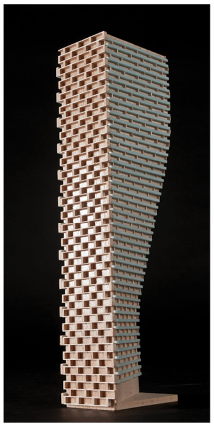
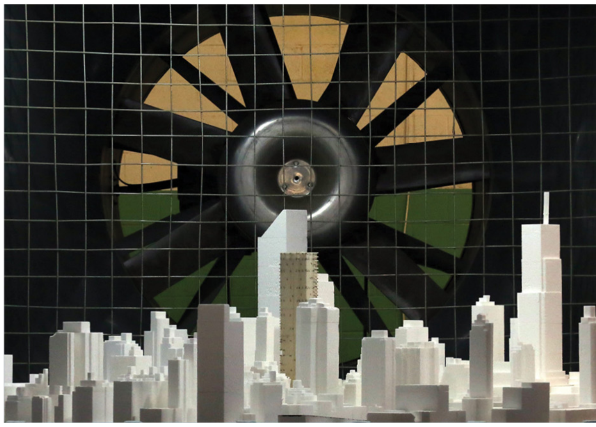
PEDESTRIAN LEVEL WIND STUDY

114 Richmond Road
Ottawa, Ontario

Report: 19-005-PLW





October 9, 2020

PREPARED FOR
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EXECUTIVE SUMMARY

This report describes a pedestrian level wind (PLW) study to satisfy the requirements of a Zoning By-Law Amendment (ZBA) application for Phases 2-A and 2-B of the proposed mixed-use, multi-building development located at 114 Richmond Road 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-4D, and summarized as follows:

1) To ensure conditions over the west edge of the courtyard to the south of Building B are suitable for sitting during the typical use period of late spring through early autumn, it is recommended that a 1.6 m tall wind barrier be installed along the west perimeter of the courtyard.

2) All other grade-level areas within and surrounding the subject site will be acceptable for the intended pedestrian uses throughout the year. Specifically, wind conditions over surrounding sidewalks, walkways, courtyards, and building access points, are considered acceptable for the intended pedestrian uses throughout the year.

3) To ensure conditions over the rooftop amenity terrace for Building B are suitable for sitting during the typical use period of late spring through early autumn, it is recommended that tall wind barriers (e.g. glazed guards and dense coniferous plantings) be installed along the perimeter and around local areas of the terrace where mitigation is required for sitting.

4) 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 or within the common amenity terrace 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 Ashcroft Homes to undertake a pedestrian level wind (PLW) study to satisfy the requirements of a Zoning By-Law Amendment (ZBA) application for Phases 2-A and 2-B of the proposed mixed-use, multi-building development located at 114 Richmond Road 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 prepared by M. David Blakely Architect Inc., in September 2020, 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 on a parcel of land bounded by Richmond Road to the north, Leighton Terrace to the east, Byron Avenue to the south, and Hilson Avenue to the west. The north edge of the subject site includes the existing 9-storey mixed-use building, referred to as Building A. Phase 2-A of the proposed mixed-use development comprises a 9-storey building, referred to as Building B, connected to the existing 3-storey Soeurs de la Visitation convent building, hereinafter referred to as Building E. Phase 2-B, which lies to the south of Phase 2-A, comprises a 4-storey residential building on the east, referred to as Building C, and a 9-storey residential building on the west, referred to as Building D.

Regarding Phase 2-A, above two levels of underground parking, the ground floor has a roughly 'C'-shaped planform, with the open side facing the east, which surrounds a historic courtyard space, and a new courtyard space. The ground floor provides restaurant space along the north elevation, residential space at the south and west elevations, and amenity space between the residential and restaurant spaces. The northeast and northwest corners of Level 2 provide additional restaurant space, while the rest of Level 2 provides residential space. Above Level 2, the building steps back on the north elevation, creating an 'L'-

shaped planform. As the building rises, the planform steps back on the north and east elevations, creating private terraces at Levels 5, 7, and 9. Levels 3 through 9 contain residential space. Building B is topped with a rooftop amenity terrace.

Regarding Phase 2-B, the grade level of Building C includes a lobby at the north elevation, amenity space along the west elevation, and residential units along the east elevation. The building rises with a rectangular planform to Level 4. Levels 2 through 4 contain residential space. The grade level of Building D includes a lobby at the southwest corner and amenity and building support spaces throughout the remainder of the floor. The building rises with a nearly rectangular planform which steps back on the east elevation at Level 5.

The near-field surroundings (defined as an area within 200 metres (m) of the subject site) include mostly low-rise suburban developments in all directions, as well as several mid-rise buildings along Richmond Road. Notably, there is a 6-storey development at 101 Richmond Road to the direct north of the subject site, a 7-storey development at 360 Patricia Avenue to the northwest of the subject site, and Hilson Avenue Public School to the direct west 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 a mix of mostly low- and mid-rise buildings, as well as some green space, from the northeast clockwise to the west-southwest, by a mix of low- and mid-rise buildings and the open exposure of Ottawa River from the west-southwest clockwise to the north, and by a mix of low- and mid-rise buildings, the Tunney's Pasture campus, and the open exposure of Ottawa River from the north clockwise to the northeast. The Central Experimental Farm lies approximately 1.7 km to the east-southeast of the subject site, and the Ottawa River flows southwest to northeast approximately 1.6 km to the northwest of the subject site.

