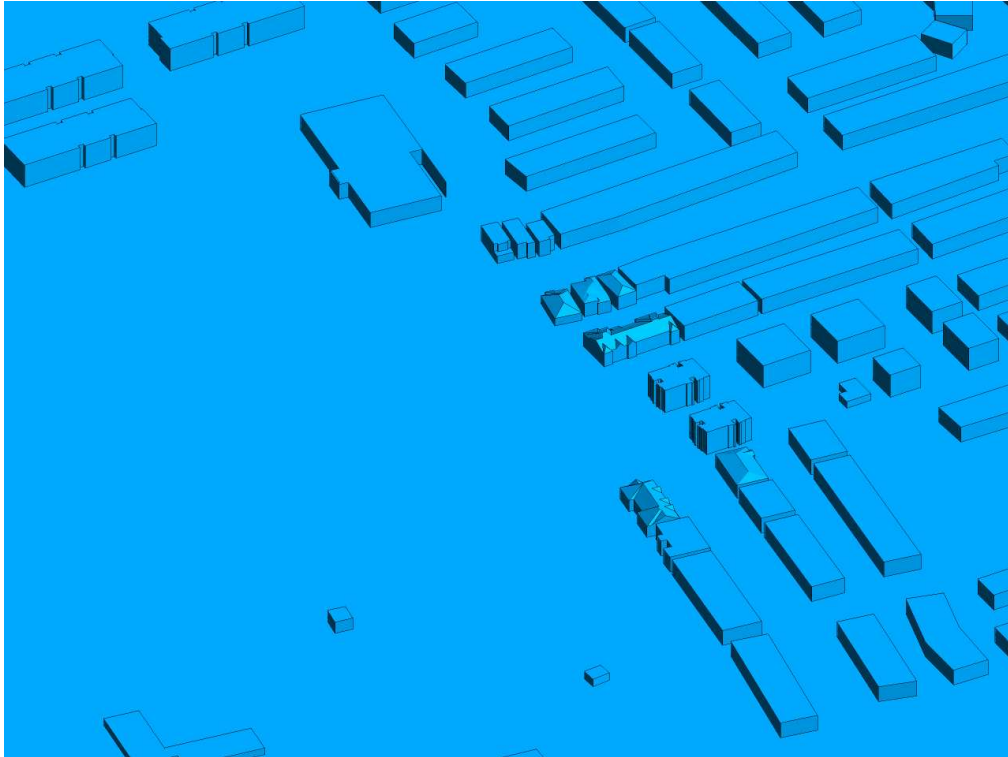


**FIGURE 2A: COMPUTATIONAL MODEL, PROPOSED MASSING, NORTH PERSPECTIVE**

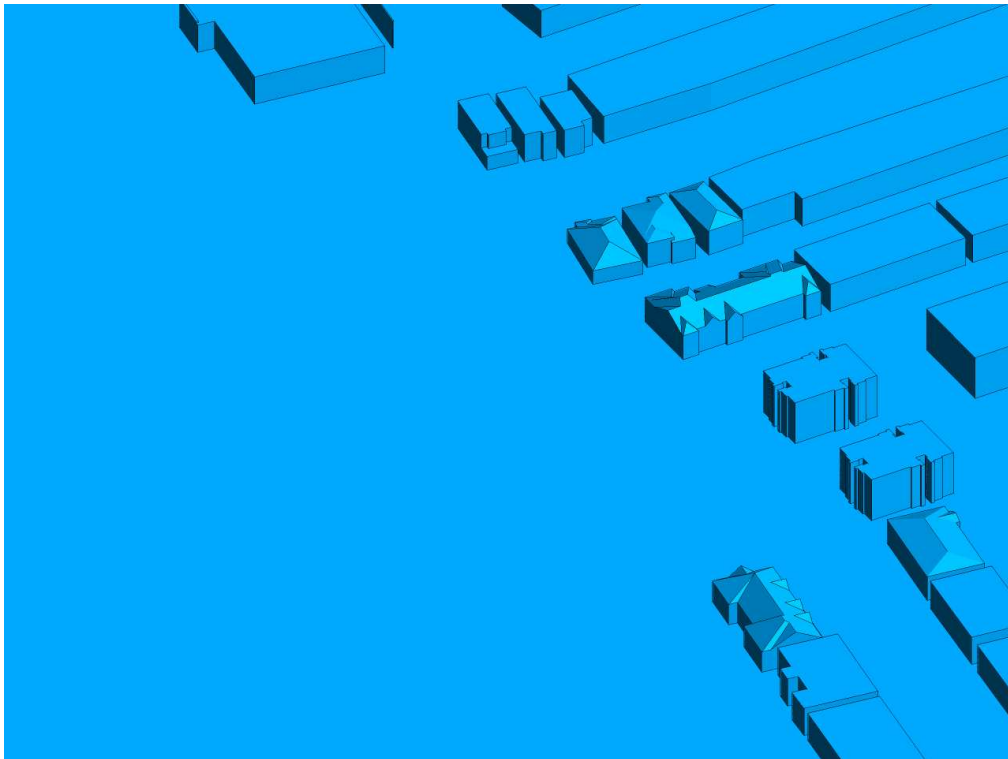


**FIGURE 2B: CLOSE UP OF FIGURE 