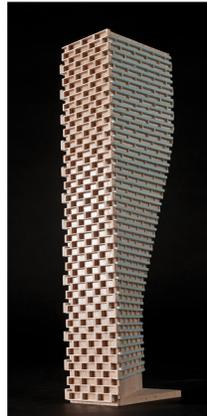


## PEDESTRIAN LEVEL WIND STUDY

1420 Richmond Road & 365 Forest Street  
Ottawa, Ontario

Report: 19-084-PLW



March 4, 2020

PREPARED FOR  
EXP

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PREPARED BY

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## EXECUTIVE SUMMARY

This report describes a computer-based pedestrian level wind (PLW) study to satisfy the requirements for a site plan control application (SPA) submission for a proposed two-building development located at 1420 Richmond Road and 365 Forest Street in Ottawa, Ontario (hereinafter referred to as “subject site”). Our mandate within this study is to investigate pedestrian wind comfort and safety within and surrounding the subject site, and to identify any areas where wind conditions may interfere with certain pedestrian activities so that mitigation measures may be considered, as 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-7B, and summarized as follows:

- 1) Conditions around the subject site at grade level, including along sidewalks and walkways, within the landscaped area and parking lot to the east of Building A, and at building entrances will be acceptable for their intended uses throughout the year.
- 2) Wind conditions within the common amenity terraces at Level 11 of both buildings will be suitable for sitting at least 75% of the time during the summer season and at least 70% of the time during the spring and autumn seasons, which is acceptable.
- 3) Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no pedestrian areas surrounding the subject site at grade level were found to experience conditions that could be considered uncomfortable or dangerous.



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## 1. INTRODUCTION

Gradient Wind Engineering Inc. (Gradient Wind) was retained by EXP to undertake a computer-based pedestrian level wind (PLW) study to satisfy the requirements for a site plan control application (SPA) submission for a proposed two-building development located at 1420 Richmond Road and 365 Forest Street in Ottawa, Ontario (hereinafter referred to as “subject site”). Our mandate within this study is to investigate pedestrian wind comfort and safety within and surrounding the subject site, and to identify any areas where wind conditions may interfere with certain pedestrian activities so that mitigation measures may be considered, as 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 provided by Lapalme Rheault Architectes + Associés in February 2020, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent satellite imagery via Google Earth Pro.

## 2. TERMS OF REFERENCE

The subject site is located at 1420 Richmond Road and 365 Forest Street in Ottawa, and is situated on a parcel of land bordered by Richmond Road to the north, Forest Street to the west, Bond Street to the south, and Croydon Avenue to the east.

The proposed development consists of two mixed-use buildings, referred to as Buildings ‘A’ and ‘B’.

Building A rises to a height of 12 storeys, and has an irregular planform. The ground floor comprises commercial space at the north, a lobby and bike storage room at the south, and residential units. Levels 2 and above comprise residential units. At Level 11, the floorplate steps back from the southwest corner to reveal an amenity terrace. The main residential entrance is located at the southwest corner of the building, while secondary entrances are located at the north, east, and south elevations.



*Perspective Rendering Looking West  
(Courtesy of Rheault Architectes + Associés)*

Building B rises to a height of 11 storeys, with a roughly rectangular planform. The ground floor comprises a gym, a lobby, a bike storage room, and residential space. Levels 2 and above comprise residential units. At Level 11, the floorplate steps back from the west side to reveal a common amenity terrace. The main residential entrance is located at the northwest corner of the building, while secondary entrances are located at the east and west elevations. Access to underground parking is provided from Forest Street. A landscaped area and a parking lot are located to the east of Building A.

The near-field surroundings (defined as an area within a radius of 500 metres (m) of the subject site) comprise mid- and high-rise buildings to the east, south and southwest, and mostly low-rise residential buildings elsewhere. The far-field surroundings (defined as an area beyond the near-field but within a 5 kilometer (km) radius of the subject site) contribute primarily suburban wind exposures from the northeast clockwise to the southwest, while the presence of the Ottawa River contributes to hybrid open-suburban exposures from the southwest clockwise to the northeast.

Key areas under consideration for pedestrian wind comfort include surrounding sidewalks, walkways, building access points, nearby transit stops, and the amenity terraces serving Buildings A and B. Figure 1 illustrates the subject site and surrounding context, while Figures 2A-2D illustrate the computational model used to conduct the study.

### **3. OBJECTIVES**

The principal objectives of this study are to (i) determine pedestrian level wind comfort and safety 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 more conservative (i.e., windier) wind speed values.

#### 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 12 wind directions. The CFD simulation model was centered on the study building, complete with surrounding massing within a diameter of approximately 1 km.

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, and 1.5 m above the rooftop amenity terraces, were referenced to the wind speed at gradient height to generate mean and peak velocity ratios, which were used to calculate full-scale values. The gradient height represents the theoretical depth of the boundary layer of

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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)



the earth's atmosphere, above which the mean wind speed remains constant. Further details of the CFD wind flow simulation technique are presented in Appendix A.