Key areas under consideration include surrounding sidewalks, walkways, bus stops, and building access points. 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[1]. 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.

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[1] City of Ottawa Terms of References: Wind Analysis
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 site for 12 wind directions. The CFD simulation model was centered on the study building, complete with surrounding massing within a diameter of approximately 820 m.

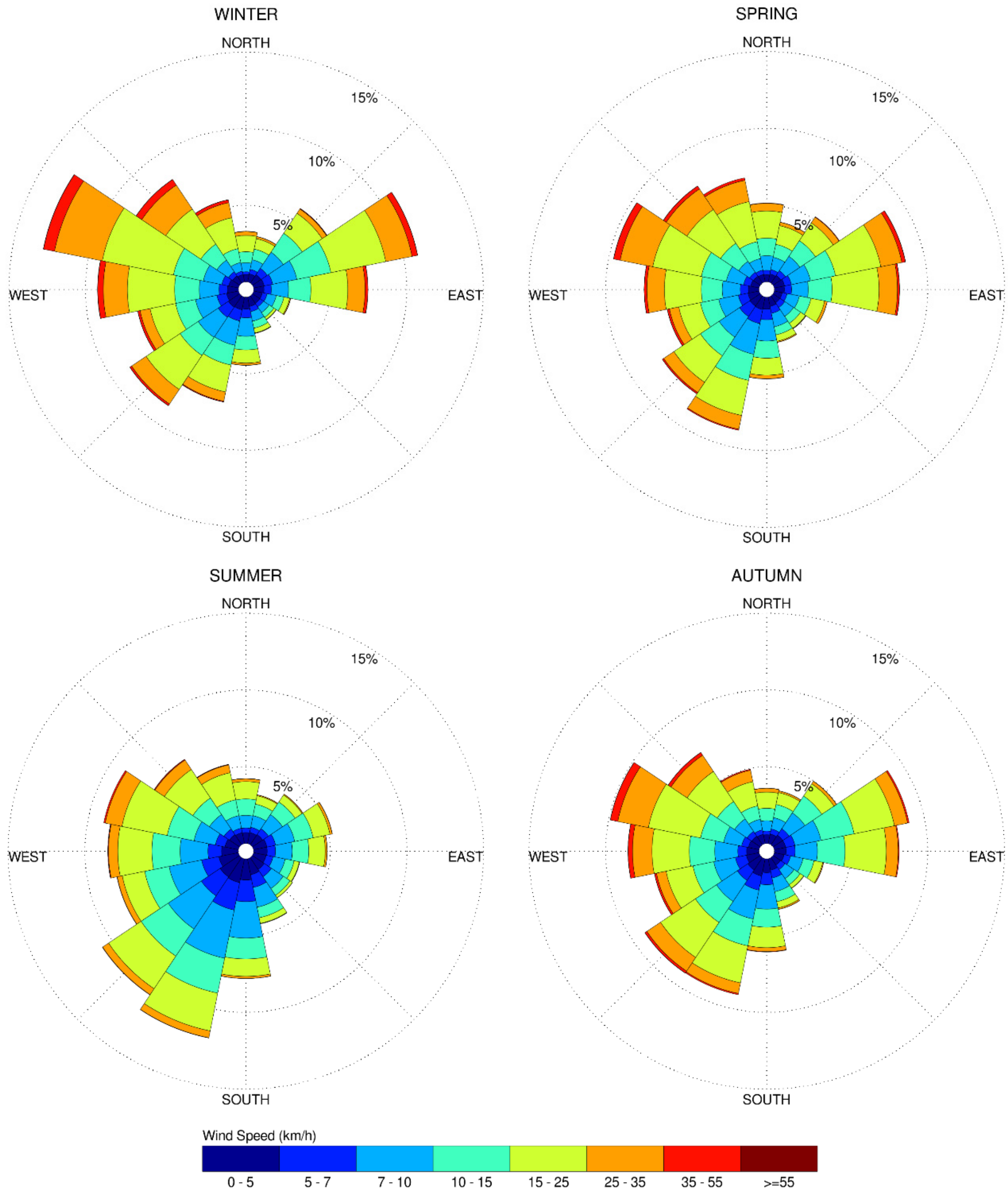
Mean and peak wind speed data obtained over the study site for each wind direction were interpolated to 36 wind directions at 10° intervals, representing the full compass azimuth. Measured wind speeds approximately 1.5 m above local grade and the amenity terrace were referenced to the wind speed at gradient 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 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 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 criteria 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 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 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
		Mean	Gust (Peak)	
2	Light Breeze	6-11	9-17	Wind felt on faces
3	Gentle Breeze	12-19	18-29	Leaves and small twigs in constant motion; wind extends light flags
4	Moderate Breeze	20-28	30-42	Wind raises dust and loose paper; Small branches are moved
5	Fresh Breeze	29-38	43-57	Small trees in leaf begin to sway
6	Strong Breeze	39-49	58-74	Large branches in motion; Whistling heard in electrical wires; umbrellas used with difficulty
7	Moderate Gale	50-61	75-92	Whole trees in motion; inconvenient walking against wind
8	Gale	62-74	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 (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 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 (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-4D illustrating the seasonal wind conditions within the common amenity terrace.