2A**



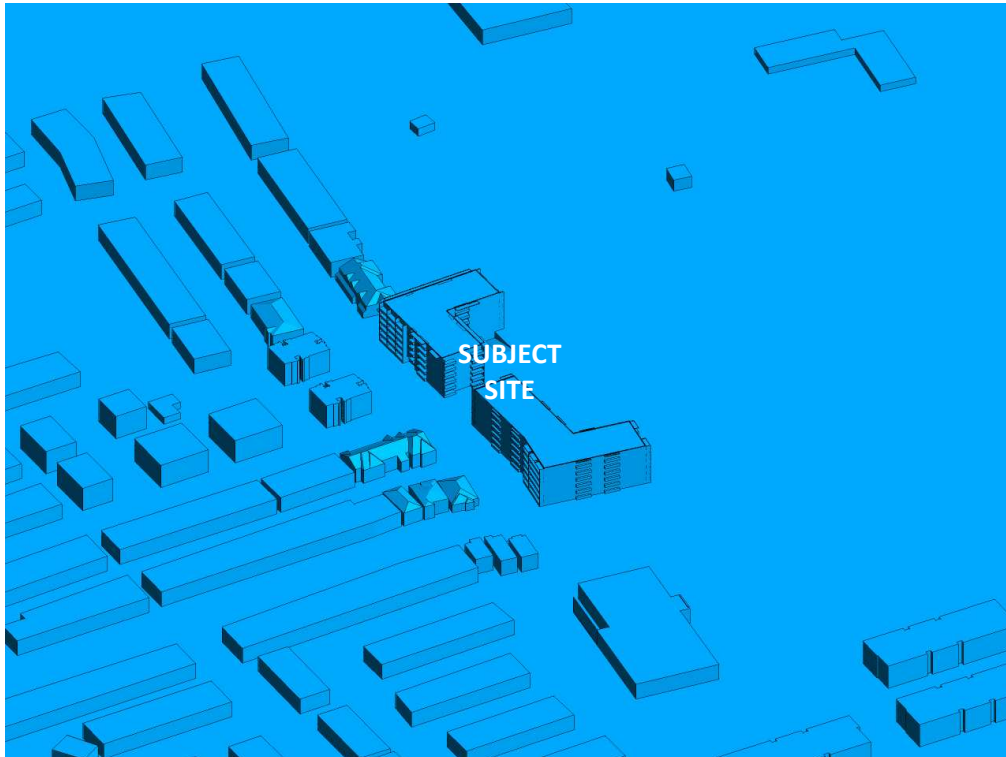


**FIGURE 2C: COMPUTATIONAL MODEL, EXISTING MASSING, NORTH PERSPECTIVE**

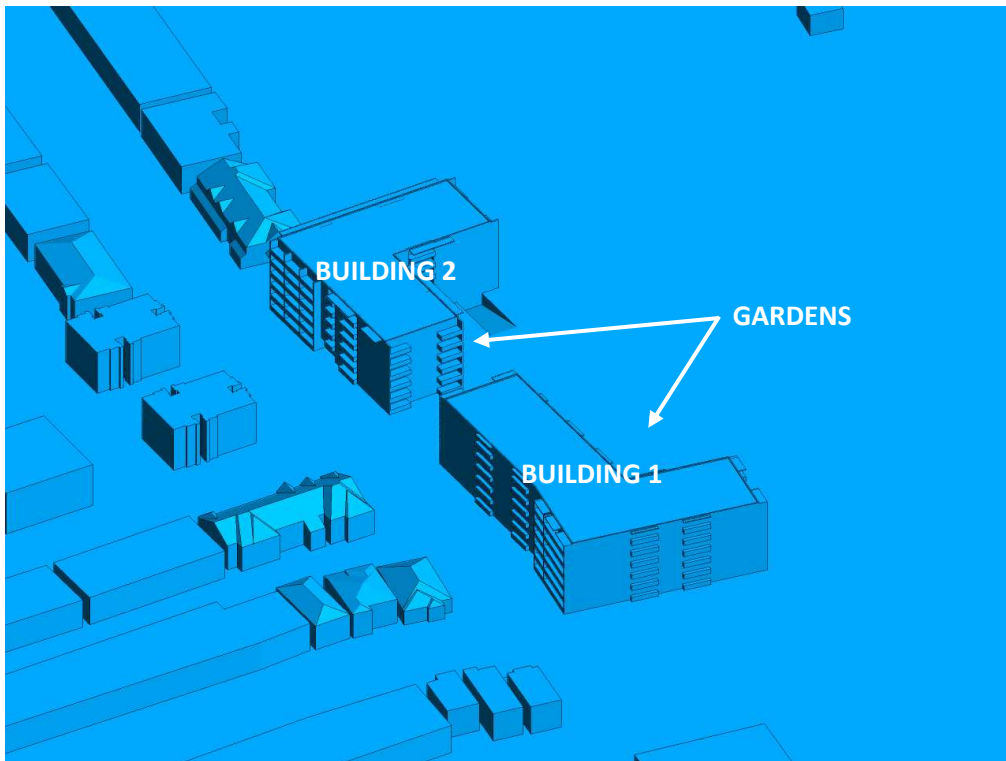