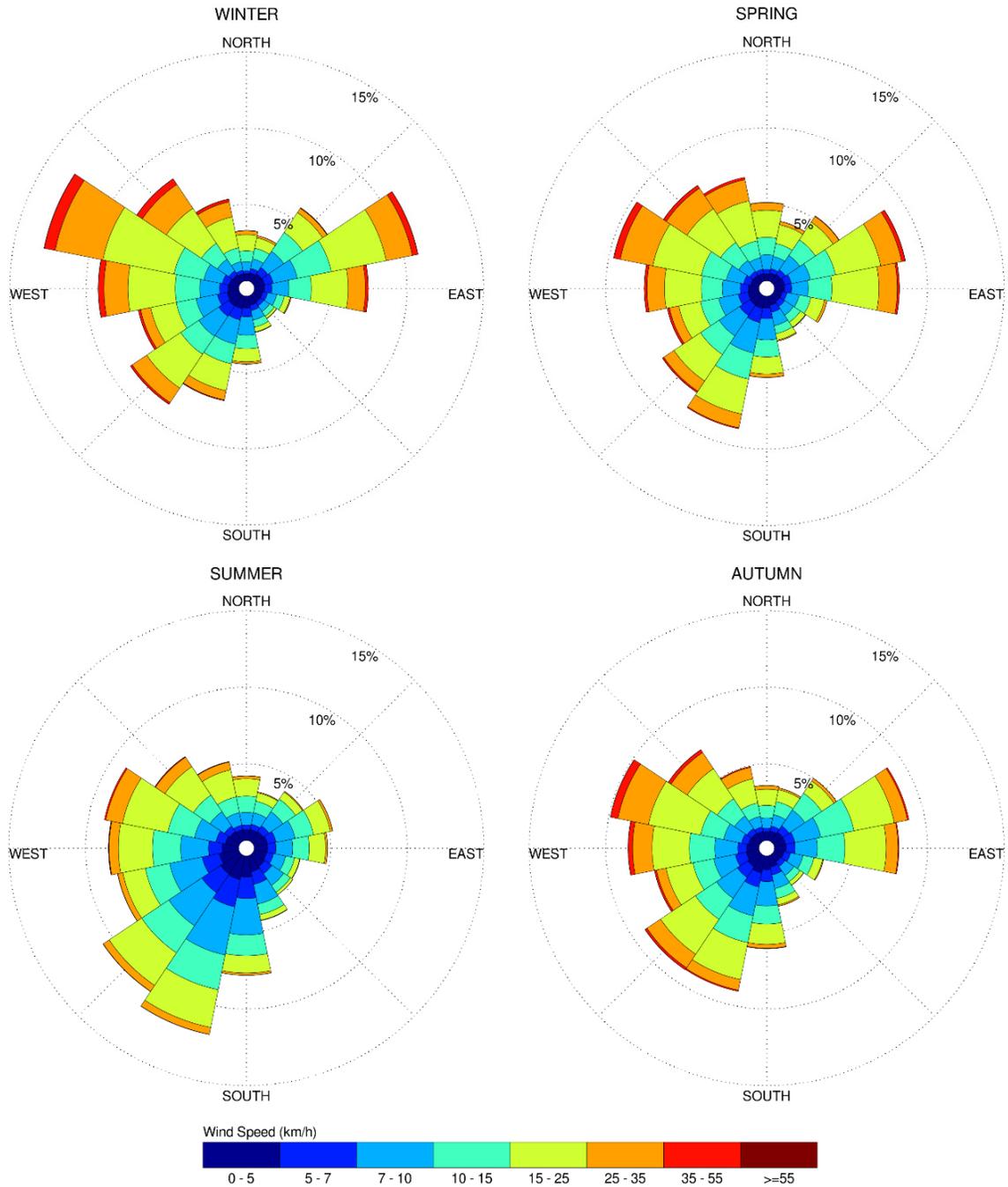
### 4.3 Meteorological Data Analysis

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 in order to determine the statistically prominent wind directions and corresponding speeds, and to characterize similarities between monthly weather patterns. Based on this portion of analysis, the four seasons are represented by grouping data from consecutive months based on similarity of weather patterns, and not according to the traditional calendar method. The winter season is defined as December-March, spring as April-May, summer as June-September, and autumn as October-November.

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 (i.e., temperature, relative humidity). The comfort guidelines assume that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Five pedestrian comfort classes are based on 80% 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 gust equivalent mean 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 gust equivalent mean 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 gust equivalent mean 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 gust equivalent mean 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 mean gust speed ranges are selected based on 'The Beaufort Scale', which describes the effect of forces produced by varying wind speeds on levels on objects.

## THE BEAUFORT SCALE

| Number | Description     | Wind Speed (km/h) | Description   |
|--------|-----------------|-------------------|---|
| 2      | Light Breeze    | 6-11              | Wind felt on faces  |
| 3      | Gentle Breeze   | 12-19             | Leaves and small twigs in constant motion; Wind extends light flags                           |
| 4      | Moderate Breeze | 20-28             | Wind raises dust and loose paper; Small branches are moved                                    |
| 5      | Fresh Breeze    | 29-38             | Small trees in leaf begin to sway   |
| 6      | Strong Breeze   | 39-49             | Large branches in motion; Whistling heard in electrical wires; Umbrellas used with difficulty |
| 7      | Moderate Gale   | 50-61             | Whole trees in motion; Inconvenient walking against wind                                      |
| 8      | Gale            | 62-74             | 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 80% 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 (gust equivalent mean wind speed of 16 km/h) was 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 (gust equivalent mean wind speed of 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 most of 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 at tested locations, the assessment of pedestrian comfort involves determining the suitability of the predicted wind conditions for their associated spaces. This step involves comparing the predicted comfort class to the desired comfort class, which is dictated by the location type represented by the sensor (i.e., a sidewalk, building entrance, amenity space, or other). An overview of common pedestrian location types and their desired comfort classes are summarized on the following page.



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

| Location Types                           | Desired Comfort Classes        |
|--|--------------------------------|
| Primary Building Entrance                | Standing                       |
| Secondary Building Access Point          | Walking                        |
| Primary Public Sidewalk                  | Strolling / Walking            |
| Secondary Public Sidewalk / Bicycle Path | Walking                        |
| Outdoor Amenity Space                    | Sitting / Standing / Strolling |
| Café / Patio / Bench / Garden            | Sitting                        |
| Transit Stop                             | Sitting / Standing             |
| Public Park / Plaza                      | Standing / Strolling           |
| Garage / Service Entrance                | Walking                        |
| Parking Lot                              | Strolling / Walking            |
| Vehicular Drop-Off Zone                  | Standing / Strolling / Walking |

## 5. RESULTS AND DISCUSSION

The following discussion of predicted pedestrian wind conditions is accompanied by Figures 3A-3D (following the main text) illustrating the seasonal wind conditions at grade level, and Figures 4A/5A/6A/7A illustrating the seasonal wind conditions within the common amenity terraces. The colour contours indicate various comfort classes predicted for certain regions. Wind conditions comfortable for sitting or more sedentary activities are represented by the colour green, standing are represented by yellow, strolling by orange, walking by blue, while uncomfortable conditions are represented by the colour magenta. In addition to the standard wind comfort class results, Figures 4B/5B/6B/7B illustrate the percentage of time the amenity terraces will be suitable for sitting on a seasonal basis. Pedestrian wind comfort is summarized below for each area of interest.