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, and walking by blue. Pedestrian comfort is summarized below for each area of interest.

5.1 Wind Comfort Conditions

Laneway and Building Entrances along North Elevation of Building E: Conditions over the laneway along the north elevation of Building E are predicted to be suitable for sitting during the summer, becoming suitable for a mix of sitting and standing throughout the remainder of the year. Owing to the protection of the façade, conditions at building entrances are generally calmer than the adjacent sidewalk. Conditions in the vicinity of building entrances along the north elevation of Building E are predicted to be suitable for sitting throughout the year. The noted conditions are considered acceptable.

Laneway, Walkway, and Building Entrances along East Elevation of Subject Site: Conditions over the laneway along the east elevation of the subject site are predicted to be suitable for sitting during the summer and autumn, becoming suitable for a mix of sitting and standing during the spring and winter. Owing to the protection of the façade, conditions at building entrances are generally calmer than the adjacent sidewalk. Conditions in the vicinity of building entrances along the east elevation are predicted to be suitable for sitting throughout the year. The noted conditions are considered acceptable.

Historic and New Courtyards Between Buildings B and E: Conditions over the historic and new courtyards between Buildings B and E are predicted to be suitable for sitting throughout the year. The noted conditions are considered acceptable.

Walkway and Building Entrances Between Buildings C and D: Conditions over the walkway and building entrances between Buildings C and D are predicted to be suitable for sitting throughout the year. The noted conditions are considered acceptable for the intended use and for any programming that require sitting conditions.

Walkway, Courtyard, and Building Entrances along South Elevation of Building B: Conditions over the walkway and courtyard along the south elevation of Building B are predicted to be suitable for mostly sitting during the summer, with a small region on the west edge of the courtyard being suitable for standing. During the spring, winter, and autumn, conditions are predicted to be mostly suitable for a mix of sitting and standing, with a small region at the west of the courtyard being suitable for strolling.

To ensure conditions over the west edge of the courtyard are suitable for sitting during the typical use period of late spring through early autumn, it is recommended that a 1.6 m tall wind barrier be installed along the west perimeter of the courtyard. Owing to the protection of the façade, conditions at building entrances are generally calmer than the adjacent sidewalk. Conditions in the vicinity of building entrances are predicted to be suitable for sitting throughout the year, which is acceptable.

Sidewalk and Building Entrances along South Elevation of Subject Site: Conditions over the sidewalk along the south elevation of the subject site are predicted to be suitable for sitting during the summer, becoming mostly suitable for a mix of sitting and standing throughout the remainder of the year. During the winter, a small region at the southwest corner of the subject site will be suitable for strolling. Owing to the protection of the façade, conditions at building entrances are generally calmer than the adjacent sidewalk. Conditions in the vicinity of building entrances are predicted to be suitable for sitting throughout the year. The noted conditions are considered acceptable.

Laneway and Building Entrances along West Elevation of Subject Site: Conditions over the laneway along the west elevation of the subject site are predicted to be suitable for sitting during the summer, becoming suitable for a mix of sitting and standing throughout the remainder of the year. Owing to the protection of the façade, conditions at building entrances are generally calmer than the adjacent sidewalk. Conditions in the vicinity of building entrances along the west elevation of Buildings B and E are predicted to be suitable for sitting throughout the year. Conditions in the vicinity of building entrances along the west elevation of Building D are predicted to be suitable for sitting during the spring, summer, and autumn, becoming suitable for a mix of sitting and standing during the winter. The noted conditions are considered acceptable.

5.2 Wind Comfort Conditions – Elevated Amenity Terrace

Rooftop Amenity Terrace – Building B: The elevated amenity terrace serving Building B is predicted to be suitable for sitting during the summer, becoming suitable for a mix of sitting and standing during the autumn, and mostly suitable for standing during the spring. While conditions will be acceptable for most of the typical use period of late spring through early autumn, it is recommended that tall wind barriers (e.g. glazed guards and dense coniferous plantings) be installed along the perimeter of the terrace and around local areas where sitting conditions are required to ensure conditions remain suitable during the shoulder months.

5.3 Applicability of Results

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 speeds and localized increases in the gustiness of the wind.

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 comfort and safety conditions is provided in Section 5 and illustrated in Figures 3A-4D. 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) To ensure conditions over the west edge of the courtyard to the south of Building B are suitable for sitting during the typical use period of late spring through early autumn, it is recommended that a 1.6 m tall wind barrier be installed along the west perimeter of the courtyard.

2) All other grade-level areas within and surrounding the subject site will be acceptable for the intended pedestrian uses throughout the year. Specifically, wind conditions over surrounding sidewalks, walkways, courtyards, and building access points, are considered acceptable for the intended pedestrian uses throughout the year.