**FIGURE 2D: CLOSE UP OF FIGURE 2C**



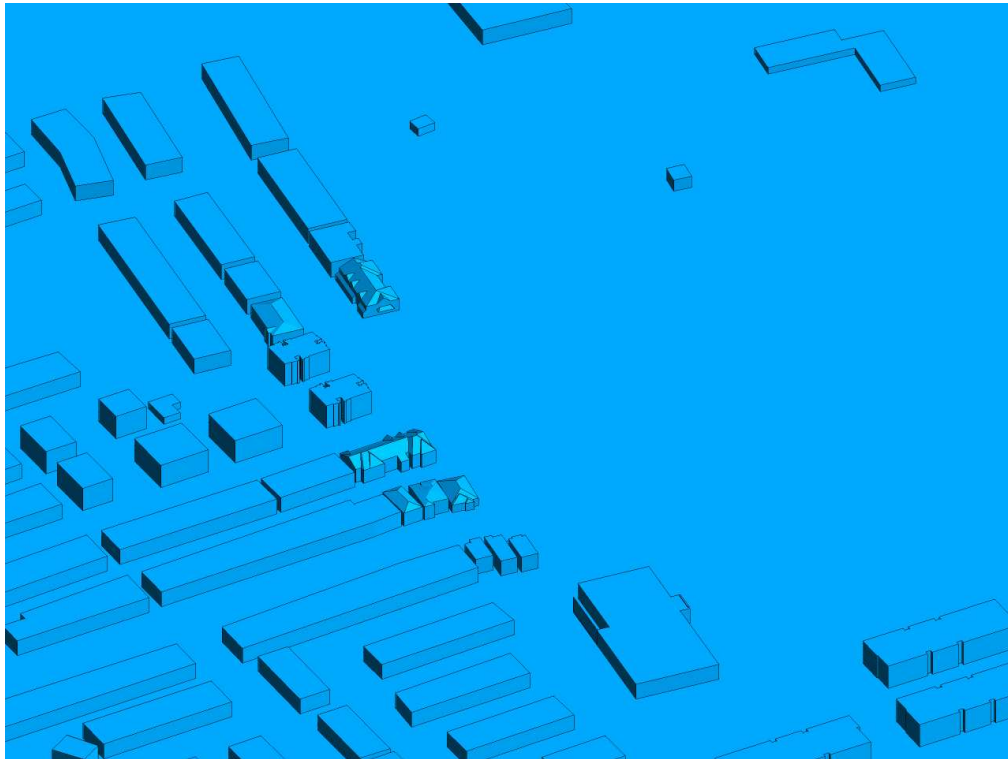


**FIGURE 2E: COMPUTATIONAL MODEL, PROPOSED MASSING, SOUTH PERSPECTIVE**

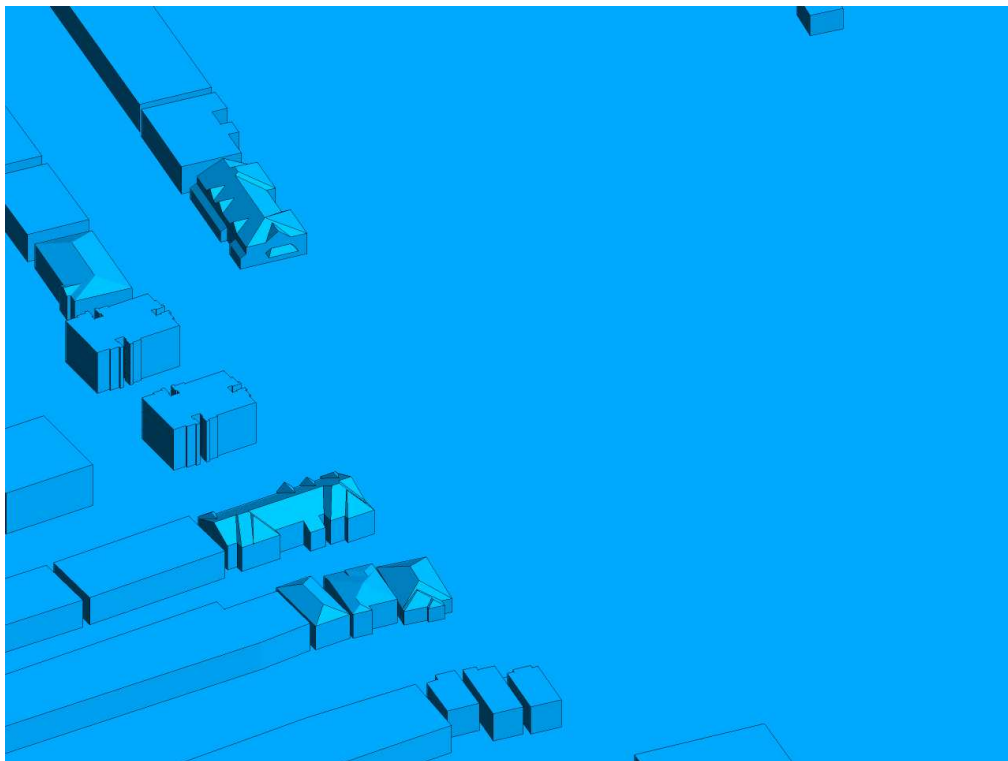