## 5.1 Wind Comfort Conditions – Grade Level

Following the introduction of the subject site, wind conditions at grade level are predicted to be acceptable throughout the year.

**Richmond Road:** The sidewalks along Richmond Road 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. These conditions are considered acceptable.

**Forest Street:** The sidewalks along Forest Street will be suitable for sitting during the summer, becoming suitable for a mix of sitting and standing during the spring and autumn, and suitable for strolling or better during the winter. In general, the area to the immediate west of Building A is calmer than locations farther from the building façade. These conditions are considered acceptable.

**Landscaped area to the east of Building A:** This landscaped area is predicted to be suitable for sitting during the summer and suitable for a mix of sitting and standing during the remaining seasons. These conditions are considered acceptable.

**Parking lot to the east of subject site:** The parking lot located to the east of Building A, and to the west of 360 Croydon Avenue, will be suitable for standing during the summer and suitable for a mix of standing and strolling during the remaining seasons. These conditions are considered acceptable.

**Driveway to Underground Parking Garage & Parking Entrance:** The driveway leading to the underground parking lot located between Buildings A and B will be suitable for sitting during the summer, becoming suitable for a mix of sitting and standing during the remaining colder seasons. The underground parking entrance located to southeast of Building A will be suitable for sitting during the summer and autumn seasons and suitable for a mix of sitting and standing during the remaining seasons. These conditions are considered acceptable.

**Bond Street:** Bond Street, located to the south of Building B, will be suitable for sitting during the summer, and suitable for a mix of sitting and standing during the remaining seasons. These conditions are considered acceptable.

**Building Entrances:** All building entrances within the subject site will be suitable for standing or better throughout the year, which is acceptable.

## 5.2 Wind Comfort Conditions – Amenity Terraces

**Building A Terrace – Level 11:** Wind conditions within the amenity terrace will be suitable for sitting during the summer, and mostly suitable for sitting throughout the year. During the spring, autumn, and winter seasons, a small region of the terrace along the south perimeter will be suitable for sitting at least 75% of the time. These conditions are considered acceptable without mitigation.

**Building B Terrace – Level 11:** Wind conditions within the amenity terrace will be mostly suitable for sitting during the summer season. While a small portion of the terrace will not meet the sitting criterion, conditions will nevertheless be suitable for sitting at least 75% of the time. The terrace will be mostly suitable for standing during the three colder seasons; Figures 4B and 6B illustrate that the terrace will nevertheless be suitable for sitting at least 70% of the time during the spring and autumn seasons, respectively. These conditions are considered acceptable.

## 5.3 Wind Comfort Conditions – Surrounding Area

Wind conditions over surrounding sidewalks beyond the subject site, as well as at nearby primary building entrances, will be acceptable for their intended pedestrian uses during each seasonal period upon the introduction of the subject site. Pedestrian wind comfort and safety have been quantified for the specific configuration of existing and foreseeable construction around the study site. Future changes (i.e., 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 site would alter the wind profile approaching the site; and (ii) development in proximity to the site would cause changes to local flow patterns. In general, development in urban centers generally creates reduction in the mean wind and localized increases in the gustiness of the wind.

## 6. CONCLUSIONS AND RECOMMENDATIONS

A complete summary of the predicted wind comfort and safety conditions is provided in Section 5 and illustrated in Figures 3A-7B. 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 similar developments in Ottawa, we conclude the following:

- 1) Conditions around the subject site at grade level, including along sidewalks and walkways, within the landscaped area and parking lot to the east of Building A, and at building entrances will be acceptable for their intended uses throughout the year.
- 2) Wind conditions within the common amenity terraces at Level 11 of both buildings will be suitable for sitting at least 75% of the time during the summer season and at least 70% of the time during the spring and autumn seasons, which is acceptable.
- 3) Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no pedestrian areas surrounding the subject site at grade level were found to experience conditions that could be considered uncomfortable or dangerous.

This concludes our pedestrian level wind study and report. Please advise the undersigned of any questions or comments.