3) To ensure conditions over the rooftop amenity terrace for Building B are suitable for sitting during the typical use period of late spring through early autumn, it is recommended that tall wind

barriers (e.g. glazed guards and dense coniferous plantings) be installed along the perimeter and around local areas of the terrace where mitigation is required for sitting.

4) 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 or within the common amenity terrace 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.

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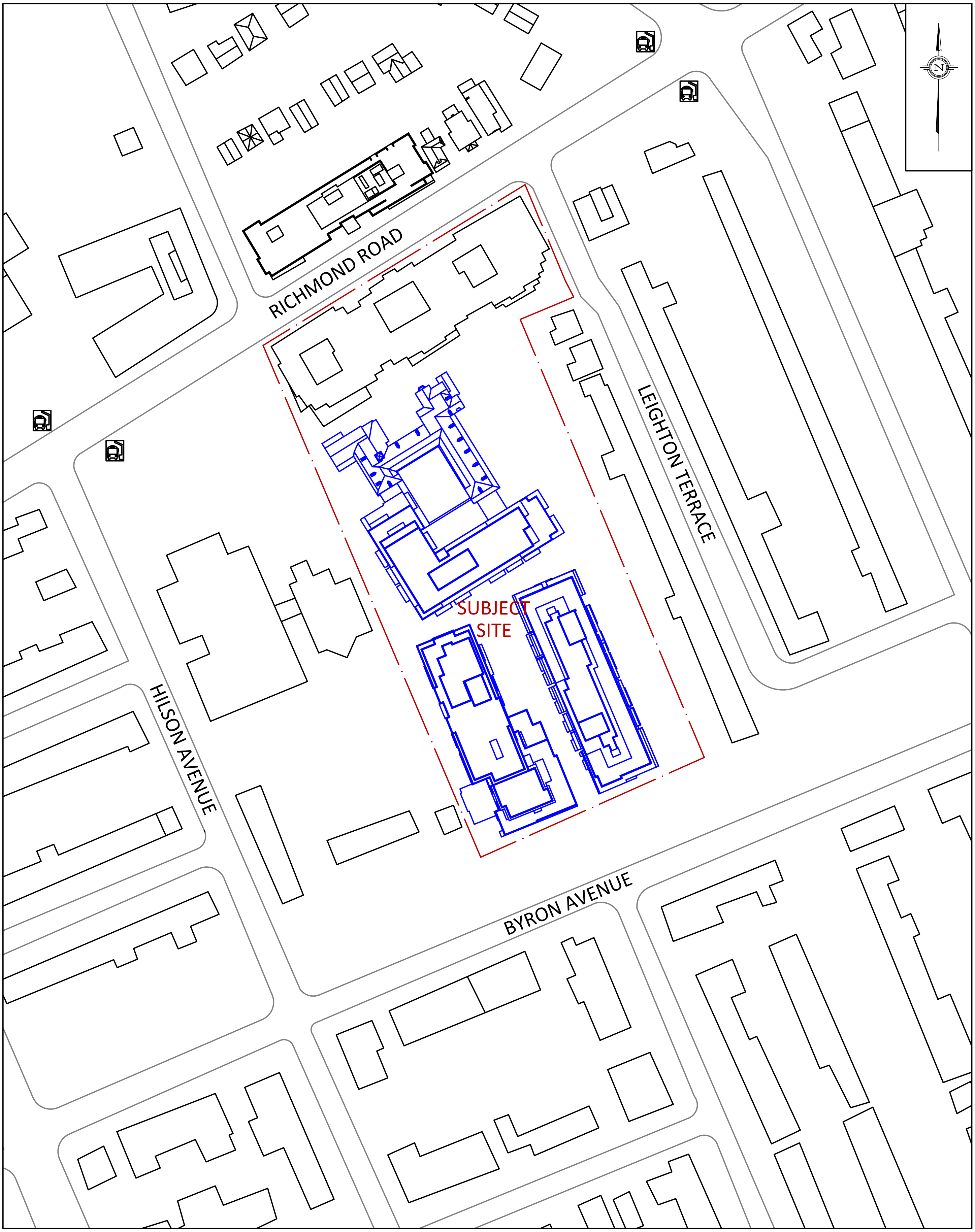

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PROJECT	114 RICHMOND ROAD, OTTAWA PEDESTRIAN LEVEL WIND ASSESSMENT		
SCALE	1:2000	DRAWING NO.	19-005-PLW-1
DATE	OCTOBER 8, 2020	DRAWN BY	N.M.P.