**FIGURE 2F: CLOSE UP OF FIGURE 2E**





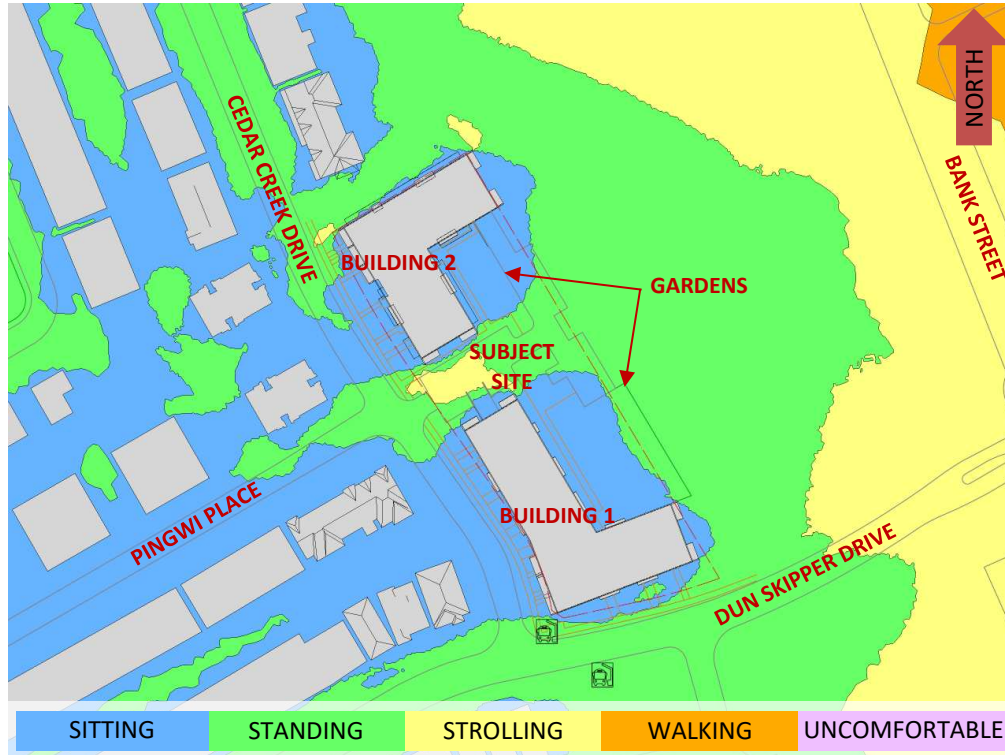
**FIGURE 2G: COMPUTATIONAL MODEL, EXISTING MASSING, SOUTH PERSPECTIVE**



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