Sincerely,

**Gradient Wind Engineering Inc.**



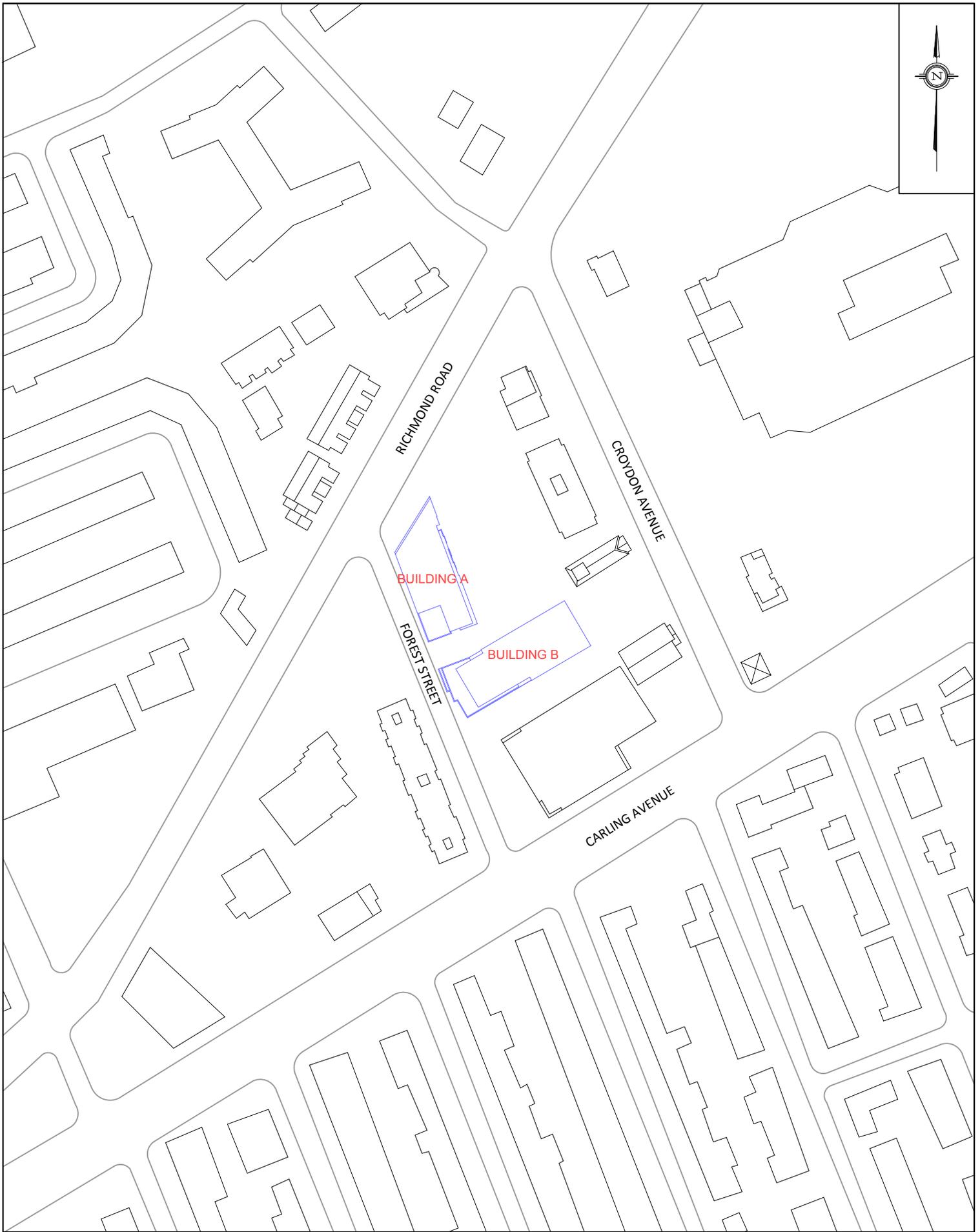
Sacha Ruzzante, MASc  
Junior Wind Scientist

Gradient Wind File #19-084



Justin Ferraro, P.Eng.  
Principal





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PROJECT 1420 RICHMOND ROAD & 365 FOREST STREET, OTTAWA  
PEDESTRIAN LEVEL WIND STUDY

SCALE 1:2500 (APPROX.)