DESCRIPTION

FIGURE 1:
SITE PLAN AND SURROUNDING CONTEXT

FIGURE 2A: COMPUTATIONAL MODEL, NORTHEAST PERSPECTIVE

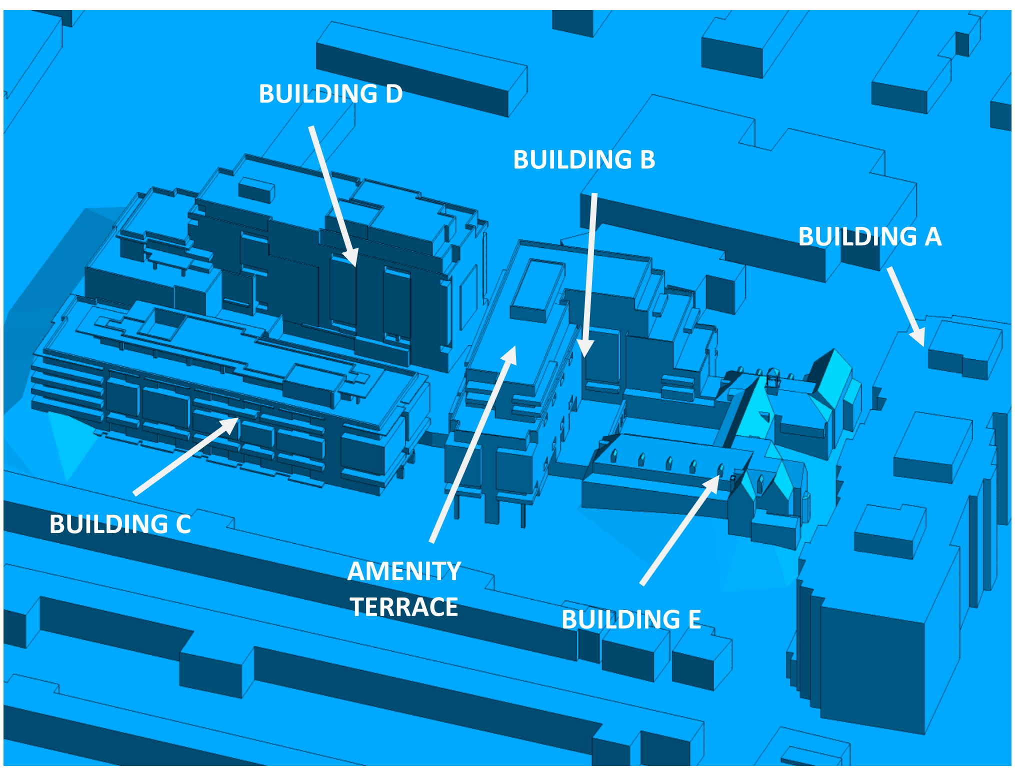


FIGURE 2B: CLOSE UP OF FIGURE 2A

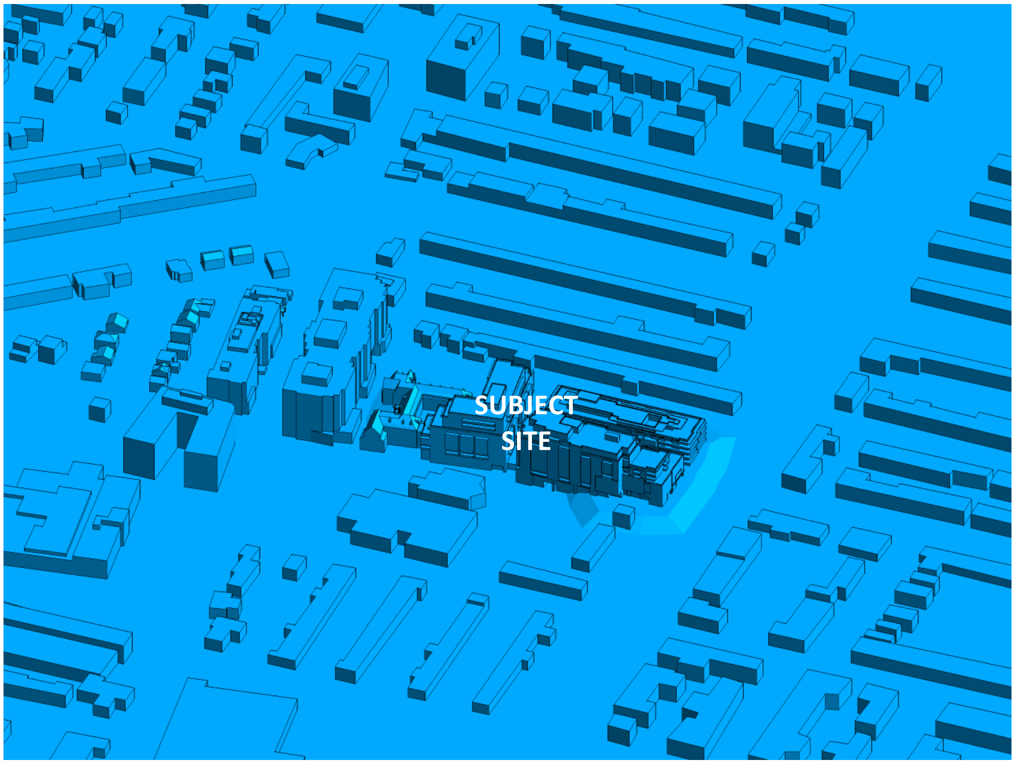


FIGURE 2C: COMPUTATIONAL MODEL, SOUTHWEST PERSPECTIVE

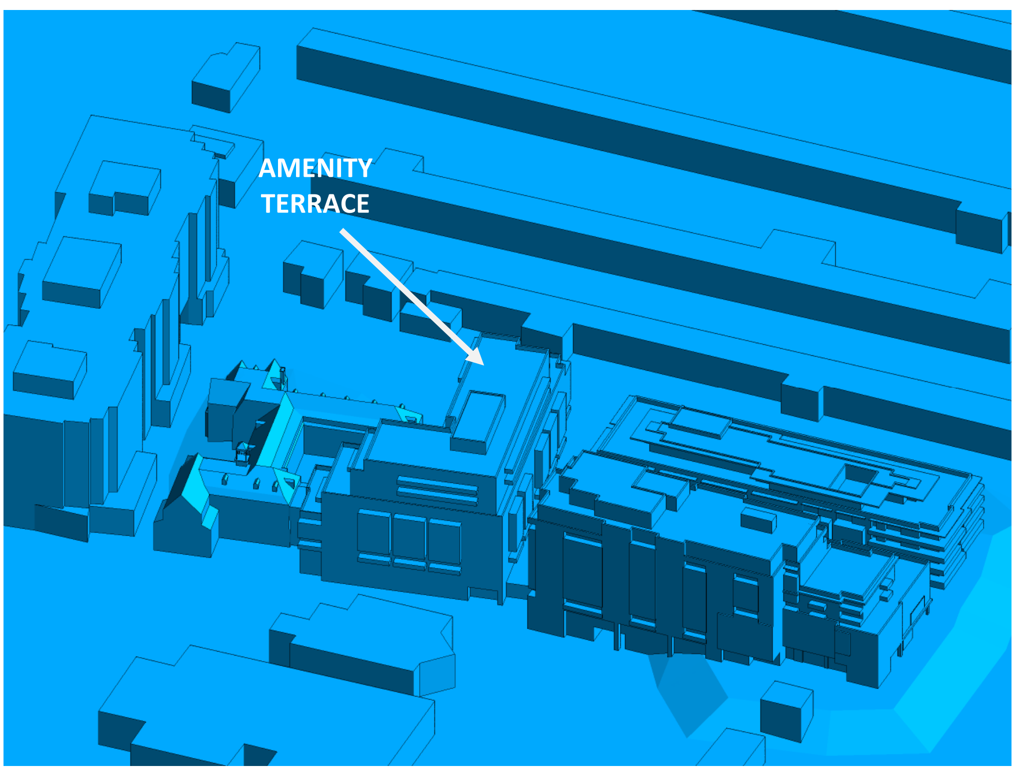


FIGURE 2D: CLOSE UP OF FIGURE 2C

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

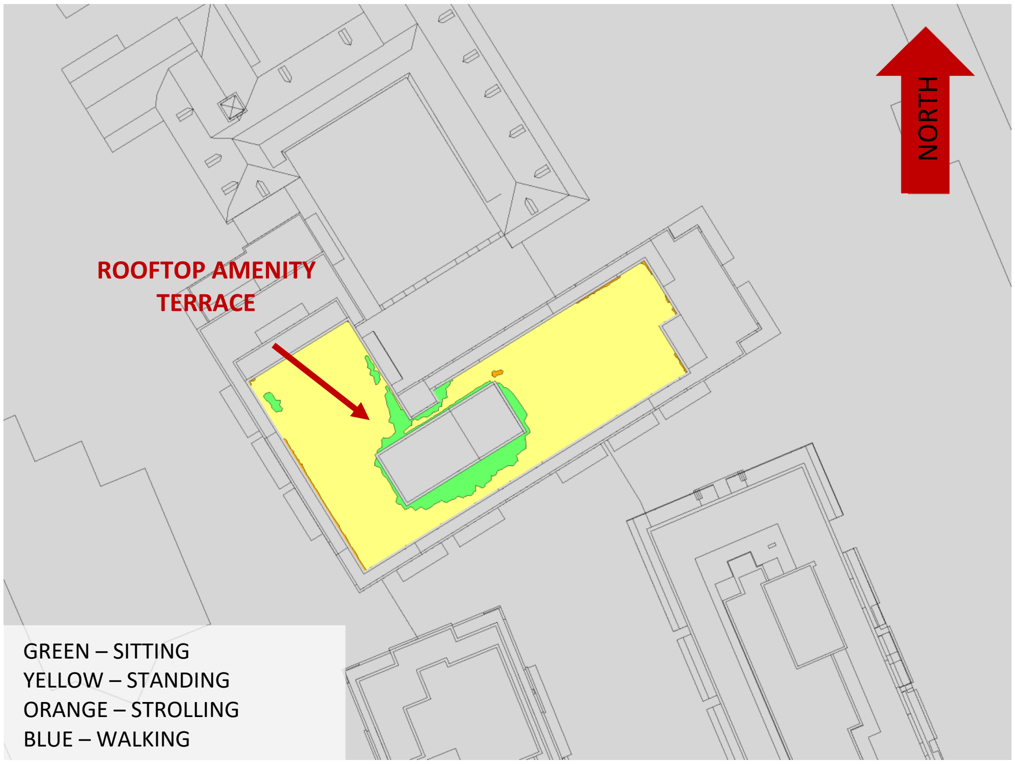


FIGURE 4A: SPRING – WIND CONDITIONS, COMMON AMENITY TERRACES

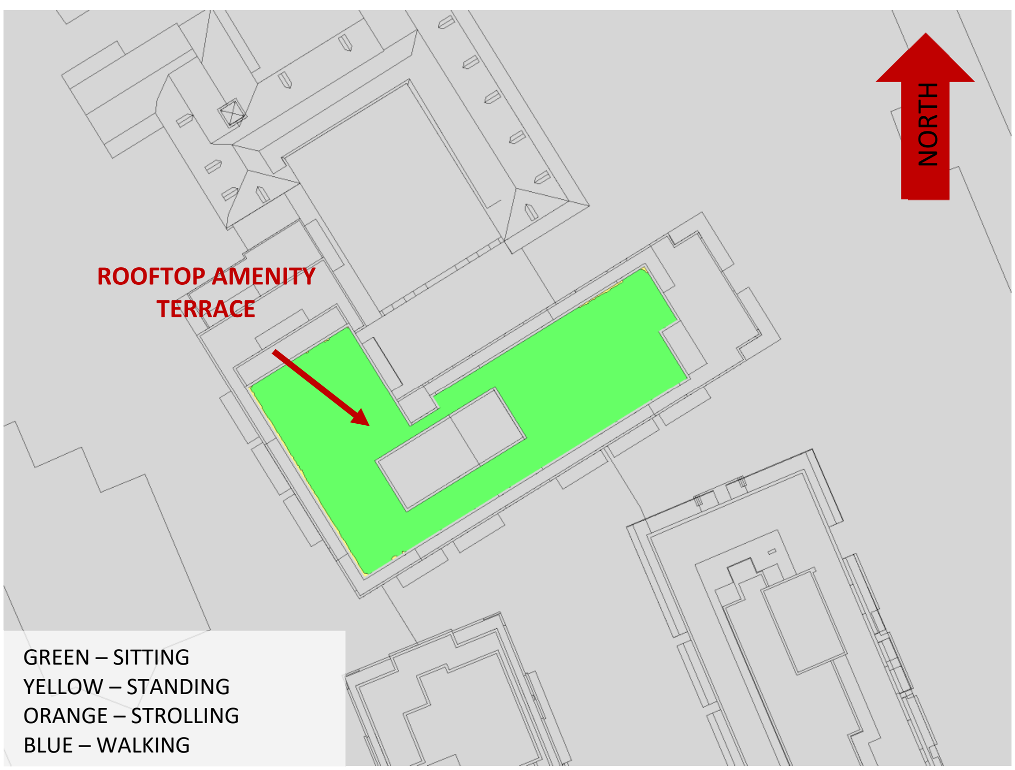