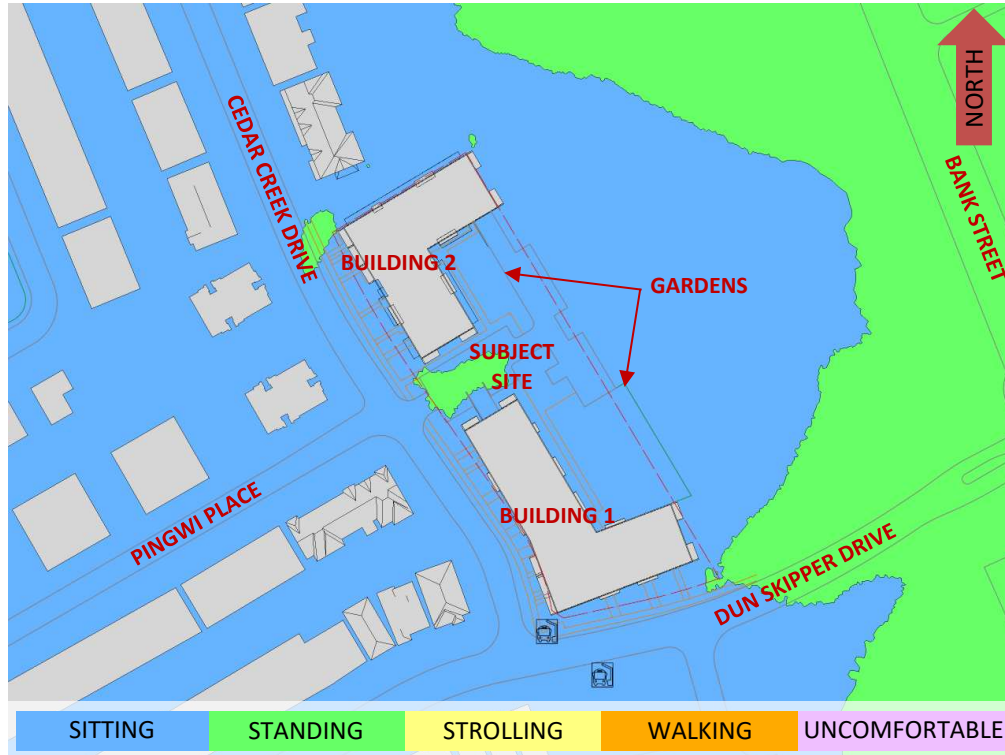


**FIGURE 3A: SPRING – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING**

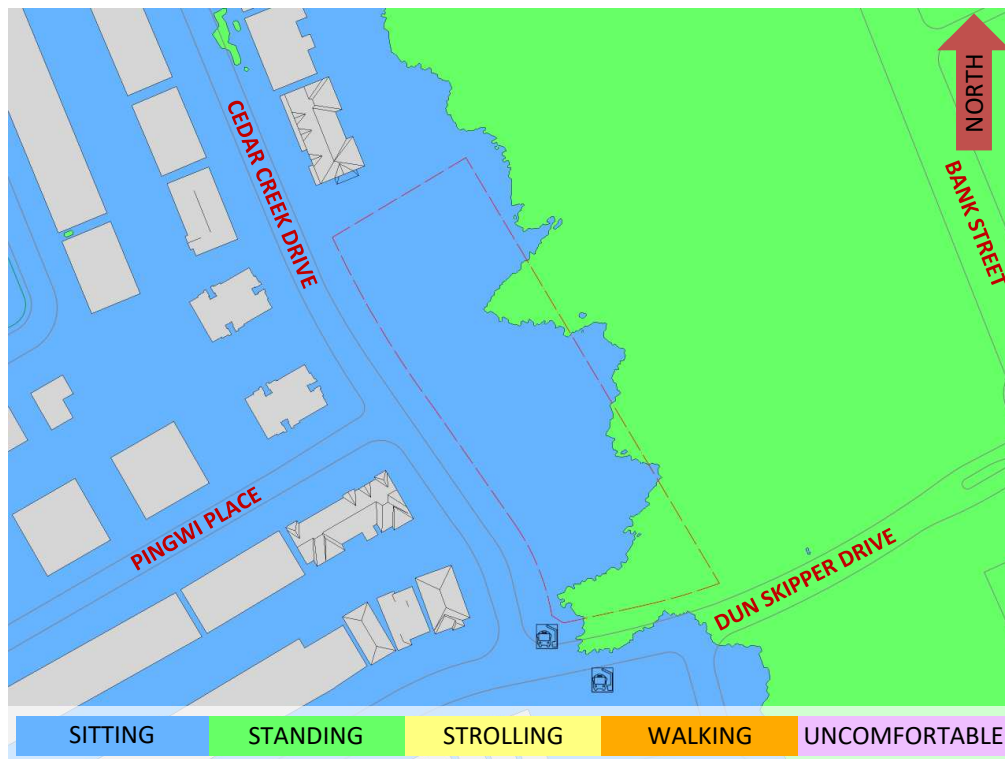