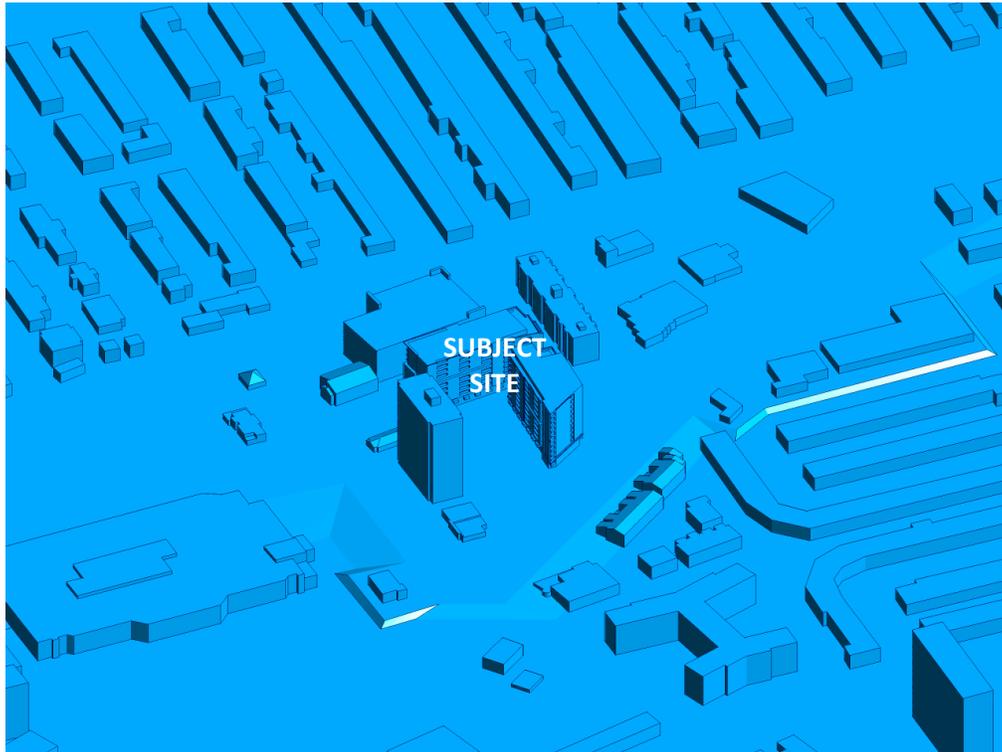
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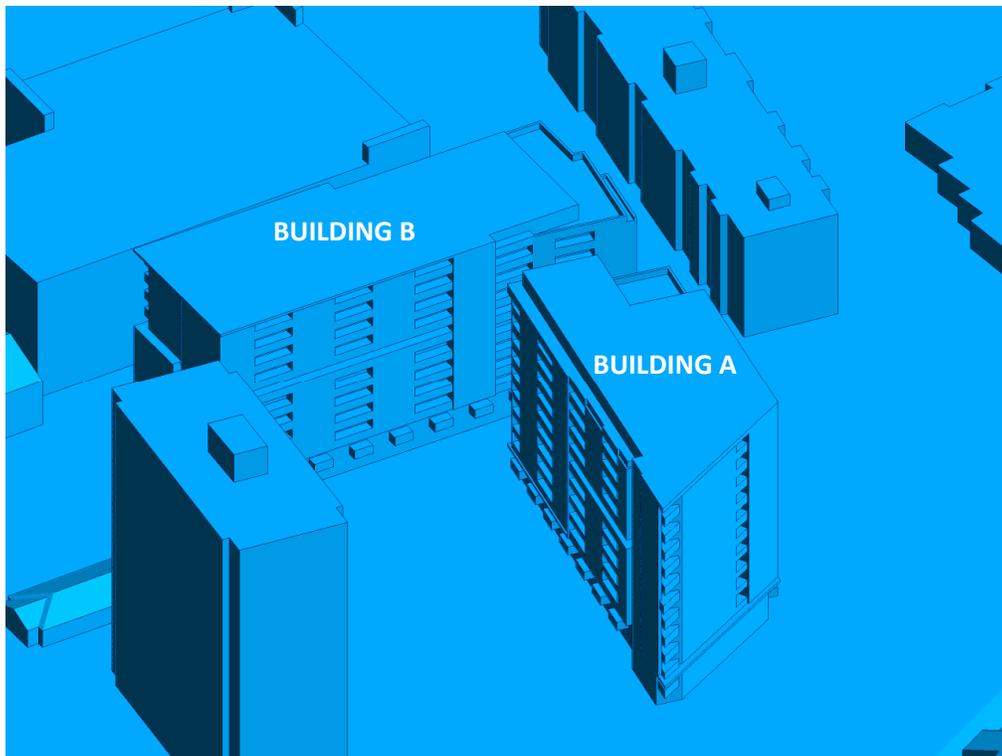
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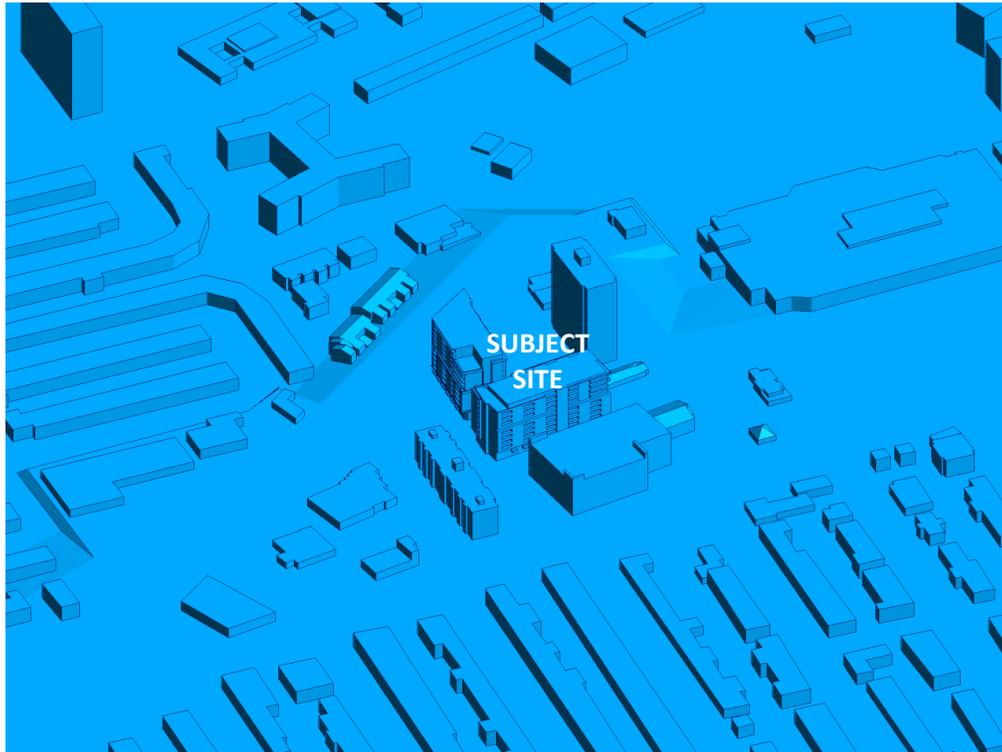
FIGURE 1:  
SITE PLAN AND SURROUNDING CONTEXT