FIGURE 4B: SUMMER – WIND CONDITIONS, COMMON AMENITY TERRACES

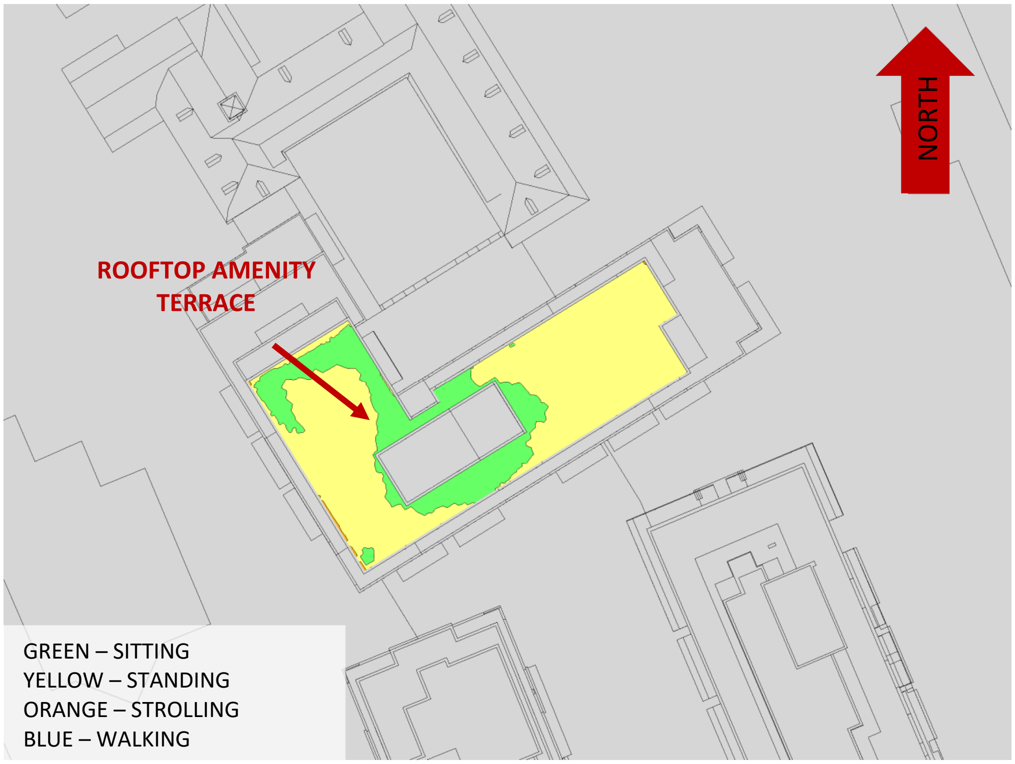


FIGURE 4C: AUTUMN – WIND CONDITIONS, COMMON AMENITY TERRACES

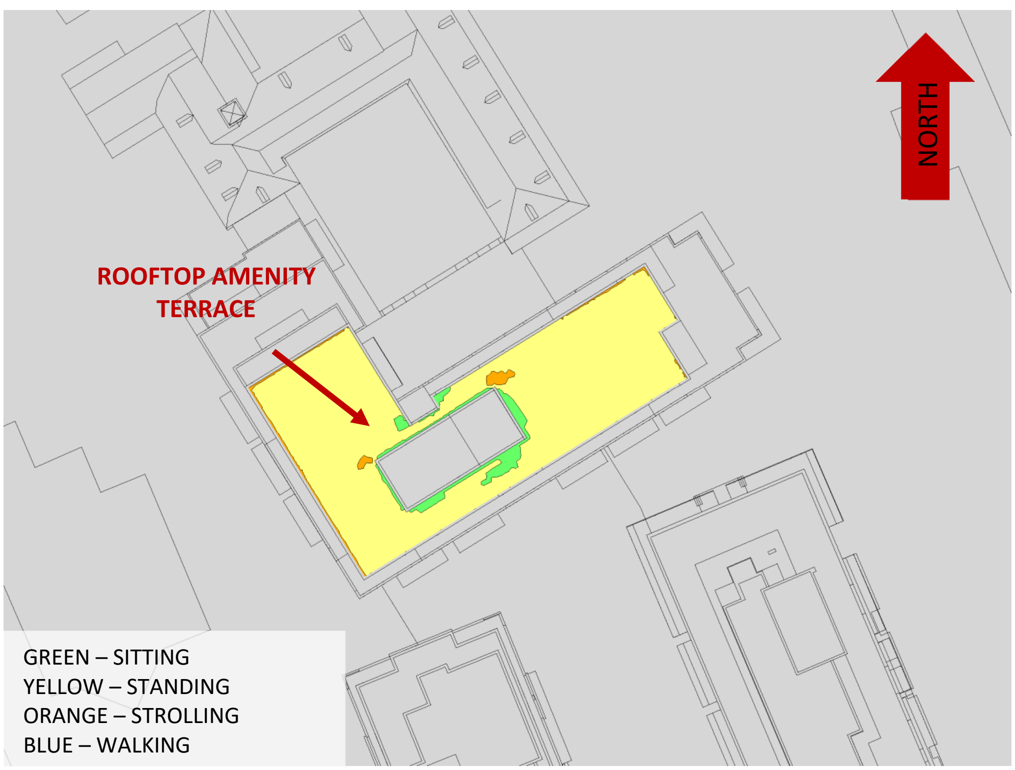
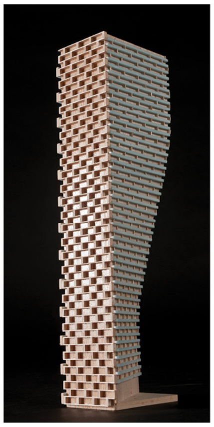
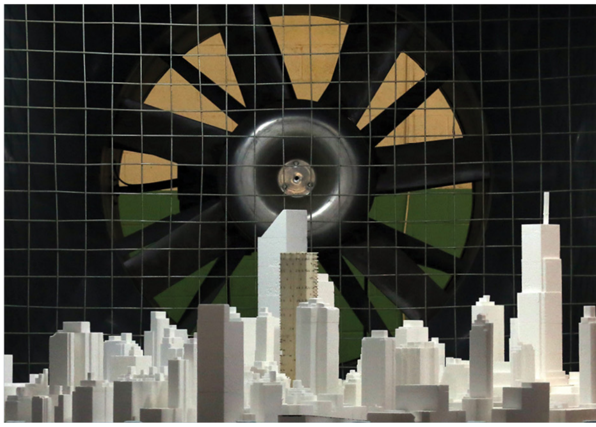


FIGURE 4D: WINTER – WIND CONDITIONS, COMMON AMENITY TERRACES





APPENDIX A

SIMULATION OF THE ATMOSPHERIC BOUNDARY LAYER

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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].

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

where, $\boldsymbol{U}$ = mean wind speed, $\boldsymbol{U_g}$ = gradient wind speed, $\boldsymbol{Z}$ = height above ground, $\boldsymbol{Z_g}$ = depth of the boundary layer (gradient height), and α 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.

α 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 α used in this study, while Table 2 presents several reference values of α. When the upstream exposure of the far-field surroundings is a mixture of multiple types of terrain, the α 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 (α) Value
0	0.23
49	0.25
74	0.25
103	0.23
167	0.24
197	0.24
217	0.24
237	0.24
262	0.21
282	0.22
302	0.22
324	0.22

TABLE 2: DEFINITION OF UPSTREAM EXPOSURE (ALPHA VALUE)

Upstream Exposure Type	α
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].

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

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

where, $\boldsymbol{I}$ = turbulence intensity, $\boldsymbol{L_t}$ = turbulence length scale, $\boldsymbol{Z}$ = height above ground, and α 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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