**FIGURE 3B: SPRING – WIND COMFORT, GRADE LEVEL– EXISTING MASSING**





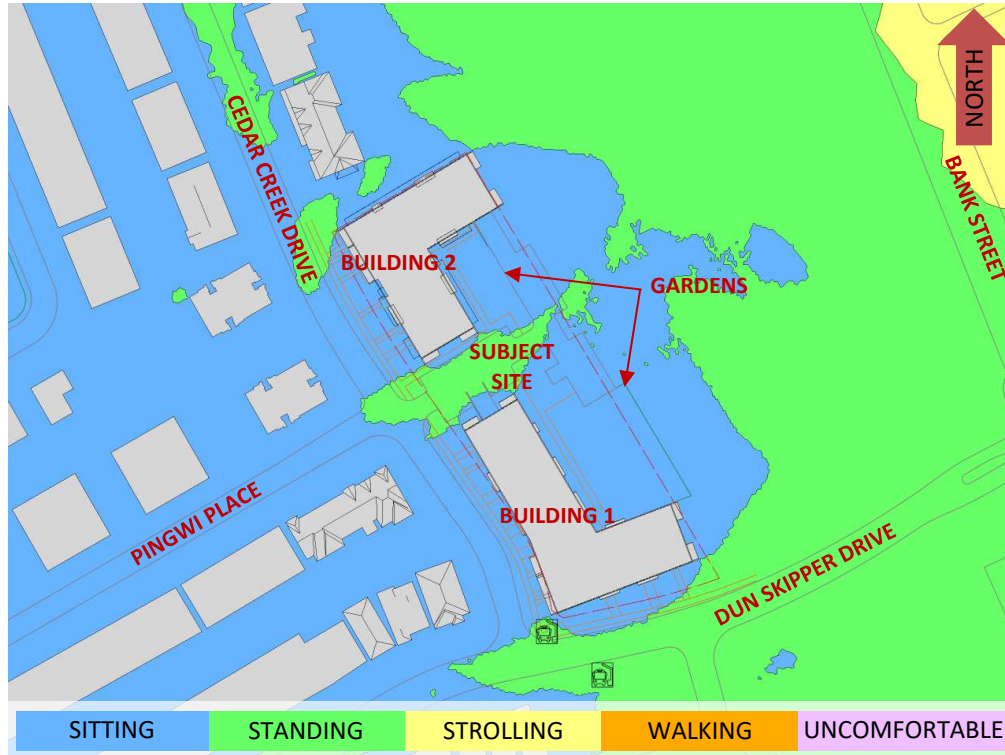
**FIGURE 4A: SUMMER – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING**