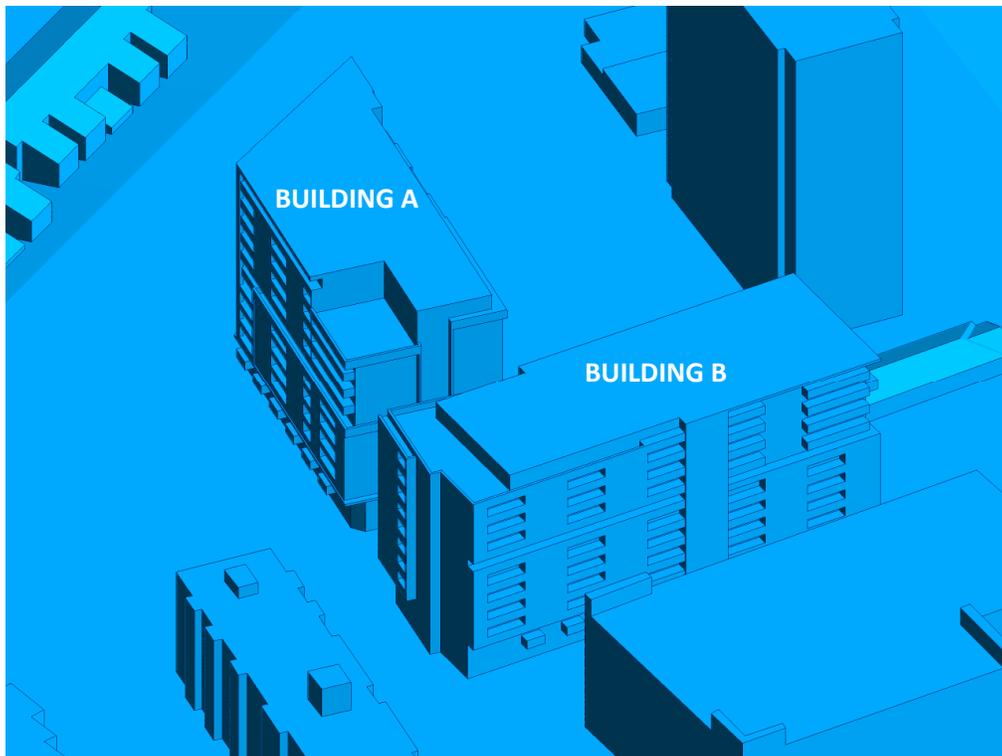
**FIGURE 2A: COMPUTATIONAL MODEL, NORTH PERSPECTIVE**



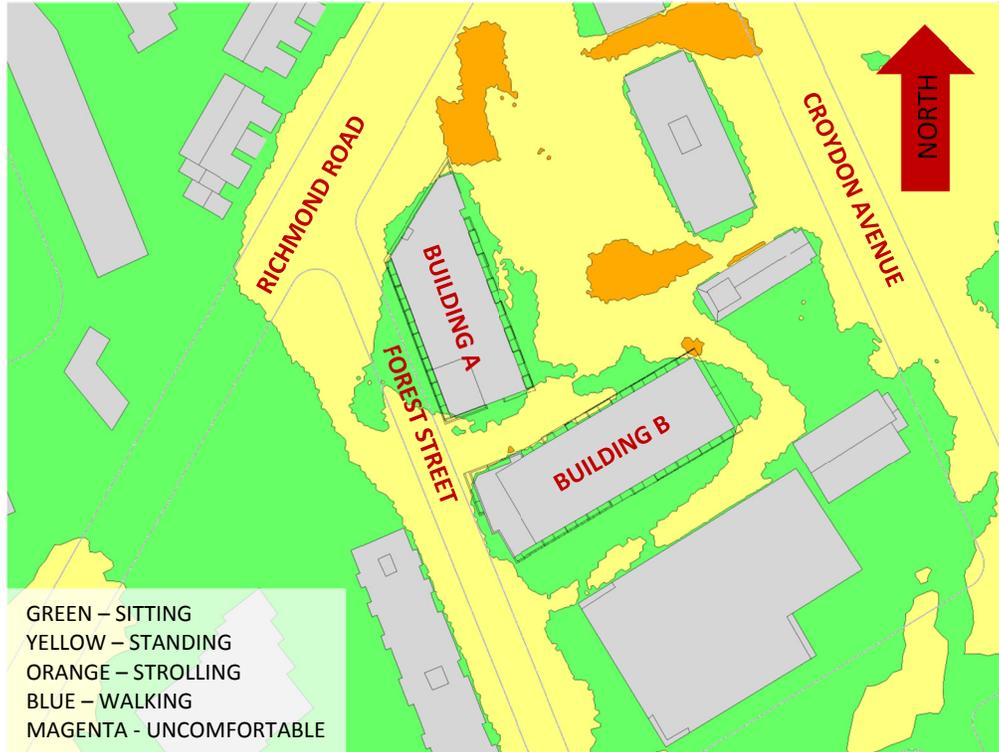
**FIGURE 2B: CLOSE UP OF FIGURE 2A**



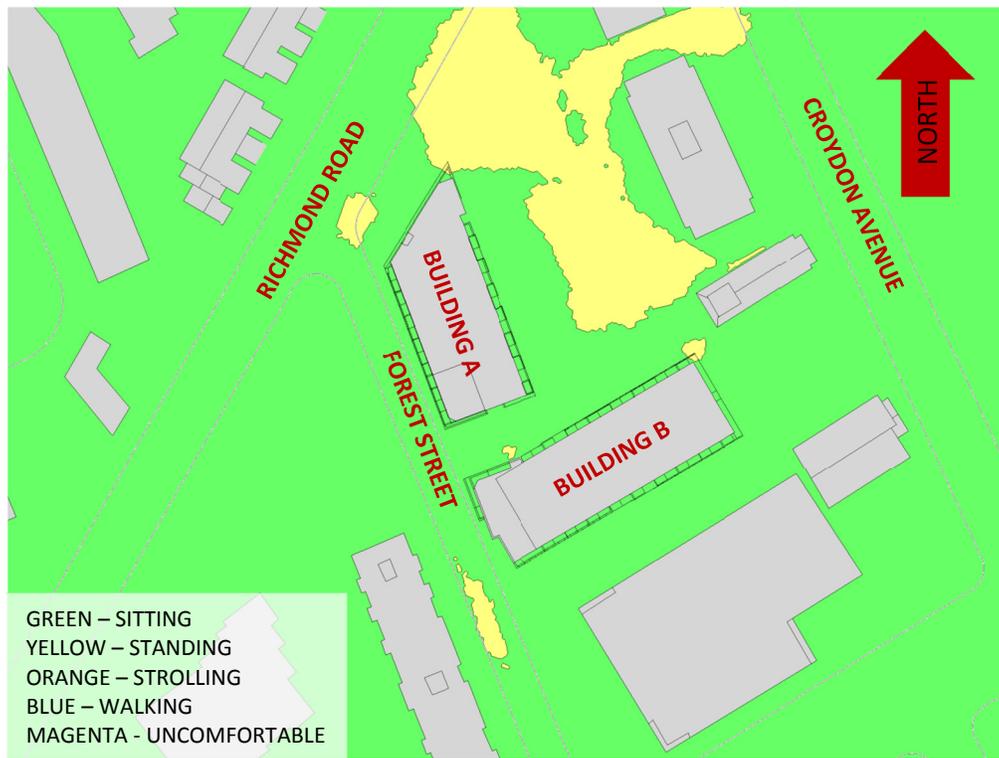
**FIGURE 2C: COMPUTATIONAL MODEL, SOUTHWEST PERSPECTIVE**



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



**FIGURE 3A: SPRING – WIND CONDITIONS AT GRADE LEVEL**



**FIGURE 3B: SUMMER – WIND CONDITIONS AT GRADE LEVEL**



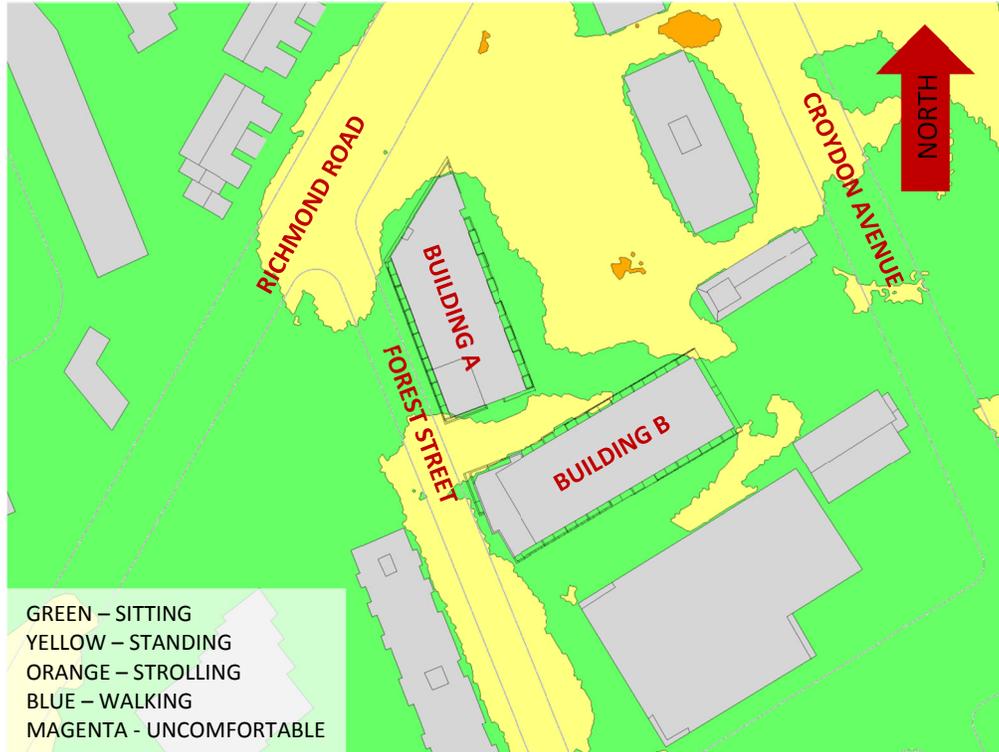


FIGURE 3C: AUTUMN – WIND CONDITIONS AT GRADE LEVEL

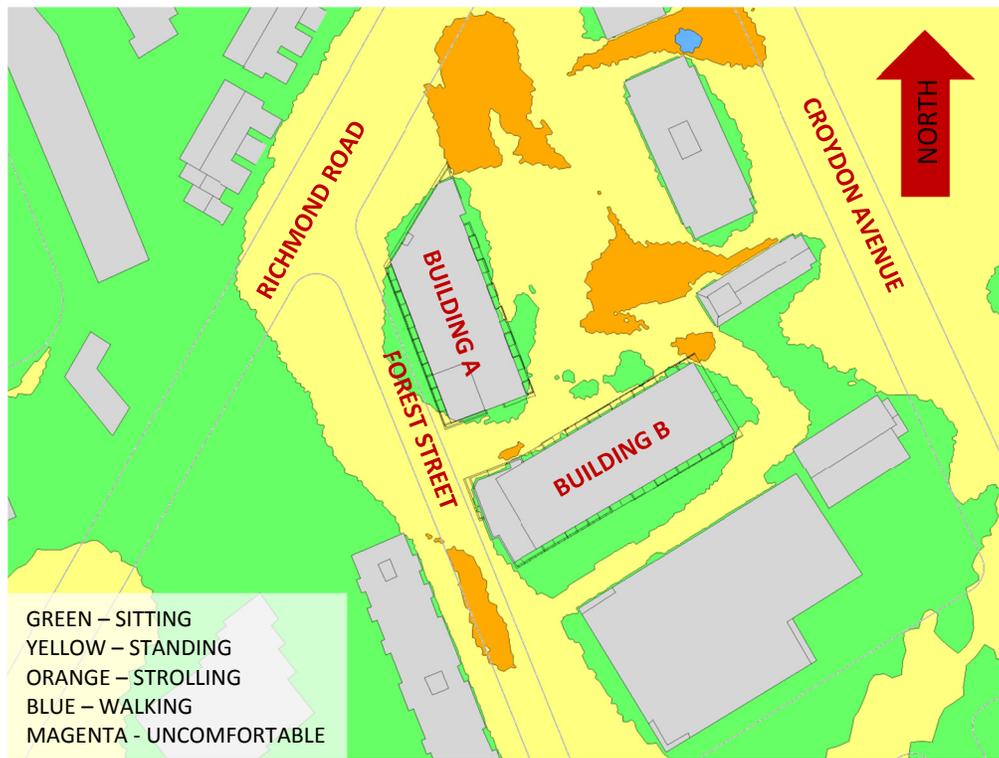


FIGURE 3D: WINTER – WIND CONDITIONS AT GRADE LEVEL





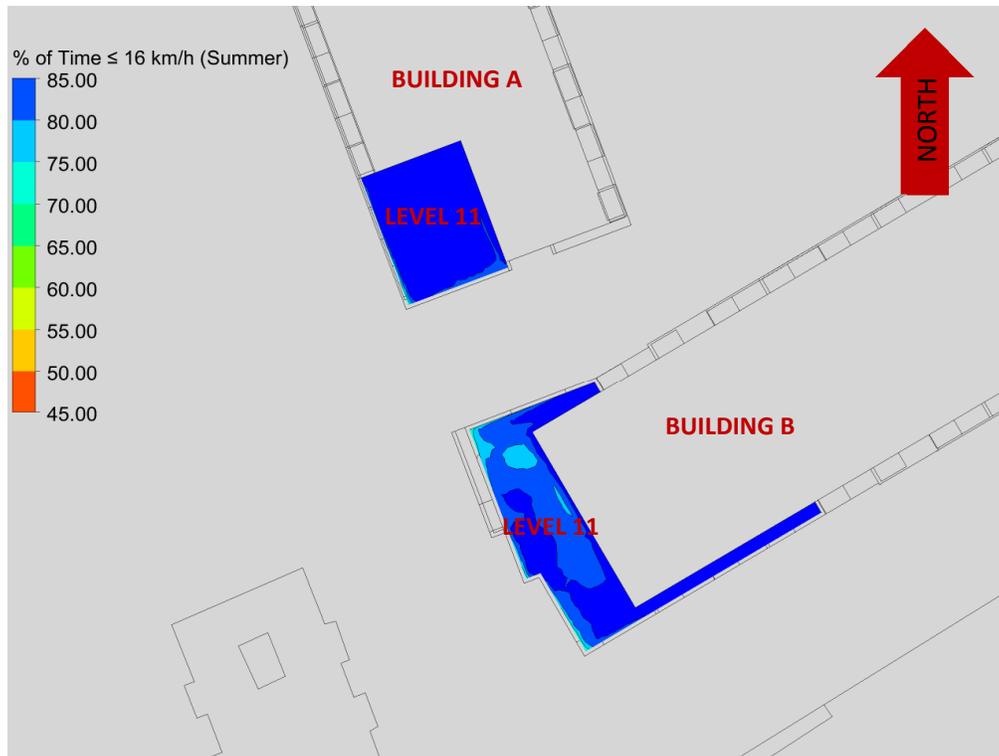
**FIGURE 4A: SPRING – WIND CONDITIONS WITHIN COMMON AMENITY TERRACES**



**FIGURE 4B: SPRING – PERCENTAGE OF TIME SUITABLE FOR SITTING WITHIN TERRACES**



**FIGURE 5A: SUMMER – WIND CONDITIONS WITHIN COMMON AMENITY TERRACES**



**FIGURE 5B: SUMMER – PERCENTAGE OF TIME SUITABLE FOR SITTING WITHIN TERRACES**



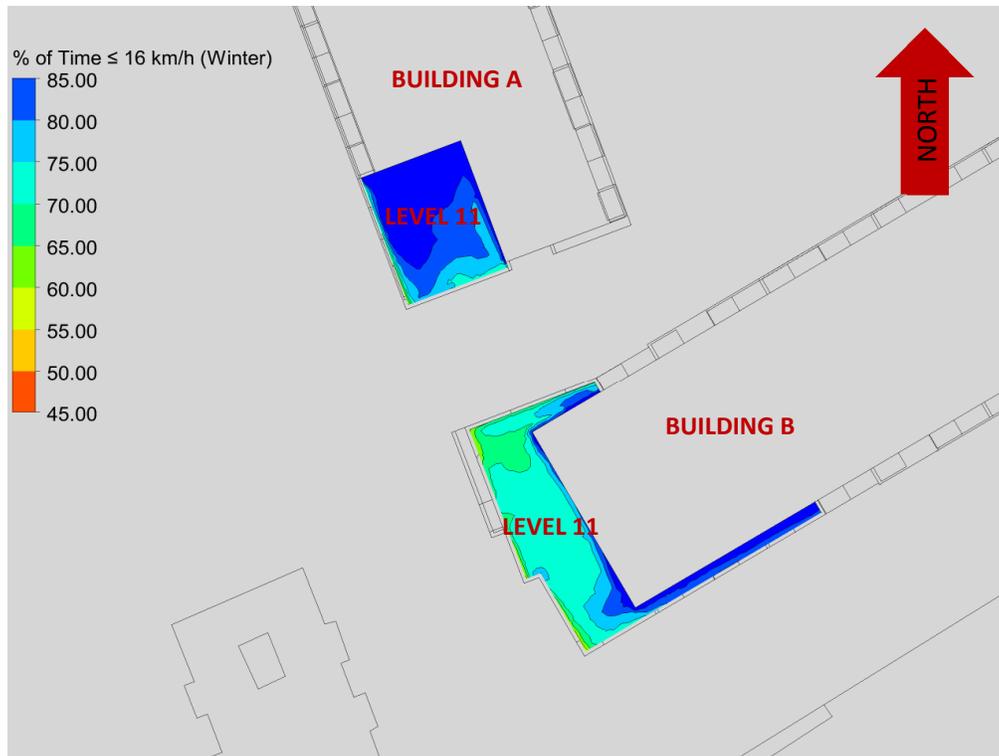
**FIGURE 6A: AUTUMN – WIND CONDITIONS WITHIN COMMON AMENITY TERRACES**



**FIGURE 6B: AUTUMN – PERCENTAGE OF TIME SUITABLE FOR SITTING WITHIN TERRACES**



**FIGURE 7A: WINTER – WIND CONDITIONS WITHIN COMMON AMENITY TERRACES**



**FIGURE 7B: WINTER – PERCENTAGE OF TIME SUITABLE FOR SITTING WITHIN 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 (i.e., 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 (° True) | Alpha ( $\alpha$ ) Value |
|-------------------------|--------------------------|
| 0                       | 0.20                     |
| 49                      | 0.25                     |
| 74                      | 0.24                     |
| 103                     | 0.23                     |
| 167                     | 0.24                     |
| 197                     | 0.25                     |
| 217                     | 0.24                     |
| 237                     | 0.22                     |
| 262                     | 0.20                     |
| 282                     | 0.19                     |
| 302                     | 0.20                     |
| 324                     | 0.22                     |

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

| Upstream Exposure Type | $\alpha$  |
|------------------------|-----------|
| 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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- [1] P. Arya, "Chapter 10: Near-neutral Boundary Layers," in *Introduction to Micrometeorology*, San Diego, California, Academic Press, 2001.
- [2] S. A. Hsu, E. A. Meindl and D. B. Gilhousen, "Determining the Power-Law Wind Profile Exponent under Near-neutral Stability Conditions at Sea," vol. 33, no. 6, 1994.
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