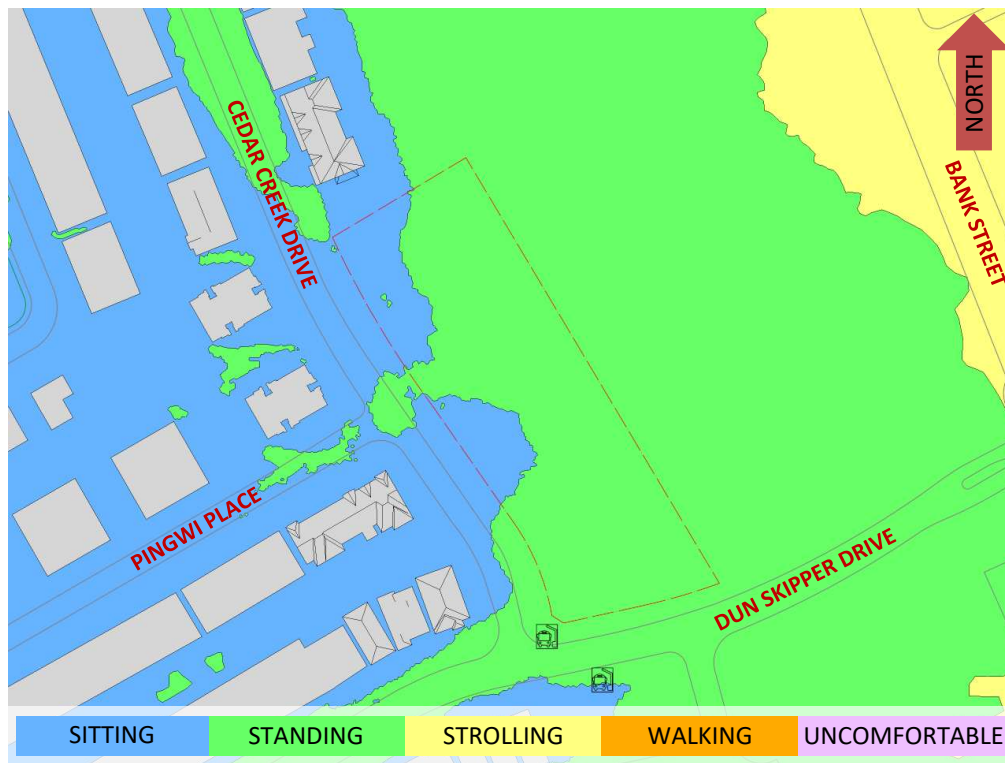
**FIGURE 4B: SUMMER – WIND COMFORT, GRADE LEVEL– EXISTING MASSING**





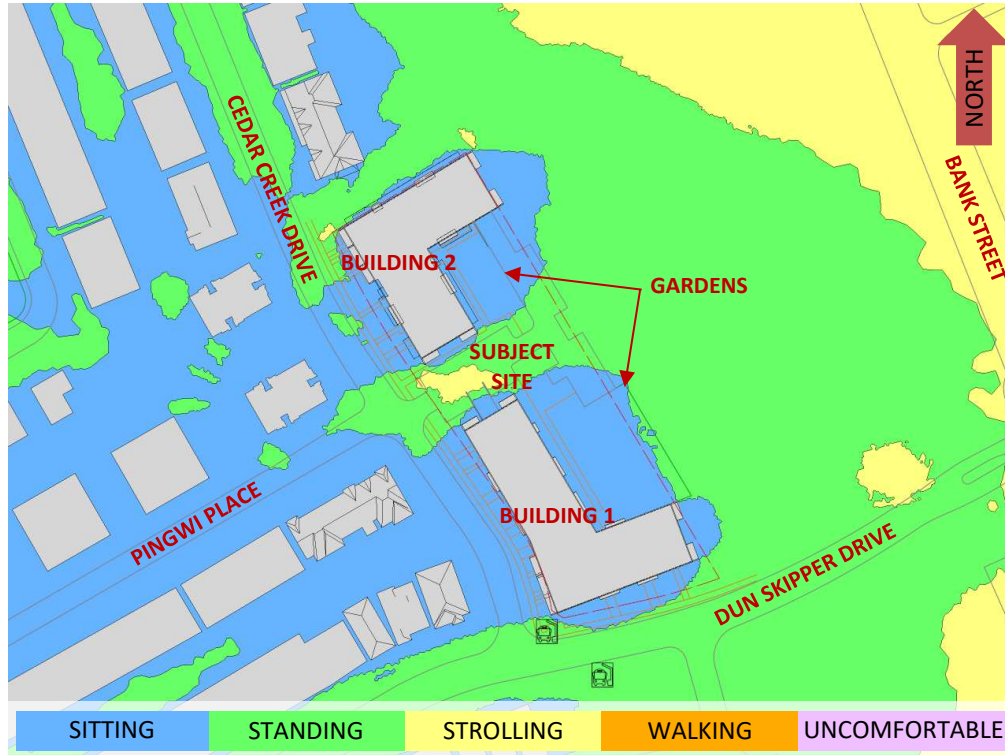


**FIGURE 5A: AUTUMN – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING**

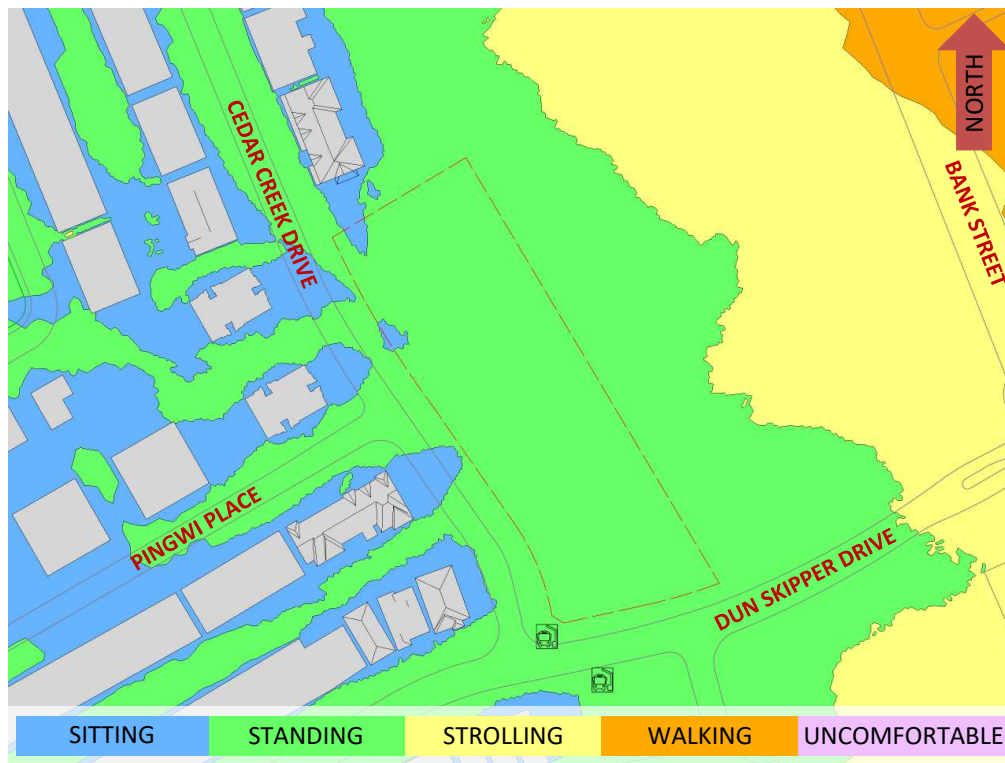


**FIGURE 5B: AUTUMN – WIND COMFORT, GRADE LEVEL- EXISTING MASSING**



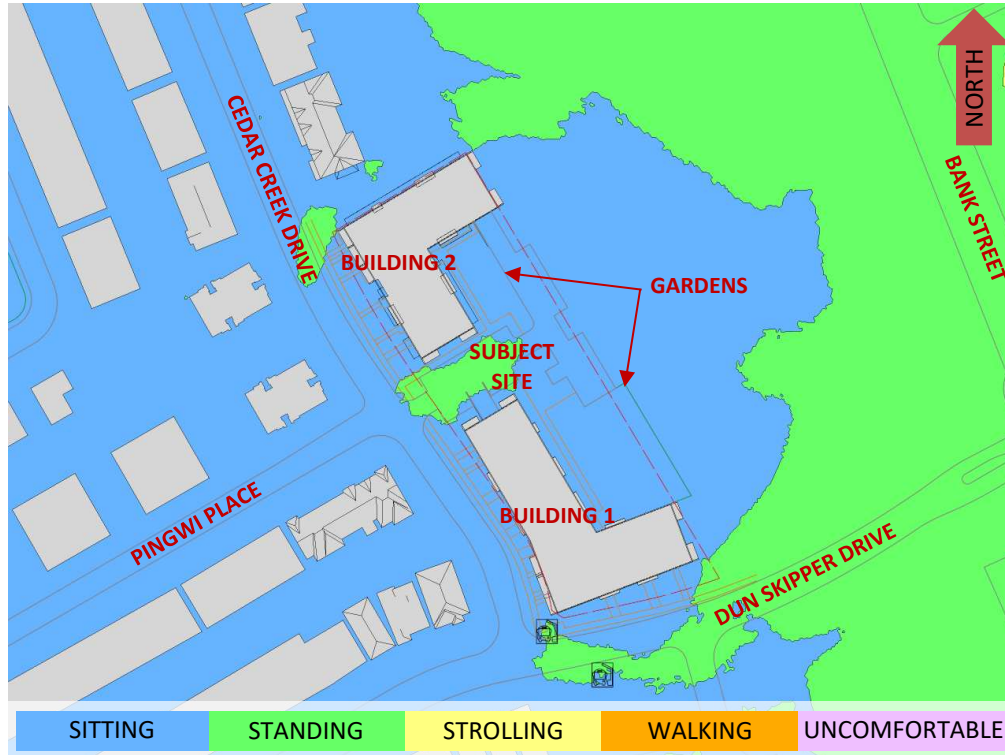


**FIGURE 6A: WINTER – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING**



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



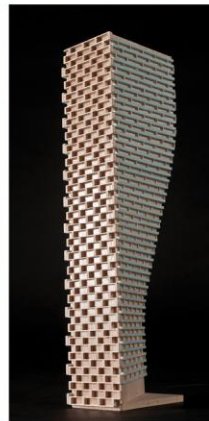


**FIGURE 7: TYPICAL USE PERIOD – WIND COMFORT, GRADE LEVEL – PROPOSED MASSING**



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## 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<br>(Degrees True) | Alpha Value<br>( $\alpha$ ) |
|----------------------------------|-----------------------------|
| 0                                | 0.22                        |
| 22.5                             | 0.20                        |
| 45                               | 0.19                        |
| 67.5                             | 0.19                        |
| 90                               | 0.19                        |
| 112.5                            | 0.20                        |
| 135                              | 0.20                        |
| 157.5                            | 0.20                        |
| 180                              | 0.20                        |
| 202.5                            | 0.19                        |
| 225                              | 0.20                        |
| 247.5                            | 0.21                        |
| 270                              | 0.21                        |
| 292.5                            | 0.22                        |
| 315                              | 0.23                        |
| 337.5                            | 0.23                        |

**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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